Placing Outer Space: An Earthly Ethnography of Other Worlds

by

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Submitted to the Program in Science, Technology, and Society
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ABSTRACT

This dissertation concerns the role of place in scientific practice. Ideas of place, I argue, shape and are shaped by science. I specifically look at the community of planetary scientists who, though they cannot step foot on the objects they study, transform planets into places. This is an ethnographic work that draws on 18 months of fieldwork during which time I encountered several different communities of planetary scientists. At MIT, I worked alongside astronomers looking for planets around other stars. These "exoplanet" astronomers transformed numerical counts of photons into complex worlds with atmospheres and weather. Data visualizations characterized the work of a community learning to see unseen planets in specific, place-based ways. I also traveled with an astronomer to a Chilean observatory where she studied the night sky hoping to find a "habitable planet." Many other astronomers share this goal and have designed various ways to detect a planet like Earth. The importance of these projects signifies that exoplanet astronomers are more interested in finding planetary kin – planets that are familiar places – than exotic aliens. To determine how the planetary places created by exoplanet astronomers differ from those in our own Solar System, I spent time at the NASA Ames Research Center with a group of computer scientists who create high resolution and three-dimensional maps of Mars. These maps reflect the kind of place Mars is today: it is available to everyone to explore, it is displayed such that you can imagine standing on the surface, and it is presented as geologically dynamic in ways similar to Earth. Even though these maps help give Mars a sense of place, Martian science is still stymied by the inability to send humans to its surface. Instead, planetary scientists travel to terrestrial sites deemed to be "Mars-like" to approximate performing geologic fieldwork on Mars. I went to one of these locations to see how, during these outings, Mars and Earth become entwined as scientists forge connections between two planetary places. These diverse scientific activities, I conclude, are transforming our view of the cosmos. Outer space is becoming outer place.

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INTRODUCTION
From Outer Space to Outer Place

> 'Space' is one of those most obvious of things which is mobilized as a term in a thousand different contexts, but whose potential meanings are all too rarely explicated or addressed.
> -Delivered by Doreen Massey during her 1998 Hettner-Lecture at the University of Heidelberg, hosted by the Department of Geography (Massey 1999, 27).

Because this dissertation is an ethnographic work, I was inclined to begin with a scene of entering the field – with a moment not unlike the opening of Malinowski's *Argonauts of the Western Pacific,* inviting the reader into an unfamiliar world. My field sites, however, were not, at first blush, exotic. I navigated through offices and computer laboratories, tracking the work of scientist informants. Only when I focused on the planetary objects of their study did something truly out-of-the-ordinary emerge. My planetary scientist interlocutors, it dawned on me, were conjuring exotic arrival scenes all the time. Imagine yourself - they might say - set down in a scalding hot ocean. You try to find land, but for as far as you can see, the surface is liquid. A dark fog hovers over you, mixing the steam from the ocean with other gases. Even if you could get out of the water, there would be no relief from the relentless dampness of the place.

This is a description of what it might be like on the surface of a planet in another solar system, on an *exoplanet.* Planets orbiting the Sun or other stars are the focus of my informants' research. These planets, along with the scientists who study them, are the focus of this dissertation. Planets beyond Earth comprise a field site that neither scientists nor myself could physically enter.

This thesis is about how people understand places they have never been. More exactly, it is about how scientists *make* the objects they cannot physically encounter into *places.* It is about how they evoke a sense of "being there" when actually *being* in the places they imagine is an impossibility. By focusing on the daily practice of scientists at MIT, NASA, an observatory in Chile, and a field station in Utah, I track how researchers imbue planets with a sense of place. In offering an account of how these scientists establish planets as places in contemporary planetary science, I show how place is more than a given category; it is also a tool of knowing, a way of making sense.

The scientists I worked with frequently discussed planets as *worlds*. While "planet" is a technical term, referring to an object of a specific size orbiting a stellar companion, "world" evokes a more humanistic aspect of these objects. In the *Oxford English Dictionary*, fifteen of the twenty definitions for "world" explicitly refer to human beings and notions of habitation. Those that refer to the astronomical dimension of world, define it as a system similar to but distinct from Earth. World is used by astronomers as a way to relate to the object they are studying; it is a linguistic step towards understanding it as a place, and, more over, as a potentially Earth-like place. Whereas "planet" is anodyne, "world" is emotive.

Before getting to the worlds at stake in this dissertation, I consider a world much closer and familiar to most readers: the Moon. The Moon is the only extraterrestrial surface on which humans have landed. Those studying the Moon first examined it with the naked eye, then with a telescope, and then with satellite imagery. Scientists have been able to run tests on rocks and soil brought back by Apollo astronauts. Recently, NASA, as well as the European and Japanese space agencies, has developed a new battery of experiments to test the composition of the Moon and to decipher its history. Such shifts in how people study and think about the Moon prompted Andrew Chaikin, a science writer, to title his keynote at NASA's Lunar Science Forum in July 2010 "Luna

2.0." He began his talk, which I attended, by claiming, "You have to be paying attention to the Moon to understand that we have a new Moon." He proceeded to describe the different worlds the Moon has been over the past half century. When Apollo astronauts landed on the Moon, they encountered "a world devoid of water." It was only in the past decade that new missions to the Moon have indicated something different; that a satellite crashing into the lunar surface suggested a significant concentration of water ice. In declaring that we now live in the era of Luna 2.0, Chaikin meant this: "The Moon we thought we knew from Apollo was changing… Now we are talking about a Moon that is a completely different world."

The notion that the Moon today is a different world than it used to be suggests that places, even those we do not inhabit, are dynamic. I tracked the making, re-making, and un-making of planets as places throughout my fieldwork. Scientists make planets into places to better understand what *being there* might be like. To understand what it is like to be on the Moon, scientists, scholars and artists have developed techniques of seeing, notions of embodiment, and practices of imagining. These methods structure place-making not only for the Moon, but also for other planets. Let me briefly consider how each are at work on the Moon before turning to planetary science, the scientific field that is at the center of this dissertation.

How one sees the Moon is an historical product. The Moon is the only object in the night sky with a discernable surface. It was not, however, always accepted as a solid surface or as a landscaped place. The Platonic Moon, for example, was a smooth orb of a divine quality (Montgomery 1999, 20). Even so, the Moon does not appear pristine to the naked eye. It is speckled, and the reason for this discoloration prompted much philosophical debate over the centuries. During the middle ages, just as many people believed the spots were evidence of mountains and valleys as believed these marks were a sign of the pervasiveness of original sin across the heavens. Even when Galileo pointed his telescope at the Moon, his interpretation of the Moon's "spottedness" as mountains and craters was not a forgone conclusion, but a reflection of his painterly training in Renaissance perspective (Edgerton 1984).

In the centuries following Galileo's observations, astronomers and philosophers visually asserted the Earth-like nature of the Moon and debated the depth of this analogy. Were there oceans? Was there an atmosphere? Were there inhabitants? What kind of world was the Moon? What arguments could be made with images? Could images generate, as opposed to simply reflect, knowledge? How accurately could drawings and maps, aided by ever more precise telescopes, depict the lunar surface? Before sending humans to the Moon, geologists had to apply terrestrial mapmaking methods to an extraterrestrial surface in order to select safe landing sites. Each new way of seeing the Moon argued for understanding it as a distinct type of place. Ways of seeing implicate a vision of what it would be like to stand on the surface of the Moon.

The Moon is unique in that imaging the distant body gave way to a few people standing on its surface. Chaikin narrated for the Lunar Science Forum audience how this transformed the Moon into a new world. The Apollo missions, which "so audaciously reached out and touched" the Moon, revealed "a world that was in some ways Earth-like but in most ways profoundly different." The embodied experience of being on the Moon and the rock samples this afforded brought about a new era of knowing the Moon.

But just as seeing the Moon was a subjective process, so too is embodied experience. For the Apollo program, sending an astronaut to the Moon was a conquering of the empty, outer, other frontier of space. But this is not the only way to conceptualize an embodied experience of the cosmos. M. Jane Young (1987) describes the Native American understanding of space and the Moon in order to critique the frontier mentality. For Zuni and other Native American tribes, space is not "outer," but rather "inner." Space is cyclical and organic. Instead of the view of the universe as comprised of inanimate objects in mathematical motion, Native American cosmologies teach of intimate relations between people, stars, and the Moon. Kinship abounds throughout the universe. This is a way of knowing, Young demonstrates, that facilitates travel to the Moon by means other than a rocket ship. She tells of one anthropologist who, when working with the Inuit in Alaska, recorded the following response to being told about astronauts walking on the Moon: "We didn't know this was the first time you white people had been to the Moon. Our shamans have been going for years. They go all the time" (quoted in Young 1987, 272). The Inuit criterion for going to the Moon was different from NASA's. Their practice of embodiment offers an intimacy with the Moon that reinforces the connection, not separation, between Earth and the Moon. To experience either the Inuit or Western way of being present on the lunar surface solidifies the Moon as a place, or even a destination. The space beyond Earth is re-imagined as one filled with places suitable for embodied experience. Just as shamans have a different way of understanding what it means to go to a place, planetary scientists similarly recast notions of embodiment. Despite the physical remove, scientists engage in place-based ways of understanding planets.

The placehood of the Moon is crafted not only as a destination, but also as a medium upon which to project the anxieties and longings of our own planet. In imagining alternative histories and connection between Earth and the Moon, we can think about the status of Earth as a planet and a place. Italian writer Italo Calvino offered a cosmology about the Earth and the Moon that highlights the ever-present ties between the two. In "The Distance of the Moon," Calvino described a time when the Moon was much closer to the Earth. The narrator, accustomed to jumping back and forth between the two spheres, was startled to find himself stranded on the Moon as it quickly began drifting away from the Earth. During this unexpected exile, he realized how much he defined who he was with respect to his relationship to Earth:

> I thought only of the Earth. It was the Earth that caused each of us to be that someone he was rather than someone else… I was eager to return to the Earth, and I trembled at the fear of having lost it… [T]orn from its earthly soil, my love now knew only the heart-rending nostalgia for what it lacked: a where, a surrounding, a before, an after (Calvino 1965, 14).

From the surface of the Moon, the narrator was overcome with grief for the world he was tragically severed from. It was also from this vantage point that he could see how the Earth was a planet and the Moon merely a satellite. The Moon could not compare with the kind of place Earth was.

By positioning oneself on an extraterrestrial surface, the Earth becomes recognizable as a planet. In this respect, the Moon provided a novel location from which to consider Earth. As Chaikin pointed out at the Lunar Science Forum, the Moon is the only surface from which one can look up and see "Earth as a planet." How scientists imagine other planets is deeply entwined with understandings of Earth and its status as a world, as a planet, and as a place.

This dissertation is not about the Moon, but about planets in our Solar System and exoplanets orbiting other stars. Planetary scientists study planets in a variety of ways and through participant-observation I tracked how scientists navigated ideas of seeing, embodying, and imagining other planets in their daily practice. I spent time with astronomers at MIT and at an observatory in Chile. At NASA Ames Research Center in California, I worked with computer scientists as they mapped Mars. Finally, I went on a field trip with geologists from NASA to the Mars Desert Research Station in the Utah desert. At each site, I consider how a different mode of place-making – visualizing, inhabiting, mapping, and narrating – saturated scientific work and produced planets as places. The rest of this introduction will reflect on the emergence of planetary science in the mid-20th century and its subsequent growth, the distinctiveness of "planet" as an object of inquiry, and the discourses concerning "place" in geography, anthropology, and science and technology studies upon which this dissertation builds. I will conclude by discussing my field sites and chapter arguments in more detail.

"The new interdisciplinary science of the solar system"

When I attended NASA's Lunar Science Forum, I was taken aback by how most of the papers drew from 40 year old data; data from the Apollo missions. When I asked a planetary scientist about this, he provided a quick gloss of lunar science. Post-Apollo, interest died down except for a few scientists who remained loyal to the Moon. When President George W. Bush proposed his vision for space exploration in 2004, which involved a return mission to the Moon, NASA was flush with new money to fund lunar science. In the mid-2000s, NASA established the Lunar Science Institute, and the Lunar Forum that I attended was only the third lunar conference of recent times. Not only did we now have "Luna 2.0," but NASA had also rebooted the science. With the launch of several recent robotic missions to the Moon, lunar scientists are only now starting to build the community and data resources necessary to reinvigorate this field. However, President Obama's reworking of the Bush vision for space exploration again places lunar science funding in jeopardy.

NASA has more reliably supported planetary – rather than lunar – science in the post-Apollo years. Even as the last decade and a half has been plagued by constant reorganization within NASA, budget requests[1] reflect a consistently strong Mars program, complemented by smaller missions throughout the Solar System. In more recent years, "Planetary Science" replaced "Solar System Exploration" as the theme encompassing Mars and other planetary missions within the Solar System, as well as lunar, comet, and asteroid science.

The discipline of planetary science itself is a product of the space age. In 1962, Elsevier began publishing a new journal, *Icarus*, to document "the new interdisciplinary science of the solar system – which is emerging to claim its own identity at the cross-roads of the allied disciplines of astronomy, geology, geophysics, meteorology, geochemistry, plasma physics, and biology" (Kopal and Wilson 1962, i). The field continued to cohere, and by the end of the decade, members of the American

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[1] NASA congressional budget requests from fiscal year 1997 are available at http://www.nasa.gov/audience/formedia/features/MP_Budget_Previous.html

Astronomical Society organized a sub-group within the AAS to be called the Division for Planetary Science.

The first decade of *Icarus* contained more articles about the Moon than Mars, as astronauts and cosmonauts raced to be the first on the surface. However, from the mid-1970s to the early-2000s (from the end of Apollo to Bush's re-prioritization to return to the Moon), there were very few articles about lunar science. Mars, however, saturated the journal thanks to the successful Mariner and Viking missions of the 1970s. Even in the lull between Viking and the Mars Pathfinder mission (launched in 1996) there were enough data and interest in Mars to keep the planet frequently discussed within *Icarus*. In 2009, after more than a decade of successful robotic missions, there were a record 91 articles about Mars. Meanwhile, as scientists refocused on the Moon, a handful of lunar science articles appeared each year and grew steadily.

When the field of planetary science was established, scientists assumed that this field would be devoted to the Solar System. Though there had always been talk and speculation about planets orbiting other stars, there was no robust way to detect these objects. In the 1970s, a half dozen articles in the pages of *Icarus* addressed the feasibility of detecting exoplanets (or "extrasolar planets" as they were initially called) and how Earthlike planets might be detected. It was not until the 1990s that astronomers began detecting exoplanets. Scientists found the first few around violent stars called pulsars that bathed their companion planet in x-rays. In 1995, Swiss astronomers announced the discovery of a planet around a star very similar to the Sun. After decades of wondering if exoplanets could be detected, the affirmative answer begged the questions 'how many are there' and 'what are they like.' As of 2011, astronomers have detected over 500 exoplanets in our corner of the galaxy.

As the abundance of exoplanets grew, so did their presence in *Icarus*. Though nowhere near as prevalent as Martian science, there have been consistently more than a half dozen articles about exoplanets per year throughout the 2000s. In astrophysics journals, however, articles about exoplanets steadily increased since the 1995 discovery, averaging more than 30 articles a year from 2005 to 2007, more than 50 in 2008 and 2009, and almost doubling to 90 articles in 2010.[2] These increases in exoplanet, Martian, and even lunar publications, reflect a growth in the field of planetary science.

Scientists who study planets, both in our Solar System and orbiting other stars, call themselves astronomers, astrophysicists, planetary geologists, planetary scientists, astrobiologists, and even computer scientists. This community is heterogeneous, based in different kinds of university departments, using different tools and methodologies, and even asking different questions of planets. It is this loosely assembled group that I navigated through between June 2009 and August 2010 in order to understand how and why these scientists thought about planets. My ethnography focuses on how Earth-based practices illuminate other worlds. Though not everyone I encountered would call his or herself a "planetary scientist," I use this term more broadly than perhaps customary to account for the diverse actors studying planets. It also reflects the purpose of this study, which is to highlight scientific ways of knowing planets.

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[2] This search was conducted across *The Astrophysical Journal*, *The Astrophysical Journal Letters*, and *The Astronomical Journal*. The number of articles reported is based on a search for "exoplanet" and "extrasolar planet" in both the title and abstract.

What is a planet?

I initially explored this question while puzzling through the circumstances of Pluto's 2006 reclassification from "planet" to "dwarf planet" (Messeri 2010). After an astronomer discovered an object thought to be larger than Pluto orbiting further from the Sun, the International Astronomical Union (IAU) moved to create an explicit taxonomy for objects in the Solar System. In making explicit what is and is not a planet, the committee in charge of writing the definition necessarily prioritized some scientific interests over others. Astronomers additionally complicated the process of crafting a definition when voicing concern for the public sentiment and the distress some school children might experience if their favorite planet was suddenly no more (semantically speaking). "Planet" operated as both a scientific and a cultural object.

As defined by the IAU, a planet is a round object orbiting the Sun that is large enough to have either captured nearby debris as satellites or expelled the debris to other orbits. Pluto failed to dominate its orbit and thus was not a planet. This reclassification had little effect on scientific practice. Scientists studying Pluto refer to themselves as planetary scientists (not dwarf planetary scientists). Though exoplanets are not planets by the IAU definition, as they do not orbit the Sun, they are still referred to and understood as planets. Whether studying Pluto, Mars, Jupiter, or exoplanets, scientists use "planet" without hesitation to describe the objects they work with.

Lorraine Daston, in *Biographies of Scientific Objects* (2000), outlines the realist and constructionist approach to thinking about scientific objects. The realist situates an object as discoverable, as something always existing but not always known. The constructionist, in contrast, depicts objects as inventions; as things molded from a historical and local context. Daston offers a middle road, that scientific objects are both real and historical. Pluto, for example, was discovered (to use the realist terms) in 1930 though it surely existed before Clyde Tombaugh's announcement. As a realist object, it has orbited the same path for millennia, but Pluto was only constructed as a planet until 2006. Whereas one initially studied Pluto to understand more about the icy outer planets, one now looks to Pluto as an example of its neighboring dwarf planets. Scientists adjusted Pluto's ontological status and in response its epistemological utility shifted.

The reason for Pluto's changed positioning is the result of scientists' reinterpretation of "planet." Planet is the scientific object I will interrogate throughout this dissertation. I am not offering a Dastonian biography of a scientific object, but rather a series of encounters with different contemporary practices organized around entities that scientists think of as "planets." "Planet" challenges what it means to be a scientific object in several ways. Daston opposes scientific objects to quotidian, every day objects. Quotidian objects "are the solid, obvious, sharply outlined, in-the-way things... They are all too stable, all too real in the commonsensical meaning of 'hard to make go away'... In contrast to quotidian objects, scientific objects are elusive and hard-won" (2). Planets, however, are both quotidian and scientific. Earth is part of our daily experience, implicated as a planet thanks to photographs from the Apollo mission.

And yet exoplanets (as opposed to Earth) are more similar to the "elusive and hard-won" scientific object. They are real only in so far as their visualizations are believable. Hans-Jörg Rheinberger prefers the term "epistemic things" when considering scientific objects. "Epistemic things" lead the scientist down a path of questioning, as they "embody what one does not yet know" (1997, 28). "Planet" acts like a heuristic in that knowledge of well-studied planets guides the scientist's understanding of newly detected planets. To label these detections "planets" immediately offers an initial way to study them. The concept of planet also guides research when scientists apply quotidian information about Earth (what a stream looks like) to make sense of an inscrutable scientific object (e.g., a satellite image of a Martian feature). "Planets" hold power as scientific objects or epistemic things precisely because they are at the same time quotidian and scientific.

The final, and most important, way in which "planets" are unique amongst scientific objects comes from the experience of *being on* Earth. To inhabit Earth is to be in a place, to move between places, to create and destroy places. Planets, I argue, are more than objects. They are imagined as *places* amenable to habitation (either by humans or other beings). This dissertation examines how scientific practice transforms planets from *objects* into *places* and how this is an essential way of knowing and doing planetary science.

The problems and promises of place

Place and Geography

When I use the term "place," I mean to index both the colloquial understanding of this word as well as the theoretical concept described in scholarship that struggles with the relationship between "space" and "place." As Henri Lefebvre (1974) famously suggested, space is not a singular, stagnant concept but it is perceived, conceived, and lived. Space is not neutral but it is produced and reproduced by human action. Space, Lefebvre argued, is social. Other French scholars contemporaneous with Lefebvre, such as Michel de Certeau (1980) and Gilles Delueze and Félix Guattari (1980), wrote about different sorts of space. De Certeau focused on how the act of moving through a space transforms it, while Delueze and Guattari proposed "striated" versus "smooth" space to stand for the difference between hierarchical, rational space and qualitative, multiple, non-reproducible space.

David Harvey (1989) and Stephen Kern (2003) advocate that space is also historical. They identify forces – economic, technological, aesthetic – that contribute to a spatial imaginary specific to any given time. Harvey looks to architecture as standing for modern and postmodern spatialities. Modern buildings or modern city plans reflect a social purpose, an assumed way that one moves through the space. Postmodern spaces, on the other hand, have little regard for the occupant. They are designed as symbols of aesthetics alone. Whereas modern architecture is utilitarian, postmodern architecture holds "timeless and 'disinterested' beauty as an objective in itself" (Harvey 1989, 66). This would suggest that our understanding of the spatiality of the cosmos is also multiple and historically changing. To offer an interpretation of the contemporary spatiality, I will introduce the term "place" and consider this term with respect to planets.

When we think about everyday spatiality, we do so in terms of *places*. We consider our favorite places, places we have not traveled to, and the places we are from. Yet this familiar conception of place is absent in the works above. They discuss space (or *espace* in the French). De Certeau mentions place (*lieu*), but only to set up space as practiced place. Scholarship in critical geography builds on these theories, but introduces place and establishes a dialectic between space and place. In the standard formulation, space is universal, empty, and a priori while places are meaning-filled, sub-sections of space. As with other modernist dichotomies, a variety of postmodern scholars, feminist geographers, and phenomenologists have critiqued the submission of place to space, seeking to understand place on its own terms.

Philosopher Edward Casey (1996) wishes to show how place was once and can again be understood not as local and particular, but universal. He begins his essay, "How to Get from Space to Place in a Fairly Short Stretch of Time" with a critique of two contemporary ethnographic works to illustrate how anthropology falls prey to assuming a pre-existing, objective geography upon which culture makes places. The anthropologists are not to blame. Instead, Casey traces this thinking back to Newton, Descartes, and Kant. It was Kant who articulated the Enlightenment stance that knowledge is first produced about the general and only after that can the local be understood. Without the general, the local is fragmentary and "not a science" (16). The general came to be tied with space, leaving the local to the poor providence of place.

To correct for the long misunderstood nature of place, Casey brings the discussion of spatiality out of the mind and into the realm of experience. With this shift, Casey begins to draw connections between place and perception, ultimately concluding, "There is no knowing or sensing a place except by being in that place, and to be in that place is to be in a position to perceive it" (18). Meaning, the fundamental act of being is an act of being in place. He goes further, "we are not only *in* places but *of* them. Human beings – along with other entities on earth – are ineluctably place-bound. More even than earthlings, we are placelings" (19).

My work seeks to emphasize the inescapable presence of place. There are two ways in which my consideration of planets as places may run counter to Casey's formulation of place. First, I show how making planets, and thus making places, is a process; a move from something less to something more. Do I necessarily have to fall back on a notion of empty space upon which place is conjured? The descriptor "outer space," the medium upon which my interlocutors focus, seems to make this unavoidable. Perhaps I would have been better served to follow the French Marxists, considering the social production of the space we have come to call "outer." In this way, I would at least have avoided the dichotomy between space and place. But it is the word "place," not some multiple understanding of space, which shows up in conversation about other planets. Astronomer and science popularizer Carl Sagan, for example, recalled on the television show *Cosmos* that when he first saw images of the Martian surface taken by Viking, he thought, "Mars was a place." Sagan described understanding Mars in one way and then, through an act of perception, understanding it in another way. Though not necessarily a seamless transition from space to place, Sagan ultimately comprehended Mars as a place.

The second way in which my understanding of place is at odds with Casey's is that he insists that human presence is a prerequisite for place. Presence is necessary because of the attending modes of situated perception. I suggest that remote presence facilitated by telescopes, satellites, and surface robots allow for sufficient perception of other planets. *Thus, actual human presence is not a prerequisite for place-making.* The daily practice of planetary scientists interprets, improves, and shifts how planets are perceived. I will offer examples of many different ways of perceiving planets, as well as the kinds (and the robustness) of places planets become.

Before leaving Casey, I wish to draw attention to the distinction he makes between earthlings and placelings. To be an earthling is to derive identity from an affiliation with the planet. Casey suggests we are placelings to illustrate how place is more universal than earth. In one sense, this frees us from a tie to the earth. We could *be* anywhere, including on other planets. My argument throughout this dissertation is that planetary scientists frequently employ this kind of imagination to make sense of what they study. Earth, Mars, and exoplanets are all cast as planets and if we are placelings on one planet, we can imagine ourselves as placelings on all planets. All planets, it stands to reason, can be thought of as places.

Anthropology and Place

One focus of this dissertation is to identify how scientific practice turns planets into places. Contemporary anthropologists have been conscious of the field's tendency to reify place, especially with respect to culture. Emile Durkheim and Marcel Mauss (1903) set an early precedent for conceptualizing the relationship between place and culture. In *Primitive Classification*, they argued that the way a village is organized, how a place is established in space, is a reflection of social structures. This morphed into a tendency amongst anthropologists to fuse understandings of place with understandings of culture. Akhil Gupta and James Ferguson (1992) urge anthropologists to move away from the assumption that specific, bounded places are containers for culture. Contemporary places are not spatially discrete; as postmodernist and postcolonial scholars have shown, multiple cultures can exist in one place and cultures can exist in multiple places. Gupta and Ferguson appeal for a more lively relationship between community and place: "instead of assuming the autonomy of the primeval community, we need to examine how it was formed *as a community* out of the interconnected space that always already existed" (8). For displaced or immigrated populations, these always already existing spaces become imagined places as the communities themselves become imagined (Anderson 1983). The imagined community that I study is organized not around the symbolic power of the nation-state, but around the symbolism of planetary place. To be part of the community is to be engaged in the practice of producing place in space. This practice is what unifies the broad spectrum of scientists studying planets. Just as the community works to construct place, the idea of place holds the community together.

In this work, I am sensitive to a variety of ways anthropologists have thought about the production of place and the complex relationship between culture, cultural difference, and place. Places are multiple and some anthropologists have shown how their own perception of a particular space is vastly different from those residing in their region of study (Basso 1996; Stewart 1996). Ethnographies of American and European aerospace institutions illustrate not only that places are multiple, but also that they extend beyond the globe (Zabusky 1995; Vaughan 1996; Redfield 2000; Mirmalek 2008; Vertesi 2009; Olson 2010).

For a place to be multiple means that it simultaneously holds different meanings; that it simultaneously represents different things to different people or different things to the same person. Peter Redfield, one of the few anthropologists to think directly about the role of place in the space sciences, motivates his study with an observation about the multiplicity of place. In *Space in the Tropics*, a history and ethnography of French Guiana, he juxtaposes two seemingly incongruous projects: the high-modernist Ariane rocket project of the twentieth century and the colonial project of the penal colony of the prior century. He opens the study by asking about the role of place: "Does it matter where things happen? Or more precisely, what might it reveal that different things happen in the same place?" (Redfield 2000, xiv). I continue to ask this question not by seeking out the clash of cultures as Redfield does with the local Guianans and the French aerospace executives, but by considering how place is multiple even within a community. Planets are made meaningful by the comparison of the alien with the familiar; by understanding a distant object through a terrestrial lens. Scientists make sense of Mars by simultaneously drawing attention to its similarities to and differences from Earth. It is being pulled closer while being kept at a distance. This makes for a place at once imagined as Earthlike and foreign.

This multiplicity of place mirrors the multiplicity of the body as described in Debbora Battaglia's edited volume *E.T. Cultures: Anthropology in Outerspaces.* Her project is to learn about the human condition by "admitting the de-exoticized alien into our ethnoscapes" (Battaglia 2006, 2) in order to understand what is "extra in extraterrestrial" (7). Studying how communities embrace the alien not as other but entangled with self can broaden the analyst's conception of what it means to live on Earth. My work turns Battaglia's approach inside out: instead of making the body the site of multiple interpretations (both native and alien), the sites as imagined by scientific practitioners become multiple, simultaneously terrestrial and extraterrestrial. Stefan Helmreich's *Alien Ocean: Anthropological Voyages in Microbial Seas* (2009b) offers a similar accounting of reversals and transformations in understandings of Earth's oceans in today's sea science. Helmreich's alien ocean stands for the limits of representing and knowing the sea, suggesting that transforming the alien into the familiar is often an incomplete project. Nonetheless, scientists who wish to know alien planets make their objects seem akin to the terrestrial in an effort to de-exoticize and bring into scientific apprehension previously unknown objects.

STS and Place

When scholars in Science and Technology Studies (STS) have concerned themselves with place, it has been with an eye towards articulating a scientific place. Scientific places come into being through an ability to produce facts. In a review article written by a geographer advocating for a sub-discipline devoted to the geography of science, Richard Powel writes, "due to a concern for the credibility of truth-claims and truth-claimants, science studies *necessarily* had to confront questions of spatiality" (2007, 210). He acknowledges Steven Shapin (1991; 1998) as one of the first to ask this question when he articulated solitude as the historical position from which knowledge was generated and later sought to situate the epistemologically weighty "view from nowhere." Donna Haraway (1991) suggests that a feminist approach to science does away with the view from nowhere, offering instead a view from a specific body and a specific location. Making concrete the often invisible connection between truth claims and location, Tom Gieryn elegantly summarizes what he calls the paradox of place and truth: "All scientific knowledge-claims have a provenance: they originate at some place, and come from there. However, as they become truth, these claims shed the contingent circumstances of their making, and so become transcendent (presumably true from everywhere, supposedly from nowhere in particular)" (2002, 113). Science studies turned to questions of place to show that the view from nowhere originates at a very specific somewhere.

The two "somewheres" STS scholars continually return to when locating science are the laboratory (Latour and Woolgar 1986; Traweek 1988; Knorr-Cetina 1999; Silbey and Ewick 2003) and the field (Haraway 1990; Kuklick and Kohler 1996; Hayden 2003; Lowe 2006; Helmreich 2009b). Scholars have shown how these two sites signify different ways of producing knowledge. The modern laboratory is seen as a legitimate site for making matters of fact because of its portrayal as generic and placeless. This is in contrast to the pre-modern laboratory, which, as Robert Kohler (2008) points out, earned its authority from the specific person who founded it (and this is still true in some cases). The laboratory of the past and the present, despite claims to objectivity and agnosticism, is socially shaped. Even the emergence of the laboratory in Restoration England was the product of a sociopolitical stance (Shapin and Schaffer 1985).

In contrast to the desired placelessness of the lab, the field derives its authority from its particular location. It is often easier to tease out sociality in the field in contrast to the lab under the guise of imperialism, gender relations, and the social hierarchies implicit in amateur involvement (Kuklick and Kohler 1996). Despite being grounded in the local, field scientists developed many ways to mimic the controlled environment of the lab. Historians of science have particularly looked at how the personal equation, the bias of the human observer, is controlled for astronomical field research (Schaffer 1988; Canales 2002).

Though scientific practice is local and situated, conceiving of the place of science in terms of the field or the lab limits our understanding of how knowledge travels. These sites are one node in a wider, dynamic network (Latour 1987; Secord 2004; Kaiser 2005b). More recent studies of the spatiality of science suggest that it is the relationship between the laboratory and the field that is crucial to understanding the production of scientific knowledge (Henke 2000; Kohler 2002; Livingstone 2003; Gieryn 2006). In my own work, I observed how the field and lab often blur together. Like the placehood of planets, the places of science are multiple and complex.

Studies in STS that focus on the places of science are the beginning of a "spatial turn" in the field. My work emphasizes this new direction, considering the mutual constitution of place and practice. I suggest that ideas of place are also at work in the forging of professional identifies. For example, making planets into places informs the planetary scientist's identity as an explorer. This is a common theme in the space sciences, but reinforced for those in search of worlds. As one astronomer at MIT described, his real motivation for becoming an exoplanet astronomer came from a desire to find "worlds." In a separate conversation with a different astronomer at MIT, the same theme came up "[We] are just explorers... We can't really go there, but we're exploring." Across the country, in my other site at NASA working not with astronomers but with computer scientists the same sentiment was uttered, "There's definitely also an explorer in me, which got put to good use [working here]." For the identity of explorer to make sense, planets must be conceptualized and circulated as places. Place, practice, and identity reinforce each other. The spatial turn in STS makes these relations ever more clear.

A Place for Outer Space

This dissertation is also informed by a small but growing group of scholars dedicated to the social studies of outer space. This sub-field is anchored in work by historians and sociologists who studied astronomy (Edge and Mulkay 1976; Pinch 1986; Schaffer 1988; Lankford 1997; Canales 2002; Munns 2003; Stanley 2007), the political and social history of human space flight (Logsdon 1970; McDougall 1985; Siddiqi 2000; Ackmann 2003; Mindell 2008), the ethnography of space institutions and projects (Mack 1990; Zabusky 1995; Vaughan 1996; Redfield 2000; Mirmalek 2008; Vertesi 2009; Olson 2010), and the cultural meaning of extraterrestrial narratives and phenomena (Young 1987; Lepselter 1997; Dean 1998; Battaglia 2006). David Valentine, Valerie Olson, and Debbora Battaglia (2009) make a plea for anthropological studies of outer space, arguing that, "outer space is a crucial site for examining practices of future imagining in social terms, and for anthropological engagement with these practices" (11). Space, they offer, allows "theorists of space and time" a venue on which to test the limits of their theory. I take up this challenge, considering how place flourishes even in the unpeopled reaches of outer space.

In writing about space, scholars often focus on one distinct sub-culture, for example NASA managers, astronauts, astronomers, or fringe practitioners. Alternatively, a particular project or object is taken as the focus in order to highlight the intersection of communities. Patrick McCray's (2008) history of Project Moonwatch describes how three communities (space buffs, vigilant citizens, and amateur scientists) participated in a satellite-tracking program at the dawn of the space age. Robert Markley's *Dying Planet* (2005) and K. Maria D. Lane's *Geographies of Mars* (2010) use a scientific object, Mars, instead of a specific project to structure a study of the development of scientific and cultural narratives about the Red Planet. My work builds on these framings by also looking at several communities interested in planets. But if Markley and Lane began with a specific object, the planet Mars, I ask how the concept "planet" continues to be in-the-making as a scientific object and how it may become embedded in the "cultural significance, material practices, and theoretical derivations" (Daston 2000, 13) of this particular web of heterogeneous communities.

Field Sites, Lab Sites, and Sites in Between

During my research on Pluto and the IAU's definition of "planet," I became increasingly interested in exoplanets. In defining planet, the IAU specifically excluded exoplanets from the definition, as little was known about the then less than 200 objects categorized as exoplanets. From what I gathered at the time, only mass and radius were known about exoplanets and not much more. They could not even be directly imaged. At the same time, a friend of mine studying aerospace engineering at MIT had just returned from something called the Mars Desert Research Station. She explained that for two weeks her "crew" simulated being on Mars. They lived in a habitat, wore space suits when they went outside, and practiced field missions an early team on Mars might be responsible for. How, I began wondering, were the simulated practice of being on Mars and the documenting of exoplanets by astronomers related as ways of knowing planets? How could a planet like Earth or Mars be related to an exoplanet? The IAU thought it too premature to make this connection. It was the challenge of my fieldwork to relate the activities at the Mars Desert Research Station, which, inspired by my friend, I traveled to, with those of astronomers at observatories and to discern how these diverse practices of place were ultimately about understanding what constitutes a planet.

My fieldwork ran from June 2009 through July 2010 and unfolded primarily at four sites. During the summer and fall of 2009, I worked with MIT exoplanet astronomers. My primary informant was Sara Seager, a professor in the Earth, Atmosphere, and Planetary Science department (with a joint appointment in physics). Seager is a prominent figure in the exoplanet community, sitting on NASA and NSF exoplanet committees, giving invited lectures, public talks, and frequently appearing on television specials about exoplanets. Seager and her colleague in physics, Josh Winn, are the primary exoplanet astronomers at MIT and have a number of undergraduates, graduate students, and postdocs studying with them. They meet on a weekly basis to discuss recent papers in the field. In addition to attending these meetings, I collaborated with two undergraduates during the summer on a research project directed by Seager and in the fall observed Seager and a graduate student prepare a paper for publication. During the semester, I also attended various seminars offered by the planetary science program to understand where exoplanet research fits in the broader field.

From February 2010 through July 2010, I was an unpaid intern at NASA Ames Research Center in Mountain View, California. I was part of the Intelligent Robotics Group and worked closely with a research group within this division called "The Mapmakers." The Mapmakers are a handful of computer scientists and one planetary scientist who, as the name suggests, make maps. They work closely with commercial organizations like Google and Microsoft as well as the United States Geological Survey in order to deliver these maps to the interested public and planetary scientists. When I arrived at Ames, the group was finishing up a deliverable for Microsoft. They were building a map of Mars from NASA satellite imagery for the application WorldWide Telescope (WWT). WWT is described as a virtual telescope, intended for entertainment and educational purposes. The graphical experience allows users to depart from Earth and virtually travel across the universe. The user can either zoom around unassisted, or take a guided tour, which plays like a movie. For the release of the new Mars map, Microsoft and NASA wanted two tours narrated by prominent scientists that showed off the high-resolution data. I was put in charge of producing these tours, working with scientists at NASA to write and storyboard compelling narratives and then with Microsoft technicians to execute these ideas. With this role, I had access to the meetings and emails concerning the completion of the map and attended weekly meetings held by the Intelligent Robotics Group. My daily presence at Ames provided me with a sense of the role of this small group within the larger NASA picture.

My participant observation at MIT and NASA gave me access to the daily work and conversations of planetary scientists. As planetary science and astronomy have strong fieldwork traditions – at the observatory and on geologic trips – I arranged two shorter trips to these sites of practice. I accompanied Yale exoplanet astronomer Debra Fischer to the Cerro Tololo Inter-American Observatory in Chile for a four-night trip to look for exoplanets orbiting the star Alpha Centauri. With NASA's Carol Stoker, I went to the Mars Desert Research Station, mentioned above, which is located in Utah for a two-week geologic field trip in which we tested a drill that might be used on future Mars missions.

Findings gleaned from participant-observation were further developed during interviews[3] with those I encountered at each site as well as other planetary scientists suggested by my informants. During my research time, the topic of exoplanets was persistently in the news and my writing is inflected with these cultural understandings. My research gave me access to just a small slice of work being done in planetary science and while I hope my findings are applicable to the greater community, I await future work to see how these ideas manifest in other contexts.

Chapter Outline

This dissertation proceeds as a journey, beginning with exoplanets and then planet-hopping closer, chapter-by-chapter, until landing on planet Earth. At each planetary stop, I consider a different kind of activity that aids in place-making: visualizing, inhabiting, mapping, and narrating. I start with the most alien planets, exoplanets different from anything in our Solar System. These planets are made into places in the most familiar way: visualizing the unseen in order to imagine what kind of world it is. I end with the most familiar planet, Earth, on which I encountered a most alien place-making practice: simulating daily life as it might be on another planet.

Chapter 1, "Visualizing Alien Worlds with the Planetary Pipeline," focuses on my fieldwork with the MIT exoplanet community. The first exoplanets found were objects larger than Jupiter, orbiting extremely close to their host stars. These planets are too far away and too hostile to accomodate human presence and yet during my fieldwork I

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[3] For a list of the interviews I conducted that were drawn on in this dissertation, see Appendix A. Participants were read a statement of informed consent prior to the interview, in accordance with the COUHES Protocol# 0906003329 approved by MIT for this project. Interviews were digitally recorded and transcribed by the author.

repeatedly encountered astronomers pouring over graphs and models of individual planets, imagining the weather and surface they might host; imagining what kind of places they were. I consider the visual and semiotic practices of this community, arguing that the successful exoplanet astronomer is one who disciplines other astronomers to see their data in such a way that a planetary place undisputedly exists. This is a pictorial and language game similar to others played in science, but with the added stakes of place-making (and unmaking).

In the second chapter, also on exoplanets, I consider the search for "Earth-like" exoplanets. "Inhabiting Other Earths through the Places and Non-Places of Astronomy" draws on my experience with Debra Fischer during a trip to an observatory in search of planets around the Sun's closest stellar neighbor, Alpha Centauri. What, I ask, is the role of the observatory in the increasingly remote and automated practice of observational astronomy? This question is accentuated when considering the search for planets like ours. Astronomers present these Earth twins as "habitable" planets: rocky planets, similar in size to Earth that are at a distance from their star such that liquid water can exist on the surface. At the same moment they are hunting for habitability elsewhere, they are decreasingly inhabiting their place of work; shifting centers of practice away from ground-based observatories and towards computers and virtual databases that can access satellite telescopes from anywhere. Yet, I show in this chapter that even as the virtual presence replaces the need to physically be in a place, place becomes increasingly valorized as a pursuit of scientific knowledge. In searching for other Earths, place is tied to the ability to dwell on or inhabit another planet.

Chapters Three travels from exoplanets back into our Solar System to the planet Mars. For Chapter Three, "Mapping Mars in Silicon Valley," I discuss my participant observation at NASA Ames and the work of creating the highest resolution 3D map of Mars yet produced. In mapping Mars, NASA is making Mars into a very specific kind of place. They view their practice as a way to "democratize" NASA data by transforming databases of images into an interactive virtual globe. I focus on the different ways these researchers curate Mars as a place, from the 3D illusion of "being there" to creating tours and narratives that introduce the lay user to Mars's past, present, and future.

In the fourth and final chapter, "Narrating Mars in Utah's Desert," I show how planetary place is not just made in outer space, but right here on Earth. Through my experience living at the simulated Mars habitat of the Mars Desert Research Station, I consider how Earth itself is transformed into a Martian place. In superimposing ideas of outer space on the terrestrial landscape, the places we moved through became multiple; simultaneously Earth and Mars. Narrative served to order these multiple exposures of place, allowing for momentary clarity and order amidst the complexity of the places we created.

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The ways by which planetary scientists construct planets as places suggest that *place* is a way of understanding. The act of "placing outer space" puts forward not a particular worldview, but a cosmicview. Some cosmologists imagine the structure of the universe to resemble what a cotton ball looks like when pulled apart. Wisps of material form a thin web of cotton, with denser nodes dotting the surface. These nodes, on a universal scale, are "superclusters" of galaxies, pulled together by gravity. Each supercluster itself resembles the structure of the pulled apart cotton. Galactic clusters form the nodes within the supercluster. The Milky Way is thought to be in a cluster of thirty other galaxies, our Local Group. Each galaxy, in turn, is filled with intriguing objects like nebulae and black holes.

The cosmicview of planetary science sets aside these structures, each more mammoth than the previous, and concerns itself with relatively tiny globes of gas and rock that orbit relatively small, stable stars. This proverbial search for and study of needles in haystacks is rich with meaning and implication. These objects are just barely on the scale of our comprehension. Scientists establish planets as objects that bear upon our own planetary existence. They enrich the connection between *being* and *planets* by offering evidence of the placehood of these objects. In doing so, planetary scientists are populating the "emptiness" of outer space with planetary places. Thus, they are offering a new vision of the universe; they are replacing outer space with outer place.

ONE
Visualizing Alien Worlds with the Planetary Pipeline

"Even before we had exoplanets, we had *Star Trek,*" an astronomer told me as she explained why the proliferation of planets might be unsurprising to the general public. Some "exoplanet" astronomers – scientists looking for planets outside the ostensibly contained unit of our Solar System – go back further than *Star Trek*, readily pointing to Greek philosophers and Renaissance thinkers who postulated that "there are infinite worlds both like and unlike this world of ours" and that "the countless worlds in the universe are no worse and no less inhabited than our Earth."[1] However, it was only at the end of the 20th century, in 1995, when science fact caught up to classical cosmology and to the last century's science fiction. Since then, astronomers have announced the detection of more than 500 planets orbiting nearby stars in our galaxy.

Exoplanet astronomers mark the beginning of their field as an empirical science in October 1995, when, at a conference in Florence, Italy, Swiss astronomers Michel Mayor and Didier Queloz announced that they detected a planet orbiting around the star 51 Pegasi located 50.9 light years away in the constellation Pegasus. However, Polish-American astronomer Alexander Wolszczan had four years earlier announced the discovery of two exoplanets orbiting a pulsar – a radiation emitting, extremely dense body formed after a star has gone supernova. Jack Lissauer, a NASA space scientist, explained in September 2010 during an MIT physics department colloquium why this should not be (and generally is not) considered the first exoplanet discovery. "It didn't create much of a stir. And the reason for this is back [to the question of] 'is anybody out

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[1] Greek philosopher Epicurus and Italian philosopher and astronomer Giordano Bruno as quoted in Seager and Lissauer (2010)

there.' The pulsar has a luminosity hundreds of times that of our Sun and most of it is in X-rays. You don't want to live around a pulsar if you are a life form anything like those in the room... The real excitement began when planets started being discovered around normal stars."

51 Pegasi is a "normal" star in that it is a Sun-like star. In the discovery paper, Mayor and Queloz include a table comparing the parameters of 51 Peg, as it is abbreviated, with the Sun. The table reports comparable temperature, surface gravity, metallicity, mass, and radius (Mayor and Queloz 1995).[2] 51 Peg b, however, is not a "normal" planet. It resembles nothing in our Solar System. It is a gas giant that orbits its host star at a fraction of the distance Mercury orbits the Sun, completing an orbit in only 4.2 days. In other words, it would be possible to argue that 51 Peg b is no more inviting to "those in the room" than planets around pulsars. Yet Lissauer is correct in observing that exoplanets have captured scientific and popular imaginations. These planets, despite putatively inhospitable conditions, are often imagined as "worlds." That is, they are imagined and described in familiar terms so as to evoke a sense that these are more than merely scientific objects.

Since the detection of 51 Peg b, astronomers in the US and Europe have started many programs dedicated to exoplanet detection. According to the Exoplanet Encyclopedia (exoplanet.edu), as of May 2011 there were 68 projects currently searching for exoplanets. Exoplanet astronomers are appointed in physics, astronomy, astrophysics, and planetary science departments. Most senior astronomers who presently consider

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[2] Interestingly, the exoplanet is referred to as a "Jupiter-mass companion" in the title of the paper, not a planet. Perhaps because of several false planetary claims in the previous decades, Mayor and Queloz are careful to use the language of "companion" as this allows for interpretation as either a planet or a brown dwarf.

themselves exoplanet astronomers completed their dissertations in other areas, but are now mentoring new doctoral students in the field. At conferences dedicated to exoplanets (a few per year), there average 200 participants. Of the thousands of individuals who have published a scientific article or a conference proceeding paper on exoplanets, 266 are authors on more than ten articles. And though this might seem a small community, published items are growing exponentially. Papers and conference proceedings per year more than tripled since 2006, with over 350 published items in 2010.[3] Before the number of exoplanets exceeded the number of scientists studying them, as is the case today, exoplanet astronomers spent much time and effort on squeezing as much information as possible out of the scant available data. They sought to make the few planets as interesting and exciting as possible.

To understand the process by which astronomers work to make "worlds" real for themselves and their audiences, I propose the notion of a "planetary pipeline."[4] I define the planetary pipeline as a sequence of exchanges between people and instrumentation (telescopes, computers, programs) in which scientists and machines (1) *collect* photons, (2) *process* data, (3) *model* phenomena, and finally (4) *imagine* planets as worlds. Sara Seager, an exoplanet astronomer at MIT who was my primary guide through the planetary pipeline, describes exoplanets as "spatially unresolved." Seager writes in the introduction to her textbook, *Exoplanet Atmospheres*: "Ultimately we would like an image of an Earth twin as beautiful as the Apollo images of Earth. For our generation we are instead limited to observing exoplanets as spatially unresolved, ie., as point sources"

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[3] Statistics generated using Web of Science® key word search for "exoplanet" and "extrasolar planet" in article and conference paper topics.

[4] This phrase comes from several different scientists who, in discussing data processing, referred to a sequence of steps as a pipeline. I do not enumerate exactly the same steps that they do, but follow their idea in spirit.

(Seager 2010, 1). It is this point source that enters one end of the pipeline. Exoplanet astronomers, employing various techniques at each stage, try to bring about some greater resolution, no matter how speculative. This desire to "resolve" the planet is how they go about understanding a place they have never been. The aim of this pipeline and of exoplanet astronomy in general is to detect exoplanets and, in doing so, fill a void: to populate outer space with *places*.

Place, colloquially understood, is a familiar spatiality. To transform these planets into place, exoplanet astronomers have the challenge of making the alien appear familiar. Each chapter in this dissertation elaborates on different techniques of such place-making. Here, I consider practices of visualization, both with images and words. Ultimately, even when the data suggest exoplanets are like nothing known, astronomers persistently comprehend these planets through allusions to familiar planets in our Solar System.

Exoplanet astronomers transform abstract data into planets through visual and linguistic representations.[5] Visually, astronomers experiment with many different kinds of representation attempting to give a "seeable" presence to unseen planets. Rhetorically, astronomers discuss and write about exoplanets using metaphors drawn from our own, familiar, Solar System. When combined, the linguistic and visual semiotics used by exoplanet astronomers create a cosmos teeming with planetary places. These scientific practices facilitate seeing planets and making places.

I contend that making planets as places suggests the making of exoplanet scientists as particular kinds of professionals. In other words, practice and professional identity are mutually constructed. Though there is no dispute that exoplanets as a class of

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[5] For more on the relationship between text and visual representations specifically in scientific texts see Lemke (1998).

objects exist, one has to convince the community of the existence of individual discoveries. As such, exoplanets as objects of inquiry are often times disputed. This ontological uncertainty shapes both the ways exoplanets are modeled (moving from singular prescriptions to multiple possibilities with respect to interior and atmospheric compositions) and fosters frustration and uncertainty during the process of professionalization. In light of this instability, anchoring exoplanets as familiar places becomes a fruitful strategy for presenting discoveries. A successful exoplanet astronomer is one who convinces the community to "see" data in the same way and to recognize that the data contain a world - to interpret the signal both as a planet and also as a viable place. In this respect, practice and identity not only shape place but also are being shaped by the pursuit of place.

As exoplanets cannot be imaged directly, astronomers have developed many ways to represent the invisible. Figure 1.1 offers a sampling of this variety, drawing on images from various stages in the pipeline. Light curves (graphs of a stars brightness, Figure 1.1a) sit at early stages in the pipeline, the result of *processing*, when astronomers are still arguing about whether a planet exists at all – whether the photons they have *collected* robustly signal a planetary presence. As they move towards *modeling*, astronomers begin to reach beyond the data, attempting to characterize the atmosphere and interior composition of planets (Figure 1.1e-i represent different kinds of models). These images are more abstract, allow for multiple interpretations, and are perhaps harder to interpret, but aim at performing an important operation: making the *planet* into a *world.*

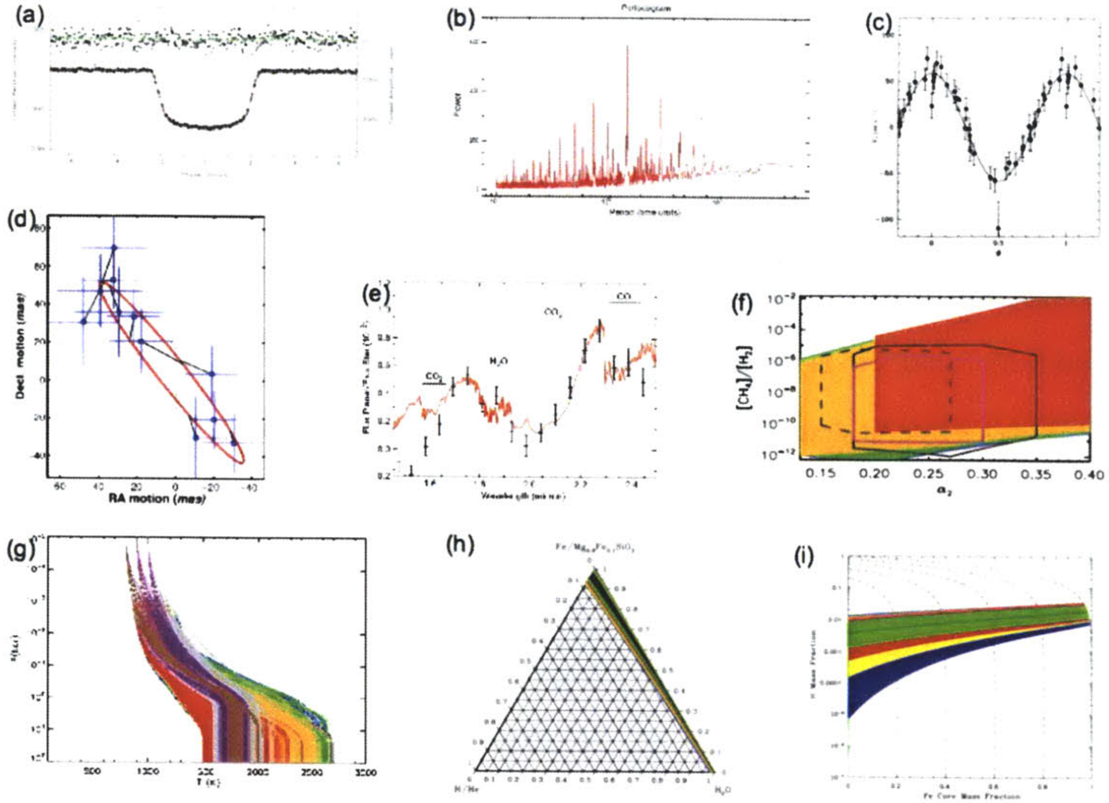

Figure 1.1: Different representations of planets. (a) through (d) are representations of planetary detections and (e) through (i) characterize planetary composition. (a) is a light curve of Kepler-5b (Koch et al. 2010). (b) is a periodogram showing dominant frequencies in the light curve of Corot-1b (Plavchan 2010). (c) is a radial velocity graph of 51 Peg b (Mayor and Queloz 1995). (d) shows astrometry data and a predicted keplerian orbit of VB 10b (Pravdo and Shaklan 2009). (e) is the atmospheric spectrum of HD 189733b (Swain et al. 2009). (f) and (g) are probability spaces for the atmospheric composition and temperature-pressure profile of HD 198733b (N. Madhusudhan and Seager 2009). (h) is a ternary diagram showing probability of interior composition of GJ 1214b and (i) plots the relationship between atmosphere and interior of the same planet (Rogers and Seager 2010). This is not an exhaustive set of planetary representations, merely the ones I encountered most during my research.

Many scholars have looked at how invisible phenomena are visualized by scientists. In the cases of brain imaging (Dumit 2004), gravity wave detectors (Harry Collins 2004), and bubble chambers (Galison 1997) the objects of interest are hidden, but nonetheless proximally close. Exoplanets are both invisible and removed in space. In imagining them as worlds and thus making them analogous to the world in which we live and work, astronomers work past the spatial divide. Visualization remains a prominent tool in this process. In pushing at the boundaries of what can be visually represented, astronomers are forging a new visual culture in Bruno Latour's sense that current practice "redefines both what it is to see, and what there is to see" (1990, 30).

Ways of Seeing and Speaking

New visual practices - new tools for and ways of seeing - shape every new era of astronomy. Galileo's drawing of the moon and his suggestion that there were features such as craters and mountains signaled a new way of seeing the moon. His ability to render the topographical nuance of the lunar surface came from his training in Italian Renaissance principles of perspective and was complemented by his insight that one might imagine lunar processes as akin to Earthly ones. As Galileo observed the play of light across the surface of the moon, he thought of how the sun rises across a mountain range (Edgerton 1984; Shea 2000). At the end of the 19th century, Percival Lowell drew a map of Mars after peering through a telescope night after night. His "objective" representation depicted a surface crisscrossed with linear formations. He offered this as visual proof of his theory that an intelligent people occupied Mars and built a complex irrigation system. Ways of seeing and ways of thinking are entwined. In the same way Galileo created a new practice of representation, exoplanet astronomers are experimenting with new ways to produce planetary inscriptions, demonstrating the many ways planets can be seen. And as the case of Lowell suggests, visualizations are often not only how one sees but also contain artifacts of what one is looking for.

"Seeing" a planet is complemented by the capacity to use language to situate objects as planets and worlds. Astronomers turn to analogies and metaphors to make sense of the unfamiliar. Most of the exoplanets detected so far are unlike planets in our Solar System. Yet, in papers and informal discussions, astronomers use phrases like "hot Jupiter," "mini-Neptune," and "super-Earth" to describe these objects. In addition, astronomers also use the cognitive and phenomenological resources of their own terrestrial experiences – of being on a planetary surface and experiencing weather, days and nights, and seasons. Such use of metaphor is not uncommon in science (Boyd 1993; Kay 2000; Hesse 1963; Hallyn 2000; Ortony 1993). Linguistic philosophers George Lakoff and Mark Johnson note that metaphor possess deterministic characteristics. In allowing us to understand new domains of experience, "metaphors may create realities for us" (Lakoff and Johnson 1980, 156). Metaphors and analogies in science link concepts or objects in one realm with those in a different realm, as, for example, when notions of physiology and mechanical practice inform one another (as illustrated in Rabinbach 1992). In exoplanet astronomy, analogies are drawn between planets orbiting the Sun and planets orbiting other stars. Astronomers fill a semantic gap by appropriating language from our Solar System to describe the new kinds of planets discovered around other stars. The comparison of planets to planets might seem less a metaphor and more a straightforward assumption. However, scientists' experiences of living on Earth and of being in this Solar System ground their analogies in historical and social contexts. Their analogies serve not only to offer language for new phenomena, but also to make new, unusual planets familiar – and, ultimately, to depict exoplanets as places. The particular metaphors of exoplanet astronomy fill a semantic void and at the same time fill a perceived physical void of *space* with *place*.

Place is more than a by-product of science. It is central to how exoplanet astronomers conduct research and construct their professional identities. This chapter captures a specific moment in the development of exoplanet astronomy as a new field of scientific inquiry. I became acquainted with exoplanet astronomers at a time when what I call the planetary pipeline was still being developed; when the theoretical aspirations of the community surpassed technical abilities and astronomers longed to know more than what the data conveyed. The frustration during this period in exoplanet astronomy is evident in projects I encountered as a participant observer with MIT's exoplanet community from May 2009 to January 2010.

Sara Seager,[6] a professor at MIT in the Earth, Atmosphere, and Planetary Sciences department with a joint appointment in the Physics department, and my guide through the exoplanet community, is a successful crafter of planets as worlds. Seager is in her late 30s, slight in her physical presence, but commands a room when she speaks. She welcomes a new visitor to her office in MIT's Green Building by ushering them to her window and showing off her 16th story view of the Charles River and Boston skyline. After this, she gets down to business – moving quickly from topic to topic, asking pointed questions of her visitor, and freely sharing opinions and experiences of her own life and work. In larger meetings, she will interject a comment or question if she thinks the topic of conversation has wandered too far off path. When I approached her about working with her group, she quickly suggested I begin right away with an undergraduate project she was supervising over the summer. Thus, my entrée to the exoplanet

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[6] A note on naming conventions in this and subsequent chapters: I received permission from each of my informants to use their real names. I often refer to senior scientists by their last name to reflect the position they have within their discipline. Other actors are referred to by their first name, either to signal their junior position or, as is the case in later chapters, to reflect the familiar relationship I had with them in the field.

community was with a couple of undergraduates who were also learning their way around exoplanet data. When the following semester began, I "graduated" to observing Seager mentor graduate students and postdocs as they worked on the challenging problem of modeling atmospheres and interior compositions of exoplanets. The projects discussed in this chapter successively work through the planetary pipeline from data ingestion and reduction to modeling to producing planets as worlds. Learning the different ways of "seeing" the data at each step (and how to train readers to see what you see) is fundamental to the student's professionalization process.[7] While focus in discussion and training is often on representations and visual practice, analogy and metaphors are readily at hand to move beyond planets and towards world-making. I end this chapter with a discussion of how Solar System analogies make the strange familiar and ultimately transform planets into places. For now, let me describe how visual representations are central to the first three steps of the planetary pipeline.

Collecting: See(k)ing Stars

Astronomers and engineers have developed many instruments and methods for studying and imaging planets in our Solar System. Ground and space telescopes and other remote sensing devices reveal visual and compositional information about the points of lights we see wandering across the night sky. Optical technology has rendered red, dusty dune hills on Mars, Jupiter's giant spot and the scar left by a recent comet

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[7] For recent STS thinking on pedagogy, see Kaiser (2005). See also Grasseni (2009) for ethnographic accounts of various tacit techniques by which modes of vision are adopted by communities.

impact.[8] Even scientists using the Hubble Space Telescope managed to capture fuzzy images of Pluto (though a planet no more), revealing a brown exterior.

But exoplanets cannot be directly imaged; they are too small and too faint compared to their host star to be optically resolved. Instead of trying to directly detect a planetary companion, astronomers started in the 1970s to train their telescopes on potential host stars and search for anomalies in their luminosity or motion. If an anomaly is recorded and there is no visible explanation (for example, a nearby binary star), astronomers declare they have detected a planet. Thus, astronomers qualify the existence of exoplanets precisely because there is no alternate visible explanation for an anomaly. To "see" these planets is not to see a sphere orbiting a glowing star, but in fact to note the visible absence of such an object.

There are two primary methods for detecting exoplanets (and several less successful ones): the transit method and the Doppler method. Both methods use a telescope to focus visible light from a target star. The transit method relies on photometry, the measurement of stellar electromagnetic radiation, to detect fluctuations in starlight. The Doppler method measures the movement of the star, looking for anomalies in motion that might be explained by a planetary companion. Seager is most interested in the transit method, as this method is currently the most promising way to find planets similar to Earth.

Astronomers keen on measuring the brightness of stars fashioned instruments throughout the 19th and 20th centuries to aid in this stellar endeavor. Beginning in the

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[8] The Mariner missions, which first launched in the 1963, were the first satellites to image the inner planets from a position beyond Earth's orbit. NASA missions have imaged Mars with the Viking missions of the 1970s and several recent landers and orbiters (to be discussed in Chapter 3). Galileo set off to image Jupiter in 1989, and was still in orbit and able to directly observe the Shoemaker-Levy 9 comet impact.

1830s, astronomers built several apparatuses that augmented the telescope in order to give the observer's eye a frame of reference from which to make accurate observations of magnitudes. In the 1880s, astronomers developed photographic photometry as an alternative to "visual" photometry.[9] An editorial in *Nature* summarizes, "The eye ceases to be the actual photometer employed. For the impression on the retina we have substituted the impression recorded on the photographic film" (Anon. 1895, 560). The light of a star leaves a circular impression on a photographic plate: the brighter the star, the greater the diameter. In the late 1890s, one way magnitude was determined was based on a logarithmic relationship between the measured diameter and known magnitudes of reference stars.[10] The mathematical relationship, the same editorial notes, "is serviceable practically, but has no physical meaning" (Anon. 1895, 560). And unfortunately, in the first decade of the 20th century as people better understood the science of photography, they realized that because photographic emulsion was more sensitive to violet light than the eye, photographic and visual magnitudes could not be compared. In the first half of the 20th century, photographic photometry was the dominant method but had many mechanical difficulties. With the invention of the photomultiplier in 1950, photographic photometry finally enjoyed expediency and success. The dominance of the photomultiplier was short lived, as electrical engineers at Bell Labs soon invented the charge-coupled device (CCD) and astronomers began to digitize their data collection. Today, CCDs have completely replaced the need for

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[9] The distinction between visual and photographic photometry is an actor's distinction. Whereas seeing with the eye through the telescope was considered a direct observation, when these techniques were first being pioneered photographic evidence was not considered direct observation (as evidenced by Scheiner (1894, 2)). Now, the distinction between direct and indirect is not related to human versus mechanical detector. Direct means to measure the planet while indirect means measuring the star.

[10] This process of calculating the magnitude from a photographic plate was called "reducing," the same word used today to describe the elimination of environmental and instrumental systematics from the data (as I will discuss more in the following section).

photographic film and are used as detectors for all major ground and space optical telescopes (as well as many personal cameras) (Hearnshaw 1997).

Most texts on CCDs use an analogy created by Morley Blouke and Jerome Kristian to explain its mechanical workings. As summarized in a 1992 paper on the current state of CCDs in astronomy: "Imagine an array of buckets covering a field. After a rainstorm, the buckets are sent by conveyor belts to a metering station where the amount of water in each bucket is measured. Then a computer would take these data and display a picture of how much rain fell on each part of the field. In a CCD system the 'raindrops' are the photons, the 'buckets' the pixels, the 'conveyor belts the CCD shift registers and the 'metering station' an on-chip amplifier" (Janesick and Elliott 1992, 6). What this analogy fails to mention is that often you are interested in the raindrops coming from only one specific cloud. Yet, the buckets collect rain from many clouds and perhaps even rain that dripped off an overhanging tree. Switching back to the language of astronomy (though this is still a borrowed analogy from signal processing), the raindrops from the cloud of interest are the "signal" and everything else is "noise." The skill and craft of CCD photometry is isolating the signal from the noise.

Data released by universities and government research institutions into public archives are often already cleaned of noise from the instrument and CCD itself. When one downloads a light curve from an exoplanet database, one presumably downloads only the flux from a single star. Though as the next section will show, even in this "cleaned" raw data, artifacts from the system often remain. These light curves are rendered as flux over time – brightness of the star over the duration of an observation. If a star's brightness does not vary, the light curve is a straight, horizontal line. Any brightening or dimming is represented by a rise or fall of this line.

During one of my trips to the visitor center at the NASA Ames Research Center, the Kepler exoplanet telescope kiosk featured a hands-on display to illustrate the "transit" signature in a light curve. Like a restless kid, before I knew what the display was trying to explain, I started cranking the beckoning handle. As I did so, a dark black sphere rotated around a light bulb. The faster I cranked, the faster the model whirled. Adjacent to this model was a camera with a CCD taking constant snapshots. The camera was connected to a computer monitor, which, in real time, drew a horizontal line indicating the brightness of the light bulb. Every time the black ball passed between the light and the camera, the measured brightness dropped, creating a U-shaped dip in the graph. Astronomers are searching for such dips in light curves - such transits - as evidence of exoplanets. However, just because the noise from the CCD has been removed from data, does not mean there are no other stray raindrops. The next step in the planetary pipeline after *collecting* is *processing* in which astronomers "clean" and "reduce" the data until they are confident only photons from the star of interest remain.

Processing: Seeing With the System

Seager invited me to join an undergraduate research project in the summer of 2009. I worked alongside two undergraduates, Sukrit and Aaron. The project concerned the Convection, Rotation, and Planetary Transits (CoRoT) space telescope launched at the end of 2006 by the Centre National d'Etudes Spatiales (CNES, the French space agency). CoRoT is gathering photometric data on stellar seismology and detecting exoplanets through the transit method. When we began to work on this project, the CoRoT team had announced seven planetary detections (named CoRoT-1b to CoRoT-7b in order of discovery).[11] More significant than discovering planets, the CoRoT data set contains information on stellar variability – how the flux, or energy output of a star, changes over time. To detect a planet, a star would ideally have little variability. If the opposite is true, the flux is not constant and the star has a complex signal, making the task of isolating the signal of the planet that much more difficult. Initial reports from the CoRoT team claimed that 80 percent of stars are variable, but there was no additional information on the timescale of that variability. Seager, who is designing a space telescope array of her own to look for Earth-sized planetary transits, wanted to know how many stars might be variable on the Earth-transit time scale. The research project I joined was designed to answer this question in order to aid Seager in assessing the feasibility of her project,[12] as well as teaching Sukrit and Aaron (and myself) what it is like to work with "real data from space."

Our first task was to get to know the data - to understand what information was contained in the light curves we downloaded from the NASA/IPAC/NExScI Star and Exoplanet Database, or NStED (a public repository of stellar data from various exoplanet surveys).[13] Understanding this data requires many levels of interpretation. There is not simply a one-to-one correspondence between phenomena and graphical output. A light

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[11] The names of exoplanets are alphanumeric; a lower case letter affixed to the star name. The star name is derived from its catalog number (for example HD 209458) if it does not have a formal name (as most stars do not). In other cases, the star is named for the survey that detected it. In this instance, CoRoT-N is the name of the star and CoRoT-Nb is the first planet discovered around that star. Subsequent planetary discoveries around the same star would be subtitled c, d, etc. 'a' is never used to denote a planet because that letter implicitly stands for the star itself.

[12] The extent to which stars are variable on this time scale also had implications for the Kepler satellite (discussed in Chapter Two). Seager sought to confirm that stars were less variable on shorter time scales.

[13] http://nsted.ipac.caltech.edu/

curve downloaded from the CoRoT database (Figure 1.2) contains signatures of the star, the instrument, and even the Earth. Knowing how to work with this data, how to manipulate it such that it serves as a representation of the star alone, requires an intimate knowledge of how and where the CoRoT satellite operates. CoRoT team members try to render their apparatus transparent, providing articles and manuals detailing the effects of the satellite's orbit, Earth's interference, and attitude control fluctuations in the light curves (see for example Auvergne et al. 2009 and Aigrain et al. 2009). What we learned that summer was how to see with the system in order to distinguish signal from noise.

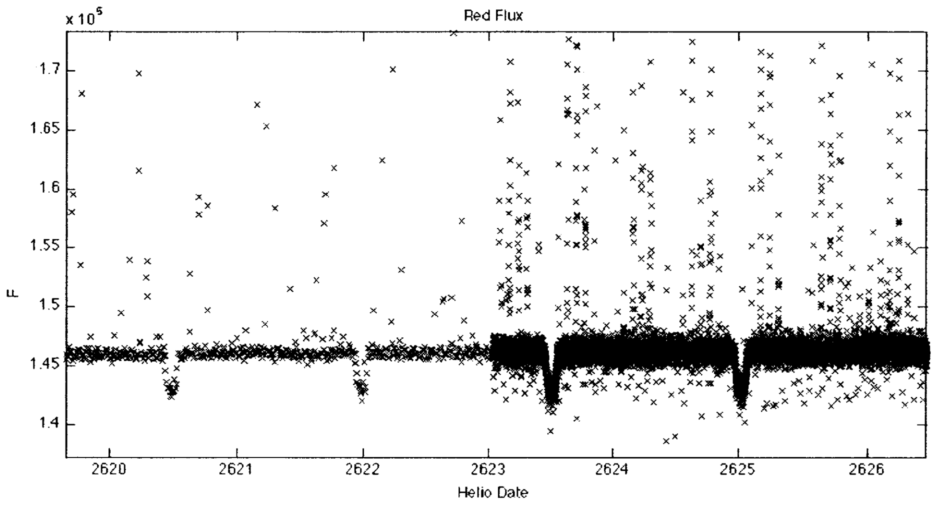

Figure 1.2: Raw CoRoT data. This is the light curve for CoRoT-1b, the first exoplanet detected by the satellite. The periodic dips in data are transits. When it seemed likely that there was a transit, the satellite was instructed to "over sample" which is why after Helio Date (short for Heliocentric Julian Date) 2623 the curve is thicker.

Distinguishing "real" data from "artifacts" is a common pursuit across many sciences. Michael Lynch writes, "The possibility of artifact is an almost inevitable accompaniment of research which relies upon specialized techniques and machinery for making initially 'invisible' theoretic entities visible in documentary formats" (Lynch 1985, 82). He observes that artifacts provide the analyst the opportunity to see more clearly how images are constructed; to make visible the sometimes invisible work of scientific practice. The skill of isolating artifacts in exoplanet astronomy comes from professional experience working with astronomical photometric data and familiarity with the specific telescope. As Sukrit, Aaron, and I were short on both of these attributes, we were quickly stymied. Our work progressed only because of two visitors who had prior experience working with the CoRoT data. Seager excitedly shared the news of these visitors, both European astronomers who had published on the planet finding capabilities of CoRoT. Simon was a new postdoc in the MIT physics department and Suzanne, a Co-Investigator for CoRoT, was in town to work with collaborators at the Harvard-Smithsonian Center for Astrophysics. The questions asked by Sukrit and Aaron at these meetings sought to elicit the personal experience of the visitors.[14] How do *they* see with the system?

The explanation of their experience worked across words, computer screens, and chalkboards. The heart of any astronomical system is the telescope. And so, Simon and Suzanne both began their separate meetings with us by asking if we had seen a picture of CoRoT – did we know what CoRoT and the CCD physically looked like? Simon drew a picture of the CCD on the chalkboard, explaining how it collected starlight. Suzanne, weeks later, opened a PowerPoint presentation on her MacBook and offered an image of the entire satellite and where the CCD was positioned. We learned from our visitors that to see the data properly we had to have an image of the whole system (star, satellite, Earth) as a lens for interpretation.

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[14] For discussions of tacit knowledge in scientific practice see Polanyi (1958) and Collins (1974). While these scholars focus on the materiality of practice and how technicians teach people how to use specific instruments, other scholars have considered how tacit knowledge remains important in non-material, theoretical work (Kennefick 2000; Warwick 2003; Kaiser 2005b).

The data coming directly from CoRoT is noisy, Suzanne confessed, and has to be properly "cleaned" or "reduced." Knowing about the instrument and its orbit allows a first order elimination of "bad data" within a light curve. Even after these data have been removed, there remains noise that impedes the detection of a planetary signal. Astronomers employ many methods to extract this signal. Continuing to draw from the language of signal processing, these methods are called filters. Simon and Suzanne used different filters to work with the CoRoT data. In both meetings, Seager was intensely interested in what these filters do and why these specific ones were chosen. As a theoretician, she rarely works with such raw data. During our meeting with Suzanne, when she explained that she prefers a "five-point box car" filter because a former boss introduced her to it, Seager was frustrated that there was not a more systematic reason for this selection. It reaffirmed why she went into theory; so much of observational astronomy is lore, Seager explained. It cannot be learned in a book.

Sukrit and Aaron were aware that the data had to be passed through a filter from reading papers published by the CoRoT team. They did not know why this was a necessary step until Simon showed us before and after images on his computer. He pointed out a cosmic ray (particles captured by the Earth's atmosphere that, when they interfere with CoRoT's line of sight, cause an intensity spike unrelated to the star) in the original data. He explained that this obfuscated the transit signal and so he removed it using a moving median filter. He then went to the chalkboard and illustrated how the filter works on a simplified data set. Seager was skeptical and asked why he bothered with this step. To convince her, he showed her the after image of his light curve and she exclaimed, “Oh, I can see the transit.” Simon justified his method by disciplining Seager’s way of seeing.

A transit of CoRoT-1b, the first planet announced by this mission, can be “seen” in Figure 1.3. This is a published representation of the same data presented in Figure 1.2. Not only has this data been cleaned of orbital and terrestrial signals and run through several filters, it has also been “phase-folded,” meaning every observed transit is superimposed so as to emphasize the curve’s shape, and thus convince the reader that a planet passes in front of the star. The paper announcing the discovery (Barge et al. 2008) asks the reader to see the data with the system in the same manner as demonstrated in our meetings with Simon and Suzanne. The paper begins by describing the CoRoT instrument, its orbit, and the CCD, explaining how data is reliably ferried from space down to Earth. It goes on to enumerate the steps taken to clean and reduce the data and finally describes how the transit curve was mathematically fit to provide the best possible planet parameters. The community considers the planet CoRoT-1b a viable exoplanet because the paper successfully argues that the visualized transit is constructed only from the starlight of CoRoT-1 and the effects of the surrounding system are removed.

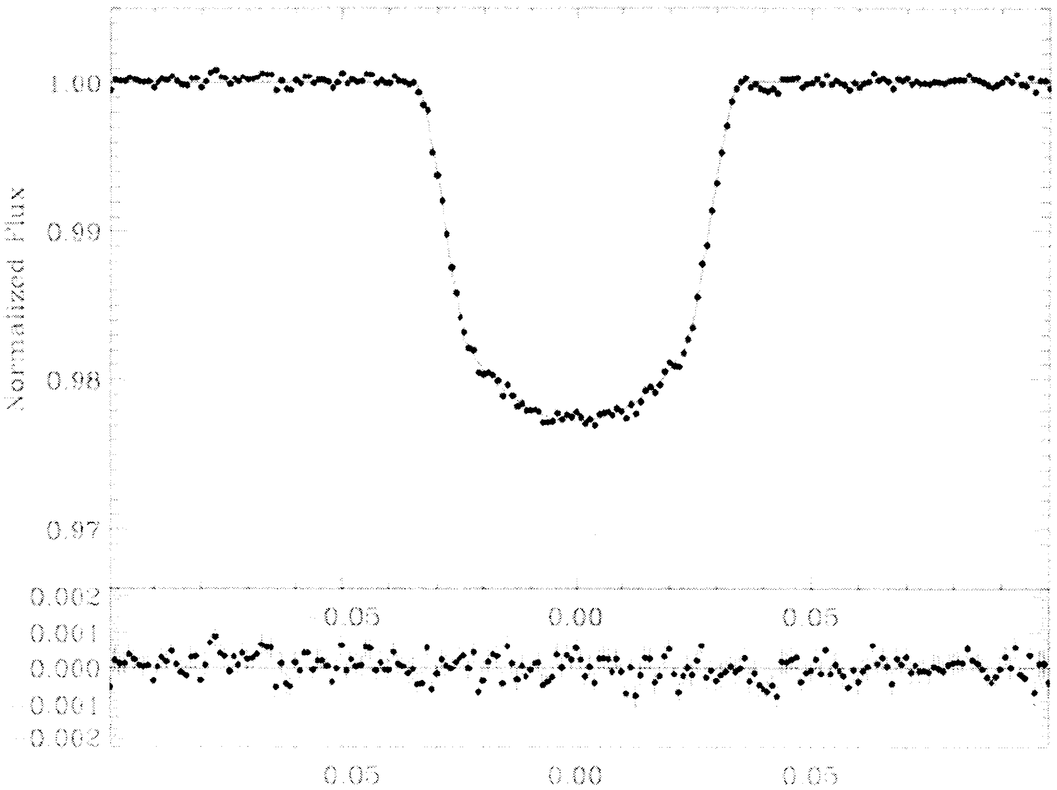

Figure 1.3: Cleaned and reduced light curve for Corot-1b. Figure form Barge et al. 2008.

Through the summer of research, Sukrit and Aaron learned how to get to know a data set. They were taught how to see with the system, which translated to knowing how to interpret light curves. To see light curves as meaningful is to see and trust the methods by which they were produced. Towards the end of the project, both undergraduates were dismayed because each step of analysis took much longer to complete than anticipated and they were not able to answer the science question that motivated the research. Seager explained several times that the process they went through was invaluable as they were learning the general philosophy of working with telescope data. Had they just read a paper describing the steps of working with the data, they would not have encountered the nuances of each step and the associated assumptions.

Modeling: Seeing Beyond the Signal

As described above, in an early step of the planetary pipeline, astronomers see with the system; they understand the orbit of the satellite, imagining its journey around the Earth in order to think through "systematics," or periodic artifacts, in the data. Thinking through the data in this manner is a mode of understanding forged before planets have been detected. Once an astronomer detects an exoplanet signal in the data and moves one step forward in the planetary pipeline toward modeling, the astronomer begins to see beyond the signal. With a spatially unresolved signal (to borrow Seager's description of exoplanets), the information extracted from transit curves[15] is the limit of what can be known with certainty about these objects. In the minds of exoplanet astronomers, however, planets are much more than point sources. The spatially unresolved exoplanets give way to planetary places as astronomers discuss, imagine, model, and speculate about being on the surface or floating in the atmosphere of these planets. The compositions of exoplanets are highly unconstrained, meaning observational data do little to limit the range of a planet's chemical and material properties. Astronomers nonetheless push these limits, as two graduate students in Seager's group demonstrated with their attempts to model atmosphere and interior compositions of different exoplanets. The visualizations they produce are more complex and harder to "see" the planet in because, in moving beyond the spatially unresolved signal, uncertainty in the form of probabilities must be introduced to the representations.

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[15] If astronomers can produce both radial velocity graphs and transit curves, the orbital period, distance from the star, mass, and radius can be determined from the exoplanet.

Consequently, exoplanets become less singularly understood, opening up the possibility for multiple interpretations of what kind of planet the signal might contain.

Atmospheres

Madhu, now a postdoc, laughed at the absurdity of his research when he explained to me that he chose his thesis topic, modeling exoplanet atmospheres, because he has always been drawn to unsolved problems. He got to this research because he kept choosing the road not taken. He described how Robert Frost's poem informed his academic path:

> At every point in life you get two choices at least and you are to make a selection. In the initial stages of life, you start from ground zero, you are broke, you have nothing. Then, the choices you make might affect your future very drastically... As you go on, the choices you make become slightly less important. At this stage, for example, if I ask 'do I work on exoplanet atmospheres' or 'do I work on planetary detection'... I'm good enough I'll be relatively successful in both. So that might have slightly less influence of where my future is. But long back, I couldn't say the same thing... The summary point is how do you come up with a coherent theory, which helps you in making a decision in each of these situations, whether you have a big or small decision. The theory is that poem... You look down each road as far as you can and then your gut feeling says maybe this is what I should take. It is all art at the end of the day.

While choosing his path in life is an art, his research on atmospheric composition is utterly systematic. Throughout the early 2000s, astronomers using Spitzer Space Telescope and Hubble Space Telescope made claims about exoplanetary atmospheres.[16]

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[16] Spectra for exoplanets are generated when the radiation from a much hotter host star passes through the much cooler atmosphere of an exoplanet during an observed transit. The molecules and atoms of the

Astronomers like Madhu are interested both in the elemental composition of the atmosphere and the temperature-pressure (TP) profile. In ascending from the surface of a planet, the pressure decreases. The TP profile is a model that gives dimension to the "spatially unresolved" exoplanet.

But how, Madhu asks in his work, can you actually say with certainty that there is water or sodium or carbon dioxide on these planets? Given the scant observations, i.e. the lack of a complete spectrum, how can astronomers confidently describe the atmosphere as one set of molecular combinations versus any other? How can a scientist present one TP profile or spectrum, and be sure that this is the only possible configuration? Madhu's work on exoplanet atmospheres problematizes two kinds of representations. The spectrum of chemical composition and TP profile, shown in Figure 1.4, are related to each other through a set of equations and are solved for simultaneously. To explain the modeling problems inherent in these representations, Madhu showed me a *Nature* article (Swain, Vasisht, and Tinetti 2008) in which the authors claim that exoplanet HD 189733b must have both water and methane because water alone does not fit the data. Madhu's point is that a wide range of water and methane concentrations and any arbitrary TP profile can fit the data. At the time of the *Nature* article, research teams were only running a few models and choosing a nominal best fit. The goal for his dissertation was not to suggest one or two models, but to provide a range of possible models and, more

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exoplanetary atmosphere absorb the stellar radiation as it passes through. A planetary spectrum, then, is made by subtracting the spectrum of the star from the spectrum of the planet and star. This is one of three other exoplanet atmosphere detection techniques, and not the main one considered in Madhu and Seager 2009 paper.

importantly, outline the physical constraints of the model in a statistically meaningful sense by computing millions of models.[17]

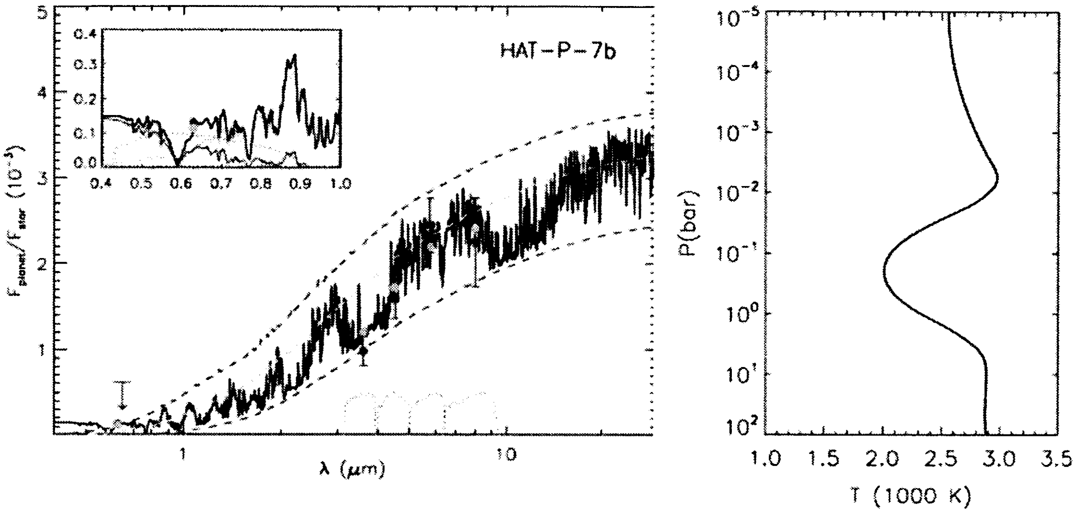

Figure 1.4: Spectrum and temperature-pressure profile for HAT-P-7b. Example of these two representations from a well-studied exoplanet. This figure is meant to illustrate the clarity of these graphs, which suggest to the reader that the spectrum and TP profile are precisely determined. Graphs from Christiansen et al. 2010.

Madhu described figuring out an inroad to this problem as a depressing undertaking – after all, if he could not solve this problem he would have to start over again with a new thesis topic. Planets in our Solar System have robust TP profiles, so he would look to these graphs for inspiration. At one point, he produced a figure containing all four giant Solar System planets (Jupiter, Saturn, Neptune, and Uranus) and Earth in the same frame. Upon viewing this congruence, Madhu recalled, "an idea struck, a very creative moment… Maybe I should find a mathematical function that could fit all the

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[17] Seager, Madhu's dissertation advisor, suggested the "million model approach" and Madhu found an elegant solution. The credit I give to Madhu in this section also deservedly belongs to Seager.

profiles. That itself was an absurd idea. Why should all planetary [TP] profiles be the same?"[18]

Yet, this is the idea he developed, proposing an elegant equation that could be applied to all planets, those in our Solar System and beyond (Madhusudhan and Seager 2009). Not only does he use the general equation to fit TP profiles and spectra from the data, he also presents the models not as a single line but as a probability space. He transforms what previous papers had presented as single solutions into a spread of possibilities which suggest visually that the atmospheric composition of these planets are far from being understood. In a field where small amounts of data are leveraged to make big claims, Madhu's intervention was to show that the visual clarity of spectral graphs is misleading and the known attributes of planets are much messier and abstract (see Figure 1.5).

In general, this approach has been well received. However, critics are quick to point out that his elegant equation for the TP profile has no physical basis. In a public talk, he pre-empted the audience and rhetorically asked, "What is this magical pressure temperature profile?" He went on, "[it] looks like a mathematical construct, why should we trust this?" His answer was a visual argument. He displayed a slide showing how the equation fits the data we have on exoplanets and, more impressively, five Solar System

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[18] A further note on what is represented in the TP profile. It is a graph of temperature (on the horizontal axis) versus pressure (on the vertical, in descending value). As pressure increases the further from the surface, at TP profile represents how the temperature changes as you move from the surface, into the atmosphere. For planets in the solar system, scientists obtain the TP profile based on a detailed spectrum. For exoplanets, no detailed spectrum is available. Analysts have attempted to solve this problem by deriving a range of TP profiles and molecular and atomic abundances based on a given spectrum by solving three equations simultaneously. This method is too computationally intense to run multiple times. Madhu proposed a parametric TP profile that would satisfy hydrostatic equilibrium and global energy balance equations. He wrote an exponential equation that proved a good fit for the solar system planets (Seager 2010). With this self-contained equation, containing six free parameters, Madhu was able to run many thousands of possibilities on the same data.

planets. In reference to the Solar System he said proudly "That's real data." Representation and analogy merge as Madhu justified his way of knowing exoplanets. His equation, derived from a particular way of seeing planets in our Solar System, is justified by disciplining the audience's sight to see in the same way. More persuasively, the equation illuminates far away planets by relating them to those nearby.

Madhu is reshaping visual practice, presenting new ideas about what can (or cannot) be seen and known about exoplanets. His way of seeing beyond the signal portrays a planet not as a single entity, but as a multiplicity of possible incarnations.

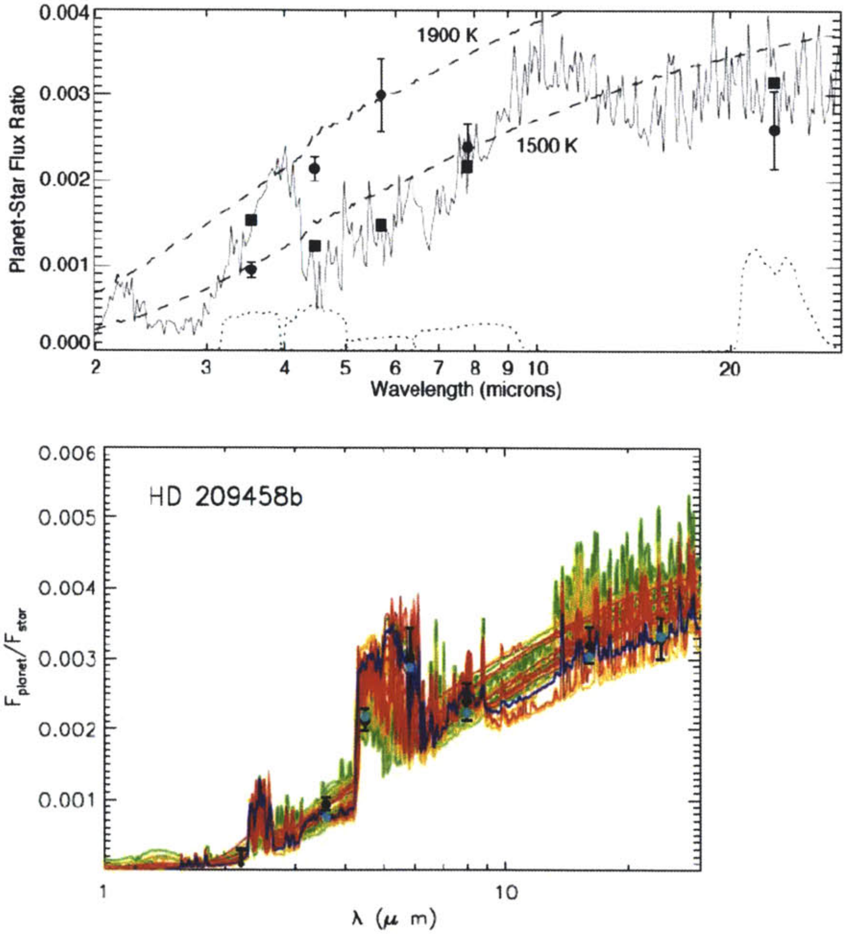

Figure 1.5: Spectra of HD 209458b. The singular top spectrum (from Knutson et al. 2008) contrasts to Madhu's multiple probability spectrum on the bottom (from Madhusudhan and Seager 2009).

Interiors

GJ 1214b[19] made headlines in December 2009. *Wired Magazine* invited readers to "meet GJ 1214b, the most Earth-like planet ever found outside our Solar System" (Keim 2009). The *New York Times* warned readers: "Call it Steam World. Astronomers said Wednesday that they had discovered a planet composed mostly of water. You would not want to live there" (Overbye 2009b). As these statements make clear, the character of GJ 1214b is ambiguous, it is not singular but multiple. In terms of mass and radius, it was one of only two "super-Earths" known at the time of its detection, making it the most "Earth-like." The discoverer, Harvard's David Charbonneau, claimed in his paper that the composition was mostly water, with an atmosphere that would make the surface "inhospitable to life as we know it on Earth" (Charbonneau et al. 2009).

Is such a specific compositional claim justifiable? As with Madhu's project, there is a similar puzzle for exoplanets of modeling planetary interiors.[20] How far beyond the data can astronomers go in speculating about a planet? An observer might be satisfied offering one suggestive interpretation that fits the data, leaving it to the theorist or modeler to be more comprehensive. In September, a few months before the discovery announcement Charbonneau shared his discovery and data with Seager. Seager suggested to her graduate student, Leslie, that this would be a good project for her to work on. As I had successfully completed my undergraduate research project participation, Seager invited me to follow the development of the research, wanting me to

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[19] The nomenclature 'GJ' refers to a catalog containing known stars within 25 parsecs of Earth. Wilhelm Gliese and Hartmut Jahreise prepared and updated the catalog at the University of Heidelberg, hence the 'GJ' honorific.

[20] In this project, "interior" refers to the core, mantle, and gas envelope. The gas envelope is the gaseous layers surrounding a rocky concentration of mass.

understand how mass and radius (quantities derived from the light curve and radial velocity measurements) are indicators of internal structure.

Leslie, in many ways, is the antithesis of Seager. She demurs where Seager asserts, is nervous where Seager is confident. Seager is impressed with Leslie as a physicist and was sure that she was ready for a project of this sophistication. Leslie decided to work on this project as she was figuring out what her thesis research would be. This short project, hopefully only a couple months of work, would serve to test whether there were enough data and theory at this point to work systematically through the problem of interior modeling. Consequently, Leslie's anxieties about her research trajectory and abilities as a scientist percolated during working sessions and meetings with Seager while developing the GJ 1214b paper.

"What we're doing is we're trying to interpret a new planet," Seager explained to me the first time the three of us sat down. From the transit data and measures of the mass and radius, it seemed that the planet must support an atmosphere, or gas layer as Leslie referred to it. Leslie sought to explain how interior composition dictates the origin and composition of the gas. The planet is conceived as a whole, where one layer affects the others. For her project, Leslie was considering three different ways this planet could have formed based on different "primordial" material. Leslie explained these planetary possibilities to me. The first is a "mini-Neptune" with a hydrogen-helium gas layer. The second scenario is a planet that does not have the hydrogen-helium atmosphere, and instead is enveloped by a water vapor layer. The last case is a super-Earth encased by a small hydrogen layer.

I was curious to know how they arrived at these three scenarios. As Madhu had showed me, there are many possible planetary configurations. Leslie and Seager wanted to present discrete cases and chose to consider "end member" cases; planets that evolved in three different ways and therefore had three different evolutionary reasons for having a gas layer. At early meetings and in early paper drafts, this clarity was not yet fully formed. Drawing again from our Solar System, Leslie explained that there are rocky planets like Earth and Mars and Venus, and ice giants like Uranus and Neptune. The mass and radius of GJ1214b falls between these two classes, suggesting other kinds of planets in this overlap region. Consequently, they chose cases based on intuition, but knew that for the purposes of the paper's argument, they must present readers with a more methodical motivation behind these choices. In the final paper, they justified their choice of cases with two figures illustrating the multiple possible elementary compositions for planets. They sought to convince the reader of the rationale behind their approach through images in addition to words.

Leslie arrived frustrated to a meeting in October. After a disheartened discussion of how she was modeling the water vapor layer, she brought up a colleague's paper that was also on the topic of modeling interiors of super-Earths. Leslie thought she had encountered what all researchers and academics fear: someone has written the paper she was working on. Seager quickly reassured her, emphasizing that Leslie's paper has better physics and contains a discussion about *how* to distinguish between different cases. Leslie was not satisfied. The other author is a postdoc and will always be a step ahead, she insisted. This should not be a concern, Seager responded, because of Leslie's proficiency at physics. But, if being the best physicist is not a satisfactory solution for

Leslie in terms of distinguishing herself, the other option was to embark on something completely different. Leslie had already been toying with studying planetary formation and perhaps this would be a more novel thesis topic. The uncertainty of exoplanets as objects fueled Leslie's uncertainty of being an exoplanet astronomer.

Frustration continued to plague Leslie's work on this project. At the start, she was confident that the data would offer some hard limits, allowing her and Seager to pronounce upon the amount of hydrogen in the gas layer. Two months after working with the data, after she had drafted a paper, Leslie concluded that there is not enough information to constrain the problem: "Who knew it would be so degenerative?" Seager hesitated, then bluntly observed that the project is in a precarious position; should they scrap the idea of publishing or figure out a way to salvage Leslie's work? Leslie was stunned, but Seager reassured her that the null finding of her work so far is not her fault. Seager and Leslie were both disappointed that there was not a bigger finding to report, but upon advice from a colleague at MIT, they decided to continue writing up the paper and at the very least to point out that exoplanet modeling is still in its infancy and such claims of mini-Neptunes and water worlds are premature. This experience made Leslie question whether studying interiors was too risky of a thesis topic. After writing this paper, she would search around for a different topic, perhaps on planetary formation. This topic is decoupled from the worry of whether or not a specific exoplanet exists and, for Leslie, provided a sturdier platform for her professional identity.[21]

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[21] Though Leslie did explore the possibility of pursuing a project on stellar evolution, in a quest for more definite answers, she returned to interior modeling for her dissertation work. Her research continued to be motivated by the work she did with GJ 1214b, proposing circumstances under which super-Earths might have liquid water on their surface (personal email to author, July 11, 2011).

By early November, however, Leslie and Seager made the decision to keep working on this modeling project and to publish a paper. Knowing that Charbonneau might announce the detection any day, Seager and Leslie worked non-stop to prepare their manuscript. Though Leslie had written a draft, Seager worked with her for several days to re-write the paper so it more clearly expressed the goals and findings of the project. Part of Seager's role as advisor is to teach students how to write, a skill they rarely have mastered before entering graduate school. In observing how Seager walked Leslie through the paper writing process, I saw that Seager also instructed her student in how to see planets in a certain way. We met on a Monday morning in early November for the first of several days of intense collaborative writing.[22] Before we got to the language of the paper, however, the first method of attacking this work was to approach it visually. Seager placed a sheet of paper on the table and suggested she and Leslie sketch out pictures of the different end members so as to understand the physical components of each scenario. As she drew each case – narrating while she drafted an icy core and a gas envelope – she ordered them by size illustrating a continuum of possibilities. In drawing this out, Seager created a pictorial rationalization for the selection of end member cases, which they next translated into words for the paper's introduction. Seager demonstrated for Leslie how to see beyond the signal, beyond the transit light curve towards multiple scenarios.

Ultimately, the paper concluded that "we can constrain GJ 1214b's composition but we cannot infer its unique true composition" (Rogers and Seager 2010). The paper does suggest, however, that Charbonneau's claim that there was liquid water on the

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[22] I did not participate in the research or the writing of this paper, but my opinion was sometimes asked for as Leslie and Seager tried to figure out how best to express a particularly sticky point.

planet's surface was unlikely. To model exoplanets is to see them as several. It is to resist the desire to ascribe a singular make-up, presenting them as unambiguous worlds. Seager, Leslie, and Madhu play with the ontology of exoplanets. They *enact*, to borrow from Annemarie Mol's (2002) characterization of the role of medicine in producing the body as multiple, an exoplanet as multiple. To do so, however, necessarily introduces uncertainty into the epistemology of exoplanet astronomy. For a new scholar like Leslie, this uncertainty in the object translates to professional frustration and uncertainty. To see beyond the signal is to see the exoplanet as multiple and recognize the fragility of one's object of study. One strategy that helps sure up the character of these objects is to reference their status as worlds and unique places. I will discuss how language is central to this process.

Imagining: Seeing Through Language

Scientific inscriptions are always accompanied by verbal or written text. Medical anthropologist Barry Saunders (2009) illustrates how learning to see and speak are coupled in the world of diagnostic medicine. Likewise, in exoplanet astronomy, while Seager mentors students like Sukrit, Madhu, and Leslie in how to interpret novel inscriptions, she simultaneously provides a new vocabulary for them to speak about what they see. Much of this language is technical, but there is a subset of more colloquial terms, discussed in this section, that do more than just describe the data. They elevate the data to a level at which the detected planets take on elements of place. Light curves and other graphs are necessary to prove planetary existence. To transform the planet from a scientific object into a world, astronomers employ linguistic strategies such as analogy and metaphor in paper writing and verbal discussions. Stefan Helmreich (2000), in his ethnography of Artificial Life computer scientists, tracks the use of metaphor in world-making. He observes, following Lakoff, that scientists, as with all people, are creatures of language and as such they are inescapably creatures of metaphor. Helmreich shows how, in conceptualizing computer simulations as self-contained "worlds," scientists draw from the language of the living world and use those images to describe and make sense of simulations. For exoplanet astronomers, language is what allows the worlds to come into being. Language and metaphor make visible the invisible and create new realities (Tuan 1991; Lakoff and Johnson 1980). When there is not enough observational data to transform planets into worlds, exoplanet astronomers see these planets through language. Language allows for a way to move beyond the uncertainty of the exoplanet multiple towards an understanding of the exoplanet as a world and as a place.

It is perhaps not surprising, then, that scientific papers are riddled with terms such as "hot Neptunes," "eccentric Jupiters," and recently confirmed "super Earths" (the prefix 'super' implies a bigger mass and/or radius). When Leslie and Seager began writing their paper on GJ 1214b, they frequently relied on the language of Earths, Neptunes and ocean worlds to think through the possible compositions of the exoplanet. The familiar associations provided touchstones, making the planet familiar as well as hinting towards questions associated with such characterizations. They were at times uneasy with their use of analogy, but had a hard time getting away from it. In an early draft of the paper, they articulated that one interesting aspect of GJ 1214b is that there are "no solar system analogs" and "we should not carry over our own biases from solar system planets." And yet, in the very next paragraph, they could not escape relying on that language and describing how the planet might have formed "like Neptune." In figuring out how to describe the water planet scenario, Seager thought aloud during one meeting while deciding what to write: "Water planets are not like any in our Solar System. Or water planets would be like bigger, hotter versions of Ganymede or Jupiter's icy moons." Each time they tried to get away from Solar System analogies, it became apparent that analogy was the only way out of the semantic gap. In the end, Solar System language served to organize the end member cases and in the paper submitted to the *Astrophysical Journal*, they were labeled "Mini-Neptune," "Water Planet," and "Super-Earth." This language is not unusual in the literature. However, a referee suggested they were over-using Solar System analogies and the planet taxonomic classes they relied on were not precisely defined. In the final paper, Leslie and Seager re-named their cases as "Gas-Ice-Rock Planet with Primordial Gas Envelope," "Ice-Rock Planet with Sublimated Vapor Envelope," and "Rocky Planet with Outgassed Atmosphere." Despite the important role analogy played in developing the project, it was erased from the final published product.

In addition to phrases of bulk classification, the discourse of exoplanet astronomy draws heavily on language used to describe conditions on Earth. Even though most of the exoplanets discovered so far are gaseous giants, in discussing their properties astronomers struggle to make them seem Earth-like even if they are far from familiar. Speculating on weather and seasonal variation is a common rhetoric in the exoplanet meetings I attended. In one meeting, we were discussing a theoretical planet in which temperature is transferred between the atmosphere and surface. On one page of a handout regarding this planet there was a graph of what the atmospheric temperature would be at different latitudes during "January." The speaker went on to say how this graph would be different in "March" and the other "spring" months. This object, which began at the beginning of the meeting as just a body orbiting a star now could be imagined to have seasonal variation and we had a better grasp of this alien world by understanding the difference between our spring and its spring. After we understood how volatile this planet's climate would be, an astronomer joked how alien people on the planet might react to the crazy weather – who would be the Al Gore of this exoplanet?

In one of Seager's research meetings, a graduate student described the atmospheric properties of a specific, existing exoplanet he had been modeling. He mentioned that the planet is "tidally locked." This prompted another student to ask about the planet's hot spot – the part of the atmosphere that would be super heated by the star's direct and constant radiation. The student simply answered that the hot spot was "down wind" from where you would expect. Phrases like "tidally locked" and "down wind" (the former is used quite frequently) are curious because of the physicality they imply. Tidally locked, for example, is an analogy drawn from our own Earth-Moon system. The Earth and Moon exert a gravitational pull on one another. One effect of the gravitational pull of the Moon on Earth is the ocean's tides. Another effect is that the Moon orbits the Earth in such a manner that the same side always faces Earth. This configuration is termed "tidally locked." Exoplanets close to their host star often end up in a similar arrangement. Whereas in the Earth-Moon system, "tidally locked" references both a dynamic configuration between two bodies and an oceanic effect, exoplanets described as tidally locked only refer to the configuration between planet and star. These planets, orbiting so close to their star, cannot sustain water on their surface. Instead of introducing another term to the planetary lexicon, tidally locked is maintained for its powerful visual resonance. To think of tides and winds on planets, even if they don't exist, allows one to imagine what it might be like to stand on the surface of such an exoplanet.

Speculating on the weather of exoplanets is a way to imagine the surface conditions. As astronomers imagine being on the surface, they transform objects into places. But, can we actually set foot on these planets? The confirmation of the first rocky planet, the first so-called Super Earth was announced in October 2009 and discovered using data from CoRoT space telescope. This planet, Corot-7b, orbits 23 times closer to its star than Mercury does to the Sun. We would not be able to take a walk across the rocky surface, as the heat from the star likely turns the rock into lava. However, in the paper announcing the refined mass and density estimates, the point is made, "If one assumes that CoRoT-7b is representative of the "super earth" population..., the structure of these planets is likely to be quite different from Neptune structure, but rather a more rocky planet like the Earth" (Queloz et al. 2009).

Exoplanet astronomers often make these worlds seem hospitable even when they are clearly like no environment we know or could survive in. In 2003 and 2004, two independent papers came out within months of each other. Each theorized the existence of planets that are the same mass as Earth and at such a distance from their host star that the planet's surface is covered entirely in liquid. One paper called these planets "Volatile-Rich Planets," the other called them "Ocean-planets." The author of the first paper, an astronomer at NASA Goddard Space Flight Center, spoke to me about this coincidence. He reflected morosely that the term "ocean-planets" is widespread in the field and that paper garners many citations, while his term has vanished from the literature. As our conversation continued, he realized why his paper failed where the other succeeded: ocean planet was a familiar, imaginable world while "volatile-rich" did not lead to an immediately recognizable kind of place.

This extensive use of metaphor in describing exoplanets – this pattern of using familiar names when discussing the unfamiliar – is common practice in exploration of the terrestrial sort. Geographer Yi-Fu Tuan (1991) notes how European explorers encountering the unfamiliar Australian desert for the first time still used the language of mountains they carried with them despite the lack of significant elevation. Tuan asks geographers to look beyond the economic and material grounds for place-making and focus instead on speech and language. "Speech is a component of the total force that transforms nature into a human place. [Speech can] make things formerly overlooked – and hence invisible and nonexistent – visible and real" (685). For exoplanet astronomy, this "force" comes from the metaphors employed by planetary scientists that link their objects of study with familiar worlds. Their speech, in a very literal way, brings a reality to unseen objects and helps them understand what kind of places their planets are.

Conclusion: Seeing is Believing

In visualizing, interpreting, and discussing their objects of interest scientists come to identify with what they are studying. As Janet Vertesi (2009) has shown, for scientists who worked with the Mars Exploration Rovers, "seeing like a rover" required manipulating one's body like the Rover's body in order to forge a physical connection. Similarly, Natasha Myers (2007; 2009) has offered examples by which biologists teach students to understand something like protein folding by using their bodies to mime the process. Elinor Ochs, Patrick Gonzales, and Sally Jacoby (1996) have suggested that these ways of relating to scientific objects conflate the scientist and the object, which structures a subjective involvement by the scientist in the physical world they are studying. Each study shows how visualizing, gesturing about, and discussing scientific objects are performed collectively. A scientist able to demonstrate he or she can "see like a Rover," as Vertesi describes, is also demonstrating that he or she has acquired the skills of the community. Learning the conventions of seeing a signal as a planet and evaluating whether a visualization adequately demonstrates the existence of a planet was often a group undertaking, as I witnessed several times amongst the MIT exoplanet group at MIT. In these conversations, it becomes apparent that learning to see is a collective activity, and it is the successful exoplanet astronomer who is able to discipline readers to see in a similar manner.

"Is this real? Do you believe this?" A paper was passed around on a Monday afternoon in June at an exoplanet meeting at MIT. This informal meeting was a weekly occurrence at which professors, postdocs, visitors, and students met to discuss recent (and often controversial) discoveries in exoplanet science. We sat on couches in a circle on the ninth floor of the Green Building, enjoying the view of clouds rolling over the Charles River. The eight of us present, slightly less than usual because spring term had ended, were discussing a paper announcing the first planet discovered by the astrometry detection method (Pravdo and Shaklan 2009).[23] To assess the paper, we went through it

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[23] Astrometry, like the Doppler Method, detects planets by observing the motion of the parent star. Whereas the Doppler Method measures the speed of the star, astrometry measures side-to-side motion of the star's position in the sky. Though astronomers have been using astrometry since the 19th century to study binary star systems, it has thus far been unsuccessful in detecting exoplanets. In the mid- to late- 20th century, several planetary detections were made using astrometry, but all were later declared erroneous (Boss 2009).

figure by figure. With each figure, Seager asked whether it was "believable." We paused at the third figure, a scattering of points with error bars depicting the radial velocity measurements. Seager said that we are "supposed to see a sine curve" in this graph (indicating the presence of a planet). One of the graduate students laughed, saying that he could also see a straight line because there were so few points and the error bars were so extended. In figure five, the authors made the sinusoidal shape more convincing by fitting the data to a curve. Upon viewing this figure, the group's skepticism did not budge, and someone imagined other reasons for this behavior, a centroid shift perhaps. Finally, we came to the figure that was the crux of the paper's argument. This was not a typical representation in exoplanet astronomy. It was a display of the predicted Keplerian orbit for the exoplanet based on the right ascension and declination measurements (coordinates in the equatorial coordinate system) of the host star for the eleven observations. The theorists, unfamiliar with this kind of representation, looked to graduate student Elisabeth, the most experienced observer, to interpret this figure. "I don't believe that orbit," she declared, but compared to the other figures this plot was the authors' most convincing visual argument that a planet existed. But all it actually told us was that the star was in two positions, not that there was a planet orbiting it. Our discussion of this paper concluded by pointing out a weakness of the paper overall: there were too many figures and the authors should have done a better job in selecting what the reader needed to see. The visual argument did not come together.[24]

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[24] It seems the group skepticism was warranted. Less than a year after this discovery, a paper came out by a different group claiming that no variability was detected in the host star and the prior planetary claim was unfounded (Bean et al. 2010). The Exoplanet Encyclopedia (exoplanet.eu) catalogs this "planet" under "unconfirmed, controversial, or retracted planets."

The language of "seeing" and "believing" is predominant in this discussion. Whether or not the authors can get the reader to "see" the data in the same way they do is crucial for community acceptance. Planets must pop out of the graphs. The persuasive power of visualizations in science has been well established and the case above makes such power quite stark.[25] Lynch and Edgerton elevate representations from the status of "by-products of verbal 'ideas' or experimental logic" (1988, 186) placing visualizations on equal footing with the surrounding text in scientific and popular articles. Attending to the practice of how astronomers discuss papers, by focusing primarily on the images often without even reading the text, suggests that the pictorial, in exoplanet astronomy, is primary to the textual or verbal way of arguing.

Visual modes of arguing extend beyond published papers. During the summer research project, undergraduate Sukrit was working on his processing algorithm and wanted to share his progress with Seager, Aaron, and myself. He performed Fourier transforms on light curves he downloaded from the CoRoT database, but when he showed us the transformed image, it still looked very noisy and failed to pick up dominant frequencies. To convince us that his technique works, he did not show us the code but instead before and after images with a test data set. That convinced us that for "clean" data - data that behaves - the transform functioned as expected. Convincing other researchers of the proper functioning of data processing is, more often than not, a visual argument.

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[25] I provide a few points of entry to the vast literature concerning visualization and science. Kemp (1997) discusses basic mechanisms of seeing for scientists. Daston and Galison (2007), in their study of scientific objectivity, demonstrate how epistemic norms are inscribed in images. Lynch and Woolgar (1990) focus on how scientific images are products of practice. Specific case studies from Holton (1998), Rudwick (1976), and Cambrosio, Jacobi and Keating (1993) focus on the emergence of specific representations and how new ways of seeing correspond to new ways of knowing.

These visual arguments are accompanied by verbal explanations. In paper writing, you have only one opportunity to explain (visually and verbally) how a graph should be interpreted. As Leslie and Seager worked on drafting the paper modeling the interior of GJ 1214b, Seager asked Madhu for feedback. He returned with only one comment, asking Leslie how one is supposed to read the ternary graph. Since the ternary graph is borrowed from geology and not customarily in exoplanet papers, an explanation was needed so a reader could understand what they were "seeing." "You get wrapped up in what the model did," Seager explained to Leslie, "but the reader wants to know what the model means." Before Leslie could start detailing the implications of the ternary diagram, she had to explain how it is visually interpreted. For the paper to be successful, Leslie must discipline the reader to view the graph in the same way she views it.

In *Laboratory Life* Bruno Latour and Steve Woolgar (1986) provide a foundation for the anthropology of science, showcasing the analytic fruits of spending extended time with scientists in their place of work. They detail the construction of scientific facts, introducing the idea of "inscription devices" that scientists employ to represent scientific objects. Latour and Woolgar spend less time on the actual visualizations produced by these devices and focus instead on the exchange of verbal and written statements. The account I provide of scientific work extends the approach presented in *Laboratory Life* with an explicit focus on scientific images. This offers a framing that accentuates the practices of seeing needed to understand the visualizations. I find this focus on images, rather than statements, reflective of how the community of exoplanet astronomers reaches consensus. They first and foremost create and circulate images, and only after an image is agreed upon are statements of fact drawn up. This was most evident both in the writing (as I encountered with Leslie and Seager) and discussing of papers.

Though exoplanet astronomers treat the images as stand alone products, the mentoring by Seager and the group conversations I described suggest a significant amount of training is needed to see like an exoplanet astronomer. Further, astronomers also discipline themselves to see even their own data in a certain way. Talking with a postdoc about his paper on binary star systems with misaligned axes (a research approach that can also be applied to star-planet systems), I asked how he created a picture of the system in his mind. He described taking oranges and moving them around in his hands to understand how the stars would move. He translates this movement into a mental picture of how the spectrum is affected by blue and red shifts. This mental picture accompanies him to the observatory where he compares what he expects to see with the data from the telescope to confirm his theory. His understanding of the system morphs from three-dimensions (when manipulating the oranges) to two-dimensions. He makes the comparison between expected and observed in two-dimensions before expanding back to stellar behavior in three-dimensions. When asked what convinced him that his theory of misaligned axes was correct, he responded, "it was looking at this graph." The data that made up that graph were processed in such a way that the final representation closely matched his mental preconception. He trained himself to see data in two ways. First, he has learned to see as a telescope sees (seeing with the system), understanding oranges in graphical form for the purpose of comparison. Second, when he sees through the noisy, only slightly processed data at the observatory, he finds the signal he is looking for. Ultimately, the representation he sought to produce is what convinces him his theory is correct (the philosopher of science would describe this as the theory-ladenness of observations).

What astronomers are mentally imagining, in terms of planetary bodies, depends on the kind of data they are looking at. Working with photometry data is a first order approximation of the size of the planet, so an astronomer starts imagining if it is a big or small planet. Those looking at radial velocity data or thinking about the star-planet system as a whole see an orbit rather than an object. When I asked Madhu, the postdoc who developed the statistical approach for the modeling of exoplanet atmospheres, what he imagines when he hears the planet name "HD 189733b" he laughs and responds, "Nothing, it's a name." When pressed, he explained that he doesn't start thinking about it as more than just an object until he starts thinking about it as a problem and then he starts imagining the different layers of atmosphere. But even more than picturing the planet in his mind, he is picturing the star planet system and how the light travels from the star, through the atmosphere of the planet, and gets collected by the telescope.

In each example, translating these graphs into visual objects is not an easy or natural task, despite claims of "seeing the planet" in the data. Seager tried to explain, "A picture doesn't jump in my mind, it's really much more complicated. I've never really articulated this, so it's very challenging… I think of the processes that are happening in, I don't know if it's a visual way, but in a very deep way inside my brain, so I don't know if I can communicate it." She tried to pick out a couple of diagrams (from her dissertation and from a presentation) to explain what she imagines when she thinks about a specific planet, but she can't quite convey the experience.

"Nobody has really said definitively 'this is what this planet looks like,'" a postdoc explained to me. Atmosphere and interior modelers have gone to great lengths to see beyond the signal, but they are still working in graphical formats. This postdoc had started producing 3D models of exoplanets, seeking to constrain the shape of exoplanets and pin down their oblateness. When I asked him what the specific exoplanet he is modeling looks like in his mind's eye, he immediately answered "squat." For him, this is the first step towards spatial resolution, towards producing a "macroscopic observation," in exoplanet astronomy. Though this resolution cannot yet be achieved, at least he can make computer models depicting the shape of the exoplanet.

This gets at a central irony in exoplanet astronomy: despite the emphasis on "seeing," exoplanets are unseen.[26] Unlike inscriptions and photographs of scientific objects (Rudwick 1976; Latour 1987; Lynch 1991; Canales 2010), there is no image of the object itself in exoplanet astronomy. Astronomers have thus crafted many different representations – from light curves to ternary diagrams to visualized statistics – to stand in for the planet. Exoplanet astronomy as a new visual culture is one with many layered and new ways of seeing. Seager elegantly described this way of seeing as understanding "data as art":

> It's sort of the way you would go and look at art… You're looking at [the light curve] on many different levels, right? One is aesthetic appreciation, like 'oh this is so beautiful I just want to swoon.' Or it's so shocking or it's just vibrant. And then I'm looking for patterns. Like in [a painting], the artist often had something else in mind. Something deeper. So we have to look a level deeper. A level deeper is now not that simple

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[26] A few exoplanets have been directly imaged such as Formalhaut b (Kalas et al. 2008). Even when imaged, the planet is still only a point source – barely distinguishable from the artifacts and dust also captured in the image.

> appreciation, but it's what's really going on here. And it gets more technical. But all this happens almost instantaneously in a very mixed up way… When you say 'what does a planet look like' this is what a planet looks like: a transit light curve.

And yet the transit light curve is only a few steps down the planetary pipeline. The exoplanet astronomer does not stop wondering what an exoplanet is like once the light curve is produced. In working to understand their scientific object, astronomers leverage abstracted graphs, mental pictures, and linguistic analogies. To make these distant objects tractable, astronomers craft planets and at the same time they are crafting them as places. Place becomes a frame by which to make the strange familiar. In pursuing places, astronomers ground their professional identities by making their planets of study seem less like ephemeral, distant objects and more like intimate, recognizable places.

Two

Inhabiting Other Earths through the Places and Non-Places of Astronomy

I am standing on the "edge of the abyss," or *tololo* in Aymara, the language indigenous to this part of Chile. To the west stretch the desert mountains of the Andes, a natural border between where I stand in central Chile and neighboring Argentina. I am careful with my footing as I walk along the mountain's edge, kicking up dust and startling small songbirds. To the east, up a small rise on the 2,200-meter peak of Cerro Tololo are the telescopes of the Cerro Tololo Inter-American Observatory (CTIO). At night, I find myself standing at the edge of what some might think of as a celestial abyss. Looking up at the stars, I place my hand on the wall housing the 1.5-meter telescope to make sure I do not fall over as I get lost in a view of the night sky as I have never seen it before. Earlier in the night, a brilliant moon outshone the clusters of stars and galaxies now observable with the naked eye. At one or two in the morning, as I step out of the observatory for the first time since the moon has set, I gaze dumfounded at the sky, brought out of my silent reverence only by the creak of the neighboring 4-meter telescope as its dome rotates to find a new stellar target.

I confess that this sort of romantic rumination was not typical of my time at CTIO. Moments before I found myself gazing up at the glorious night sky, I was inside the observatory's control room, where I had been sitting for several hours. Perched in a dimly lit room with a linoleum floor and a drop ceiling, accompanied by four other people and three times as many computer monitors, I was struggling to keep my eyes open. My trip outside was practical – meant to wake myself up with the fresh, mountain air rather than provoke a starlight-induced reverie. This moment exposes a dichotomy between mundane work and sublime celestial wonder in that I encountered during my brief peek at the practice of observational astronomy. The notion of sublime captures the greatness of the natural setting, the technological setting, and the scientific aspirations of those occupying these observatories. I contrast this with the mundane tasks carried out at the telescope. I use "mundane" to signal activities and things that are both ordinary and earthly (as opposed to heavenly).

In observational astronomy, the mundane is the gateway to the sublime; the repetitive tasks have the potential to yield fantastical results. The sublime and the mundane are motifs that guide this chapter's focus on the search for Earth-like planets. An Earth-like planet is one that has similar conditions to our Earth and thus might support an environment and even life that we might find familiar. Every astronomer I spoke with, even if their work dealt with "new and weird" planets, was keenly following projects aimed at finding a "true Earth analog."

I went to Chile from the 18th to 23rd of March in 2010 to understand a modest project of this kind lead by Yale astronomer Debra Fischer. Fischer is using the Doppler method and looking at only two stars, hoping one will host an Earth-like planet. The summer prior to my Chile trip, I attended a science team meeting held in a conference room at NASA Ames Research Center. This meeting was convened to discuss the first data received from NASA's Kepler satellite. Kepler is a space telescope launched in 2009 that employs the transit method and continuously surveys 100,000 stars in search of an Earth-like planet. In both ethnographic experiences, I witnessed the mundane ways data that might contain "the holy grail" of exoplanet astronomy were discussed.

Within this chapter, the observing eye of astronomy, trained on detecting another "Earth," moves along a trajectory that travels ever further from our own Earth. I begin at CTIO, a grounded, mountain-top setting, and then proceed to a discussion of Kepler, which, to avoid interference from Earth's atmosphere, orbits around the Sun trailing the Earth. My final stop is at a theoretical Archimedean point, an ideal point from which an observer claims to have an objective view. The Archimedean point described by my planetary scientist interlocutors is one imagined by theoreticians who ask what Earth would look like as an exoplanet. Here, the observing eye is placed at such a great distance from Earth that when it looks back, Earth has dissolved into nothing more than a point, what Carl Sagan called a "pale blue dot" and what Sara Seager calls spatially unresolved. These places and non-places juxtapose the sublime desire to find a planet like our own with the mundane qualities of astronomical practice.

As I proceed from CTIO, to Kepler, to an Archimedean point, I keep my eye on the notion of "habitability." Astronomers speak of "habitability" as they describe Earth-like planets. "Habitability" is a word that captures the lofty aspiration of their project (to find a planet that might be occupied by life), while maintaining a utilitarian feeling.

I also suggest that habitation, in addition to being a research goal, serves as a useful frame within which to consider the changing role of observation[1] within astronomy. I use the phrases *observing at, observing with,* and *observing from* to signal the dominant modes of observing characteristic of CTIO, the Kepler satellite and an Archimedean point. These different modes of observing reflect different modes of

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[1] Like many works preceding this one, I am discussing observation in the context of astronomy. Lorraine Daston and Elizabeth Lunbeck (2011) have recently edited a volume that considers the history of observation across disciplines. Their metaphorical notion that "observation discovers the world anew" (1) is quite appropriately borne out in the search for habitable exoplanets.

habitation. When *observing at*, the astronomer lives at the telescope facility, fully inhabiting the environment of the telescope. When *observing with* a satellite like Kepler, there is no observatory to inhabit, so the astronomer instead inhabits a sociotechnical network. The materiality shifts from buildings to Internet infrastructure, but both are still intensely social activities. Finally, when *observing from* an Archimedean point, an astronomer inhabits a cognitive space, an imagined isolation neither grounded on Earth nor in a network. There is hesitancy on the part of astronomers to abandon emplaced practices of astronomy. Even as inhabiting a specific location becomes less necessary for current practice, the rhetoric of the importance of being there persists.

Most of the planetary scientists' offices I visited during my fieldwork were adorned with pictures of their research: an artist's conception of a discovered exoplanet or high resolution photographs of Martian terrain. Sara Seager's office at MIT has an artist's conception of an exoplanet that looks eerily familiar. During one of our conversations, she gestured to her picture and asked, "Do you know what that is?" Not sure of what she meant, I hesitated and said, "Well, it looks like a true Earth analog." Seager nodded, "I mean that's why I have it... That's my image of a planet I want to find." As no habitable planets have been detected to date,[2] Seager, like many others, would like to be the first to announce such a discovery. For now, the picture reminds her of the sublime wonder she must keep in mind, but also put aside while writing papers, proposals, and code.

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[2] Several astronomers have claimed to have detected habitable planets. In a recent case, the announcement that Gliese 581g was in the habitable zone (Vogt et al. 2010) made national news (Overbye 2010). The exoplanet group at MIT discussed the scientific paper with skepticism, wondering if the planet was just an error in the data. Discussing this planet again several weeks later, they reported that at an exoplanet conference in Torino, an astronomer questioned this discovery based on a more complete data set. While the discoverer remains convinced that this planet exists, it is widely considered "uncomfirmed."

The Sublime Aspirations of Habitability

Back on the mountaintop, somewhere in the crowd of stars we gazed up at were Alpha Centauri A and B. This binary system, composed of two stars similar to our Sun, is the closest stellar object to our Solar System. Detecting a planet in this system would be a discovery of note. So far no astronomer has detected large planets around these stars. Planetary formation simulations suggest that if planets do exist around Alpha Centauri they will be closer in size to the Earth and possibly orbiting in "the habitable zone" (Guedes et al. 2008). The habitable zone of a star, defined in its most basic terms, is the region in which liquid water can be sustained on a planet's surface. In our Solar System, Earth is the only planet residing within the habitable zone.

"Habitable planet" is the term preferred by astronomers when discussing Earth-like planets. To describe the importance of such a discovery, astronomers make appeals to history and humanity that call upon the language of the sublime. In a 2008 report by the Exoplanet Task Force, the authors suggested that discovering an Earth-like planet would complete the Copernican Revolution. If such planets were detected, gazing at the stars would tempt us "with wild dreams of flight" and we would "refocus our energies to hasten the day when our descendants might dare to try to bridge the gulf between two inhabited worlds" (Luine, Fischer, Hammel, et al. 2008, 5). A similarly breathless statement was issued in the Exoplanet Community report the following year: "Astronomy has been an important preoccupation of humans for thousands of years, but the most profound questions—'are there other worlds and other beings?' reach back to the origin of *homo sapiens*" (Lawson, Traub, and Unwin 2009, 1).

The astronomers I spoke with were no less sensational when they tried to explain their motivation to search for habitable planets. "I don't want to feel anthrocentric [sic] or Earth-centric… I want to see the validation that, you know, it's more than just us in some sense," a postdoc told me. In drawing the connection between exoplanet astronomy and astrobiology, he remarked that figuring out whether or not other life exists drives him. "In the end we want to find other Earths, we want to find something similar to us. Or at least just an indication that there's something that can yield life somewhere else."

Exoplanet astronomers carefully distinguish between the search for life and the search for habitable planets (which does not necessarily imply the existence of life). Fischer, my host at CTIO, pointed out that astrobiology "profoundly underlies this whole search [for exoplanets] and is rarely sort of discussed. I mean, not as the upfront story but without that we wouldn't be doing what we're doing." When I asked why, she perfunctorily responded, "Because we were penalized for looking for little green men." A professor at MIT echoed this sentiment, saying that it is increasingly acceptable to talk about life even though it was taboo only ten years ago. "Especially since this [search for life on other planets] doesn't have anything to do with intelligent life. We're not listening; we're not looking for civilization necessarily. We're looking for an atmosphere that's like the Earth, that's been processed by living things."

Even when discussing habitable planets removed from an astrobiological context, biological similitude remains a dominant metaphor. Jack Lissauer, a Principle Investigator on NASA's Kepler mission, likened the spectrum of exoplanets that must exist to a planetary zoo. In a podcast recorded prior to the mission launch, Lissauer explained that the planets found by astronomers so far are easier to spot, like hippos and rhinos in a zoo. "But what's most important to us, is the primates. And Kepler is sized so that it can detect the primates of the planet population. The planets that are analogous to our Earth" (Carpenter 2009). This metaphor calls attention both to its anthropocentrism and its somewhat off-register scales of comparison. If Lissauer were true to the scales invoked by the metaphor, in which hippos are easy to spot, it would make more sense to compare habitable planets to beetles, not primates. But these imagined planets have an aura about them; they are like yet not like Earth in the same way humans are like yet not like primates in the zoo. In describing habitable planets as "primates," Lissauer calls upon a biological metaphor to underwrite the epistemological warrant for this search.

What then are the stakes of a search for a habitable planet aside from the direct consequence of locating extraterrestrial life? Is there a spatial curiosity accompanying the biological curiosity? To detect a habitable planet is to embrace the possibility that places on Earth can be reporoduced elsewhere and that amidst the "inhospitable" exoplanets, there are exoplanets we humans are capable of inhabiting - of *being* on. More explicitly, I at numereous times and under various circumstance heard astronomers baldly state that finding another habitable planet will allow earthlings to finally know our "place in the universe."

For engineer Stephen Dole, habitable planets are destinations for humanity, as he explains in *Habitable Planets for Man*. Writing post-Gagarin but pre-Armstrong (and with a hint of the burgeoning environmental movement, as he writes that Earth has already been exposed as "a tiny oasis in space"), he offers a quantified accounting of what is meant by "habitable planet." He is not concerned with how to get there, but in providing a probability that such planets exist and where they might be located. Defined simply, a habitable planet is "an acceptable environment for human beings" (Dole 1964, 1).

For contemporary exoplanet astronomers, searching for habitable planets might be fueled by the grandiose aspirations of finding a destination or searching for life, but with respect to daily practice, it is the solution to a statistics problem. Inspiration might strike while gazing up at the night sky, but the real work happens in front of a computer and discourse is dominated by methods of data processing and analysis. Though the Kepler team would like to announce the detection of dozens of habitable planets, the minimum requirement for mission success is a numerical pronouncement of Earth-like planetary plenitude. The Kepler telescope is focused on a sample of stars in one region of the sky that will be a statistical representation of the entire galaxy. At the science team meeting at NASA Ames, excitement grew not from romancing the idea of Earth-like planets, but by revealing how clean the data were.

Fischer's project, at CTIO and Yale, to find a habitable planet around Alpha Centauri, relies on statistics and calculation in a different way than the Kepler project. Her research is designed to measure two stars constantly for several years. Once she amasses enough data, she will compile her observations and analyze them to detect a signal through the noise. At the observatory, the word "planet" was mentioned only a few times and "habitable planet" was absent from conversation. Instead, we discussed the instrumentation and sources of error in data streaming in from Alpha Centauri.

And yet, Fischer designed this project because of the allure of finding a habitable planet around our closest stellar neighbor. The first time I saw Fischer speak in October

2009, she delivered a charming talk to a group of scientists and social scientists gathered at the Radcliffe Institute for Advanced Study in Cambridge. She was practiced in describing her research, knowing how to interest a diverse audience with artistic renderings of the planets she has discovered and tales the delight expressed by school-aged children in the new planets. She calls her research on Alpha Centauri A and B "Project Longshot," because those are the odds of detection. Even so, she is not alone in her pursuit. A mere 65 miles north of Cerro Tololo, the European Southern Observatory hosts the La Silla Observatory on a 2,400-meter peak. On a clear day, standing on Cerro Tololo and facing north, one can see the glint of the many silver observatory domes of the European institution. There, Michel Mayor (famed co-discoverer of the first exoplanet), is demanding that the High Accuracy Radial velocity Planet Searcher (HARPS) affixed to the 3.6-meter telescope spends part of its time focused on Alpha Centauri A and B. The close proximity of these two teams creates some tension. Fischer, during her talk at Radcliffe, joked how when she looks over at La Silla's peak, she secretly hopes to see clouds covering their sky.

Mundane practice and inhabiting observatories

Anthropologist Valerie Olson demonstrates how words such as "habitable" and "habitability" are prevalent yet unwieldy in the aerospace lexicon. These terms are used at the interface of professional worlds, between space architects and engineers, for example, to guide the design of lunar, Martian and other structures intended for extraterrestrial human working and living. Engineers view habitability as a design requirement, reducible to a single metric, whereas architects attempt to intervene and preserve the aesthetic worth of these structures, mitigating "the 'uncanniness' of [...] 'unhomely' space vehicles" (Olson 2010, 179).

Though the invocation of habitability is very different for my interlocutors than for Olson's, there are a few common threads. Space architects seek to personalize or at least humanize space structures, perhaps to create *places* in the midst of (outer) space. Similarly, for exoplanet astronomers, habitable planets become places in part because of their *location*. These planets are designated habitable because they are located in the "habitable zone." Terrestrial geographers and anthropologists of the late 19th and early 20th centuries first used "habitable zone" to describe climates suitable for human (and other fauna and flora) populations. The peaks of high mountains and large swaths of desert were beyond the "habitable zone" for these early scientists (c.f. Anon. 1886; Seligman 1917). The term trickled into planetary science by the mid-century, considering not the habitability of regions of the Earth but of the potential habitability of regions elsewhere in the universe. Astronomer Su-Shu Huang was the first to designate a "habitable zone" on a stellar scale as the region around a star in which a planet would receive neither too little nor too much energy (i.e., heat) (Huang 1959).[3]

A *New York Times* article in 1961 which discussed the predecessor to the Search for Extraterrestrial Intelligence (SETI) used both the term "'habitable' zone" and "'liquid water belt'" to describe the kind of (yet undetected) planets from which scientists hope to detect radio signals (H.M.S 1961). The "habitable zone" was very much a term of

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[3] The determination of too much or too little energy is presumably based on terrestrial conditions. Huang provides a circular justification. From his definition of habitable zone, he concludes that main-sequence F, G, and K stars are the most likely to host planets capable of life. "It is interesting to note," he concludes, "that our sun, which is a main-sequence G2 star, does support life abundantly on at least one of its planets, fully in agreement with the present conclusion." Also in this article, Huang speculates that if planets existed around Alpha Centauri (Fischer's star of interest), it is unlikely that they could orbit completely within the habitable zone due to the dynamics of the multi-star system.

astrobiology (or exobiology, as it was then called) and less prevalent among traditional planetary scientists. In the early-1990s, on the cusp of the detection of exoplanets, planetary scientists brought the concept of the habitable zone into a discussion focused more on planets than on the life they might host. Significantly, James Kasting, Daniel Whitmire, and Ray Reynolds (1993) published an article in *Icarus*, a leading journal of planetary science, articulating a definition for habitable zones based on the presence of liquid water. In the conclusion, the authors state the conditions under which the concept of "habitable zones around stars would assume a high level of significance." The conditions were a successful result of either "the direct telescopic search for other planets" or SETI (ibid., 126). The first condition was met in 1995, and as the authors correctly predicted, "habitable zone" has become a defining term for the practice of exoplanet astronomers. The habitable zone carves out a place for habitable planets to exist.

Interestingly, the *practice* of finding such a place, such a "habitable" planet, is becoming unmoored from the sorts of terrestrial *places* traditionally associated with astronomy. Location has always been epistemologically important to astronomy, but now the place of authority is just as likely to be virtual (in the case of Kepler) or imagined (as with the Archimedean point), as it is to be an actual observatory. It was the observatory, however, that used to be the undisputed authoritative site of astronomical practice.[4] Historians and early astronomers wrote observatories into a narrative of seclusion, describing a near religious communion for scientists with the stars. For

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[4] For a history on the role of observatories in modern astronomy, see (2004). For the social history of observatories, with an emphasis on gender roles, see Pang (1996) as well as Nisbett (2007) who addresses themes of gender and national interest alongside the economic history of establishing observatories. Several volumes in the history of astronomy focus on astronomy beyond the observatory in the form of expeditions, notably 19th century solar eclipses (Canales 2002; Pang 2002).

example, Percival Lowell wrote at the turn of the century of the scientific purity afforded by newly established mountaintop observatories: "[The astronomer] must abandon cities and forego plains. Only in places raised above and aloof from men can he profitably pursue his search, places where nature never meant him to dwell… Withdrawn from contact with his kind, he is by that much raised above human prejudice and limitation" (quoted in Lane 2009, 137). Drawing attention to this genre of romancing the mountaintop, historian of science Simon Schaffer pointed out in a lecture delivered in Cambridge, UK on February 16, 2010, histories of astronomy are often written as histories of confinement. As a recent example of this refrain, Schaffer refers to an essay by Michel Callon from *Acting in an Uncertain World.* There, in a chapter entitled "Secluded Research," Callon describes a visit he and his son made to the Pic du Midi observatory in the French Pyrenees. This piece demonstrates uneasiness with the narrative of solitude, yet doesn't question its veracity. Observatories, Callon writes, were designed as monasteries in which to contemplate not God but the heavens. Observatories as laboratories strive to be unaffected by the world. In the modern observatory, scientists interact as little as possible with the instrumentation so as not to disturb the finely calibrated machine. However, Callon observes, the observatory is nonetheless still in the world and the environment (in the form of clouds and light) ultimately intervenes. Callon's purpose in identifying astronomy as "the pursuit of extreme seclusion" is a critique of the increased exclusion of the layperson and the amateur from the scientific process (Callon 2009, 40). Schaffer, in his lecture and other recent writing on 19th century astronomy, seeks to shatter this illusion of astronomy as a secluded science by offering instances of the social and cultural influences of observatories on the greater world in the imperial (not to be mistaken for empyreal) context (Schaffer 2010a; 2010b).

The observatories about which both Schaffer and I write are animated by technical and social interactions within and beyond their locations. As I consider three modern day "observatories," CTIO, Kepler, and an ideal Archimedean point, I gesture towards new presences associated with contemporary observing practices. Astronomers searching for habitable planets themselves *inhabit* each observatory in a different way. When observing *at* CTIO, astronomers inhabit the facility completely as they live and work on the premises. Yet, as I will show ethnographically, the work done at the observatory is removed from the act of observing as there remains a physical divide between the instrument and astronomer. To observe *with* Kepler, meanwhile, a space telescope that is entirely uninhabitable, work is accomplished solely through a sociotechnical network. There are similar practices associated with CTIO and Kepler, though the latter is freed from the myth of seclusion signaled by the Chilean brick and mortar observatory. Finally, in my third case, theoreticians seek to observe *from* an Archimedean point, which here represents an ideal observatory. Though it lacks materiality, astronomers cognitively inhabit this point in an effort to make progress towards understanding Earth-like planets even before they have been discovered. I begin where the observers' gaze is most emplaced on Earth; I begin at the observatory.

Observing at CTIO

Debra Fischer enthusiastically welcomed me to join her on an observing run to CTIO. Though many other astronomers told me that observing was actually quite boring and they didn't know what I would learn by being there, I insisted that being bored on the top of a mountain in South America was itself interesting. I went to Chile in order to understand the place(s) of the observatory. Understanding the observatory as embedded in a country, not just as a space apart atop a mountain, began when I landed in Santiago and continued during my one night stay in La Serena and my journey up the road to the observatory. As I lived and worked for several days at the facilities on the summit, I experienced the place of the observatory as being caught between the technological sublime of the landscape and the technological mundane of instrumentation, data reduction, and paper writing with which Fischer and her two students, Matt and John, occupied themselves.

Santiago

My trip to CTIO was scheduled to depart the US on March 17, 2010, just three weeks after a magnitude 8.8 earthquake shook south and central Chile. The costal town of Concepción and the surrounding region experienced major destruction from the earthquake and ensuing tsunamis. The sensitive instruments at CTIO, located further inland but well within the earthquake's zone of attack, reportedly shook ferociously. The CTIO facilities were presciently designed to withstand a magnitude 9 earthquake and I was told that astronomers experienced no disruption in their observations.[5]

Though the capital of Santiago was relatively unscathed, the international airport suffered major damages. After being closed down for three days, the airport re-opened in early March with limited services. By the time I arrived, early in the morning on the 18th,

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[5] An even larger earthquake (magnitude 9.5) devastated the same area while Jurgen Stock was scouting mountain locations for CTIO. He reported that the earthquake did not affect Santiago, but were felt quite strongly around La Serena (Stock 1960a).

most domestic and international flights were proceeding as scheduled, but there was still an air of organized chaos on the ground. Due to the earthquake, Chilean officials decided to postpone changing the clocks for day light savings time to avoid further confusion, though the time system on the airplane reflected pre-earthquake adjusted time. I am still confused as to whether I landed at 6:30 or 7:30 in the morning. After claiming my bags in the international terminal (which aside from a few fallen ceiling tiles, appeared undamaged), I followed signs to the domestic terminal, which was temporarily being housed under a large tent in the parking lot. Temporary ticket counters and two security lines were set up on one side of the tent separated by thin sheets from the gates. After passing through security, I sat in a folding chair and watched passengers for earlier flights queue up in three cordoned aisles. To announce the boarding of a new flight, an airport worker erased information about the now departed flight from a white board at the front of the aisles and wrote the new flight information with a nearly dried out black marker. When my flight to La Serena appeared on the white board, I got in line where a woman checked my ticket and broadly gestured behind her to the tarmac. I followed other passengers climbing up stairs to board Airbus 318s. The three aisles for three separate flights merged into one stream after our tickets were checked, and we were left to sort ourselves out and climb on to the correct airplane. I followed the gentleman in front of me aboard a jet and confirmed with the flight attendant that this plane was, in fact, headed for La Serena.

As I waited for my bags in La Serena, I was surprised to see Debra Fischer and her graduate student, Matt, there as well. We had unexpectedly been on the same plane. They were supposed to have arrived at La Serena a few days earlier, but because of the earthquake, they had been unable to switch their tickets to an earlier flight. Fischer looked like a seasoned traveler in her grey slacks, a striped button down shirt and a black polar fleece vest; all pieces were tailored yet loose fitting. Matt, in his California Academy of Science t-shirt and faded jeans looked like a science grad student. After retrieving our bags, we found the car waiting to shuttle us to the CTIO off-mountain headquarters in La Serena.

La Serena

The administrative facilities in La Serena, a two-hour drive from the telescope, were originally built in the early 1960s, a few years after the planning for CTIO began. The brainstorming for what would eventually become CTIO began in 1958 after a Chilean astronomer approached astronomers at the University of Chicago about establishing an observatory in Chile.[6] At this time, there were only a handful of observatories in the southern hemisphere, and none at a particularly high altitude. The Association of Universities for Research in Astronomy (AURA) on behalf of the National Science Foundation partnered with the University of Chile and by 1962 had, as a result of a multi-year survey lead by Jurgen Stock, settled on the Cerro Tololo peak. After this decision was made, AURA began constructing the facilities at La Serena to house the un-built observatory's first administrator, science staff, and maintenance workers.

By 2010, the infrastructure has been much expanded. Now, there exists a research complex that houses the dozen or so resident astronomers as well as a few administrators and IT technicians. There is also a lecture hall and library forking off

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[6] This history of CTIO comes from two accounts written by Victor Blanco, the observatory's director from 1967-1981 (Blanco 1993; 2001).

from the main lobby. In addition to this building, there are several maintenance buildings, houses and apartments, as well as a "motel" where visiting astronomers stay. Our logistics coordinator directed Fischer, Matt, and myself to this complex and gave us keys and room assignments. This 9-bedroom strip of rooms (each with a private bathroom) and communal lounge was pre-fabricated in the US and sent here in the late 60s. I dropped my bags on an unadorned table and gazed longingly at the twin beds, but it was not yet time to rest. For astronomers visiting CTIO, La Serena is a liminal place – the observing trip has begun but one is not yet on the mountain. During our day in La Serena, we met and discussed progress on Fisher's project and instrument development. At night, we stayed up late in preparation for the subsequent nights of observing. We did so by exploring the restaurants and sites along La Serena's coast.

Fischer is collaborating with Andrei Tokovinin, a resident astronomer who observes at CTIO on some nights and resides within the La Serena complex. He is the instrument builder for the new spectrometer that Fischer is making to improve the performance of her telescope. As soon as we stored our bags in our rooms, Fischer, Matt, her other student John (who had arrived several days earlier), and myself went to meet with Tokovinin to discuss the status of the spectrometer.

Fischer designed Project Longshot to use the radial velocity, sometimes referred to as Doppler, detection method. In contrast to the transit method (discussed in the pervious chapter), where one collects the fluctuating brightness of a star (photometry), radial velocity uses spectroscopy – the careful measurement of stellar wavelengths – so as to most accurately detect red and blue shifts. These shifts in the spectrum indicate movement of the star. A red shifted star (one in which light waves are elongated) is moving away from the observer and a blue shifted star (with compressed waves) is moving towards. Slight changes in the shift, a wobble back and forth between red and blue, indicate the presence of an astronomical companion pulling on the host star.

Astronomers detect the subtle shifts in the spectrum caused by a companion exoplanet, especially Earth-sized or smaller ones, in several ways (though there are skeptics who claim that detecting a small planet from a ground based as opposed to space observatory is beyond the capability of current instrumentation). Fisher uses a technique she learned as a postdoc, working for Geoff Marcy at the Lick Observatory. Marcy and Paul Butler, when they first began trying to detect exoplanets, followed a technique pioneered by the Canadian astronomer Bruce Campbell. In order to measure the shift of the spectrum, there needs to be a baseline against which to measure. Right before the CCD collects an imprint of the starlight, the light passes through a cylinder of a gaseous element for spectral comparison. Marcy and Butler improved upon Campbell's technique by using iodine as this element instead of the dangerous and unstable hydrogen fluoride (Lemonick 1998, 67-70).

Fischer continues to use this technique. When she first began Project Longshot at CTIO, she was using a "vintage" spectrometer that "was lying in the basement [of CTIO] just completely ignored and we dusted it off, polished it up, and sent a fiber to the 1.5-meter telescope." Even with the iodine cell, the resolution was not good enough for the precision she needed. But, with what she called "NSF stimulus money" she won a grant to build a new instrument specifically for the telescope. The new spectrometer, which Tokovinin is fabricating, will be precise enough to detect an Earth-sized planet orbiting around Alpha Centauri, if there is one to be found. Fischer, who had no experience with instrument design before this project, also works with two postdocs who were not in Chile for this observing run. These researchers were nonetheless able to participate in the "face-to-face" meeting with Tokovinin thanks to the video conferencing capability of Skype, a communication application Fischer ran on her computer. As the meeting wrapped up, Tokovinin and Fischer both marveled at how much they accomplished that day. This meeting expedited what might have taken days to discuss over email. They concluded that there is something to be said for face-to-face collaboration, leading me to believe that being at the observatory is as much about social interactions as instrument proximity.

Our meetings ended around four in the afternoon. Tokovinin was catching a 6:30 transport up the mountain and could not join us for dinner, but the four of us decided to go out in La Serena. As this was Matt's and my first time here, we were excited to see what kind of place this was. As La Serena is located on the Pacific Coast, we decided to eat near the ocean where the resort hotels are. Elsewhere in the city are a university, a shopping mall with an English and Spanish movie-theater, and an historic district where tourists (Chilean and others) go to buy craft goods and tour the 19th century missionary churches. Our taxi drove us on the road adjacent to the beach. The hotels all displayed vacancy signs, indicating that even though the air was still warm tourist season had long ended (and travel plans were disrupted following the earthquake). We asked the driver to recommend a restaurant and he dropped us off in front of an intentionally rustic looking restaurant. A sign hanging above the front door read "Gastronico." Once we entered, and were seated, we noticed that the walls were adorned with astronomical pictures taken by the Hubble Space Telescope. Sitting beneath a spectacular picture of M51, the

Whirlpool Galaxy, we realized that the name of this restaurant was a Spanish pun on astronomy (*astronomía*) and gastronomy (*gastronomía*). Our cab driver, it seemed, had a wry sense of humor in depositing the fare he picked up at the observatory headquarters at the astronomy themed restaurant. Over pisco sours and empanadas we talked about places we have visited and would like to visit. Fischer was relaxed amongst her students, offering advice on relationships and mortgages. This easy night of conversation reflected her friendly, insightful, adventuresome, and supportive nature when discussing either science or life. A different cab took us back to CTIO's La Serena facilities, I said goodnight to my new friends and though I knew I should stay up as late as possible in preparation for tomorrow's all-nighter, I could not resist falling into bed.

Ruta 41 and D-443

We had a noon transport up the mountain scheduled for the day after we arrived. The four of us loaded our bags into a minivan and a driver was charged with getting us safely up to Cerro Tololo. Our van wound through the desert mountains as we climbed 2.2 kilometers to the peak. The scenery of this drive was startlingly similar to a drive I made weeks earlier along the California coast on Highway 1, traveling from San Francisco to Los Angeles. Just as there, the road in Chile hugs the mountain and if you swerve too far to the outside, there exists only a thin guardrail to prevent your vehicle from tumbling over the cliff's edge. The only break from the dusty brown landscape was a vast, cerulean reservoir we encountered about a half an hour outside of La Serena. We marveled at the sight until the driver, noting our amazement, shook his head and sadly told us that to build this reservoir many small towns were displaced. The settlers were forced to move up the hill and refashion their communities.

Our time on the road was brief, but represented several ways in which CTIO is tied to different local, global, and universal spatialities. The history of how this road came to be illustrates how ties between local custom and American influence culminate in the greater mission of securing access to a clear night sky. When Cerro Tololo was first selected as the sight for the observatory, the only road to the peak was a mule-trail.[7] Before a more sophisticated road was paved (one of the first construction tasks), it was a real journey to get to Tololo. It was a two-day trip from La Serena, with three hours spent in a car and seven to ten hours walking or on a horse's back, with mules hauling equipment. The leader of the "seeing expedition" that selected Cerro Tololo and CTIO's first director, Jurgen Stock, described such travel as requiring "four wheels, four legs, and two legs" (Stock 1960b, 1). The ride I received took approximately an hour and a half and required only four wheels.

Stock, perhaps exhausted from hiking up and down Chilean peaks for two years, made road building a priority during the first years of CTIO construction. AURA purchased the region surrounding Cerro Tololo in late November of 1962 and road construction began in December. Due to the challenging terrain and to several changes of oversight, the road to the summit was not completed until September 10th of the following year. The project started out under the direction of a Czechoslovakian engineer who had been living in La Serena for more than a decade, Zoltan Timkovik. Jurgen

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[7] The mule-trail only existed because when Jurgen Stock began surveying the area in 1960, he hired local workers to build a path to Tololo's summit. Before Stock began frequenting Tololo, it is unclear if there was a formal path to the top. This and other details from Stock's expedition are recorded in The Stock Reports, letters written from Stock to his supervisor, Donald Shane, at the Lick Observatory. Thank you to Ana Veliz, the CTIO librarian, for scanning and emailing me the first 16 of the 31 reports.

Stock quickly took over Timkovik's role and was himself on the side of the mountain supervising blasts and the work of the construction team. Richard Kroecker, an American contractor responsible for the road to Arizona's Kitt Peak (CTIO's 'sister' observatory), came down to Chile to advise Stock's roadwork in February of 1963. Kroecker suggested that instead of drilling and blasting, tractor work might more efficiently complete the road. Equipment was shipped from the US and Kroecker assumed responsibility for construction of the road. No sooner had Kroecker installed his equipment on the mountain then he and Stock had a "personality conflict." For several months, they disagreed and argued over the best technique and route by which to fashion the road. When Kroecker left Chile, he left behind an incomplete road. Moreover, he attempted to elicit more money from AURA, citing poor weather and Stock as unduly delaying his construction effort. To finish the road, Stock requested help from Rolf Korp who completed the summit road with neither drama nor complaint (Edmondson 1997).

After such a tribulation, the President of AURA, Frank Edmondson, suggested they follow a US tradition and hold a ceremony to inaugurate the opening of the road. The event, held in December 1963, featured speechmaking by local and national figures in Chile as well as by Americans, ribbon cutting, and the sprinkling of holy water by the Archbishop of La Serena. A second ceremony was held a year later in celebration of the completion of the observatory's cornerstone. This ceremony had for entertainment a choir of Chilean folk singers accompanied by women dancing Chilean national dances such as the Cueca. The president of AURA fondly recalls a woman holding him firmly by the hand and teaching him the dance (162).

I am inspired to read the local, global, and universal twists in the road because of Peter Redfield's ethnographic work on the French space program in French Guiana (2000; 2002). His cross reading of postcolonial studies with science studies seeks to articulate the terrestrial locality of outer space. Redfield's road is a strip of the only paved road in French Guiana that passes in front of the space center where Ariane rockets are launched. He discusses the closing of this stretch of road and the debate it created between the space center (populated and run by French citizens) and the local authorities and activist groups. The debate centered on the spatiality of the road and its belonging to both the local (a local that is still fighting against colonial after-effects) and the global/technological complex of the space program (which is pursuing the colonial enterprise beyond the globe).

Redfield explains that when the road closed, cars were circuitously diverted around the space facility. French Guianans interpreted this action as an estrangement. Flow was disrupted and traffic, formerly connected to the global enterprise of space exploration by this road, were re-assigned to more local paths. The road leading to CTIO, in contrast, was meant to be an opening, symbolic not of estrangement but inclusion connecting the local towns to the expanse of the universe. North American, colonial, and indigenous ceremonies commemorated the building of this road and the potential it had to make Chile a gateway to the cosmos.

However, the construction of the road, despite the ceremonial joining of different traditions, served to re-affirm the North Americanness of the Chilean telescope project. Before the road, Chileans were essential to the scouting and early building work led by Jurgen Stock. His progress reports detailed the local people and animals that supported his expedition. Not only did workers accompany him up the mountain to labor, on several occasions he describes small parties held on the peak for the few families that lived on the side of Tololo. One evening the Ramos family joined him on the summit with cake. They enjoyed a festive evening and "a view of the moon and Saturn concluded the pleasant day" (Stock 1960c, 2). There was even the occasional uninvited (and unwelcome) guest that camped with Stock's crew on the summit. However, with the importation of machinery and the laying of concrete, local knowledge and animals were no longer needed to summit Tololo and the observatory was marked as a place for North American astronomers.[8]

In the retrospective accounts of AURA's settling of Cerro Tololo, there are few mentions of the communities that were displaced[9] - and are still being displaced as our van driver informed us on the trip up the mountain. Redfield, attending to the different things that happen in the same place, describes the complex, overlapping spatiality of the space program in French Guiana. Similarly, CTIO is not secluded on a mountaintop, but is situated in a landscape with multiple histories and ties to the local, even if there are actions (intentional or not) that exclude the local.[10]

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[8] Chilean astronomers were involved in CTIO planning from the beginning. A Santaigo astronomer, Carlos Torres, was Stock's second in command. However, a few comments in Stock's letters make it clear that Stock never viewed Torres as a colleague.

[9] Victor Blanco (1993), the second director of CTIO, does mention that fifteen families lived on the land AURA purchased to build CTIO. They were goat herders, so in order to keep the observatory's water source clean the Ramos family in particular had to be displaced downstream. Blanco remarked that moving this family "created a difficult human-relations problem" resolved by making the family land managers of the area surrounding CTIO (excluding the summit). At some point, the Ramos family turned their house into a bar-discotheque, which resulted in increased night-time traffic on the Tololo road. This situation "was promptly terminated" as it severely interfered with observing conditions. The other goat herders whose animals did not interfere with the water supply were charged rent but allowed to remain on the land.

[10] Histories written about CTIO maintain an aura of isolation. During Chilean political unrest in the 1970s (the rise of the communist party followed by a government overthrow and rule by junta), CTIO remained at full operation. Blanco (2001, 13-14), who was director at the time, proudly recalls that they were able to remain autonomous from the local situation and almost no nights of observation were lost.

Cerro Tololo

We arrived at the summit of Cerro Tololo in time for lunch. I dropped off my bags in my private room and walked down the breezeway that connected the dormitories to the cafeteria. The cafeteria was an airy room, made more so by the floor-to-ceiling windows on one end that looked over the Andes mountain range. These windows slid open so one could step out on the edge of the mountain. There were a dozen or so hefty wooden tables, some of which sat four people while others were pushed together to accommodate six or seven. The Chilean staff of CTIO (administrators and maintenance workers, all men) always occupied the long table closest to the TV that often broadcast a soccer game. I picked up a tray and utensils and went through the small buffet, selecting an assortment of salads, fruits, and desserts. John had warned us that everything here was very sweet. I delighted in this at first, but by the end of my stay, I was craving salt and savory.

Though on the first day, we were still day-shifted and lunch was lunch, on subsequent days this meal would be my breakfast (followed by a nap). Dinner became lunch and the cafeteria would pack a bag of sandwiches and cookies and a thermos of tea or coffee for dinner at the telescope. John, Matt and I always met for breakfast, but Fischer was mysteriously absent, we assumed hard at work, during the day. We only saw her at the 6 PM "lunch" before heading up to the observatory.

On the day of our arrival, no afternoon nap was needed, and there were still several hours before the night of work could begin. Fischer had a Skype conference call scheduled, so John, Matt and I explored the facilities. The tour we guided ourselves on brought us in contact with both the technological sublime and the technological mundane.

I marveled at the large telescopes sitting on top of the mountain, with the Andes to one side and the ocean to the other. When we entered an imposing observatory, the landscape disappeared and we encountered workrooms and instrument rooms, with wires and machinery spilling out of casings.

Our trip from the sublime to the mundane began as we left the cafeteria, setting our sights on the summit. We put on hats and sunglasses to shield us from the dangerously high UV exposure on the peak, and hiked up from the dormitories towards the telescopes on the summit. As we walked up the dirt pedestrian path (at night, we drove a car on a paved road so as not to kick up dust that would interfere with observational conditions), we passed small clusters of telescopes that adorn the side of the mountain. We investigated each one, noting a set of four dedicated to astroseismology and platforms for three telescopes not yet built. The summit, which was leveled around the same time the original road was built, houses six telescopes. Fischer observes on the second largest, 1.5-meter telescope which is adjacent to the silver domed 4-meter telescope (see Figure 2.1). The grandeur of the observatories coupled with the minimalist geometric white markings against the dusty ground (reflective guides between telescopes used in the pitch black of night) evoke a technological sublime amidst the natural sublime of the view of the mountains from the summit of one of the highest peaks. The awesomeness of the natural sublime of Kant and Burke gives way to, according to Kant, a realization of humanity's ability to dominate nature. The observatory is a resolution of the natural sublime, a material domination of nature leading to a rational domination of knowing the universe. It is also a manifestation of the technological sublime as described by Leo Marx (1964). The observatory is perhaps even the quintessential South American technological sublime. Marx quotes a passage from 1844 that describes the sublimity of new forms of transportation: "Steam is annihilating space... Caravans of voyagers are now winding as it were, on the wings of the wind, round the *habitable globe*" (quoted in Marx 1964, 196; emphasis mine). With the railroad and the steamship, the globe began to shrink as humans traversed more of its area. The planet as a whole, beyond the places where people resided, became habitable.

Figure 2.1: The Technological Sublime. Debra Fischer on the catwalk of the 4-meter telescope. The 1.5-meter telescope is to the right. Photo by the author.

More than a century and a half later, it is an iodine filter nestled in an observatory that is annihilating space and helping Fischer to find another habitable globe. Then and now, people viewing the globe and universe through the frame of the technological sublime experience a shrinking of space and an expansion of the reach of habitability.

While human spaceflight extended the perceived habitable environment of Earth (Olson 2010), the search for other Earths extends the imagination of habitability even further into outer space. In doing so, new places are imagined. Matt and I stopped to enjoy our first encounter with the technological and natural sublime, while John, already familiar with CTIO, led us on to "our" telescope.

As we entered the white housing of the 1.5-meter telescope, the technological sublime was replaced by a technological mundane. The mountain vista was no longer present as we drilled deeper and deeper into the workings of the telescope and spectrometer. John was eager to show us the instrumentation of our telescope. We dropped our bags in the control room and began our tour of the machine in the dome where starlight first enters the instrument. This was not the encased, streamlined telescope that gentleman astronomers of centuries past peered into. The guts of this telescope, in the form of trusses and wires and parts I could not identify, poured out of the assembly. I would not have recognized it as a telescope. But the telescope did not end in the dome. We followed a fiber optic cable that connected the two parts of the telescope together. On one end was the assembly in the dome and on the other end, encased in a room separated from the dome by several doors, was an equally complicated apparatus. This was Fischer's spectrometer (see Figure 2.2). Now, in this cramped room, John pointed out the parts of the spectrometer: the iodine cell, collimator, echelle grating, slit, prism, camera optics, and CCD. The sense of triumph over nature was replaced by knowledge of how much meticulous work and testing went into this contraption. The technological mundane dominated the heavenly sublime.

Figure 2.2: The Technological Mundane. The image on the left is the telescope optics in the dome. On the right is the spectrometer housed in a nearby room. Photos by the author.

Because the workings of the telescope were separated in space – half in the observatory dome and half in the instrument room – it was impossible to take in the whole system at once. It is also so finely calibrated that there were few parts we could move around. The experience of being at the observatory, as far as I could tell, had little to do with interacting with the instrument.[11] And yet, this was the justification people often gave me for going to observatories. At the meeting in La Serena the previous day, Fischer commented that once the new spectrometer is running and once data of a higher quality are being collected, she will have a team at CTIO. She paused, then said on second thought, the team could just as easily be at Yale. But, she went on, "there is something to be said for being here." The others at the meeting nodded in agreement and Tokovinin recalled an "extremely rewarding night spent at Magellan [another Chilean observatory], seeing, touching the instrument." Tokovinin took on a hushed tone when recalling such a night. He cited practical reasons for needing to be at the telescope; that, as an instrument builder, seeing the telescope first hand allows him to better understand

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[11] The purpose of this particular run was replacing the old iodine cell with a new one, so there was more interaction with the instrument than usual. Fischer hand delivered the cell, wrapped carefully in foam, and spent some time during the nights swapping in and out the new cell for calibration purposes.

its outputs. And certainly there are still practical and, as I discuss below, compelling social reasons for observing at a telescope. However, one allure of the mountaintop observatory is still connected to the sublime. The experience I had of being overwhelmed by the night sky is mediated by the technology that allows one to understand, scientifically, cosmic phenomena. Being on the mountain offers a first-hand account of how the technological mundane gives way to sublime knowledge.

And yet, during most of the time we spent observing, we neither saw nor touched the instrument. Instead, we worked almost exclusively from the control room.

1.5-meter Control Room

The control room had low ceilings, no windows and was not much larger than a small classroom. There were two tables pushed together in the center of one of the walls, around which three people could comfortably work. Also along this wall were a printer, a mini fridge, and a coffee station and microwave. On the other side of the room, an L-shaped desk ran the length of two of the walls. On the desk were approximately eight monitors and above the monitors was a continuous shelf. This was adorned with control boxes, a stereo, some journals, and other miscellaneous instruments. The room was lit with dim, yellow fixtures, inviting the feeling of nighttime even without windows. On one of the walls hung university pennants from Delaware, Stony Brook, Georgia State, Vanderbilt, and Yale.

Through the computers, a telescope operator controls the telescope and collects data from the CCD. Our telescope operator, Manuel, was there for our whole observing run. Even when a visiting astronomer is not physically present, a telescope operator is at the facility. Fischer told me that most telescope operators at CTIO are Chileans with some kind of technical degree. They know a bit of programming and easily learn the specifics of the telescopes they operate. Though Manuel spent most of his down time watching TV, and his English was not very good (and only John spoke Spanish), on occasion he would ask about the research we were doing and respond with informed questions.

During our first night, inspired by the novelty of being at the observatory, Fischer (after getting a refresher course from Manuel) showed Matt and I the digital sequence for moving the telescope between Alpha Centauri A and B. The observations for this project simply involve pointing the telescope at A, taking an observation (ranging from several minutes to almost an hour), then moving the telescope to B, taking a similar observation and repeating this process for the rest of the night. In other words, it is tedious. As Fischer's method is to combine data over the entire three years of observation, there is no significant data being produced by any individual observation.

Consequently, it did not take long for the excitement of being at the telescope to wear off. Fischer and Matt relinquished control of the telescope and allowed Manuel to reposition it as needed. Telescope operators fit well into the category of "invisible technicians" that historian Steven Shapin (1989) writes about. He examines the historical relationship between Boyle and his assistants in order to explicate the moral and political dynamic of scientific practice. The scientist's mastery of knowledge establishes and reinforces control over the technician's skilled but routine work with artifacts. From this position of power, it is the scientist who determines how visible the technician is from the public point of view. Telescope operators, in the hierarchy of scientific work, are similar to assistants in Boyle's time or the laboratory technicians of today. They are responsible for smooth operation of experiments but, aside from a thank you to the observatory staff in published papers, their role is still largely invisible in the written record.

In one interview I conducted, an astronomer described his relationship to the telescope operators: they are "professional observers who are happy to observe for us and they do as good or better job than we do. We just give them instructions and they do it." When observing is routine, the astronomer admitted that he does not need to be at the observatory. "But then sometimes it's much better to be out there." He elaborated,

> There are often a lot of decisions that you need to make during the night about whether to observe one target rather than another given the weather conditions, given the information you just learned the previous night… You might just notice something at the telescope that someone who wasn't as invested in the project wouldn't have noticed, some error you're making or some better way of doing things… And another important reason to go is to get to know the people who work there and who maintain these instruments and who build these instruments. That can be really valuable because you learn things that aren't in the manuals and those can give you a lot of really helpful information.

As this astronomer suggests, there are many different ways to *be* at, to *inhabit*, the observatory. The visiting astronomer, when present at the observatory, can redirect the routine of the telescope operator in a way that might better serve his or her research. At the same time, one accrues social capital that might be helpful when not physically present at the observatory.

The telescope operator, in contrast, inhabits the observatory in a very different way. Being there is the entire part of his or her job; unlike the astronomer, work done at

CTIO does not connect to work done elsewhere. The act of observing requires both the telescope operator and the astronomer. The telescope operator must perform his or her part of observing at the telescope but the astronomer can observe (in the sense of orchestrating and organizing data collection) from the observatory but also back at his or her home institution after the observing run.

Because Fischer's and her students' tasks were not time or place sensitive, much of our time spent inhabiting the control room of the 1.5-meter telescope was not devoted to the search for a habitable planet. Instead, we each worked on our own projects. John was busy writing a paper, what he considered his first real paper on exoplanets. Matt spent some time working on a problem set for his class at Yale. For my part, I worked on a conference talk I was delivering in a few weeks. Fischer shifted between working on various collaborative projects, instructing Matt and John in their research, and explaining the finer points of observing and instrumentation to me. At one point, her daughter called on Skype and chatted with us all.

Observing at

What is the significance of "being there" when "there" is not significantly different from the "here" of one's office? For anthropologists, "being there" is the essence of ethnography. Clifford Geertz ascribes the potency of anthropology, for better or for worse, to the ethnographer's ability to convey to the reader that she or he has achieved an "offstage miracle" and actually "been there." (Geertz 1988, 5). When discussing the degree of immersion[12] in a foreign culture, Kirsten Hastrup (1995)

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[12] Anthropologist Stefan Helmreich (2007) offers an alternative to thinking about fieldwork. Rather than "immersive," it might be fruitful to think of ethnographic work as "transductive." He develops this rubric

acknowledges that most anthropologists assume that the more embedded one is, the better one's findings. She quotes Margaret Mead: "As the inclusion of the observer within the observed scene becomes more intense, the observation becomes unique" (146). A graduate student described his experience at the observatory (in the observed scene) with excitement. He was collecting data for an exoplanet known to transit and told me that, "it's much more satisfying to see it [at the observatory]. You're like, 'I hope it transits,' even though you know it is going to transit because you know what you're looking for, but it's still kind of fun. Like, 'oh my God, a transit!'"

In "being there," the anthropologist hopes more intimately to know the people and culture about which he or she writes. Astronomers observing at the telescope are also there for reasons of social cultivation. Astronomers resisted this reason when I presented it to them, and in conversations, were more willing to hint towards sublime reasons for being there. They gestured towards a desire to achieve an "intimate sensing" of the cosmos (Helmreich 2009a). When pressed on this, and as I experienced when I observed the observers,[13] the primary reason for going to the observatory is closer to the anthropologist's own reason for going into the field. Astronomers build social relationships while at the observatory.

Just as the anthropologist lives in the field, the astronomer dwells at an observatory, staying in the dorm, eating in the cafeteria, working in the bowels of the machine. Though astronomers told me that the importance of "being there" was being

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for his own approach to an anthropology of sound, but suggests that transduction attends to how presence coalesces. Whereas the subject and field are already merged in an immersive approach, the transductive approach draws attention to how this immersion came to be. For example, what are the material and sensorial means by which the astronomers (and myself as an anthropologist) enter a state of "being there" at the observatory?

[13] As Helmreich has observed, the anthropologist of science can find oneself in the curious position in which one's field is coextensive with the field of one's informants (Helmreich 2009b, 21).

able to "see" and "touch" the instrument, in practice this rarely occurred. "Being there" did, however, afforded a unique social experience. The evenings were spent in close collaboration between an advisor and her students. Astronomers could take the time to build rapport with the telescope operator. There was a cloistered feeling not because CTIO was an isolated and cut off place (as I have discussed, it is embedded within local and global networks), but because, as we worked at night, there was no constant barrage of email and interruptions that plagues one's workday. When not in the operating room, there were informal encounters and conversations with other astronomers at meal times.

As I mentioned already, even when astronomers are not at the telescope, it is common for telescope operators to collect data for them. Some telescopes can be remotely operated, meaning that an astronomer can oversee data collection from a distance. The summer before I went to CTIO, I participated in a remote observing run with a graduate student, Elisabeth, at MIT. I sat with her for two nights while she accessed NASA's Infrared Telescope Facility in Mauna Kea, Hawaii. At MIT, students and faculty remote-observe from a room in Building 56 (the Earth, Atmosphere and Planetary Science headquarters) that is equipped with the necessary computers and video conferencing equipment. Elisabeth, who has a lot of experience observing both at observatories and remotely, masterfully orchestrated the data collection. There were three monitors of importance in the conference room. Two were computer monitors perched on a desk and the third was a television screen on an AV stand. The television displayed a live feed of the telescope operating room in Hawaii. On top of the screen was a webcam, which presumably projected our setup onto a television or computer in Hawaii. We only engaged with the TV at the beginning of the night when discussing the evening's plans with the telescope operator who popped in and out of our view for the rest of the night.

We mostly focused on the two computer monitors on our desk used to control the focus and exposure times of the telescope. During a particularly long exposure, I asked Elisabeth about the room's setup. Why, I wondered, was there a second desk stacked on our computer desk? This created a somewhat cramped feel. Elisabeth laughed and explained that another graduate student wanted to recreate the feeling of being at an observatory. Sometimes, if you are remote observing with a telescope halfway around the world, the time difference works out such that you are observing during daylight. To create a more observatory-esque ambiance, the remote observer can close the makeshift black out curtain, turn off the lights, and turn on the lamp mounted beneath the top desk. The observer can now feel that he or she inhabits the control room. In effect, mimicking the arrangement of the control room makes the observatory feel connected to a remote observatory and, as Mead offers, enables the observation to become unique. What is not replicated in this configuration is the remove from one's daily life facilitated by inhabiting the observatory. When I was at CTIO, I did not do anything during daylight but sleep. When I remote observed at MIT, I took catnaps before and after observing so that I could carry out a normal workday. As one astronomer put it, remote observing is "no fun at all." Despite trying to recreate the ambiance of the control room, one is not "fully there," as at an observatory.

Astronomer Mike Brown, in his memoir detailing how he crushed the hopes and dreams of millions of American school children by making the discovery that lead to Pluto's demotion, reflects on the strangeness of remote observing. In his case, when using the Keck observatory in Hawaii, the control room is not at the summit but several thousands of feet below. As with remote observing from MIT, there is a video link that allows the astronomer to communicate with the operators on the summit. "We talk to the people there and control the instruments there, but we don't go there ourselves," Brown describes.

> The first time I used a telescope like this while being in a control room miles away, I felt strangely disconnected from what was going on. I couldn't walk outside and feel the wind and humidity. I couldn't check for cloudy patches or impending fog. I couldn't hear the reassuring clanking of the dome and rumbling of the telescope. How could I do astronomy this way? (Brown 2010, 77)

Nearly perfectly, Brown answers. His technical performance does not suffer from remoteness, however he does remark on the incongruity of looking out the window and seeing torrential rain at the base of the mountain and then looking at his beautifully clear data streaming from the summit. The jarring disconnection between environments mirrors a disjunction of practice that Brown also observes occurring at the observatory. Brown was looking for an object larger than Pluto, which he hoped to dub the tenth planet. He was at Keck to follow up on a candidate that might just be this planet. With reverence, he recalls, "My first view of Object X through the giant Keck telescope – or at least on the computer screen twelve thousand feet below the giant Keck telescope – still amazed me. I was about to get the first peek at the composition of something that might be bigger than Pluto, something that only a handful of people on the planet even knew existed." And then in the next breath he remarked, "everything went so perfectly that it was, to be honest, an incredibly tedious night" (79). The mundane invades the realm of the sublime regardless of whether one inhabits the control room at the observatory, miles away from the telescope, or from half way around the world.

What is interesting is that being "fully there" at the observatory has little to do with the nuts and bolts of scientific work. I was much more involved in collecting data when I observed with Elisabeth than when I was at CTIO (in part because the telescope operator Elisabeth worked with was only in charge of moving the instrument, not logging data). Inhabiting the observatory has to do with creating the social ties that enhance scientific work: between teacher and student, astronomer and telescope operator, and astronomers from different universities. One goes to the (seemingly isolated) observatory to build connections.

Some astronomers will plainly admit this, but others cling to some (indescribable) greater purpose of being at the observatory. The need to *observe at* the telescope is a relic from the days when the astronomers did need to intervene with the instrumentation during an observing run. Then, being there was an epistemological necessity. But there was still discomfort in making a specific place important – romanticizing the idea of being there – with regards to the observatory. Le Gars and Aubin (2009) discuss the tension between the place and non-place of the observatory. They look at the failed Mont Blanc Observatory constructed at the turn of the 20th century to elucidate how the observatory is caught between the laboratory and the field. The observatory, they argue, strives for the authoritative placelessness of the laboratory but is always rooted in a specific place. This location is even part of the observatory's authority (for example, its precise altitude was central to the science being conducted), and thus could never fully be "de-placed." The editors of *The Heavens on Earth* (Aubin, Bigg, and Sibum 2010), which examines the multiple roles of the observatory in the 19th Century, suggest, with reference to the work of Michel de Certeau, that observatories are *spaces* of knowledge. Space, de Certeau suggests in *The Practice of Everyday Life*, is practiced place (1980, 117).[14] An observatory as a space must be one that is occupied by people - one that is inhabited - and one in which practice occurs. These legacies of observing at the telescope are perhaps responsible for the persistent feeling amongst astronomers that being at the observatory is the authentic way of doing astronomy. Even when an astronomer like Elisabeth cannot travel to the telescope, she creates an aura of being there in an attempt to make practice feel as it should.

With space-based telescopes, however, there is never an illusion that one can go to the observatory. This frees the astronomer from a need to observe or mimic observing at a specific facility. With Kepler, there is no control room to replicate. Observing with Kepler, the next stop for the observing eye that guides this chapter, requires inhabiting not a physical space but a network.

Observing with Kepler

At CTIO, we rarely spoke of the larger project of finding a habitable planet. Perhaps, I thought, this was because we were performing preliminary data collection and mostly focused on instrument development. The promise of this project will not be borne out for several more years. The Kepler satellite, on the other hand, is still collecting data,

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[14] Note that de Certeau is a French thinker and, like his countryman before him (Henri Lefebvre (1974)) distinguishes between place (*lieu*) and space (*espace*) in a way that is opposite to those writing in English. English writers (myself included) commonly take space as a geometric entity and place as its meaning-laden counterpart (though this dichotomy, as I discuss in the Introduction, is frequently and fruitfully challenged). Translations of French work often flip this distinction. Thus, when I refer to de Certeau's notion of "space" it is much more in line with my use of "place." Additionally, for de Certeau, place belongs to "the proper," whereas space is forged by those acting out of place.

but with so many stellar targets, the analysis of these data has already yielded several exoplanet discoveries. I attended a Science Working Group meeting in July 2009 hoping to hear discussions about the importance of detecting an Earth-like planet. How, I wondered, did Kepler astronomers discuss and imagine these potential planets? In other words, I went looking for sublime musings; for discussions on the significance of habitable planets and how astronomers imagined inhabiting, emplacing themselves on, such planets. After all, in text on the Kepler website and in the news media, Kepler's goal of finding a habitable planet is portrayed as being of great significance for humanity. Just before its launch in March 2009, a *New York Times* article began, "Someday it might be said that this was the beginning of the end of cosmic loneliness" (Overbye 2009a). Similarly, *National Geographic* ran an article about Kepler and other searches for Earth-like planets. The author wrote that such planets, "hold the promise of expanding not only the scope of human knowledge but also the richness of the human imagination" (Ferris 2009, 93). The meeting did have an air of excitement. The excitement came not from speculating about habitable planets, but from marveling over how "clean" the data were. The light curves presented were "beautiful" not because of planetary signatures, but because of the precision achieved by Kepler's technological superiority to other space-based observatories.

Precision was also the goal at CTIO. The difference between Fischer's spectrometer and Kepler is that Fischer can make slight adjustments to the telescope based on data collection during the design phase (though, as I point out, this rarely happened while observing). Once Kepler was launched, engineers could no longer adjust its optical performance. My distinction between *observing with* Kepler versus *observing* *at* CTIO tries to encapsulate the disconnection between Kepler scientists and the Kepler satellite. One reason astronomers inhabit an observatory is to achieve an intimacy, or at least intensity, with their research. With Kepler, one cannot go to the observatory so instead one inhabits a sociotechnical network. This preserves a second reason astronomers go to the observatory: to strengthen social ties. At the Science Working Group meeting, there were talks and discussions all day and meals were eaten together. Like being at the observatory, there was a certain remove from normal work life. However, because we were meeting during the day, I noted that many of the astronomers sitting with their laptops open were just as likely to be responding to email as taking notes or working with data. Before discussing this meeting in more detail, I will briefly narrate how Kepler became a space telescope in search of habitable planets.

Getting to an Earth-Trailing Heliocentric Orbit

The Kepler mission, named for that great astronomical thinker of the past, was ahead of its time. A decade before astronomers confirmed the existence of exoplanets, NASA scientist Bill Borucki was already determining the instrument specifications for the photometric detection of an Earth-sized planet. The promise of planets was thick in the air when he wrote, "detection of planets as small as Earth or Venus appears beyond the capability of ground-based systems, but might be possible when space-based platforms and extremely stable detectors become available" (Borucki and Summers 1984, 132). Astronomers in other subfields were similarly stymied by limited technology and convened in 1984 to discuss the limits and potential of high-precision photometry. Borucki was an editor of the "Proceedings of the Workshop on Improvements to

Photometry" and presented photometry's role in the search for other solar systems, specifically ones with Earth-sized planets (Borucki and Young 1984).

Over the next decade, Borucki secured money from NASA to develop a series of photometric test beds, focusing his work on increasing precision. In the early 1990s, NASA proposed a new funding model for exploring the Solar System and beyond. Instead of NASA suggesting specific targets and piecing together missions from a variety of proposed spacecrafts, mission directors, and science projects, NASA introduced Discovery-Class missions. These missions were to be smaller in scope, awarding funds to fully envisioned projects in which a Principal Investigator proposes a science target, mission architecture, and a team. Borucki thought his project well suited this new funding scheme. He gathered a team, designed a mission, and proposed to measure the "Frequency of Earth-Size Inner Planets" when the first call for Discovery-Class missions was announced in 1994 (this mission had already been rejected once before in 1992 by a NASA funding stream that preceded Discovery). NASA declined the proposal, citing its similarity (in expense) to the Hubble Space Telescope. Borucki was not deterred. He continued organizing workshops and building instrument demonstrations to enhance the proposed mission. In 1996, the second call for Discovery missions was announced. Under the new name of Kepler, Borucki again proposed a space-based mission to detect Earth-like planets. Again, the mission was rejected and though Borucki worked to demonstrate feasibility, the Discovery program rejected Kepler for a third time in 1998. Kepler was not a mission for the 20th century. Only after a complete technology demonstration and an abundance of exoplanets had been discovered was Kepler awarded with a Discovery-Class Mission. In 2001, the idea for a space-based telescope that would survey thousands of stars in order to determine the frequency of Earth-sized planets, an idea hatched in 1984, was finally ready to be implemented with Borucki as the PI (Borucki 2010).

Kepler was not always described as a search for "habitable" planets. Originally, Borucki referred only to "Earth-size planets." However, as "habitable zone" began to saturate the exoplanet literature in the mid 1990s, "Earth-size" was no longer a sufficiently interesting target. Three years after Kasting, Whitmire, and Reynolds (1993) offered a definition of habitable planet to the planetary science community, and a year after the discovery of the exoplanet orbiting 51 Pegasi, Borucki's planet hunting project embraced this metric. In a paper describing his then unfunded mission, the strategy of detecting an Earth-like planet was linked to the habitable zone (Borucki et al. 1996). By the following year, a paper discussing the (still unfunded) Kepler mission featured the term "habitable zone" in its title (Borucki et al. 1997). Currently, the banner of the official website for the (now funded) Kepler mission contains the phrase "A Search for Habitable Planets."

Kepler was launched in March 2009. To limit the observational interference from Earth, Kepler does not orbit around Earth but around the Sun in an orbit similar to Earth known as an Earth-trailing heliocentric orbit. Its photometric sensors point at a patch of sky in the Cygnus constellation (its "field of view"), taking measurements of 100,000 stars every thirty minutes. This generates an unimaginable amount of data. But because one of the data sets might contain the signature of a habitable planet, the PIs and Co-Investigators tightly control access to the data. Consequently, the Science Working

Group meeting was the first time that most members of the science team were seeing Kepler data.

Kepler Science Meeting, July 2009, Mountain View, CA

Kepler was a topic of frequent discussion during most of my time with the MIT exoplanet community as astronomers eagerly anticipate the fulfillment of the missions promise to find a habitable planet. Sara Seager is one of nine participating scientists, working within the fourth tier of participation (after Principal Investigator [of which there are two], Co-Investigator [nineteen] and Science Working Group [ten]). Seager presently has a minor role in Kepler and this will likely remain the case until follow-up atmospheric data have been collected for Kepler exoplanets. However, she corresponded with Borucki on my behalf and ensured my attendance at a Kepler Science Team Meeting in the summer of 2009. The meeting was two days long and held at NASA Ames Research Center in Mountain View, California (a site to be discussed at greater length in Chapter Three).

In a small lecture hall in Building 245 (a building I would frequent during my longer stay at Ames), roughly 40 scientists affiliated with Kepler gathered early on a hot July morning. Most of the people present were affiliated with NASA Ames, SETI or American universities. There were a handful of Europeans, as one of the Co-Investigators is from Aarhus University in Denmark and successfully petitioned to use Kepler data for astroseismology research. A neuroscientist and myself were the only two people who appeared "out of place" at this meeting. The walls of the auditorium were adorned with cosmic, terrestrial, and biological images. There were glossy large-print photos of the

Martian surface, a comet shooting through the Earth's sky, a volcano erupting, a close-up of a green tree frog. The scale from biota to planetary was fitting for a meeting of a mission designed to find a habitable planet.

This was the first gathering of affiliated scientists since the processing of the commissioning data. As such, there was anticipation in the air for what promised to be "beautiful data." To summarize the procedure of the two-day meeting, an astrophysicist deadpanned that like any NASA talk, this one would start by claiming success and then work back from there. Appropriately, Borucki welcomed us to what he said would no doubt be an exciting meeting, announced the flawless performance of Kepler thus far, and then before diving into the planetary candidate light curves, worked back to the operational level of the Kepler mission. As such, the first talks of the meeting were delivered mostly by NASA employees and discussed activities at a management level. As the meeting progressed, "the professors" (as a university professor described his ilk to distinguish them from NASA scientists) increasingly assumed the podium and began replacing the flow charts on PowerPoints with equations and graphs. Operational level discussion gave way to physics and science questions. There was no discussion about the likelihood of finding a habitable planet or even a re-visiting of what "habitable" means. All of the talks were about data calibration, data processing, the data pipeline, and who had access to what data when.

Being on a large science team like Kepler can be frustrating.[15] Most university astronomers work on projects like Fischer's, where one has complete control over data

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[15] The frustration I note in the Kepler project surrounds the individual's access to data, the positioning of the "I" amongst the collective "we." Peter Galison (2003) has tracked the changing position of the collective we, and attending changes to claims to knowledge, as instruments and projects have grown in scale. Sharon Traweek (1988) has shown how, embedded with in the design of particle accelerations are

and can go to the observatory if warranted. Without the physical observatory, Kepler scientists' only connection to the project is through data. To inhabit Kepler (like one inhabits CTIO) requires access to the data. The PIs and CoIs kept data secretive during the first few months. The data were not being circulated, which meant physical presence at an authorized computer bank was necessary in order to do work (or even view the light curves). From NASA's point of view, this controlled against leaks and possible "scoops." I quickly realized that many of those attending the meeting, members of the science team, did not have permission to see the Kepler data. NASA, as a publicly funded agency, is contractually required to release science data after a set number of days. Those present were quickly becoming anxious that the public would have access to the data before or at the same time that they did.

"Public" became a word of negotiation between the academics and NASA. When Boroucki tried to assure the audience that there was a system in place by which data "goes to the public" (where this public included the scientists in the room), the academics countered that they should have lead-time before the public release to examine the data. They attempted to distinguish themselves from NASA's use of "public" in order to gain a more advantageous position with respect to data. Speaking with a member of the science team after these discussions, I asked how the scientific public was different from the general public. The astrophysicist responded defensively that all members of the public have access to the data NASA releases and are, in fact, quite interested in this mission. Public, in this setting, was a blurred concept meaning either all interested consumers of (scientific) news, working astronomers, or working astronomers not including members

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assumptions as to how groups produce scientific facts. The "we" of science is apparent in several other studies of large-scale collaborations, including Harry Collins (2004) work on gravitational waves and Galison on the bubble chamber (1997).

of the Kepler science team. The conversations on public data consumption concluded with the formation of a committee to further address this problem and hopefully assuage the frustrations of the academic members of the non-core science team.

Without access to data, scientists did not feel like they were part of the mission. They could not inhabit Kepler's sociotechnical network because they had access to neither the observatory nor its products. Because it was a space telescope, they could not observe at Kepler, but without access to data, they were unable to even observe with Kepler.

Space telescopes shatter the façade that being in close proximity to the instrumentation is vital to current astronomical practice. With this forced remove between instrument and scientist, the act of observing is distilled to one's ability to navigate within (in the case of Kepler) a large and distributed scientific team. One advantage of the physical observatory, as motioned to above, is the sociality fostered between scientists. The team meeting still offers an opportunity to come together, suggesting that more so than offering a place of practice, observing with Kepler offers a place of sociality. The act of coming together, of being at a specific place for a specific amount of time, is important for Kepler. But instead of the place of work being at the observatory, it can be at any conference facility. However, the physical coming together is not in itself enough to fully stand in for the role of the observatory. Astronomers desire access to data in order to feel that they are observing with Kepler. Inhabiting the distributed network of either ground- or space-based observatories is as much (if not more) about the abstract notion of access to data and the social networks that care for and interpret that data as it is about the concrete, physical location.

Observing from the Archimedean Point

The drama of the search for a habitable planet is still unresolved. Fischer and her team observe at CTIO, measuring the Doppler wobbles of Alpha Centauri A and B. The NASA team observes with Kepler, systematically going through their survey of 100,000 stars hoping to find a telling transit. Both teams inhabit networks and places on Earth to search for habitable planets. This is primarily a game for observational astronomers, but theoreticians have carved out a complementary project. Carl Sagan (1994) refigured the planetary imagination when he asked readers to ponder the Pale Blue Dot, the picture of Earth taken from so far away that it looks like a star. Theoreticians have risen to this challenge, producing articles and books that treat our home planet Earth as an exoplanet. The Earth-as-exoplanet argument takes place neither on a mountaintop nor in a conference room, but at an imagined extraterrestrial Archimedean point. To observe from an Archimedean point, theoreticians cognitively inhabit a place not of this world.

The Earth as a Distant Planet: A Rosetta Stone for the Search of Earth-like Worlds (Vazquez, Pallé, and Montañés-Rodríguez 2010)[16] is a recent publication in this genre of theorizing. The cover of this text features a spiral of Earths (a take on the famous whole Earth image, though flipped from its original orientation so that Africa is more familiarly facing "up") against a black sky dotted with stars. This evocative image resonates with a New Yorker comic that first appeared in 1996 and exoplanet astronomers often use in their public talks. In this comic, a spaceship is flying through a dense field of Earths (this time, the North American side is the dominant face) and the

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[16] This mode of theorizing is by no means fringe. Sara Seager co-authored an article with these authors to demonstrate, "the light scattered by the Earth to a hypothetical distant observer as a function of time contains sufficient information to accurately measure Earth's rotation period" (Pallé et al. 2008). Articles such as these appear in the top-ranked astrophysics journals and are well regarded by the field.

caption reads, "Well, this mission answers at least one big question: Are there other planets like ours in the universe?" The joke points to an improbable scenario in which the discovery of an Earth-like planet will be truly a twin (or triplet, etc). Yet the iconography of multiple literal Earths remains popular in sincere literature, as the aforementioned book cover illustrates.

To study Earth as an exoplanet, astronomers take Earth data, either in the form of satellite images or "earthshine" (light from the Earth reflected off the night side of the Moon), and reduce these highly resolved data sets into a single point source to mimic our perception of exoplanets. Then, they run various models to see if it would be possible to extract the complexity they just erased. *The Earth as a Distant Planet* provides several examples of this spatial reduction. Whereas beautiful satellite images of continents and oceans illustrated the first chapters of this book, representations of Earth in Chapter Three, entitled "The Pale Blue Dot," are light curves and spectra; line drawings meant to resonate with the data astronomers currently produce for exoplanets (as I explained in the previous chapter).

In some cases, astronomers have harnessed satellites beyond Low Earth Orbit in order to study Earth as an exoplanet. For example, in a paper entitled "Alien Maps of an Ocean-Bearing World" a group of university astronomers in conjunction with NASA's EPOXI team (a satellite designed for close encounters with comets) used Earth data from this satellite to see if it was possible to distinguish oceans from landmasses (Cowan et al. 2009). In the title of the paper, the "Ocean-Bearing World" is in actuality Earth and the "Alien Maps" are highly abstracted representations of Earth. As EPOXI observational data offer higher spatial resolution than exoplanet data, the first step was to integrate over each image, reducing them to single pixels. Then, they take the position of a naïve observer, assuming "no prior knowledge of the different surface types of the unresolved planet" (917). After examining the spectra, the team "discovered" that at times the planet appeared optically blue and at other times optically red suggesting two kinds of surface types. The final step of the analysis was to construct an alien map of this ocean/land planet. Figure 2.3 appears in the paper as a comparison between an actual map of Earth and the alien map reconstructed from spatially unresolved data.

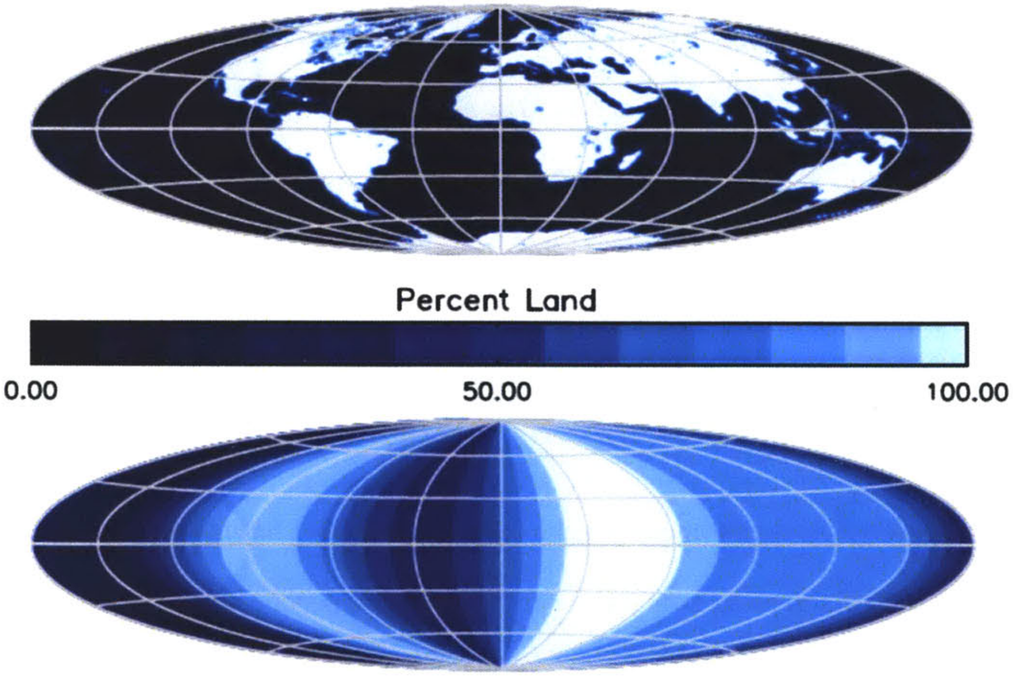

Figure 2.3: Alien Map of an Ocean-Bearing World. The top map is a cloudless representation of the Earth. The bottom map is made from reduced EPOXI data. Though the reconstructed map is not latitudinally resolved, it represents some ratio between land and ocean. Image from Cowan et al. (2009).

Decades before these astronomers produced alien maps of Earth to understand exoplanets, James Lovelock (1979) thought to search for signs of life on Earth as a model for how such a task might be accomplished on Mars. His idea to test the Martian atmosphere provided no more evidence for little green men or microbes on Mars than any other experiment in the 1970s. However, taking the global view of terrestrial life led him to develop his popular Gaia hypothesis, which surmised that both organic and inorganic materials on Earth feed off of each other to create one large organism at the scale of the entire planet – Gaia. Lovelock's attempt to treat the Earth as an alien world, though initially a strategy for understanding a different world, ultimately taught him more about our own planet.

Lovelock and the authors of "Alien Maps" could not observe the Earth as a globe from their position on its surface. As stated in "Alien Maps," "These data reveal Earth as it would appear to observers on an extrasolar planet, and can only be obtained from a relatively distant vantage point" (Cowan et al. 2009, 916). This notion of a "distant vantage point" appears repeatedly in *The Earth as a Distant Planet.* The authors talk of an "extraterrestrial observer," suggesting that the Earth-exoplanet connection must be made by first assuming a remote gaze from which to observe Earth and then returning to Earth and refocusing the gaze outward. They historicize the position of the observer and the viewing of Earth-as-planet in the first chapter of their book. From on the ground mapping, to hot air balloon photography, from satellite images, to Apollo, they reflect on the potency of seeing "our planet as a whole" (Vazquez, Pallé, and Montañés-Rodríguez 2010, 12).[17]

When writing about Earth as an exoplanet, astronomers observe from an Archimedean point. Hannah Arendt (1963) wrote of her apprehension about such

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[17] Many scholars have written commentary and critique on the images of Earth taken during the Apollo missions. For an overview of the iconography, see Cosgrove (1994). Jasanoff (2004) discusses how the environmental movement harnessed these images. Garb (1985) suggests alternate readings for Earth images.

thought experiments, especially with respect to outer space. For her, the hidden threat of physics and astrophysics is the abstraction of thought from reason and common sense, which inevitably happens, she argued, when leaving the terrestrial realm, even if only in thought. Arendt questioned the assumption that scientific pursuits, specifically the "conquest of space" necessarily bolsters the "stature of man." Pursuing the Archimedean point threatens the erasure of humanity from life in the sense that humans would forget their *place* in the world. Arendt expressed these thoughts before the Apollo missions and before images of Earth were taken from the somewhat Archimedean point of the lunar orbit. While philosophers fretted (Heidegger [1966], as another example, expressed fear when confronted with images of the Earth taken from the Moon), scientists enthusiastically anticipated this sublime landscape. Vazquez et al. quote astronomer Fred Hoyle circa 1950: "Once a photograph of the Earth, taken from outside, is available [...] once the sheer isolation of the Earth becomes plain to every man whatever his nationality or creed, and a new idea as powerful as any in history will be let loose" (quoted in Vazquez, Pallé, and Rodríguez 2010, 11).

Four decades after the isolation of the Earth became "plain to every man," exoplanet astronomers are overcoming this isolation by searching for proof of other habitable planets. The Archimedean point is no longer afloat (as Arendt describes from Copernicus suspended in the sun to Einstein's man drifting freely in space), but is finding ground on other Earths. For Arendt, the threat of the Archimedean point is that "once arrived there and having acquired this absolute power over his earthly habitat, [man] would need a new Archimedean point, and so ad infinitum. In other words, man can only get lost in the immensity of the universe" (Arendt 1963, 278). However, the

Archimedean point for exoplanet astronomy is not forever elusive. In searching for exoplanets with solid, Earth-like surfaces, astronomers seek an alien Archimedean point with a foothold on another planet. Contrary to Arendt's fears, habitability elsewhere does not forever condemn humanity to endless wandering, but, as astronomers see it, offers a firm notion of Earth's place in the universe. It is from this vantage point, one grounded on, albeit, an imagined planet, that astronomers theorize about Earth as an exoplanet. *Observing from* the Archimedean point requires astronomers to cognitively inhabit this point such that it makes sense to "look back" and observe Earth.

The Earth as a Distant Planet contains one chapter on biosignatures (eerily titled "Biosignatures and the Search for Life on Earth") and a few sections scattered throughout on habitability. But mostly, it is about Earth as a planet; Earth as a geologic and geographic entity. Likewise, the article "Alien Maps of an Ocean-Bearing World" mentions habitability only in passing, and the "Alien" in the title refers again to a geographic, not biologic, other. In these moments, when astrobiology is put aside, another project shines through: the search for another planetary home. Making the connection between current practice and future practice, the authors of *The Earth as a Distant Planet* write, "In the near future, the application of sophisticated methods will give us the opportunity to detect and study planetary bodies similar to our Earth. The day we arrive at another Earth-like planet, we will already have in our possession detailed cartographic maps of it, taking advantage of the knowledge we have acquired in finding out about our own planet" (5).

Conclusion: Home Worlds

In searching for habitable planets, astronomers themselves carve out spaces to inhabit. They embed themselves within the networks of observatories, both on the ground and in space. Astronomers even cognitively inhabit an imaginary Archimedean point from which to imagine the Earth as an exoplanet. But when they are most fully inhabiting their research – at the observatory, at a meeting, or while working with data – the figure of the habitable planet is least present. When astronomers are entrenched in mundane (in the sense of routine) practice, the sublimity of their object of pursuit is forgotten.

But what exactly are Debra Fischer and the Kepler team pursuing? What is a habitable planet? An astronomer will likely give a denotative answer, that a habitable planet is one capable of harboring liquid water on its surface. But there is also a connotative understanding of habitable that hangs over astronomical writing and discussions. In a more colloquial sense, a habitable planet is a planet humans could call home. Exoplanet astronomers are unknowingly entering the philosophical discussion about what constitutes a home. Phenomenologists like Martin Heidegger and Gaston Bachelard write about the home as a sublime place, essential to human *being*. Contemporary feminist critiques of this conception of home, like geographer Doreen Massey, seek to erase the nostalgia of home and suggest instead a multiplicity of home created by global flow and networks. Exoplanet astronomers enter this debate, supporting the idea of multiple homes but holding on to the aura of Home.

In *Being and Time,* Martin Heidegger writes that being-in is the existential state of being human and being-in-the-world is the essential state. One achieves this state by the simple act of dwelling, of being "in" (Heidegger 1927, 80). In a later essay, "Building Dwelling Thinking" (1951), he continues to write about this connection. He restates that dwelling, or inhabiting, is a primary mode of human being. Heidegger recalls the Black Forest in which he was born and to which he later returned. A peasant hut symbolizes harmony between dwelling in the world (dwelling alongside Heidegger's conception of nature) and building as the home is structured to best handle weather and winds.

In *The Poetics of Space*, Gaston Bachelard (1958) also probes the home as a way to understand human being. What he is doing is not psychoanalysis, but topoanalysis. "The house image," he claims, "would appear to have the topography of our intimate being" (xxxvi). His work is a corrective for the phenomenologist who busies himself with trying to understand the universe. The key to understanding the greater world, Bachelard insists, is to first consider the home. "[Our house] is our first universe, a real cosmos in every sense of the word" (4). Heidegger is concerned with how buildings become dwellings and the ontological stakes of such a transformation. Bachelard, however, wishes to show how the home image pervades one's life always and in every way. Ultimately, "all really inhabited space bears the essence of the notion of home" (5).

Both Heidegger and Bachelard suggest that the forging of homeplaces is one way humans relate to and understand the world and this happens through acts of dwelling and habitation. But homes can be larger than a single house. The idea of home and all of its topoanalytic weight applies to one's home town, home state, home country, and even home planet. Heidegger goes so far as to identify Earth as "the house in which mortals dwell" (quoted in Casey 1998, 290).

But "home" and "world" are not static, homogenous terms. Heidegger and Bachelard are both nostalgic for their childhood home (and perhaps their pre-war childhood selves). This masculinized view of the home, one of comforting domesticity and peace, has been critiqued by feminist geographers and thinkers who wish to show how women's experience of the home is quite different from men's (Rose 1993). The phenomenological resonance between space and being (as opposed to time and becoming) also invokes a damaging fixity on ideas of place and home (Massey 1994a). Encompassing both of these critiques, bell hooks (1990) offers a reading of home as a (dynamic, feminine) site of resistance in African American cultures.

Further, terrestrial homes are increasingly losing their sense of locality. Geographer Doreen Massey (1994b) recontextualizes home in response to David Harvey and others who are fretting over the spatial upheaval triggered by globalization. She embraces the upheaval as a way to think about place and home not as static and bounded, but a product of social interactions, a part of flows not fixity. For Massey, you can never go home again because there is no singular idea of home.

As exoplanet astronomers write and talk about habitable planets, they are caught between Heidegger and Massey. A habitable planet is a promise of finding home, of finding a planet suitable for housing life as we know it. There is a wistful, possibly nostalgic pursuit in finding an Earth as we never knew it. Perhaps astronomers will detect an Earth-like planet still in the early stages of nurturing life. This would be a glimpse of the long ago laid foundation of our planetary house. But in astronomical practice, the search for habitable planets is also entrenched in ideas of unboundedness, multiplicity, flows, and networks. Astronomers' observing at CTIO and with Kepler inhabit networks which span the world and extend into space. They are seeking to "understand our place in the universe." But to do so it is sometimes necessary to break free from our home planet, as theorists do when observing from an Archimedean point and turning the gaze back on Earth.

"Home" is at once sublime and mundane. Bachelard's home represents our "intimate being," while Massey's home is more a product of daily practice. As the exoplanet astronomer searches for other homes, other habitable planets, she or he also encounters the sublime and the mundane. Searching for habitable planets is both about being mesmerized by the abyss of the night sky and spending endless hours in a control room mindlessly moving a telescope from one star to the next.

THREE
Mapping Mars in Silicon Valley

Exoplanets, like Dastonian scientific objects, are elusive. Astronomers employ conventions of seeing to argue for their existence. If a scientist successfully isolates a planet in the data, she comes to understand it by imagining the planet as a place one can step foot on or even inhabit. The narrative of this dissertation now travels away from Alpha Centauri, leaving the realm of exoplanets and considering instead Earth's neighbor: Mars. Unlike exoplanets, scientists do not debate the existence of Mars. The placehood of Mars, however, remains elusive. Mars is a stalwart of science fiction literature, often used as a mirror for terrestrial aspirations and fears. Popular and scientific understandings and perceptions of Mars have changed over time, influenced both by available technology as well as social and political currents. The question I ask in this chapter, then, is what kind of place is Mars today?

My fieldwork took me to the NASA Ames Research Center in Mountain View, California, where I spent six months (from February through August of 2010) with a group of half a dozen computer scientists who call themselves the "Mapmakers." The Mapmakers work on internal NASA projects as well as external projects under two Space Act Agreements[1] that NASA has with both Google and Microsoft to present Mars to the Internet-using public through applications like Google Earth and WorldWide Telescope. Both of these applications are web and desktop programs that allow a user to view images of planets and other cosmic objects, zooming in or out and panning through an

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[1] NASA was established in 1958 with the National Aeronautics and Space Act. The Space Act outlines provisions under which NASA can arrange contracts with other entities. For partnerships not explicitly discussed in the Space Act, Space Act Agreements are drawn up that stipulate legally enforceable commitments.

interactive map of the universe. As those responsible for presenting how Mars looks and the experience of virtually visiting Mars for scientists and the public using these applications, the Mapmakers might be the most influential actors in producing the contemporary placehood of Mars.

Scientists and artists have envisioned Mars as many different kinds of places. In *Dying Planet*, Robert Markley (2005) portrays Mars as a planet with claims to historical, epistemological, and social narratives and suggests that conceptions of Mars, shaped by both science and science fiction, reflect American and European utopian hopes for the future and fears of the ecological destruction of Earth. He characterizes Percival Lowell's canal-crossed Mars of the late 19th and early 20th century as reflective of a technological dystopia in which an advanced civilization was desperately trying to cultivate the remaining water from a parched world. This vision of Mars replaced prior depictions of Mars as a host for advanced, progressive civilizations. As belief in canal-building Martians declined but understandings of Mars as a dry and inhospitable world captured scientific thought, science fiction authors began to write Mars as a place of rugged explorers.

The Mars imagined and crafted by the NASA Ames Mapmakers has its origin in the early 1970s when the robotic probes Mariner and Viking began taking photographs of the surface. Planetary cartographers arranged these images to create photomosaics of the Martian surface. With each new mission flown to Mars, satellites captured higher resolution images. The mapping of Mars is a continuous process, with today's mapmakers producing photomosaics that incorporate the latest images downloaded from satellites currently orbiting Mars. Ronald Greeley and Raymond Batson (1990), in their textbook *Planetary Mapping*, contrast the evolution of terrestrial and planetary mapmaking. They describe how terrestrial ground surveys charted local and regional terrain, but it was not until the advent of aerial photography and satellite imaging that cartographers produced accurate, global maps. In contrast, planetary cartographers began with a global perspective and have only been able to achieve a sense of local cartography thanks to robotic landers surveying the surface.

Greeley and Batson, in describing the role of satellite imagery in planetary mapping, portray it as a move towards increased accuracy, suggesting a more robust representation of reality. As photographs are more precise than hand drawings, the logic goes, the map can come to stand for reality. Planetary cartographers, including the Mapmakers at NASA Ames, establish Mars as a place through the process of mapping, and more specifically, through the process of appealing to the realism of maps.

Critical theory questions the claim that increasingly precise scientific measurement leads to maps that are more authentically real. Since the late 1980s, critical cartographers have concerned themselves with disrupting the connection between reality and representation in maps. J.B. Harley (1989), in "Deconstructing the Map," rejects the assumption that more exact science will produce maps that are more real. Cartographers use scientific methods to argue for the neutrality and realism of their maps. To show that, despite the cartographer's contrary claim, these maps are still first and foremost a representation, Harley offers a Derridian deconstruction. Derrida offers that the level perceived as literal is still nothing more than metaphorical: for example, a photomosaic map is *not* a window into reality but continues to stand for something deferred.

I suggest that for Mars, the photomosaic is a metaphor for the map itself. Meaning, Mars is mapped in order to capitalize on the relationship, embraced by cartographers and questioned by social theorists, between maps and reality. To map Mars is to make Mars real. The map of Mars is proof that Mars has a reality in the common, terrestrial sense. This sense is one that establishes Mars as a place.

The photo-realist map of Mars suggests an objective view of Mars, one not capable of making an argument because it serves simply as a reflection of reality.[2] Farman (2010) notes that in Google Earth, the ability for users to add layers and redraw boarders undermines the objective map, but without questioning the master, scientific map atop which the layers lie. Writing of an earlier satellite composite of Earth, critical geographers Wood and Fels offer a way out of being seduced by photo-realism. They quote Barthes to summarize this seduction. For Barthes, the power of the photograph is that it has not been transformed. "In order to move from the reality to its photograph it is in no way necessary to divide up this reality into units and to constitute these units as signs, substantially different from the object they communicate; there is no necessity to set up a relay, that is to say a code, between the object and its image" (quoted in Wood and Fels 1992, 51). Wood and Fels go on to show that this is not true for photographic maps. Through the process of mosaicking, the images must be divided up and then pieced together. There does exist a code between object and image in the form of pixel values, which are translated into colors. Finally, mathematical transformations in the form of projections are necessary to transform the photograph into a map. All of this can

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[2] Harley, in the same article, makes the important point that maps cannot reflect a neutral reality because they are richly infused with social assumptions. As Harley puts it, maps work precisely because the "rules of measurement" reinforce and are enforced by the "rules of society" (6). In appearing to represent an objective geographic truth, cartographers and their maps naturalize the social.

be said about satellite maps of Mars. They are of course not a direct representation of reality. I will show the difficult and time consuming technical work that that Mapmakers perform to produce these maps.

This chapter examines two shifts in contemporary understandings of Mars. The first is how Mars is perceived as more than just a cartographic representation, but as a reality. The second is how Mars then goes from being perceived as more than just a reality, but as a place. The movement from the image to reality – which, as I argue, is still only an illusion of reality – is predicated on scientific mapping. In scientific mapping, the role of the author is obfuscated. The Mapmakers create software to produce maps, so that the human hand is not directly involved in the production of the actual image. This "mechanical objectivity" (Daston and Galison 2007) offers an illusion that the map is a direct reflection of the real. In the second shift, from a sense of the real to a sense of place, the author reappears.[3] As I will discuss, this happens in the form of a scientist offering an expert way of seeing Mars to either other scientists or various publics.

To return to the question I posed at the beginning of this introduction, what kind of place is Mars today? The placehood of Mars is structured by the illusion of reality as it is successfully captured in maps. During my fieldwork, I repeatedly encountered three themes surrounding the discussion of maps and embedded in the maps themselves. I call these Democratized Mars, Three Dimensional (3D) Mars, and Dynamic Mars. The

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[3] This second shift is evocative of how, in Daston and Galison's (2007) narration of the epistemic waves of objectivity, trained judgment follows mechanical objectivity. In trained judgment, the skilled scientist inserts him or herself back into the system by which objective statements of fact are derived.

Mapmakers strive to bring Mars to the people, a process I call "democratizing Mars."[4] Users can virtually fly around and view Mars from many angles, including from the surface. The Mapmakers produce this experience through 3D imaging techniques. These maps are interactive not only because of the 3D visualization, but also because the Mapmakers annotate the surface with expandable metadata about the geologic past, robotically mediated present, and potentially human future of Mars. Mars, then, is presented as a dynamic planet, no longer, as it was in the late 19th and early 20th century, a dying planet.

As I demonstrate throughout the chapter, though the Mapmakers maps strongly argue for Mars as an object of scientific study (and implicitly something without sociality), it is far from neutral. A place is not "naturally" scientific, but must be established and maintained as such through social and political practice.[5] The map of Mars embeds current ideals of the programming community, implicit assumptions that to know Mars is to be on Mars, and the notion that Mars might be an exciting place for human exploration.

Democratized Mars

Data from NASA's planetary missions are archived online in the planetary data system (PDS).[6] The website is difficult to navigate. One can select "Mars" from a side bar to then be confronted with different search tools linked to missions, like the Mars

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[4] Farman (2010) also describes digital maps as a move towards a democratized cartography. While he is wary of the hidden powers and ideologies that these 'democratized' maps conceal (and I share these concerns with him), I consider in this chapter the genuine spirit of openness I encountered in my fieldwork by those creating these new digital maps.

[5] For an explication of this notion, see Jessica O'Reilly's (2008) work on the maintaining of Antarctica as a peaceful place of science.

[6] pds.nasa.gov

Global Surveyor Image Search or the Mars Orbital Data Explorer. Each search tool asks the user to input filtering criterion like latitudes and longitudes or orbit numbers. PDS is not browsable, but only searchable by a knowledgeable user with a specific target. The necessity of skill to explore planetary images is the perceived problem that the Mapmakers are trying to fix. They offer the map as a solution. The map is an attempt to privilege no user, to allow all equal access to NASA's wealth of planetary imagery. As with any map, this map of Mars is not value free or neutral, but reflects choices made by the authors, in this case the Mapmakers. The notion that data should be freely available is an ideological choice, one indicative of the Free Software and Open Source movements very much alive in the social worlds of the Mapmakers. The map comes to embody and even argue for this ethos. To understand that democratized data is a choice, not a given, recall the debate over Kepler data recounted in Chapter Two. That, too, was a NASA project, however at different levels of the hierarchy data were fiercely guarded. As NASA is publicly funded, democratized data is a requirement, but how, when, and with what ease these data are released is highly contested.

Though the Mars maps produced for Google and Microsoft are not open source, the Mapmakers also seek to democratize their cartographic process. A significant initiative of the group is to make the tools they developed for efficient mapmaking and planetary image manipulation open source. Not only should everyone be able to see the map of Mars, but they should also be able to make their own.

Mars@Silicon_Valley

Through the act of mapping Mars and making these maps widely available through popular applications, Mars is repositioned as closer in kind to Earth than to other planets. That Mars can be mapped suggests that Mars is a place with a geographic reality similar to Earth. Before examining the process by which these maps are produced, I will describe the Mapmakers place within NASA Ames.

NASA Ames Research Center must first be understood in reference to its place in Silicon Valley. Ames is just eight miles southeast of Stanford University in Mountain View, California. It is in the middle of Silicon Valley, which stretches from Stanford south to San Jose. Silicon Valley, as the name suggests, is a flat costal expanse in contrast to the rolling hills, Victorian houses, and high-rise buildings of San Francisco. The San Francisco Bay borders Silicon Valley on the east while the Santa Clara Mountains, green in the summer and sandy brown in the winter, sit to the west. Unassuming one or three story buildings quietly announce themselves along suburban roads with simple signs that read "Hewlett Packard," "Xerox PARC," "Apple," and "Microsoft." More recently, Yahoo, Facebook, and Google have established themselves between Highway 101 and Route 280. NASA Ames can be found between Motorola and the Computer History Museum.

Ames was established in 1940 under the direction of the National Advisory Committee for Aeronautics (NACA). Facilities were constructed on the land of Moffett Field, a military base in Mountain View that was used first by the Navy and later the Army. In 1958, NACA was incorporated into NASA and so was Ames, where research on aerodynamics was flourishing (Hartman 1970). Under NASA's guidance, Ames branched out from aeronautics and into the life and biological sciences.[7] In the early 1960s, Ames began building ties with Bay Area scientists. In the early 1970s, as Silicon Valley was forming thanks to the arrivals of Steve Wozniak, Bill Gates, Steve Jobs, and others, Ames director Hans Mark encouraged Ames researchers to pursue collaborations and partnerships beyond NASA. Ames began conducting research projects funded by both NASA and associated universities. They began sponsoring research with benefits beyond NASA's primary goals. In the 1990s, however, Ames suffered a number of criticisms brought about by a disagreement in management practices between an increasingly bureaucratic NASA headquarters a more casually run Ames. Personnel and budget cuts accompanied several negative center reviews. No longer able to offer competitive salaries amidst Silicon Valley's dot com boom, Ames set up a career-transition office to help employees find jobs at neighboring organizations.

By the late 1990s, Ames managed to thwart NASA Headquarter's plans to close the Center. As NASA worked to minimize redundancy, specifying strengths of each center, Ames repositioned itself as the center with expertise in astrobiology, aviation system safety and capacity, and, thanks to Silicon Valley's influence, information technology. At the same time, Ames, a campus that, like all NASA facilities, one needs a badge to enter, began holding events to bring the community into its space. It held open houses to show off its robots and wind tunnels and established a NASA Research Park in the former military buildings where several universities like UC Santa Cruz and Carnegie Mellon established "Silicon Valley campuses." Carnegie Mellon, for example, offers an IT masters degree program as well as a bicoastal electrical and computer engineering

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[7] This history of Ames comes from the resident historian, Glenn Bugos (2009). Glenn was a great source of help while I was at Ames, helping me navigate the archive and suggesting people to speak with.

Ph.D. program that can be completed in conjunction with work performed at the Pittsburgh campus.

In 2004, NASA re-committed to human space flight with the Constellation program designed to return humans to the Moon and later Mars. With this focus on human exploration, Ames's relevance was again threatened, and so Center director Scott Hubbard created Code T (NASA's nomenclature for organizational hierarchy), the Exploration Technology Directorate to emphasize the role that information technology (IT) must play in the future of human (and robotic) exploration. But Ames's budget and workforce continued to shrink. Simon "Pete" Worden became the center director in April 2006. Worden is credited with breathing new, young life into Ames. He began recruiting young engineers enthusiastic about space exploration. He brought in Chris Kemp, who had a record for launching successful Internet start-ups, as the Director of Strategic Business Development. Kemp was later promoted to the Chief Information Officer at Ames in 2008 and the Chief Technology Officer of IT for all of NASA in 2010. On Worden's wishes, Kemp created several Space Act agreements with nearby companies, including Google and Microsoft. In a *New York Times* article published shortly after my own arrival in the Bay Area in 2010, the journalist observed that the partnership between Google and NASA "is making Mountain View a stop along the virtual route to Mars" (Vance 2010).

During the 2004 creation of Code T and the alignment of IT research, one small group within Code T, the Intelligent Mechanisms Group, was renamed the Intelligent Robotics Group (IRG). The IRG logo, shown in Figure 3.1, depicts a robotic arm reaching out to touch the extended finger of a human arm from above. The allusion to

Michelangelo's Sistine Chapel reconfigures the human as the divine being responsible for the creation of intelligent, if inferior, robots. The logo captures the primary goal of the group, which is to develop tools to assist humans and robots working together in planetary exploration. Illah Nourbakhsh, a robotics professor at Carnegie Mellon University (CMU) in Pittsburgh, took a leave of absence in 2004 to serve as IRG's lead. During that time, Terry Fong, who had received his PhD in robotics from CMU in 2001, joined IRG. When Nourbakhsh returned to CMU, Terry became the head of IRG and was still the director when I arrived in February 2010 to work with the Mapmakers, a group within IRG.

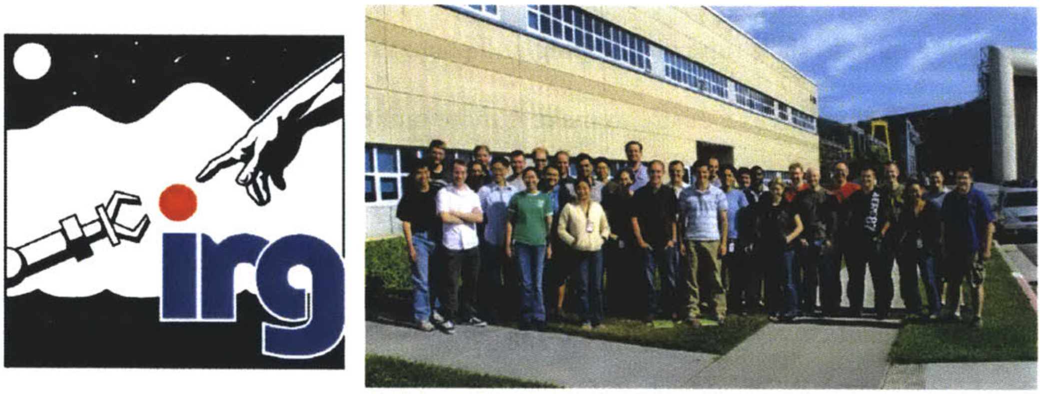

Figure 3.1: Intelligent Robotics Group. On the left is IRG's logo and on the right is a group picture of IRG staff and summer interns taken in the summer of 2010 in front of Building 269. The author is sixth from the left, in the front row. Terry Fong, in a black t-shirt on the left, set the timer on his camera before running into the frame.

When Terry situated IRG in Ames for me, he told me that there are 2,500 civil servants and contractors at Ames. Code TI, the Intelligent Systems Division and a branch of Code T, has 250 employees. IRG, nested within Code TI, has about 25. IRG, as casually described by one member, is a "weird and diverse group of engineers, scientists, and planetary scientists who come from all walks of life." Despite the relatively small group, IRG tackles many different projects and collaborates with other groups at Ames, at NASA, and in Silicon Valley. The first time I met Terry, he explained that IRG projects are all about exploration. With robotic exploration, IRG focuses on both hardware and software to make more efficient remote explorers. In addition to robotic reconnaissance, the group has several projects based on remote imaging. One project, Gigapan (an outcome of the Space Act agreement between NASA and Google), employs a camera set-up that takes a gigapixel (billion-pixel) panorama. These images are then posted online or shared amongst research groups, and users can explore the scene by panning, zooming, and annotating.

The Mapmakers are part of IRG, working on some of the groups other projects but spending most of their time on mapping and photogrammetry work. What ties their various projects together is a desire to make it more intuitive for scientists and members of the public to explore NASA's planetary data sets. The Mapmakers are a young group; some fresh out of college, some with Master's degrees, and a couple seasoned PhDs (though still young by NASA standards). This reflects IRG's overall demographic. The weekly meetings, which Terry sometimes ran dressed in his ultimate Frisbee clothes, felt more like a research group meeting at a university than a government meeting. Most of the Mapmakers work in the "Pirate Lab," one of several computer labs IRG occupies. The Pirate Lab is a cavernous room with a dozen or so workstations. Each workstation has at minimum two monitors. The room feels as though it was thrown together, with each person tailoring his or her computing needs and scrounging the NASA hardware bins for the appropriately ergonomic mouse. The windowless room is lined with white boards, which occasionally facilitated a brainstorming session but often remained unused.

Metal bookshelves are filled with texts mostly on computer programming, but also some planetary science books and cardboard boxes filled with electrical odds and ends.

During my time at Ames, I sat near the entrance to the Pirate Lab, at the only PC, necessary for my work with Microsoft's WorldWide Telescope, in a sea of Macs and UNIX boxes. I sat near the other members of the Mapmakers who worked in the lab: Ted, Mike, and Zack. Ted commuted to Ames from San Francisco, Zack from San Jose, and Mike from a few blocks away in Mountain View. Michael, who was the head of the Mapmakers before returning to graduate school in June 2010, had his own office across the hall. He often worked at home, preferring to work at night and sleep during the day. On the rare occasion he worked at Ames, he would often forgo his private office and work from his laptop in the lab. Ted, Mike, Zack, and Michael ranged in age from early 20s to early 30s, but shared a similar aesthetic. Their clothes were utilitarian, cargo pants (whose useful pockets were several times commented upon) on the bottom accompanied by a casual shirt (often a free t-shirt advertising a tech product or one with a joke about programming). There were often side conversations in the lab, unrelated to the current projects. Zack, the youngest Mapmaker discussed which digital SLR camera to buy with Mike. In turn, Zack gave Ted advice on high quality, yet affordable, headphones. After any of us would take a trip – Mike to China, Zack to the Biosphere in Arizona, or me to the observatory in Chile – we would gather around a computer and share photos. Occasionally, Zack would project a funny youtube video onto the large, imposing monitor he brought in from a different IRG lab. The daily patter in the office, filled with conversations about electronics, travel, pop culture, and other minutia of life created a collegial environment.

During my first couple of months, I was one of two women in the Pirate Lab. When the other woman moved to a quieter cubicle office, and after the summer interns arrived, I was the only woman in an office of more than a dozen men. I was also the only woman amongst the Mapmakers. Added to the fact that I was a social scientist working not on the technical aspects of the project but on public outreach, I had a hard time shaking my status as outsider. My colleagues were always courteous and often inclusive, but my female "otherness," as Diana Forsythe (2001) might label it, persisted throughout my stay.

Terry ran IRG so as to feel least like NASA (meaning minimally bureaucratic). Tuesday was designated as meeting day - every project or sub-group had a meeting and the last meeting of the day was attended by all of IRG. This structure gathered all of the "unproductive" meeting time into one day, leaving the rest of the week open for project work. To ease the tedium of back-to-back meetings, we also had group lunches on Tuesday. Though we often ate together in small groups at the Ames cafeteria, on Tuesdays everyone ate together in our building. During the lunch hour, held in the same room as the afternoon group meeting, we would sit around the conference table and informally talk about work or what we did over the weekend. The afternoon meeting was given over alternately to project updates and to mini-talks mostly given by researchers in IRG or from elsewhere at Ames. Wednesday was designated work at home day, which meant that Mondays, Thursdays, and Fridays were the days the most people could be found tooling away in the Pirate Lab. People would drift in between ten and noon and stay until they made sufficient progress on the bug they were fixing or the code they were writing. For all these reasons, the culture of IRG felt more like a start-up that could have been located elsewhere in Silicon Valley than a part of NASA. This relaxed environment was accompanied by a passion for the projects. Everyone believed in their work and either saw a public benefit or were inspired by the problem they were solving such that they were willing to stay late or work at home to finish it. When Congress cancelled the Constellation program and most of NASA was ashen, Terry encouraged IRG to see this as a great thing for their group. In the Tuesday end of day meeting on February 2, 2010, Terry described the atmosphere of NASA in light of the new budget to be one of shock, change, and chaos. But for IRG, this was an opportunity because, with the cancellation of the human flight program, NASA would have to refocus on IRG's strength – robotic research.

Open Source

Michael, who introduced me to the Mapmakers, came to IRG in August 2005 in response to a job announcement Terry had circulated on a number of computer science related lists. He had graduated from MIT months earlier with a master's degree in computer science and had moved out to the Bay Area in search of a job. He was hired to work with a senior researcher, Larry, on processing images from the Mars Observer Camera's (MOC) stereoscopic data. Larry had already worked on the software that takes stereo pairs from ground-based rovers, like Pathfinder, to create terrain models.[8] The manufacturer of MOC, Michael Malin of Malin Space Science Systems, wanted to know if the same kind of process could be applied to images taken by his camera from orbit.

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[8] MOC was mounted on the Mars Global Surveyor, which launched in 1996. This was the first successful American mission to orbit Mars since Viking 2 in 1975. Launched one month after Surveyor, Mars Pathfinder was the first robot to land on Mars that could traverse the surface. Despite several failed missions, Mars satellite and robotic exploration remained active throughout the 1990s and 2000s. The two Mars Exploration Rovers, launched in 2003, operated on the Martian surface for more than five years.

Shortly after Michael arrived at IRG, he met Ross, a planetary scientist who was a postdoc at Ames but not part of IRG. Michael recalled that Ross attended a talk he was giving about the new project to create a "stereo pipeline"[9] for the orbital images. Ross was frustrated that scientists did not have cheap and reliable ways to make terrain models. Michael recalled how he and Ross "had this notion that we wanted to build this automated tool so we could build a lot more models and democratize the whole process and get the data out there to the people so they could have access to it and hopefully, obviously, make more discoveries and what not." Ross corroborated this first encounter and the original goal of creating "something that built topography and was free for everybody to use."

This conversation about an open source stereo pipeline began in 2005 and by 2009, Michael and Ross, aided by two other members of the Mapmakers, Zack and Mike, as well as an intern Kyle, released the first alpha version of "The Ames Stereo Pipeline: NASA's Open Source Automated Stereogrammetry Software." Stereo Pipeline is currently the only free system that runs on commodity hardware that can make terrain models from NASA's Planetary Data System. This is not to say that it has a wide user base. Michael admitted that, though well documented, it is not particularly user-friendly and remains a niche and largely unpublicized application for planetary scientists.[10]

But in developing Stereo Pipeline, Michael, who had not previously known much about planetary science, was suddenly building these "amazing 3D models of Mars" and

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[9] The Mapmakers, like astronomers, use the term "pipeline" to reference a sequence of steps by which data are processed. In Chapter One, I used "pipeline" analytically to draw attention to the practices by which scientists transform planets from objects into places. The stereo pipeline, as I will discuss, takes raw data and produces a 3D model that helps the viewer gain a Martian sense of place. In this respect, the pipeline developed by the Mapmakers does similar work to the pipeline I elaborate on in the first chapter.

[10] Even in Ames, when I asked planetary scientist how they made terrain models, only those with personal connections to the Mapmakers knew of Stereo Pipeline.

only his close collaborators were seeing them. To him, the next logical step was figuring out a way to share these views with as many people as possible and in general to make NASA's data more easily accessible. By this time, Chris Kemp had been in discussions with Google about joint projects. Google, whose headquarters are a short bike ride from Ames, had recently hired two engineers who formerly used Google software to do Mars mission planning for NASA from Arizona State University. They were already thinking about how to expand Google maps beyond Earth, and Michael and his colleague at Ames, Matt (who eventually went to work for Google), were the perfect partners to achieve this vision. The idea was to extend Google Earth, a desktop application that incorporates satellite imagery, topographic maps, and other geographic content to create a virtual globe of Earth, to Mars. Mars in Google Earth was released on February 2, 2009.[11] At this point, Michael was handling not only the partnership with Google, but also working with the United States Geological Survey (USGS) and a new contract with Microsoft to make a model of Mars for its WorldWide Telescope. WorldWide Telescope is Microsoft's response to Google Earth. It distinguishes itself as a virtual telescope, providing access to the universe, not just planet Earth. With this influx of work, it was necessary to expand the team, and the Mapmakers quickly grew from two or three researchers to the seven that were there when I arrived.

The Mapmakers hope to "democratize" Mars using two platforms. The first is the public platform provided by Google and Microsoft, [12] which allows users to explore and

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[11] The Mapmakers also do significant work with lunar data. Their first release for Google was http://moon.google.com, which went live in 2008. The Moon in Google Mars was released on June 20, 2009 to commemorate the 40th anniversary of Apollo 11 landing on the moon. For the purpose of this chapter, though, I focus on the work they do with Mars images.

[12] It might seem counter-intuitive that I can discuss the open source ethos in the same sentence as Microsoft, the "evil empire." From informal conversations, it did seem that most Mapmakers identified more with their Google work and the Google way of doing things. However, the partnership with

navigate a map of the planet's surface. The second way they democratize Mars is to make the tools for mapping available as open source code. Anthropologist Christopher Kelty writes about the culture of the Free Software community and its attending geeks. He names the community a recursive public, a public that maintains the means by which they came together as a public. Geeks, Kelty shows, care deeply for initiatives like Free Software and Open Source[13] and the ideologies they represent. They "use technology as a kind of argument, for a specific kind of order: they argue *about* technology, but they also argue *through* it" (Kelty 2008, 29).[14] The argument that the Mapmakers propagate is that NASA's data, produced through public funds, *should* be available and, further, available to manipulate, to all who are interested. The reason for this openness is that, as the map establishes Mars as a geographic and scientific place, in a democratic society such a place should be accessible to all.

Stereo Pipeline was released as an open source product in 2009. It works along side the Mapmakers' other open source initiative, Vision Workbench, also released in alpha in 2009. Vision Workbench contains basic computer vision tools that Stereo Pipeline utilizes, but can be used for more applications than just the mapping of planetary surfaces. To make Vision Workbench truly "open," a task assigned to Mike (the

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Microsoft was not seen as particularly at odds with the openness that the Mapmakers wanted to achieve with respect to Mars data. They were comfortable with the developers they worked with at Microsoft Research, the more experimental and "hacker" arm of Microsoft. They did comment on the frustrating fact that World Wide Telescope only ran on Windows machines, but this did not dampen their enthusiasm for the project.

[13] Kelty deftly works through the differences (and similarities) between Free Software and Open Source and the evolving relationship between these two terms and their attending communities. He explains that they are two movements with the same material base, but different ideologies. See specifically his Chapter Three. I use "Open Source" in my discussion because that is the language used by the Mapmakers

[14] Anthropologist Gabriella Coleman (2004) similarly discusses the buried politics of Open Source and Free Software movements. She characterizes this community as having a "political agnosticism," meaning that even as programmers deny any political allegiance their coding initiatives belie an ethic devoted to free speech and transparency. Elsewhere, Coleman and Alex Golub (2008) articulate the hacker ethic as a particular kind of liberalism. I recognize what I call the Mapmakers moves towards "democratizing" in this framework.

"hacker" of the Mapmakers), required many levels of bureaucracy, as he described it, before Headquarters would sign off on its release. With permission granted, Mike uploaded the code for Vision Workbench to Github (a website that hosts code, facilitates network sharing, and manages version control). When he announced this achievement at a Mapmakers meeting in May 2010, everyone applauded and showed genuine excitement for this accomplishment. Welcome to "this brave new world of open source," Michael intoned. For the Mapmakers, openness is an unquestioned good.[15] In practical terms, open source allows for more fluid collaborations with those outside NASA, as there is no fear of sharing proprietary code. Ames in general, and IRG in specific, has been the primary instigators of the open source movement within NASA. In 2003, Ames engineer Patrick Moran wrote a technical report on "Developing an Open Source Option for NASA Software." He outlined three benefits NASA would enjoy if it were to embrace open source: "(1) improved software development; (2) enhanced collaboration, in particular across organizational boundaries; and (3) more efficient and effective dissemination" (Moran 2003, 3). IRG tries to make most of its projects open source, but this is not without the time consuming process necessary to obtain permissions from NASA Headquarters. In many ways, it is easier not to implement code as open source. To address these issues, as well as promote open source within NASA, Ames hosted the Open Source Summit in March 2011.

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[15] I use this term "unquestioned good" to reflect that in daily conversations, this community does not assess whether or not to pursue open source initiatives. This also echoes Kelty's and Coleman's ethnographic observations that openness is increasingly the "obvious" choice (specifically Coleman 2004, 510). It is worth noting, however, that one Mapmaker was uncomfortable with my use of the word "unquestioned." In the past, he, and he assumed others in the group, made the conscious choice that openness was a good thing to pursue in his professional and personal life. Just because the community no longer questions the goodness of open source, does not mean the individual did not question this choice before joining the initiative (personal email to author).

As Kelty observes, after UNIX established itself as the model for developing code, "the norms of sharing have come to seem so natural to geeks" (119). The Mapmakers, channeling these norms, saw fit to make their code and data widely available so as to democratize NASA products. When I asked Ted why it was important to make a map of Mars for both Google and Microsoft, he responded that it was all about providing the broadest possible access to the data. "My goal with these types of projects is to make it more useful to people. I want anyone who wants to, to be able to explore all the awesome data that NASA has… Cool stuff should be discoverable. Folks in the general public should be able to just jump on the Internet and explore this stuff."

Open Data

The unquestioned good of sharing code is synonymous, for the Mapmakers, with the unquestioned good of sharing data. The Mapmakers make this argument for open data through the technology of maps. When I first met Michael for lunch at a Thai restaurant on Castro Street in Mountain View, he described himself as a modern day cartographer. His first assignment to integrate me into the group was to read John Nobel Wilford's *The Mapmakers*. Wilford offers a narrative for the history of cartography, from the Greeks to the space age. He focuses on the techniques of mapping and their technical maturation while providing enticing stories of famous cartographers and notable expeditions. Though he recognizes the social and political aspects of maps, as a historian he is more interested in maps "as interpretations of place" (Wilford 2000, 16). He speaks even more grandiloquently about the relationship between maps and places when describing the radar mapping of the planet Venus. After seeing the map of Venus for the first time, one Venusian scientist recounted to Wilford, the planet took on a new character. Wilford interpreted, "mapping a place made it seem real for the first time" (295).

Perhaps informed by Wilford's notion of mapping, the Mapmakers similarly see their practice as making Mars more real for scientists and the interested public. And in making Mars real, it takes on attributes of place. Michael described to me the role of mapping in place-making: "before places, like California for example, are settled and before we really are living and being at a place… there are people who start the process of exploring those places and mapping them out." For a place to come into being, then, it must first be mapped.

In this musing, Michael was working out the relationship between the map and the territory. Jean Baudrillard (1983), in trying to describe the postmodern condition as one with no grounding reality, observes that it is now the map that precedes the territory; that image and reality become indistinguishable. Whereas mapping has long been associated with laying claim to territory (see for example Patricia Seed's [1995] discussion of Dutch mapping of the New World), Baudrillard emphasizes that the map now comes prior to the territory. Moreover, the map is the medium in which to know or negotiate the territory; it can even exist without a territory. In mapping Mars, Baudrillard's prophesy reaches an apotheosis. Mars has been mapped before humans have stepped foot on its surface. The map is the only way to experience the distant territory, and it is the goal of the Mapmakers to make this experience widely available. And even as the map of Mars suggests a postmodern reading, it works as a map and as an argument because of a more traditional, realist positioning. For the realist, there is a solid reality and representing it is unproblematic. Therefore, in offering an unproblematic, transparent representation in the map of Mars, the Mapmakers establish Mars as a solid reality; a territory; a place.

And even as they claim that mapping is a process of displaying the real, they acknowledge that every step of presenting Mars is predicated by choices. Many of the choices they make are understood through the frame of freedom of information, and so any design decision that results in the display of more information is considered the way to proceed. Ted, who joined NASA and the Mapmakers in May 2009 and who was coming from a job where he used geospatial data to make maps for web applications, acknowledged that a lot of work and thought goes into the process of selecting what information to display and how to display it. Mapping and data visualization are very closely related for Ted. When I asked if mapping from images, like the NASA data, involved less decision-making he responded in a characteristically clipped and excited manner, "I would say it's easier to visualize the information when you're starting from image data. Making a map, which is what we're doing, is an easy way to take a lot of diverse data and visualize it in one place. It's easy because there's a geographic component to it and because it's natural for us to map – map as a verb – from that two or three dimensional model space to something that we can engage with in the real world." The map as an entryway into the real is intuitive because, as Ted put it, there are "natural graph axes" suggested by geography. Ted admits his authorial role in the early stages of mapping, but as the finished map offers an illusion of reality, and the map becomes synonymous with the real, he retracts his agency.

Since the early 1990s, following Harley's lead to deconstruct the map, critical geography and cartography has been explicitly investigating the cultural construction of maps and attending to the power relations within which mapping unfolds. In one of the key works in this vein, *The Power of Maps*, Wood and Fels (1992) discuss how maps serve interests and suggest that Western culture, perhaps all culture, is pre-disposed to maps. They locate the power of maps in the erasure of the author. Cultural geographer Denis Cosgrove (1999) claims that the increasing attention to questions of authorship has brought mapmaking under critical scrutiny in geography and other fields in the humanities and social sciences. Further, new technologies such as satellite photography and GPS produce maps that appear more objective and seem to unveil the author behind older, hand-drawn maps. In working with the Mapmakers, I had privileged access to the authors of highly technologically mediated maps and was able to learn both how they produced maps and the extent to which they sought to erase themselves as authors. As I will discuss at greater length in the next section, this erasure was done through the creation of an autonomous program to produce Mars maps. Removing the authorial trace is another technique to strengthen the illusion of reality and present the maps of Mars as scientific products. And once they are established as scientific products, the open source ethos suggests that the maps should be available to all.

When I got to Ames, Google Mars and Google Moon had already been made part of Google Earth, but the team was in the midst of working on the first deliverable for their partnership with Microsoft Research. Microsoft Research released the WorldWide Telescope (WWT) in May 2008. Unlike Google Earth, WWT did not originally focus on planetary data but used data sets from telescopes like the Sloan Digital Sky Survey and the Hubble Space Telescope to create a map of not just our planet or the solar system, but of the universe. As educator Roy Gould put it when introducing WWT at a Technology Entertainment Design (TED) talk[16] in February 2008, "Until now our view of the universe has been disconnected and fragmented." WWT was meant to give amateur astronomers and educators a more "holistic view of the universe."

WWT is designed such that you can "fly" through the universe using either a mouse and keyboard or an Xbox (Microsoft's gaming system) controller. By stitching data sets together, there is continuity between flying around the Sloan Sky map and then zooming in on a beautiful, color enhanced Hubble image. The Mapmakers were brought into this project to create a "Mars mode" for WWT. Microsoft wanted Mars to be featured in a new release and to focus on the most recent data sets from NASA. In addition to the color base map of Mars from the Viking mission and the mosaic of images from the MOC camera, the Mapmakers and Microsoft decided to take the largest data set of Mars available and thus create the highest resolution map of Mars. This data set comes from the High Resolution Imaging Science Experiment (HiRISE).

HiRISE is on the Mars Reconnaissance Orbiter (MRO) and has been imaging Mars since 2006. The pictures it takes can resolve objects less than a meter across. From orbit, it has taken pictures of the Phoenix Lander and resolved the Mars Rover tracks. It has taken pictures of individual boulders rolling down a hill. HiRISE also plays a part in democratizing Mars as the camera is nicknamed by the team "the people's camera" and takes requests via a web interface called HiWish for ideas of what to image. Because the resolution is so high, after four years HiRISE has only imaged one percent of the planet.

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[16] http://www.ted.com/talks/roy_gould_and_curtis_wong_preview_the_worldwide_telescope.html

The challenge for the Mapmakers was to take this one percent that is spread all over the surface and figure out a way to process the terabytes of information contained in this set.

The Mapmakers also had to work with WWT's file formats and map projection to create Mars for WWT. When making Mars for Google Earth, the Google engineers used the same map projection for Mars that they did for Earth. This is the Simple Cylindrical projection. It is similar to the classic Mercator Projection in that latitudes and longitudes are parallel but different in that they are equally spaced (in Mercator Projections, parallels near the equator are closer together than those at the poles).

All projections create distortions. As landscape architect James Corner offers, maps do not mirror, they re-shape. Different projections imply different socio-political structures. The Mercator projection orients towards the north, distorts near the poles, and countries in the northern hemisphere are spatially favored. In contrast, Corner describes Buckminster Fuller's Dymaxion projection, which does not distort the poles and can be unfolded and re-oriented in different ways so as not to statically favor one land mass over another (Corner 1999). The Simple Cylindrical projection used by Google Earth, based on Mercator, distorts the terrestrial - and consequently Martian - poles because, as Mapmaker Ross exaggeratedly put it in a public talk about Mars in Google Earth, on Earth "no one cares about the poles" (Beyer 2009).

On Mars, however, the poles are extremely important for science as they contain the only known deposits of water ice on the planet and experience seasonal melting. Consequently, they have been extensively imaged. WWT decided to implement a different projection for planetary mapping, the same projection they had used for the whole night sky. Jonathan Fay of Microsoft developed the Tessellated Octahedral

Adaptive Subdivision Transform (TOAST) projection, which distorts every part of the surface a little bit (as opposed to a few parts of the surface a lot). Like the Dymaxion projection, it is based on a triangular geometry[17] and also like the Dymaxion, the poles are only slightly distorted. Figure 3.2 shows the how Mars's north pole is differently projected in WorldWide Telescope versus Google Earth.

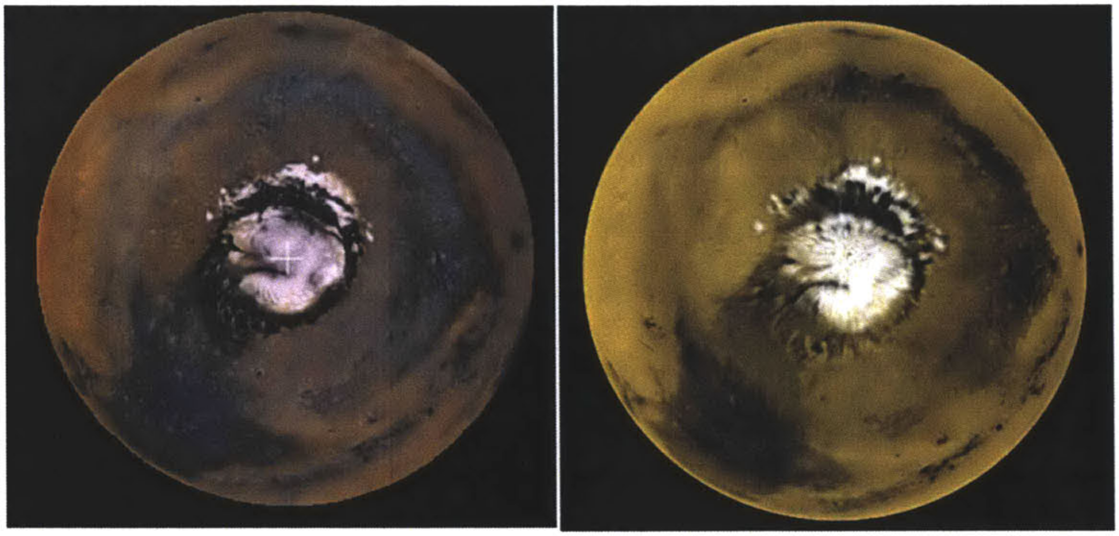

Figure 3.2: The North Pole of Mars. The image on the left is from WorldWide Telescope and on the image on the right is from Google. Both maps use the same data (Viking base map), but there is less detail and greater distortion of the poles in the Google rendering.

The different projections suggest the different ways people use Mars in Google Earth versus WWT. The advantage of Google Earth's simple cylindrical projection, like the Mercator projection, is that even though there is distortion at the global level, when you zoom in to the lowest level there is very little distortion. Scientists use Google Mars in a variety of ways. For example, planners for the Mars Exploration Rovers orchestrate traverses in Google Mars. While Google Mars and Google Earth prioritize the local, the TOAST projection, which becomes more distorted the more one zooms in, highlights the

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[17] The scheme that TOAST uses to model a sphere as a polyhedron is the Hierarchical Triangular Mesh. This is based on an earlier solution to the problem called the Octahedral Quaternary Triangular Mesh. The geographer Geoffrey Dutton who invented this model acknowledges that he was inspired by Fuller's Dymaxion projection and the geodesic dome (Dutton 1996).

regional or global projection.[18] As I was at the end of my stay at Ames when WWT was released, I did not get to see if and how scientists would use WWT as a tool. Mars in WWT was built with an eye towards the "holistic," as Gould stated in his TED talk. Consequently, the poles appear more "real" in WWT, even if that means a sacrifice in local fidelity. The TOAST projection ensures that even at the highest level, the map appears coherent. This attests to a global geographic realism.

The Mapmakers view a democratic Mars, where data and tools are available to all, as unproblematic. This, like all cartographic decisions, is a choice informed by an ideology not universally shared. For scientists, the wide release of NASA data sets holds more serious implications. One Mars scientist I spoke with who is not involved with mapping efforts expressed frustration with the public seeing the data before scientists have had the chance to make a responsible decision about how to analyze it. She gave an example from her time working on the Phoenix Lander mission. The Lander discovered some "white stuff" when it scraped back the surface soil and the team was still discussing the nature of the debris when the data were released. According to this scientist, MSNBC and the Daily Show broke the story before the team made an official statement about what turned out to be ice on Mars. To keep up with the public, science teams are increasingly forced to make hasty assessments of data that might have benefited from more research. For this scientist, a democratized Mars is not necessarily a better Mars. Just as the Mapmakers consider democratized data a universal good, so to is presenting Mars in three dimensions. The legacy of offering the public a three-dimensional glimpse of Mars began in NASA Ames' backyard.

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[18] Thanks to Bill Rankin for suggesting that the projections themselves suggest a different relationship between the user and Mars.

Three-Dimensional Mars

The Viking missions were sent to Mars in the 1970s with the hopes of detecting evidence of possible life. Though the outcome of these experiments were negative, Viking did, in another sense, breathe new life into Mars. Images from this mission were the first to portray Mars in three-dimensions. Since then, depicting Mars in 3D has been considered both an exciting tool for public outreach and a necessary representation for scientists studying Mars. NASA Ames has always been a part of the 3D initiative, from the early work by Stanford professor Elliott Levinthal, who popularized the 3D view of Mars taken during Viking, to the present work the Mapmakers are doing in automating and expediting 3D models of Mars. Mars as a three-dimensional object affords a certain intimacy with the planet. 3D enhances the illusion of realism because it claims to offer viewers a sense of "being there." To map Mars in three dimensions is to suggest that Mars is a destination, both virtually and physically. 3D, however, is not easily come by. The realism viewers claim to gain by looking at 3D is the product of meticulous social and technical engineering. The work needed to see in 3D is more apparent in early Viking 3D products, but becomes close to invisible thanks to the current tools produced by Mapmakers and other scientists.

"Mars in 3D"

On January 15, 1979, five hundred scientists attending the Second International Colloquium on Mars gathered in an auditorium at the California Institute of Technology to watch the premier of a film entitled "Mars in 3D: Images From the Viking Mission."[19] Audience members received stereo glasses (and were assured that they would fit

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[19] A DVD of this film was given to me by Glenn Bugos at the NASA Ames History Office

comfortably over their prescription spectacles) for viewing. The lights dimmed and the first chord of a synthesized soundtrack reverberated throughout the room as the first movie frame instructed the scientists on the best way to experience the illusion of the 3D images. After the NASA logo was displayed against a startlingly red background, the title and credits of the film were superimposed over a series of stills as the viewer came ever closer to Mars. First displayed was Mars as seen from Earth, then Mars as a crescent during the Viking Orbiter's approach, and finally a 3D image of a canyon on the surface of Mars.

The narration of the film began with a shot of writer/director/scientist Elliott Levinthal dressed in a white blazer and black tie standing in front of a picture of the Martian surface. The scene is monoscopic, he tells the viewer, as "there is nothing exciting or flattering about pictures of your narrator in stereo." What he is going to present to us in this film is "the three-dimensional character of the surface of Mars as revealed by the Viking cameras." The film proceeded in three parts. In the first part, he walked the audience through 3D images taken by the Viking orbiter. The camera zooms and pans across craters, what look like dry river beds, and the mythically named Olympus Mons to give the illusion of flying over the surface.

In the second part of the film, the narrator introduces the viewer to the Viking Lander. Stereo images and video from the Lander test center at NASA's Jet Propulsion Laboratory depict a full-scale test spacecraft perched in front of an artist's conception of the surface of Mars that was painted before Viking landed. Levinthal explained the hardware and when he described the collecting arm, it slowly extended towards the crowd. He instructed the audience to "move your head slowly from side to side and you will observe an interesting effect." An article describing the premier of "Mars in 3D" reported: "The long arm of the Viking Lander Surface Sampler reached out dramatically, closer and closer to each one in the audience. It seemed as though one could put out one's hand and touch it. If one moved from side to side the groping shovel followed one's every move. The more than five hundred spectators burst into applause" (Nicholson 1979).

After Levinthal explained the stereo cameras and the Viking model demonstrated their operation, the audience was transported to the surface of Mars and the film panned across a panorama taken by the first Viking Lander. The cameras on Viking were separated by nearly one meter, which made it difficult to experience the effect of 3D. Levinthal had to coach the audience on how to achieve the proper illusion: "Concentrate first on the horizon. The prominent rock on the ridge is an ideal starting point. Relax your eyes until you begin to see the stereoscopic effect. After achieving fusion, slowly move your eyes along the horizon. Now shift your attention gradually to the foreground... Many people have difficulty fusing the bottom half of the image. Don't feel left out if you can't see the nearest rocks. Enjoy the more distant vistas along the horizon as we take you on a three dimensional journey over the surface of Mars."

In addition to this movie, stereo pairs from Viking were circulated in a NASA published book, *The Martian Landscape.* In the text preceding the pairs, the author gives guidance similar to Levinthal's. He goes further and comments on the effect of fusing a stereo pair:

> There is, however, one fairly reliable guide to the viewer's success. If, as he peers through the stereoscope, you ask him if he sees the third dimension and he responds noncommittally 'yes,' then you know he has not. Wait a few minutes and you will hear

> an exclamation of surprise and wonder. Then you know he has seen it. The effect is so unusual, literally drawing you into the scene, that very few people come upon it without excitement (Mutch 1978, 145).

In both accounts, the 3D encounter with Mars takes effort on the part of the viewer. That Mars becomes so real, "you may get the impression you can actually step from your chair and onto the surface" (145), is due to the (poorly concealed) illusion of stereoscopy.

"Mars in 3D" was the pet project of Levinthal who worked in the Genetics department in the medical school with its founder and Nobel Laureate Joshua Lederberg. In December 1959, the Rockefeller Center gave the Department of Genetics seed money to found the Instrument Research Laboratory (IRL). In April 1960, NASA began funding the IRL to encourage Lederberg and associates to pursue the developing field of exobiology, a term coined by Lederberg.[20] After more than a decade of working in industry, Levinthal joined Lederberg at the IRL in 1961. Their first NASA-commissioned project was the design and prototyping of a self-contained apparatus, the Multivator, intended as a biochemical laboratory to measure samples of atmospheric dust or soil for signs of life.

Levinthal worked on several more NASA projects, including the Mariner 9 Photo Interpretation Team and he served as the Deputy Team Leader on the Viking Lander Imaging Science Team. Mariner 9 was the first craft to orbit Mars and imaged approximately 85% of the Martian surface during its nearly twelve-month mission duration. This mission changed the geographical understanding of Mars. While earlier

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[20] NASA Ames History Office, NASA Ames Research Center. Moffett Field, California. PP04.02, Elliott C. Levinthal Viking Lander Imaging Science Team Papers, 1970-1980. 11 : 59. "Stanford's Trip to Mars," Address delivered to Medical Alumni Reunion Day. May 22, 1976. This collection will be referred to as NASA ARC, Levinthal Collection hereafter. See also Wolfe (2002) for Lederberg's role in constructing exobiology as a peaceful and scientific venture, and Dick and Strick's (2004) account of NASA's role in the rise of exobiology and the subsequent transformation into astrobiology.

Mariner missions captured images of what looked like a crater-riddled, almost Moon-like surface, photographs from Mariner 9 revealed a planet with volcanoes and canyons and many more geologically interesting features than originally thought. For the Viking missions, NASA launched two payloads in 1975. The two landers both made it safely to the Martian surface and the orbiter completely imaged the surface at a higher resolution than Mariner 9. Viking was also the first mission to collect stereo pairs of images and thus the first capable of showing Mars in 3D.

Viewing images in 3D had been a source of entertainment for more than a century before the Viking mission. Starting in the 1820s, vision researchers devised several mechanisms for creating the illusion of three dimensions using stereo pairs. Art historian Jonathan Crary describes the stereoscope as a significant development in visual representation because it did away with a set point of view; there is a changed relationship between the observer and the object of vision. This is why, a century after the sterescope first appeared, audiences marveled at the disconnection between themselves and what they viewed. The most enthusiast response to "Mars in 3D" came from the moment when the observer bobbed his or her head around to see the extended collecting arm from a different perspective. The object was not static, nor was the viewer's relationship to it. In the mid-19th century, the stereoscopic effect was greeted with enthusiasm because, unlike traditional painting, it felt more real. As Helmholtz wrote in the 1850s, "These stereoscopic photographs are so true to nature and so lifelike in their portrayal of material things, that after viewing such a picture... we get the impression, when we actually do see the object, that we have already seen it before and are more or less familiar with it" (quoted in Crary 1990, 124).

This correlation between "realism" and 3D remains its primary appeal, despite the artifactory mediation needed for viewing. In a press release containing information about a screening of "Mars in 3D" at Stanford's Dinkelspiel Auditorium on April 28, 1979, the film was described as portraying "ridges, outcrops, drifts, and craters of the Martian terrain" in "vivid, realistic detail."[21] Moreover, Levinthal's film was designed to offer the public access to the way scientists were seeing Mars. The film was made on his own accord, with support but not funding from NASA (who were producing their own public outreach film meant to encompass the whole Viking mission, not just the stereo imagery). Levinthal tried to get NASA involved numerous times, writing on March 2, 1979 to Geoffrey Briggs at NASA Headquarters reporting that 2,000 people attended the screening at Stanford.[22] In late September of 1980, Levinthal explicitly asked NASA to take over the production and distribution costs. Bryon Morgan, the chief of motion picture productions at NASA responded saying that NASA is not in a position to cover these expenses. "You are to be congratulated for having done a fine job. NASA is not to be congratulated for the way they have buried it."[23] Ultimately, The Planetary Society, Carl Sagan's enterprise, took over the marketing and distribution starting in 1982.

One of the reasons NASA declined to take on "Mars in 3D" was the budgetary uncertainty of the post-Apollo period. The San Francisco section of the American Astronautical Society (AAS) went so far as to establish the Viking Fund,[24] which hoped to raise $1 million by July 1980 to donate to NASA so as to continue the study of the red

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[21] NASA ARC. PP04.02, Levinthal Collection. 9 : 50. "Prof Makes 3D Photos of Mars." ND.

[22] NASA ARC. PP04.02, Levinthal Collection. 9 : 46. Letter to Geoffrey Briggs. March 2, 1979.

[23] NASA ARC. PP04.02, Levinthal Collection. 9 : 81. Letter from Byron Morgan. October 1, 1980

[24] The Viking Fund was proposed by Eric Burgess who also had the idea that the Pioneer probes should carry a message about its origin. After pitching this idea to Carl Sagan, the Pioneer plaque was designed (see Vakoch (1998) for an analysis of the symbolism of the plaque).

planet. In an effort to reach this goal, the Viking Fund held a screening of "Mars in 3D" at San Jose State University and requested donations of $3 ($2 for students) to attend. In a letter from the audio-visual coordinator of the San Francisco Section of the AAS to a skeptical Levinthal, Bill Copeland explained that the purpose of the Viking Fund is not to undermine NASA but "to demonstrate support for NASA and space activities in general." He continued, "I personally have become involved with this and other space activities to open men and women to the awareness that we are not doomed to a dying planet. The intelligence and spirit of man can expand into infinite space." Copeland enclosed material to familiarize Levinthal with the Viking Fund's mission. These stressed the role of the individual in making Mars science happen, inviting the public to "explore Mars in depth" and join in the "do-it-yourself" initiative.[25]

The letter from Copeland connects "Mars in 3D" to the final act of the techno-political sea change that occurred in the Bay Area and elsewhere in the late 1960s and 1970s. Several historians have nicely teased out the changing view towards technology in America at this time (Moy 2004; Turner 2006). "Geeks" re-imagined technology as the key to salvation as opposed to destruction. This was especially potent in the Bay Area, where Stewart Brand and his *Whole Earth Catalog* encouraged the commune movement by giving them access to technologies that would liberate them from "the establishment." The Viking Fund, like the commune, expresses that in the face of government disappointment, technology enables the individual to continue to pursue a way of life deemed satisfactory. This harmony between tech culture and alternative ways of living still flourishes in the Bay Area and particularly amongst my NASA interlocutors.

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[25] NASA ARC. PP04.02, Levinthal Collection. 9 : 42. Letter from Bill Copeland. Not dated.

Making Mars 3D

Since the Viking mission, 3D has been a standard output for Mars imaging systems. Engineers improved the optics, switching from television to digital imaging and placing the lenses of stereo cameras closer together to make fusing stereo pairs easier for the viewer. Producing 3D anaglyph images of Mars, like those presented in "Mars in 3D," remains a relatively simple task. Transforming these images into regional models and global 3D maps is the complex problem the Mapmakers work on.

Sophisticated 3D models take time to build and producing them efficiently and at the planetary scale, is a significant computer science problem and one at the heart of the Mapmakers' work. Though they work on the problem of 3D, the Mapmakers very rarely look at 3D images. Instead of spending research time looking at the Mars surface, the Mapmakers' screens are filled with lines of code. While working on the WorldWide Telescope (WWT) project, I was the only member of the team regularly looking at how representations of Mars looked in 3D. I did not realize until several months into the project, that some of the Mapmakers had not seen the maps they were producing of Mars. They had to crowd around my Windows station to get their first glimpse of the 3D Mars they coded for WWT.

The Mapmakers are interested in the challenge of producing high resolution and terrain model maps for a variety of reasons. Zack, who has done extensive terrain modeling of the Moon using data from both Apollo and more recent missions, had the toughest time articulating what it means for him to work on 3D modeling. When I asked him about working with lunar data, he explained what that work is like by describing the kind of processing one needed to do with the images in order to clean them up. When he thinks of lunar and planetary images, he is not imagining the final product that the scientists often work with. In order to do his job – create his models – he needs to understand the process behind the final images. As with exoplanet data, the mission team often does a preliminary cleaning of the data before public release. Zack told me that the processing they do to "dewarp" the image interferes with the geometry of the way he produces 3D models. He has to do a lot of "book work" to make the processed image and his code work together.

At the end of months of coding and days of processing, Zack has on several occasions been the first person to see a 3D model of certain areas of the Moon; he has been the first person to see the Moon from a new perspective. When I asked him what that experience is like, and whether it helps him understand the Moon better, geographically speaking, he responded, "No, I'm just like, it's pretty! That's what I do, I make pretty things. And I like to stitch them together and make even bigger pretty things." He gets quiet before continuing,

> I don't know, I'm actually really proud of them. What I want to do is I want to get LMMP [Lunar Mapping and Modeling Project] finally finished because I want to print it out somehow and make a giant poster or do a canvas print and, like, hang it. I feel like I've done just as much work as an artist on anything else. I've spent an absurd amount of time [on it]. I've refined it. Even though it's trying to convey information, it took a lot of work to get there… I don't know why I think it's cool, I just think 3D's cool.

Here, the aesthetics of scientific work are not hidden within practice, as Lynch and Edgerton (1988) diagnose in the case of astronomical image processing. Because 3D is an illusion, a visual construct, creating a model is "cool" precisely because it is not simply "real" but a product of coding and image work.

3D is an aesthetic "coolness" at the end of a challenging computer problem. Zack's primary research focuses on what is called "bundle adjustment." Bundle adjustment is one approach to 3D modeling in which multiple camera locations are solved for in order to triangulate where features are located on a surface. Thus, you have a set of cameras and images and with knowledge of the coordinates and angles of the camera, the relationship between images can be reconstructed and a terrain model can be developed. Zack also described bundle adjustment as "really cool" and said that one of the reasons he liked doing bundle adjustment was precisely because at the end of it, you have a 3D model.

Ted's role on the mapping projects is to manage the data flow (data wrangling, as he sometimes called it). For a project like WWT, the amount of data, the system that had to process it, and the sequence in which it had to be processed made Ted's job quite challenging. He had to learn a lot to make the system work, and it took the better part of a year until the Mars product for WWT was delivered. Unlike Zack, Ted does not work on code that directly leads to a 3D model. His approach to building a data management system could be used on a variety of projects. Whereas Zack sees his 3D models as art he created, Ted understands the 3D models the Mapmakers produce more as tools. They are tools of engagement for both scientists and the general public. "Architecting the systems," he told me, "comprises the bulk of my work, but what I'm really interested in is coming up with ways for people to engage with data." Ted considers the 3D maps to be tools that connect the data collected remotely with ways people understand being in a place. It is a bridge between physically visiting a place and being able to understand a place. 3D maps are "an interface between our long range sensing devices and our inherent cognitive tools for mapping spaces." Mars in 3D, from the toolmaker's perspective, is the best way we have right now to experience and understand Mars.

The 3D maps that tools like Stereo Pipeline produce are not anaglyphs or stereographs for which special viewing glasses are needed. They are in a perspective rendered view. This makes the illusion of 3D seem even more real and close to hand, as no additional artifact is necessary to experience 3D. Crary speculates that one reason stereoscopes did not catch on in the 19th century (and 3D has never really become the visual norm, even after the blockbuster success of the 2009 movie *Avatar*[26]) is because it is not phantasmagoric enough. The Frankfurt School argued that a spectacle is phantasmagoric only if the mechanisms of production are concealed (Crary 1990, 132). The bulky glasses needed for viewing 3D remind the user of the illusion. With the perspective rendered view, however, the illusion disappears. *This* is the terrain of Mars. It can be quantified, studied, and explored. The cognitive distance between being there and virtually being there is diminished. Mars itself becomes less an illusion and more a reality.

I asked Michael to show me how images from the Planetary Data System (PDS) get made into maps – to show me the machinery and reveal the terrain model as an illusion. He decided to show me how an image from MOC can be imbedded in Google Mars. I had installed Stereo Pipeline and ISIS (the USGS image processing software that Stereo Pipeline interfaces with) on my computer. I opened up a command line and Michael walked me through the procedure. After downloading the experimental data record (EDR) of an image from PDS, the first step is to import it to ISIS. This created a

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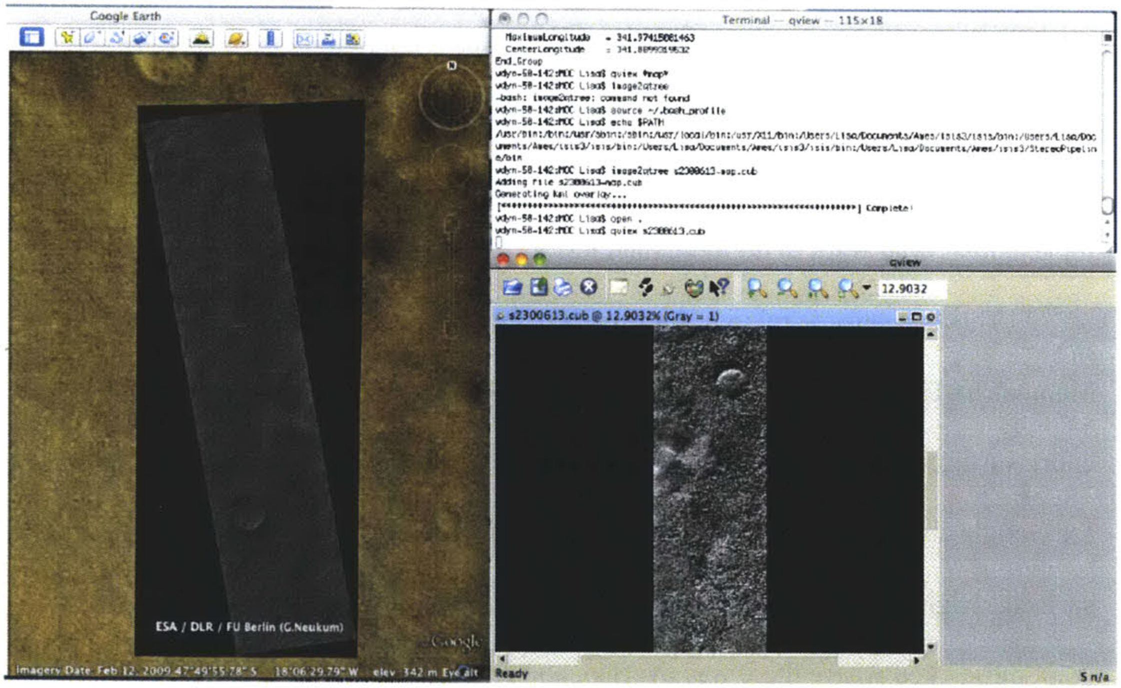
[26] See the short piece by film scholar Thomas Elsaesser (2010), in which he historicizes the current iteration of 3D cinema and why digital 3D does not rectify the earlier problems faced by 3D movies.

.cub ("cube") file, readable by ISIS. The next step is to sync with the camera data. The EDR contains information on when the image was taken and the camera model in ISIS will use that information to calculate the angle from which the image was taken. Next, Michael told me to type the command "moccal" which calibrates the image based on information about MOC, reducing the pixel contrast to make a clearer picture. From there, it is a simple command, "cam2map," that transforms the image into a map projection. In order to get this image into Google Mars, I just needed to type one more command to convert the .cub file into .kml (Google's geographic file format) and then simply open up the .kml in Google Earth (the final product is shown in Figure 3.3).



```
  MaximumLongitude   = 341.97415081463
  CenterLongitude    = 341.88993019532
End_Group
vdyn-58-142:MOC Lisa$ qview *map*
vdyn-58-142:MOC Lisa$ image2qtree
-bash: image2qtree: command not found
vdyn-58-142:MOC Lisa$ source ~/.bash_profile
vdyn-58-142:MOC Lisa$ echo $PATH
/usr/bin:/bin:/usr/sbin:/sbin:/usr/local/bin:/usr/X11/bin:/Users/Lisa/Documents/Ames/isis3/isis/bin:/Users/Lisa/Doc
uments/Ames/isis3/isis/bin:/Users/Lisa/Documents/Ames/isis3/isis/bin:/Users/Lisa/Documents/Ames/isis3/StereoPipelin
e/bin
vdyn-58-142:MOC Lisa$ image2qtree s2300613-map.cub
Adding file s2300613-map.cub
Generating kml overlay...
[******************************************************************] Complete!
vdyn-58-142:MOC Lisa$ open .
vdyn-58-142:MOC Lisa$ qview s2300613.cub
```

Figure 3.3: Screenshot taken during tutorial. The upper right is a terminal in which I typed commands to manipulate the images. The bottom right shows an orthogonal image I downloaded from PDS. On the left is this same image map projected and overlaid on the map of Mars in Google Earth.

This simple sequence maps a single image and mostly uses ISIS commands. Stereo Pipeline allows one to process two images, match them, and create a terrain model. In Stereo Pipeline, a single script can be run that, given a map projected stereo pair, will produce the model. I never had a chance to run this because when Michael tried to walk me through it, we encountered a bug. Michael did explain what Stereo Pipeline does to create 3D models and Digital Elevation Models (DEMs). Given two images the program finds corresponding pairs between the images. With a relationship established between the two images and knowledge of the camera position, a point cloud can be generated. A point cloud is a grid of locations over a surface that, for each point, provides x, y, and z coordinates. The next step is to convert the point cloud into a polygonal "mesh." A mesh draws lines between the points in the point cloud, transforming a discrete grid into a series of triangles. The surface is now connected and can be visually rendered by most 3D browsers. From the point cloud, Stereo Pipeline also can output a DEM, which is the quantitative result of the 3D processing and useful for scientists who want to do more than just look at their 3D creations.

This sequence is relatively straightforward. The daunting task that faced the Mapmakers for projects like Google Mars and WWT was to apply this sequence to the entire surface of Mars. The images had to be map projected (in two different ways, one for Google and one for Microsoft), stitched together, and then made 3D over the whole surface. High resolution images from MOC and HiRISE were also embedded on the map, mosaicked where there was overlap, and rendered in 3D. Architecting a system to do this, what the Mapmakers came to call the Plate File system, was the challenge of these projects.

In presentations about their work, the Mapmakers describe how they created the Plate File system. Maps of Mars are used to illustrate the products of this system. The

Mapmakers proudly acknowledge themselves as authors of the software architecture, but on the maps in Google Mars and WWT, they are not listed as authors. As with traditional maps, the erasure of the author elevates the map from an aesthetic piece to one that is scientific and objective. Even Zack, who understands and articulates his role as author in creating pretty and cool maps would not suggest he be credited in the public presentation of the maps. His work, after all, was on the problem of bundle adjustment, not cartography.

The stage at which they position themselves as authors – the stage of tool building – speaks to the genre of objectivity to which their project appeals. Lorraine Daston and Peter Galison (2007) categorize the historical progression of objectivity, from truth-to-nature, to mechanical objectivity, and a contemporary notion of trained judgment. Interestingly, the Mapmakers appeal more to mechanical objectivity. Though there is a certain amount of trained judgment – manual touchups – that occur in the final stage of their cartography, the conceit is that their software machine produces a map of Mars. And in calling the product a map, they suggest the creation of an objective real.

Because the Mapmakers are more often than not working on lines of code than actually interacting with 3D models of Mars, such models are still greeted with excitement. During one Mapmakers meeting, Ross arrived with a box that he joked came to him "from the Internet." He explained that someone had contacted him asking if there were terrain models of the Moon from the Lunar Reconnaissance Orbiter Camera (a recent high resolution lunar imager). Though these models have not been released, Ross pointed the guy to the models USGS produced using the Apollo Metric Camera. Ross opened the box to show that, in thanks, this guy sent him a model of the Apollo 15 landings site that he produced using a 3D printer. Though we in the room were no strangers to 3D, we all nonetheless fawned over the model. Being able to hold the model and turn it in our hands added yet another dimension to what it means to interact with 3D renderings of other places.

Doing Science in 3D

In contrast to the Mapmakers, planetary scientists have a different relationship with 3D maps. The Mapmakers see 3D as part of their scientific mapping work, helping to establish the map of Mars as something real. Enhancing the illusion of reality demands the persistent erasure of the author. The Mapmakers claim authorship to the programming tools, but not the maps. For planetary scientists working with 3D, on the other hand, 3D helps them transform Mars from something simply real into a *place*. To do so, they position themselves as experts who know how to see the 3D model in a way such that it reveals something new about Mars. Scientists position themselves within the model, sometimes as an author, and in doing so understand Mars as a place.

Most scientists whom I visited pointed to the 3D glasses, either blue-red or polarized, sprawled on their desks or took them out of a drawer when I asked about how they worked with 3D data. Many others worked with 3D in a perspective rendered view. This is the view used in Google Mars and WorldWide Telescope, by which 3D models are converted into a 2D image which gives the illusion of a third dimension. Figure 3.4 shows a 2D image, a perspective rendered 3D image, and an anaglyph (red-blue) 3D image to illustrate the different appearances of each form. That there are several different representations of 3D confirms it as something far from real, but rather a convention of seeing. Nonetheless, scientists persistently rely on 3D as a way to more authentically experience the place of their research.

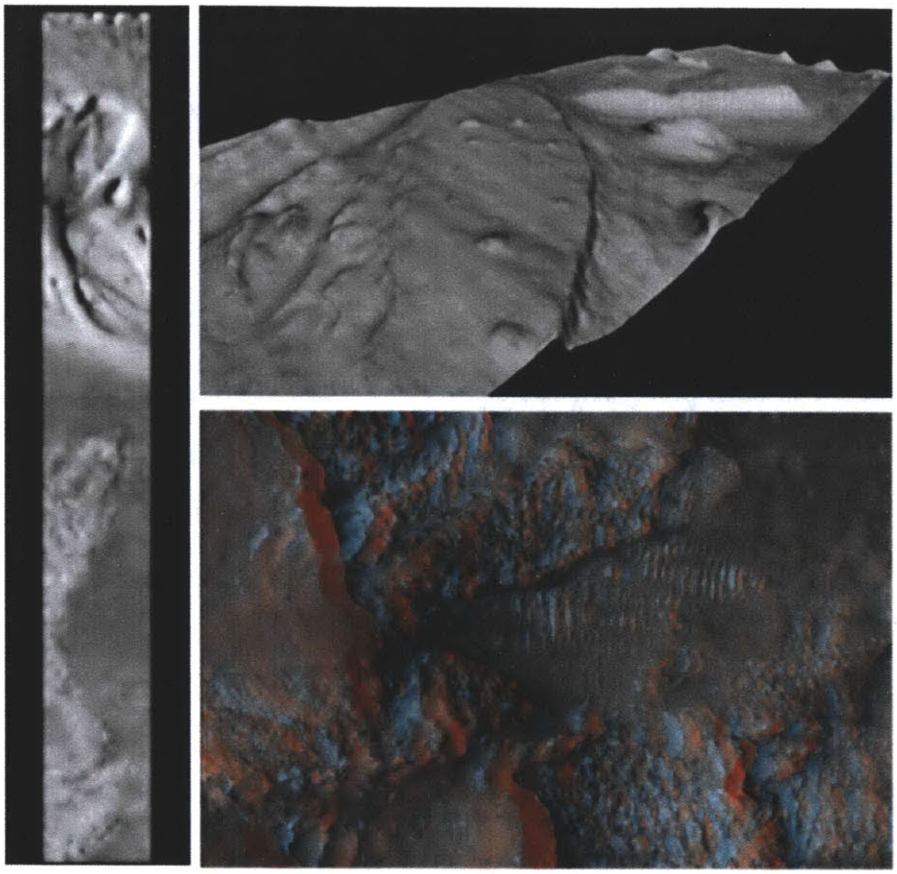


Figure 3.2: Renderings of Mars. On the left is a 2D image, on top is a perspective rendered image. Both of these are MOC images from the Stereo Pipeline documentation (Broxton et al. 2010). On the bottom is an anaglyph image from HiRISE. With proper glasses, this image appears 3D.[27]

How do researchers describe the scientific gain of making Mars into a three-dimensional place? Ross, the Mapmaker whose training is in planetary science and who works primarily on planetary research projects, has been working with Mars data since he was a graduate student. When he and Michael first started working together at Ames on creating a stereo pipeline for MOC, Ross already had years of experience with the dataset and was able to help Michael navigate the data. One of the reasons he is attracted to

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[27] Image from http://hirise.lpl.arizona.edu/anaglyph/singula.php?ID=ESP_020866_1475

studying Mars is because, as he described in an interview, "Mars can give us a very good sense of place. We have rovers there, we have a perspective of what it's like to be there, and we can imagine ourselves there living, working, exploring." When I asked him to describe what he meant by a sense of place, he stumbled. "Oh gosh. I can't really. I've kind of struggled with that. Like I said, I'm very visual and very three dimensional and so part of what I enjoy doing in planetary science is not necessarily scientific but just kind of personally joyful. Specifically, what would it be like to be there or walk around and kind of be in those places and see them?" For Ross, a high-resolution image

> Helps, in my mind, to understand what it would be like if I stood there and I looked out. What would I see and what would that experience be like… I mostly sit in this small office underground and look at images from far away across the solar system. So that kind of imagination helps get me out of the basement, so to speak. That's what I mean by [sense of place].

In describing this mode of work as personally joyful and explaining the various ways he positioned himself in the frame, Ross can be thought of as the author of this particular way of seeing. It is his role as an expert scientist with a guided perspective that enables a shift from Mars being real to more specifically a place.

Ross took me on a tour of his research one day and showed me how surface images and terrain models figure into his Mars and other planetary research. He described various projects, showed me associated images, and explained how the numerical matrix of data that produces the images contains valuable information for his research. If most conclusions were derived through quantitative work, I asked, why do images, or at the very least 3D visualizations, remain such a central part of research? He admitted that sometimes one does not actually need the visualized model.

> A visualization like this, kind of a 3D visualization, happens at the beginning and at the end [of a project]. The first thing you want to do when you get a terrain model is *look* at it. See what it *looks* like. But as you note, you can't really do much with that but make screen shots to make it look pretty in a paper. You really do need to go to the numerical models and extract things like this or perform Fourier transforms and really, you know, work with the terrain model as numbers to do quantitative science. So you do that, and then at the end you visualize it again for whatever it is you're trying to show and you put that in your paper.

3D models in papers are rendered in a specific way to highlight a relevant feature and make an argument. The author of the paper is the author of the image and the image suggests a specific sense of place for the region in question.

3D enhances the illusion of reality because it suggests what it is like to be there. In *Mapping Mars* (2003), science writer Oliver Morton tells of another Mars scientist, Bill Hartmann, and his propensity for thinking about Mars in three dimensions. Hartmann is both a scientist and a popularizer of Mars and the Mapmakers selected his book, *A Traveler's Guide to Mars*, to annotate the Martian surface in Google Mars. Morton describes how as a teenager in the 1950s, Hartmann studied the Moon through a telescope. "[H]e built plaster of Paris models of his favorite crater, Walter, to try to appreciate what it might be like from ground level, to turn a planetary object into a place. He wanted to answer the question that has driven him ever since: To see what it would be like to be there" (128-129).

Similarly, one woman I spoke with at Ames, Ginny, works with HiRISE imagery to study erosional processes on Mars but does not often use terrain models (because they take so long to build, she explained). However, she regularly looks at anaglyphs. She used to make them in Photoshop before the HiRISE team began producing them automatically. A pair of red-blue glasses sat on her desk, ready for use. When I expressed surprise that she looked at anaglyphs so regularly, she explained. "You know why? Because it gives you a sense," she paused, searching for an appropriate description. "The lay of the land, so to speak. You get to see what's up and what's down… If you look at it in the anaglyph you really get a sense for how they relate to each other, these features, which you may not if you are just looking at it in 2D. For me, I find it real helpful, just kind of a quick look of what it looks like." 3D serves to orient the scientist in these cases. "The lay of the land" it provides is equivalent to "the sense of place" Ross used to describe his own way of understanding Mars.

In making Mars three dimensional, the Mapmakers enhance the scientists' sense of being there. 3D enables Mars to become a new kind of place. In producing maps of Mars, the Mapmakers complicate the relationship between map and territory; the image and reality. As the map precedes the territory, and in 3D no less, the map offers up Mars as a real place, ready for exploration. Creating Mars as a destination is enhanced by the third trope of contemporary planetary mapping practices: Dynamic Mars.

Dynamic Mars

Democratized, three dimensional, and the topic I turn to now, dynamic Mars come together in web and desktop applications like Mars in Google Earth (also referred to here more simply as Google Mars) and Microsoft's WorldWide Telescope. Mars is democratized in the sense that these programs "bring Mars to the people," as NASA scientist Jim Garvin once enthused to me. These applications make 3D maps of Mars using perspective rendered digital elevation models provided by the Mapmakers. Finally, the way Mars is presented in Google Earth and WWT – the maps of Mars being developed – argue that Mars is not a static object, but rather a dynamic place. This occurs in two ways. First, tours and annotations highlight the interesting geology and processes of Mars, portraying it as an active planet. Emphasizing a past and present filled with changing land masses, flowing water, and chaotic winds implies that there is an equally energetic future; a future humans should be involved in. Second, unlike traditional paper maps, the user can navigate between points in a manner that feels like flying over Mars. While working with the Mapmakers, I learned the way they wanted Mars to be dynamically experienced. Both of these dynamisms enhance the placehood of Mars by establishing a subjectivity that differs from a static map. In learning to move around Mars in a specific way, the subject's perspective shifts from that of a bird's eye omnipotence to an immersed perspective. With the tours, an authorial voice appears in the form of an expert scientist, instructing the viewer on a particular understanding of Martian place. This is a popular version of what I described in the last section as the process by which the scientist authors images for a scientific community. I will discuss how these two dynamisms intertwine by recounting my experience producing virtual tours for WWT.

WWT and Google Mars do not simply serve up a blank map, but heavily annotate Mars and highlight certain ways of viewing and interacting with the planet. For example, the Mapmakers and Google decided to include certain geographic "layers" called the "Mars Gallery." Most layers bring Mars into a more human or terrestrial context. For example, there is a "Historic Maps" feature that layers Giovanni Schiaparelli or Percival

Lowell's hand drawn maps from the 19th century on the globe. The USAF map from 1962 looks about as precise as Lowell's, suggesting to the user that knowing Mars is a recent phenomenon. Also in the Gallery is a feature that allows you to locate the various rovers and landers on the surface. These robots become landmarks, providing both a sense of scale and a way to navigate the planet that is linked to human history. In this sense, applications like WWT help to "bring Mars closer," as Michael once described. Because the maps are infused with information about current missions and findings, they present Mars as a "place we are actively exploring." As it has been said more generally about maps, they "discover new worlds within past and present ones" (Corner 1999, 214). Maps of Mars establish the planet as a newly interesting destination by drawing upon images and stories of the past and present.

For the user looking for a more directed encounter with the red planet, the Mapmakers created tours for both clients. A tour is an audio-visual scripted presentation that tells a specific story about Mars. When I joined the Mapmakers in February of 2010, they were hard at work on Mars for WWT. I was assigned the task of producing two tours that would be launched with the next release. Originally, Mars mode in WWT was to go live in early March, but the complexity of this project led to delays on both Microsoft's and NASA's side. The final product was publicly released on July 12, 2010.

Chris Kemp, the CIO at Ames (and the person responsible for the Microsoft partnership)[28] had already gotten Goddard's Jim Garvin, former Chief Scientist of NASA, to author one tour. For the second tour, I approached Carol Stoker who is at Ames and who I already knew because of my trip with her to the Mars Desert Research

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[28] Kemp was also invested in the Microsoft project because it was a high profile use of NASA's cloud computing platform, Nebula, which was one of Kemp's main initiatives. Kepler data is also "on the cloud."

Station the previous fall (see Chapter Four). Whereas the maps themselves lack authors, these prominent Mars scientists or popularizers explicitly lent their names to the tours. As experts, the scientists enhanced the authority of knowledge contained in the Mars maps. Additionally, they offered a specific perspective, a specific way of seeing Mars that argued for Mars as a dynamic and scientifically interesting place.

Jim was enthusiastic about his tour from the start. He came to our first teleconference with several ideas for a tour that would get people excited about Mars. His first idea was to build a tour based on a white paper he authored that detailed future landing sites for a human mission to Mars. Another possibility he suggested would be a tour highlighting what he called "exotic Mars." He explained that we forget how alien Mars is because we so often try to understand it through terrestrial analogies. This tour would review spots on Mars that are "so non-terrestrial." We decided to pursue the first idea. Since these tours are meant to be broadly educational, Michael and I decided that this tour should begin with a geologic history of Mars and then conclude with the possible human landing sites.

The script I wrote for this tour alluded to a changing Mars. I discussed how each era of Mars – Noachian, Hesperian, and the present Amazonian[29] – was characterized by different geologic processes. Volcanic activity and meteor impacts shaped the surface of the Mars today's satellites image. I had ended the section of the tour that discussed the different eras of Mars by writing, "The remaining water dried up but volcanic activity continued, and the Mars we know settled into existence." Though I wrote about Mars's past with dynamism, I seem to suggest that Mars now is not as exciting as it was in the

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[29] This scheme was developed at the USGS in the mid-1980s. Each era is named for the region exemplifying the presumed geology of that time. On Martian nomenclature, see Greeley and Batson (1990, 103-107)

past. When Jim edited this script, he made a few changes to this section that destabilized the sedate Mars I presented. He included that the water "mostly" dried up and the Mars we "think we" know settled into existence. He added an additional sentence: "However, Mars is a dynamic world, with dramatic climate upheaval and we have barely begun to 'read its textbooks' even over the past millions of years."[30] Jim wanted to show that Mars is not a solved mystery but an evolving world in need of more study.

Carol's tour marked Mars as dynamic in a different way. The tour we put together was based on her experience as a Co-Investigator on the Mars Phoenix Lander. She had been in charge of assessing the habitability of the Phoenix landing site. Similar to habitable exoplanets, habitability on Mars is defined as an area "capable of supporting living organisms with capabilities similar to terrestrial microbes" (Stoker et al. 2010). A site is deemed habitable if there is evidence of present or past life. Habitability can be both a claim about the current state or a description of how the site used to be. Results from Phoenix provided a "tantalizing glimpse" of a "potentially habitable" area and the team recommended a more rigorous search for life near Phoenix's landing site in the north polar region of Mars (Stoker et al. 2010). Again, the mystery of whether or not Mars has ever hosted life remains open and should, on this model, be an inspiration for future missions.

Carol and Jim recorded the narration of the tours and I created the fly-over of the Martian Map, with overlays of additional pictures and text as needed. The first tour I visualized was Carol's. In WWT, I stitched together slides of rotating Mars, a zoom in to one region of Mars, a zoom out and back in to another, and various pans. This was the way I intuitively thought to interact with the map. I got a draft of the tour done in time

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[30] Personal correspondence with Jim Garvin, March 18, 2010.

for a meeting in the middle of May with Microsoft, at which Michael was going to present the first signature tour. The night before the meeting, Michael told me he did some quick polishing. The Microsoft team loved what he showed them. We watched the changes he made together in the Pirate Lab. The visual feel was completely different from what I produced. Whereas I kept approaching the globe head on, Michael almost always presented Mars from a tilted vantage point, so the viewer felt like he or she was on a ship orbiting the planet. My cinematography made Mars feel static, whereas Michael's made Mars feel dynamic and interactive. It never even occurred to me to present the Mars map the way he did, a way in which the user had a more immersive experience. Effectively, he trained me to see Mars the way he did so that I could create the same feel for the second tour. As he said after we watched Carol's tour together, "Really make it feel like you're flying around Mars."

Michael had learned to see Mars in this way after years of working on this cartography project. Like most of the Mapmakers, he did not have much knowledge of Mars before joining NASA. He always suspected Mars was an interesting place, because it was the target of so many robotic missions. He closely followed the Mars Exploration Rovers, and recalled feeling like "we" were getting familiar with two spots on Mars, though Mars was still such an "alien world." It was not until he got to Ames that he began to see Mars as quite Earth-like, geologically speaking. "I've begun to think of it much more as just another place that is as rich and interesting as Earth is. Like, Earth is a very special, very complicated and interesting natural environment. And Mars, it turns out, is too." Knowing that it has a past, and a past rich with water, makes Mars more familiar for Michael.

A summer intern, Kyle, heard I was interested in understanding the kind of place Mars is, and sought me out one day to explain how Mars became a place for him. He told me that when he was here a previous summer, he was working with some Mars imagery, mosaicking images by hand to think through how an automated matching program might work. He was looking at two images of the same spot, and realized that a dot that looked like a boulder in one image was in a different place in the next. He soon realized he was looking at one of the Rovers moving across the landscape. Kyle recalled that the moment he realized what the movement was, the images suddenly took on a dimension of place. Dynamism on the surface became, for Kyle, the way in to thinking about Mars not as a scientific object, but as a place.[31]

Michael changed my perspective of Mars by showing me how to view and display Mars as an interactive planet that the subject is immersed in. In general, WWT can change other visitors' perspectives of Mars. When talking with Zack who was still working out the aesthetic worth of his maps, he tried to guess how artists justify their products. "They like to say they're changing the world, but I think they're full of it," Zack said cynically of artists.

"But you're kind of changing a different world," I couldn't help but point out.

"Yeah," Zack agreed, "so like we're changing the perspective, we're making Mars, instead of just being some little pink dot in the sky it's now actually some place that you've somewhat explored yourself. That you were able to see that, 'Hey, I can associate this terrain with something I've seen back home,' or 'I can see erosion on Mars' and think that at some point in time it was *alive*" (emphasis mine).

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[31] To specifically connect rovers to a sense of place on Mars intuitively gestures towards one definition of "rove": "to travel from place to place" (OED).

WWT tours offer a new view of Mars – a new understanding of Mars as a place – because of the emergence of the author in the form of the expert scientist. Maps of Mars have historically argued for certain scientific understandings. When Percival Lowell drew maps that were decorated with geometric patterns, he was seeking to legitimize his notion that Mars hosted an artificial landscape (Lane 2005). Deciding that Mars should be presented in 3D offers a sense of intimacy with the remote planet. Along with annotations and tours that portray Mars as a dynamic planet, Mars in WWT and Google Earth becomes a strong platform from which to mount an argument. As a dynamic place, these maps argue, Mars is well worth continued scientific study and future human exploration.

Conclusion: Escape from Silicon Valley

In early March, a month after joining the Mapmakers, I met up with Michael and Ted for a workday in San Francisco's Mission district, closer to where they both live. We gathered at Café La Boheme shortly after lunch and joined the other clientele who were socializing over coffee, meeting up to discuss nonprofit ventures, or lining the sides of the café and working on their laptops. Ted and Michael brainstormed about how to fix a problematic sequence of code and occasionally Michael stepped out to participate in a telecon. I was reading a paper Jim Garvin wrote about human exploration of Mars and starting to storyboard his tour. Michael and Ted worked back and forth on their separate computers, one editing the code and the other trying to run it. One of the reasons we decided to meet in the city was that we were going to head over to the California Academy of Sciences, the San Francisco science museum, after our work day and meet up with Jonathan from Microsoft Research. After the museum closed, we were going to work with the planetarium staff to see if WorldWide Telescope could be projected on the theater's dome (as it is designed to do). Jonathan arrived at the museum before us and was already in the control room of the planetarium uploading the latest build of WWT to the planetarium servers when we showed up. While Jonathan configured WWT, Ted and Michael continued to work on their code and were joined remotely by Mike who was working to fix the same problem while at a conference in Texas. With each of our heads down, focused on our laptop screens, it took a moment to realize that Jonathan had gotten his system working and projected Saturn on the planetarium's dome.

Not only was Saturn on the dome, in the next moment the whole universe was on the dome. Ted, Michael and I left the control room and settled into the empty theater and Jonathan gave us an impromptu tour of the cosmos. As he zoomed out to show us the structure of the universe, courtesy of the Sloan Digital Sky Survey, Ted marveled at how many people and computer hours were spent so we were able to have this privileged view of the universe.

It is this view of the universe that the Mapmakers are trying so hard to share with a greater audience. This night at the museum in early March was preparation for an event to be hosted there a month later. Once a week, Cal Academy keeps its doors open into the late evening, dims the lights, brings in DJs, and hosts a 21+ event called NightLife. On April 8th, the Cal Academy had invited Michael to give a tour of 3D Mars at the "Extremely Cosmic" NightLife. I attended this NightLife with a friend and met up with several other IRG members there. While waiting for the 8:30 planetarium show, the second of two, we toured the exhibits and listened to the DJ for the night, the Space

Cowboys. While waiting in line to enter the theater, I gathered that something was not working. After finally being allowed to enter, the planetarium director welcomed us and said he had good news. Though the software was not working for the earlier show, it was now working and we get to be the first audience to see spectacular cosmic images courtesy of WorldWide Telescope. After an introduction to the universe from the director, he handed control over to Michael who gave some history about the early maps of Mars by Lowell (perhaps a bit lost on the slightly tipsy audience), before turning on the elevation model and taking us on a ride through Valles Marineris. The switch from the 2D maps to the 3D fly through was greeted with gasps and applause from the audience. Michael continued to talk about the geologic history of Mars and explained one theory about seasonal water flow across the surface. Michael shared with the audience that when he learned this about Mars, he realized that it was not a boring featureless "rock in space" but a "truly vibrant place."

Mars, as presented to the public at this NightLife event, is democratic in that it belongs to more than just science and scientists. It is displayed in 3D so as to best imagine being on the surface. And, as Michael summarized, it is a dynamic, vibrant place. That the map exists at all argues for Mars to be taken seriously as something real. The techniques that enhance the illusion of reality – portraying Mars as democratic, 3D, and dynamic – craft Mars in a certain way. This experience at NightLife captures the kind of place Mars is today. These three aspects are pervasive in the Mapmakers representation of Mars. But even for the Mapmakers, the map is sometimes not a satisfying indication of reality. There is a deeper longing for the territory the map conceals. Ted told me about an experience long before he came to NASA when he was looking at panoramic photos of the surface of Mars taken by the Pathfinder mission of the mid-1990s. He recalled, “There was this sense of almost being there. There are these incredibly high-resolution color photos from the ground on Mars that you can explore… And that’s when I kind of started to get more of the sense that this is not something on the front page of a CS Lewis book, a line drawing of an imaginary world. This is a real place we can go to.” But of course, despite a strong desire in the space community, humans have yet to go to Mars. In the next chapter, I look at how scientists “go” to Mars without leaving planet Earth.

FOUR
Narrating Mars in Utah's Desert

I arrived in Grand Junction, Colorado on November 14, 2009. I was naively shocked to learn that there was no cabstand at the airport. A kind stranger offered to drive me to my hotel, saving me the hour wait for a taxi. I was wearing hiking pants, a North Face jacket, and carrying a large backpack instead of a suitcase. The friendly driver asked if I was going on a hiking vacation. I hesitated. Answering yes would be less than exact. Answering no would require me to explain that I was meeting a bunch of folks from NASA the next morning and we were going to drive to the Mars Desert Research Station (MDRS) in Utah for a two week simulation of Martian exploration. As my Best Western was in sight, I answered yes and offered profuse thanks for the late night lift. The driver handed me my backpack and wished me happy trails. In my field notes the next morning, it is evident that I was getting ready to 'play Mars.' "In this foreign land," I wrote, "the aliens are friendly and though there are buildings, they talk of this land as their desert." Looking out that window of my motel room, I glanced at a dusting of white powder. "And here, it actually does snow on Mars."

This is the beginning of the narrative I wove for myself while at the MDRS. It is the tale of a graduate student wishing to understand how a place might be simultaneously experienced or imagined both as Utah and as Mars. To interrogate this phenomenon, I placed myself within another narrative: that of researchers trying to make use of MDRS to think about what it might mean to live and work on Mars. Narratives allow actors to stabilize the messiness and multiplicity of place. I encountered the structuring of many different narratives while at and when considering MDRS. Geological and areological (as the study of Mars is termed) narratives tangled with each other when deciding whether or not the examined landscape was significant for its connection to Earth's past or to Mars's present. An astrogeological narrative, one woven in the mid-20th century, justified geology as a science not just for this Earth, but for other planets. Finally, whether MDRS occupants knew it or not, their experience was inescapably informed by expectations set by narratives of science fiction and visions of Mars's future. In what follows, I weave these together with my own ethnographic narrative, and conclude by speculating as to whether there is a utopian narrative that organizes the multiple narratives, imaginations, and places at work at MDRS.

I was invited to go to MDRS by Carol Stoker, a planetary scientist whom I met at NASA Ames in July 2009 during a short visit. At our initial meeting, Carol welcomed me into her office to talk about her research projects. Carol is a slender woman with long, slightly wavy, light ginger hair. She wears large glasses that accentuate her inquisitive eyes. She was born in Utah, and has a certain brusqueness of personality and a hint of a drawl that speaks of being raised in an environment shaped by a reverence for Butch Cassidy's Wild Bunch. At 18, Carol left home and hitchhiked to California. She intended to imbibe the 1960s counter culture of Haight-Ashbury, but the fever was already subsiding. She returned to Utah for a Bachelor's degree and went on to earn a PhD in astrogeophysics from the University of Colorado, Boulder in 1983. When she arrived at Colorado, Carol quickly made friends with fellow students who, like her, were inspired by Viking images of Mars and were disappointed by NASA's inability to mount a human mission to the red planet. After years of plotting and thinking about exploring Mars amongst themselves, they convened a conference in 1981 called "The Case for Mars." At this conference, the Mars Underground - a group that grew out of conversations amongst Stoker and her classmates - officially announced and established itself.[1]

Over the next decade and a half, they continued to hold Case for Mars conferences every few years. The founding members of the Underground moved away from Colorado, and Carol landed at NASA Ames in 1985 and has been there ever since. When I visited, her office was decorated with Mars memorabilia. A Looney Tunes' Marvin the Martian figurine looked down from a bookshelf and a flag depicting Mars, designed during the Mars Underground's heyday, hung above her desk. Carol explained that much of her research is "analog research." Planetary scientists travel to places on Earth that are "Mars-like" - analogous to another planet's terrain - to test out equipment or do geological research. She suggested that these sites have been cultivated in the past twenty or so years out of frustration by people who would rather be using equipment and doing geology on Mars. Carol freely admitted that she was and still is one of those people.

Carol's research at analog sites involves the testing of drilling equipment that might be used on Mars. Her two primary analog sites of recent years are Rio Tinto, a river in southwest Spain, and the Mars Desert Research Station (MDRS) outside of Hanksville, Utah. During an MDRS field season, typically November through April, groups of six apply for two-week access to the facility. MDRS differs from Rio Tinto, she explained, because it is a simulation. Not only do people go there to test out equipment (as it is one of the best analog terrains of Mars Carol says that she has seen) but they can also enact a simulation of being on Mars. In Rio Tinto, the team might stay

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[1] For more on the Mars Underground, see Chaikin (2008, 123-153).

in motels or tents. At MDRS, they live in a cylindrical habitat, outfitted as an early settlement on Mars might be. There is also the implied obligation (which most MDRS crews embrace) to wear simulated space suits whenever leaving the habitat. Carol was planning a few missions to MDRS in the upcoming months with two goals: first, to test the latest drill her engineers were building, and second, to make the argument to NASA that this site could produce good science and should be supported by the agency. At the end of the meeting, I asked if it would be possible to join one of her crews. She said she would keep me in mind should a spot open up.

MDRS is the second analog station established by the Mars Society, a non-profit organization that advocates for human exploration and settlement of Mars. Robert Zubrin, who began attending the Case for Mars conferences in the late 1980s, established the Mars Society in 1998, two years after the sixth, and last, conference.[2] Shortly after its founding, the Mars Society entered a partnership with NASA to establish the first analog site, Flashline Mars Arctic Research Station (FMARS), located in the Arctic on Devon Island. Carol was there to help raise the roof, literally, for the habitat. However, after one season of joint operation, the Mars Society's goals of public relations and grassroots advocacy created tension with NASA's focus on science and research (Fox 2006, 43). The two organizations agreed to part ways.[3] During the summer field season, the Mars Society continued to simulate missions from the habitat, while NASA crews established a tent city some kilometers away. Several NASA employees remained on good terms with

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[2] Carol served on the Mars Society steering committee for the first ten years of its existence.

[3] A more volatile account of the split between NASA and the Mars Society is written in a memoir by Zubrin, citing conflict of personalities and discrepancy over financing between him and the NASA PI, Pascal Lee (Zubrin 2004, 260-263).

the Mars Society, Stoker included, and continued to do research at FMARS, and have been equally enthusiastic about Zubrin's plan for a second station.

Zubrin narrates how the site for the desert analog station was chosen in his memoir, *Mars on Earth*. Filmmaker James Cameron spoke at the Second International Convention of the Mars Society in 1999 about his planning for a 3D IMAX Mars movie. In scouting for filming locations, they came across this swath of desert. Cameron's search coordinator exclaimed to Zubrin, "It's Mars!" (2004, 159). Following up on this lead, Zubrin and the Mars Society decided in the spring of 2001 that the MDRS would be built in a red Jurassic desert a few miles down the road from Hanksville, Utah.

In late September 2009, Carol emailed me asking if I was still interested in accompanying her to MDRS. I was immediately brought up to speed on the project through a series of teleconferences. We would be testing out a prototype of a drill she named the Mars Underground Mole (MUM). The November mission was the first of a multi-year project. As such, we would be occupied with scouting future drill sites. Carol, Jhony (a NASA engineer), Susana (an astrobiology graduate student affiliated with the European Space Agency),[4] and I would be at MDRS the whole time. Larry (a NASA engineer) and Mary Sue (a NASA geologist) would be there for the first few days and then replaced by Josh (a student who interned with Carol) and Kevin (a NASA project manager). Unsure of what to do with an anthropologist, I was the appointed timekeeper, tracking the kind of tasks with which people filled their day.[5]

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[4] Carol is collaborating on this project with Bernard Foing from the ESA. Each crew going to MDRS for this project were intended to reflect this international collaboration.

[5] Carol requested I compile the data I collected into a poster, which was presented at the National Lunar Science Forum in July 2010 (Messeri, Stoker, and Foing 2010).

In past chapters, I focused on the planetary placehood of exoplanets and Mars. The imagination of exoplanets, and to a lesser extent Mars, is of somewhat singular entities. These planets are "places" at the scale of their entire globes. But Lori, a planetary scientist I met at Ames, pointed out the problem with thinking of individual planets as homogeneous things. When she first began researching Mars, she indeed thought of it as a singular planetary body. But the more she studied, the more she realized, "Like the Earth, there are places on Mars that are different from other places... You wouldn't look at Earth as a planet and say, 'Oh, well the Grand Canyon formed and that has to do with the polar caps and Antarctica.' You just wouldn't do that because Earth is too big and too complex. I guess I started to realize that Mars was more complex in its history."

As Lori points out, Earth is varied and the connection between different locations, geologically speaking, is a complex puzzle. Our experience of different places on Earth is often informed by the landscape. My own research occurred in several different landscapes. There was the Boston skyline, with the Prudential Center and Citgo sign reflecting off the Charles River; the Andes mountains, where observatories extended the summits by several meters; and the brown hills, strip malls, and understated technology complexes of Silicon Valley.

Zubrin, in *The Case for Mars*, remarks on the epistemological power of landscape, "But all that Mars holds will forever remain beyond our grasp unless and until men and women walk its rugged landscapes" (2000a, 1). In place of hiking on Mars, Earth-bound scientists have trekked through analog landscapes, hoping these activities will allow for a certain knowing of Mars. I call this juxtaposition of Mars on Earth a "double exposure" of place (and, indeed, sometimes a "multiple exposure"). In Figure 4.1, I offer a snapshot of this photographic metaphor as an illustration of how the landscapes in these analog sites are simultaneously comprehended as earthly and otherworldly.

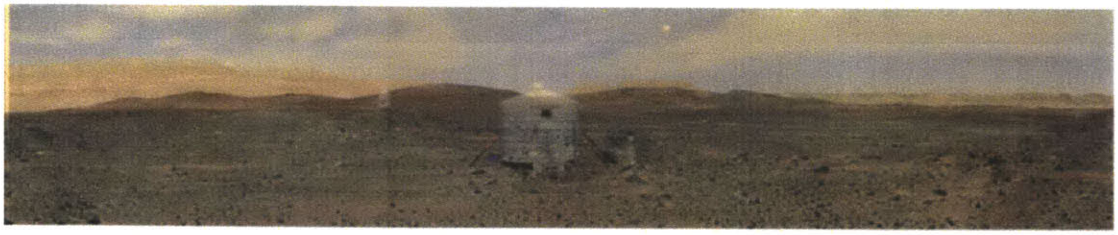

Figure 4.1: Double Exposure of Place. The Utah landscape of the Mars Desert Research Station is set against the Martian Landscape of the Easter Hills.

How, then, to make sense of these landscapes infused with multiple meanings? Cultural geographers and anthropologists have suggested a variety of techniques to make sense of the multiplicity of landscaped places. Geographers have carefully decoded the complexity of landscapes to avoid writing about them as singular in their materialities and meanings. In contrast to the early geographers who distinguished between cultural and natural landscapes (Sauer 1925), the social-theory-infused geography of the 1980s suggested that more than the visible forms of landscape, it was pertinent to understand the social relations of landscapes.[6] Denis Cosgrove (1984; 1985) was particularly influential in showing that even the idea of landscape (in the colloquial sense of landscape painting) is a product of a particular time, when geometric perspective was first learned and taught. Thus, the idea of landscape embodies the power dynamics of that moment. Landscape, he concluded, is a way of seeing, and the attending visual ideology

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[6] This has been accomplished in a variety of ways: as a mode of production (Lefebvre 1974; Harvey 1989; Zukin 1993), gendered (Rose 1993), and as sites of contestation (Duncan and Duncan 1988; Duncan 2005; Mitchell 1996). For a general overview of writings on landscape in geography, see Mitchell (2005).

was bourgeois, individualist, and exercised power over space. For Cosgrove, landscape is both a social product and a detached way of structuring the world.

While I align myself with geographers who take a more interpretive view of landscape, I suggest narrative as a device that offers structure to the complexity of landscapes. Geographer Nicholas Entrikin (1991) describes the synthetic attributes of narrative. Drawing from Bakhtin's concept of the chronotope, a unified space-time entity that guides mythic tropes, Entrikin applies this concept beyond literary genres in order to imagine places as unified space-times. "In narrative, events are given meaning through their configuration into a whole" (308). By imbuing a place or landscape with narrative, its messiness and multiplicity resolves into something with fixity (however illusionary this may be). One planetary geologist described to me the appeal of geology, suggesting a narrative quality. "I like the story of how something came from something to what it is today. They all fit into some kind of temporal line."

In *The Anthropology of Landscape*, Eric Hirsch (1995) suggests that the difference between a geographic and anthropological approach to landscape is that geographers tend to view landscape as an image and thus de-emphasize landscape as a representation. Anthropology, in contrast, should understand landscape as a process as opposed to something static. Hugh Raffles, in his history and ethnography of the Amazon river, captures this dynamism with his phrase "in the flow of becoming." He offers a "biographical landscape," suggesting that how people shaped the river informs our imagination of it today (2002, 5). Landscape and identity are mutually constituted, as Fred Myers (1993; 2000) similarly recounts in his study of aboriginal Australians.

As suggested by the idea of biographical landscape, actors animate landscapes through a relationship between remembering and imagining. Keith Basso elegantly summarizes, "instances of place-making consist in an adventitious fleshing out of historical material that culminates in a posited state of affairs, a particular universe of objects and events – in short, a *place-world* – wherein portions of the past are brought into being" (1996, 6). In his ethnography of the place-making practices of the Western Apache, Basso observes, "oral narratives have the power to establish enduring bonds between individuals and features of the natural landscape" (40). These stories shape conceptions of the landscape and one's self. Understanding the narrative that orders a landscape highlights the process by which it was produced (and is being produced).

Like Myers and Basso, I too am curious about the mutually constitutive relationship between the desert landscape and its (transitory) inhabitants. What kind of place-world, narratives, and identities construct and are constructed by geologists, planetary geologists, engineers, and astronauts through analog research in the American west?

Many geologists I met shared with me the following mantra: every rock tells a story. The rocks surrounding MDRS told stories that unified various places and times. The geologist that accompanied us for the first several days of the mission, helped us understand the *geological narrative* of the place. The geological narrative is pieced together by decoding clues embedded in present rock formations to make sense of the past. In the 1950s, well before MDRS was built, some geologists wished to extend the geological narrative beyond Earth. Geology, they argued, could be a way of knowing not only on Earth, but also on the Moon and other planets. Though this was not a move favorable to the entire discipline, support from the Apollo program allowed for the first threads of an *astrogeological narrative*. The astrogeological narrative is not a way to understand the past of this planet, but the present of a distant planet. For the Apollo mission, astrogeologists trained astronauts in geology. Instead of focusing on the terrestrial story of a rock, they taught astronauts to decipher a story that would connect a rock on the Moon to a rock on Earth. Following Apollo, upon viewing satellite imagery from Mariner, Viking, and subsequent missions, planetary scientists spun astrogeological narratives for rocks on Mars.

Whereas the first astrogeologists were trained in traditional geology programs, those studying Mars today are just as likely to come from a planetary science background. Often, they are more familiar with the geology of Mars, the study of which is called areology, than the geology of Earth. They do "fieldwork" using images from satellite and robotic missions. When they go into the terrestrial field, it is in search of analog sites deemed similar to Mars. Consequently, during such fieldwork they synthesize an *areological narrative*. This reverses the astrogeological narrative, in which another planet's present is understood through the lens of Earth, such that Earth's present is understood through the lens of Mars. With the areological narrative, a planetary scientist makes sense of a terrestrial place through a familiarity with formations and processes they have studied on Mars.

The geological narrative brings the past into the present and the astrogeological and areological narratives invoke the presents of different locations. At MDRS specifically, there is also a rich science fiction narrative at work. The MDRS facility is imbued with elements from speculative musings concerning the future habitation on

Mars. This environment invites participants, at times, to pretend they are on Mars. In entering a science fiction narrative, participants bring elements of the future – of another place's future – into the present.

The future evoked by the science fiction narrative at MDRS has a very specific past cultivated by figures from Apollo and the Mars Underground. As NASA continually defers human inter-planetary missions and commercial space flight blossoms, it is likely that Mars travel, if it occurs, will look very different form how it was imagined by 20th century Mars scientists and science fiction writers. MDRS feels, in some ways, like a remembrance of a soon to be forgotten future.

At MDRS, landscapes contain traces of different times (past, present, and future) and places (Mars and Earth). I capture these juxtapositions in the metaphor of the double or multiple exposure. This metaphor is perhaps outmoded, a product of the analog, not digital, age. This makes it a fitting match for MDRS, an analog (in a different sense) research station that also seems to be facing obsolescence as a new vision of human space exploration unfolds.

This chapter teases apart the multiple times and places at work in four multiply exposed landscapes. The landscapes I present at the beginning of each section are static photographs, but the stories I will tell about them reveal dynamic processes. I focus on how, through narrative, scientists order these landscapes multiple. Three of the narratives that I examine – the geological, areological, and science fiction – unfolded while I was at MDRS. The geological and areological narratives occurred during our time spent outside of the habitat, in the Utah landscape. The science fiction narrative returns to the habitat, during which I will describe what living at MDRS was like for my crew. The second landscape, which is ordered by an astrogeological narrative, offers a prehistory to explain why the premise of establishing a Mars outpost in the Utah desert is unproblematic for the occupants and advocates of MDRS.

Landscape 1: The River in the Rock Bed. A Geological Narrative.

NASA geologist Mary Sue stands in front of an outcropping atop a rock quarry outside of Hanksville, UT. She is drawing the layers in her field book. Note in this image that to the right of Mary Sue there are varying layers in the bottom quarter of the outcrop, and to the left it is more homogenous. Photo by the author.

We began mission day two hunting for a drill site that, based on the Google Earth satellite imagery Carol studied prior to our mission, looked promising. After a comparison of maps, none entirely reliable, we thought we knew how to get to the point of interest. With GPS and paper maps in hand, we loaded into a four wheel drive truck and Carol, acting the part of the commander, joked that we were "launching at 10 am" after a successful "pre-flight check." The ignition was fired and we headed down the bumpy desert road. At some places, the road was marked by rows of stones on either side. In other places, there were only tire tracks to suggest we were following the designated path. After a rainfall, the road blends into the rest of the surrounding landscape. We took a guess at where to turn off the main road to find our destination. At first, the dirt road was similar to the one we left. But after some twists and turns, the road became more groomed and it was apparent we made a wrong turn.

We did not find the site from the satellite picture but we did find a quarry, accessible both by these back roads and the main paved road that connected us to the nearby town. We stepped out of the car to explore. Because it was a rock quarry, the cliff face was exposed and we were offered a privileged view of the geologic strata in this area. Geologist Mary Sue's eye's lit up and the strata triggered her imagination. After taking in the whole formation, she guided me to a specific point on the rock, shown in Landscape One. Within the rock there was layering between red and grey. Mary Sue explained that this was silt and sand stratification, which was evidence of a rapidly changing environment. As she followed the strata along the face of the wall, suddenly, in this Utah desert, Mary Sue saw the signs of an old river. She stood in front of the wall with her arms wide open, imploring me to see how the silt suddenly subsides. Thanks to this cross section, we saw that the gap in silt was refilled with newer rock. This means, she explained, that a stream used to run through this place. Using other geological clues, Mary Sue told me that not only did water flow here, but it was a raging river, full of energy. As she reconstructed what this place used to be, the dry desert slipped away and in its place was the damp swamp or forest that would have filled this area 150 million years ago, before plate tectonics moved its position further and further away from the equator.

Through a geological narrative, the site we stood in became multiple. It was no longer merely a rock quarry, but an exotic place where the rocks spoke of mysteries long since past. Mary Sue, in telling a story that connected the clues hinting at past riverscapes, gave order to the chaotic rock formation. In the middle of the immaterial, invisible river, Mary Sue spotted a discolored area a few meters up. She began spinning tales of what this discoloration might be. Her final proposal was that it was an island. In the middle of the river, she suggested, a small island formed and the discoloration might be evidence of the gathering of organic material. We did not have time for a closer inspection, however. Carol, frustrated that we could not find the site we were looking for, decided to enlist some local help in the form of the resident geologist of the Bureau of Land Management (BLM).

Buzz Rocko, a name wonderfully befitting of the man who helped us space enthusiasts make sense of the local geology, greeted us at the BLM with a look suitable for a rancher or cowboy. He was tall and slender, wearing jeans and a plaid shirt, accessorized with aviator sunglasses and a white cowboy hat. Buzz was soft and slowly spoken, but with a sharp sense of humor. Carol explained the drill sites we were looking for, emphasizing the geologic formations to which she hoped to gain access. She was careful to stress the NASA affiliation and assured Buzz that we would do no ecological damage; clearly nervous that he would deny us land access. Buzz did not take much convincing, and after Carol's fifteen-minute justification, he responded simply, "I think I might be able to accommodate you."

Buzz first led us back to the quarry, in order to show us the difference between the Morrison and Sumerville formations. Mary Sue was interested in discussing the island she found in the rock wall. Buzz stepped right up to the discoloration and took out a knife to chip away at it. As a piece crumbled off in his hand, he declared that it was actually a piece of petrified wood. The imagined island disappeared, and was replaced by a forest that flourished many thousands of years after the river had dried up. The petrified tree was no less fantastical than the island. Mary Sue sighed in amazement that after 140 million years, one can still see the structure of the tree trunk.

What I witnessed in this episode was "how landscape is assimilated to narrative structure" (Myers 1991, 64) in a way quite similar to anthropologist Fred Myers's account of Pintupi place making in the Western Desert of Australia. Myers recounts a time when he was with a group of men who found an oddly colored rock in the landscape that they could not identify. They called upon the elders - the traditional owners of the area who possessed knowledge of the land's legends. Returning to the site, "the men chipped off a bit and examined the colors, then dug around the area to expose more of the rock" (64). An elder proclaimed the rock to be part of the Kangaroo Dreaming. Two men in the dreaming had speared a kangaroo five miles away. Here, the elder concluded, must be where they gutted it. The discoloration of the rock was the result of the kangaroo's stomach contents.

For Pintupi and geologists "the landscape itself offers clues about what may have happened. Not only does it reveal something about the invisible, but it offers a link to the invisible forces that created it and whose essence is embodied in it" (67). What is invisible to most people when gazing at a rock formation, but revealed through the geologist's narrative, is the landscaped past: the geological history of the place upon which one stands. The invisible forces are those of plate tectonics, powerful water channels, and sweeping winds.

To uncover the invisible is to learn how to see. Historian Martin Rudwick (1976) has written about the rise of a visual language in geology. He argues that the proliferation of pictorial representations arrived at a time when geology was establishing itself as a discipline at the turn of the 19th century.[7] With new modes of representation came new modes of seeing. Becoming a geologist became inextricably linked to a certain way of seeing. The enduring quality of this facet of geology was apparent during the time I spent with Mary Sue. She was only with us the first few days of the mission, but during that time, she taught the rest of us to see as she does.

There were several different techniques by which she taught us to make sense of the landscape. My first lesson came during the drive from Grand Junction, CO to Hanksville where we would formally begin our mission at MDRS. Mary Sue frequently

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[7] Recall that in Chapter One, I work through the way exoplanet astronomers learn to see planets in the data. This way of seeing, like the visual language of geology, is developing as the discipline matures.

gestured to the stark landscape, describing how to recognize the most prominent geological formations. The Morrison formation, which spans from northern Arizona to southern Canada, is lightly striated, ranging in color from ash grey to a rusty red. Formations, she explained, are named for the first place they were studied. This formation was first documented in Morrison, Colorado. We were well into Utah by this point in our drive, but the landscape created a geological connection between where we presently were and the place we just left. As we drove, Mary Sue apologized when she hesitated before naming a formation. She had meant to brush up on this area before coming. When we arrived at Hanksville, we stopped in the Hollow Mountain convenience store, where the owner, Don, greets all new crews coming to stay at MDRS. He is also in charge of bringing water and other essential supplies out to the MDRS habitat, or "hab" as it is customarily called. At Hollow Mountain, which as the name suggests is carved into the side of a small mountain of rock, there was a display of books about Utah. Mary Sue purchased *Roadside Geology of Utah*, so that she could retroactively understand the geology we just drove through. This book focuses on the formations visible along the major highways in Utah. It confirmed that at mileposts 91 and 92 along Utah 24, the Morrison formation hugged the highway.

The next morning, before we set out for the field, Mary Sue introduced me to another geologic representation. In her room (we slept in narrow bunks, about the length of a twin bed, and twice the width), she had pinned to the wall a large, beautifully colored topographic map. On the left there were vivid reds and oranges. She points to where we are; a region colored in mossy yellows, greens, and blues. Each color corresponds to the dominant formation. The map was laden with other symbols, indexing who surveyed the area, what references exist in the geologic literature, where the fault lines are, and what period the formations are from. As a visualization, it encompasses location, time, movement, and provenance. By locating us on the map, Mary Sue was able to later narrate the time traveling we would be doing that day.

The map on her wall was only useful in identifying the top layer of rock. In the field, which was cut through with canyons, dry river valleys, and rifts, multiple formations were exposed, one atop the other. On November 17, our third day in the field, we drove out to Angel Point, a lookout onto one of the deepest canyons in the area. Carol organized this excursion to find the Carmel Formation, which she thought might be of a suitable composition for testing the drill. We got out of the car at Angel Point, and hiked a little ways to the canyon overlook. There were several minutes of confusion, during which Carol, Mary Sue, Larry, Susana, and myself tried to figure out which layers were which. Mary Sue took out yet another visual tool, a stratagraphic column (see Figure 4.2). Buzz gave this to us the previous day during our stop at the BLM. It is a chart that displays strata in an ideal, vertical column, capturing the relative thickness of the different layers. The newest layer, the ground we walk on, is at the top. Along the left, the layers are labeled with the corresponding geologic period. Most of the layers around MDRS were formed during the Jurassic period. As Rudwick points out, the columnar representation is a theoretical construct. Faults and folding are not depicted, and the strata are in an orderly horizontal position. This grammar of geology's visual language "is far removed from straightforward observation and... embodies complex visual conventions that have to be learned by practice" (Rudwick 1976, 166).

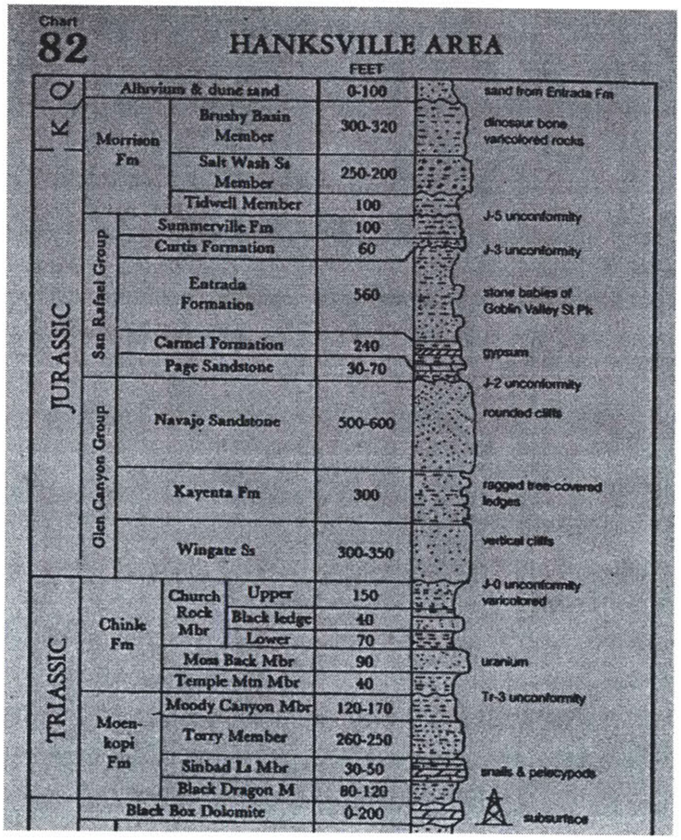

Chart 82

HANKSVILLE AREA

				FEET	
Q	Alluvium & dune sand			0-100	sand from Entrada Fm
K	Morrison Fm	Brushy Basin Member		300-320	dinosaur bone varicolored rocks
JURASSIC		Salt Wash Ss Member		250-200	
		Tidwell Member		100	
	San Rafael Group	Summerville Fm		100	J-5 unconformity
		Curtis Formation		60	J-3 unconformity
		Entrada Formation		560	stone babies of Goblin Valley St Pk
		Carmel Formation		240	gypsum
		Page Sandstone		30-70	J-2 unconformity
	Glen Canyon Group	Navajo Sandstone		500-600	rounded cliffs
		Kayenta Fm		300	ragged tree-covered ledges
		Wingate Ss		300-350	vertical cliffs
TRIASSIC	Chinle Fm	Church Rock Mbr	Upper	150	J-0 unconformity varicolored
			Black ledge	40	
			Lower	70	
		Moss Back Mbr		90	uranium
		Temple Mtn Mbr		40	Tr-3 unconformity
	Moenkopi Fm	Moody Canyon Mbr		120-170	
		Torry Member		260-250	
		Sinbad Ls Mbr		30-50	snails & pelecypods
		Black Dragon M		80-120	
	Black Box Dolomite			0-200	subsurface

Figure 4.2: A section of the stratigraphic column of formations in the area around Hanksville, UT

Mary Sue, fluent in this language, still needed a few moments to match the story on the paper to the story playing out in front of her. Finally, she proclaimed, "OK, I know where we are." She had located us not in place, but in time. Recognizing that we were standing on a formation from the Jurassic period brought the past into the present. She next trained us to see as she did, pointing to the lowest layer in the canyon and explaining that it was Wingate sandstone, the first and oldest of the Jurassic formations in this region. She built up the story from there; next came Kayenta, then Navajo, that thin layer is Page, which meant that we were actually standing on the Carmel Formation. With a new understanding of our place, Carol appraised the Carmel Formation. Even though there were several good drill sites, the location was too far away from the hab. It would be too long of an excursion for a future crew in full simulation, dressed in space suits and unable to eat, use the bathroom, or scratch their noses. Testing the drill here would defeat the purpose of the simulation.

The days spent with Mary Sue, who unfortunately had to leave half way through the first week, was a lesson to all of us about how to see like a geologist. When I asked what I could do to hone my geological skills, she simply responded, "The more rocks you see, the better geologist you are. And that's just a fact." In a similar vein, Carol remarked that when she is with Mary Sue she knows that she is not a geologist. Unlike Mary Sue, she cannot distinguish between the many similar looking formations. However, even Mary Sue needed to brush up her knowledge of this region. She had done field camps here as a student, so had a baseline familiarity. With the *Roadside Geology* text, she jogged her memory of the general lay of the land. The map on her wall, helped fill in some finer details. Finally, it was the trip to the BLM, the personal guidance from Buzz and the stratgraphic column that allowed Mary Sue to finally "know where we are." She learned to see the landscape and offered a geological narrative, which transformed what to us looked like jumbled or indistinguishable rock formations into a temporal and consequently spatial ordering.

The narratives she uncovered at the quarry or from Angel Point remain just that, stories. With geology, there is a healthy amount of disagreement when it comes to interpreting formations. While it is true that every rock tells a story, for each person this story might be different. In an interview with planetary geologist Jeff Moore several months after this trip, he warned me about the subjectivity of geologic knowledge, especially as it pertains to geology on other planets. "I think everyone who wants to be a planetary geologist should have the experience of trying to map a small piece of the Earth," he suggested. On Earth, he explained, one can be standing on the surface with access to all the samples and equipment desired, and yet there are often as many interpretations as there are people studying the geology of an area. However, with Mars, "people look at a few pictures and make proclamations that they understand how a place is based upon a very limited data set." If we draw from lessons of terrestrial geology, a claim of such definitiveness should be received with skepticism. The lesson we learn from Earth is not only that landscapes come to stand for multiple places throughout time, the narratives that organize a landscape's coming into being are also multiple.

The first several days of our mission felt, to me, like a series of false starts. We sought out and found different formations, but to get to each was a journey of wrong directions, inaccurate maps, and savior by the local guide. Carol was nonetheless content and optimistic with the reconnaissance. After all, she explained, this is all about "getting to know the place."

Landscape 2: The Astronaut Geologist. An Astrogeological Narrative.

Jim Irwin (left) and Dave Scott (right) prepared for the Apollo 15 mission with extensive training in field geology. The USGS mock up of the Lunar Rover (called the Grover) is in the background. Image Source: NASA photo S-71-39711; USGS Open-File Report 2005-1190, Figure 087a.

The double exposure of Landscape Two juxtaposes a soon to be enacted lunar scene against the stark backdrop of the American west. Jim Irwin manipulates a scoop of soil and Dave Scott looks on, preparing for the science objectives of Apollo 15. The canyon cutting through the middle ground stands in for Hadley Rille, the lunar channel near which Apollo 15 would soon land. Irwin and Scott were not hired for their geologic skills but instead, like almost every other astronaut, for their Right Stuff. Both had distinguished careers in the Air Force and graduate level training in aerospace engineering. How, then, did two test pilots find themselves in the Arizona desert, saddled with mock lunar equipment, identifying basalts? How did geology become the discipline for uncovering the story of the Moon and other planets? The emergent astrogeological narrative that makes sense of this multiple exposure of place is rooted in a mid-century debate over how best to know other places. Without the acceptance of this narrative, a place like MDRS would never have come to be. Also layered within this landscape is a second narrative: that of the frontier. The American frontier, though long settled, frames the training astronauts as they prepare to journey to the extraterrestrial frontier. Astronauts demonstrated that geologists and cowboys had roles to play on the lunar surface.

Historian Matthew Shindell (2010) nicely shows that geology's prominence in lunar science and later planetary science was not universally accepted. Rather it was contested from within and without the discipline of geology. Shindell draws attention to the role the physical chemist Harold Urey played in questioning geology's place in Solar System science. Urey viewed geology as a more qualitative field, insufficient (and unnecessary) compared to the quantitative results of his research. Further, Urey believed that the Moon was of a different origin than the Earth and the descriptive work of comparative geology would fall prey to misguided preconceptions (203).

Prior to the space program, the occasional geologist would gingerly dip a toe in the extraterrestrial waters. In 1938, the geologist Herman Fairchild, with apologies, suggested that geology might have something to offer the field of selenology (the study of the Moon). More daringly, with breakthroughs in solar system science looming, Jack Green and Dael Wolfle (1960) suggested that distinguishing selenology from geology set a dangerous precedent of coining a field and associated terms for each planet in the Solar System. Instead, "*Geology* and the *geo* terms can be extended from their earthly meaning to cover similar processes and features of other cosmic bodies… Wherever they occur, a caldera is a caldera, sulfur is sulfur, and a reverse fault is a reverse fault" (1071). Geology, they argued, was not tied to Earth but was perhaps what tied Earth to other planets.

During the same year that this article was published in *Science*, Eugene Shoemaker became the first head of the newly established Astrogeology Branch of the United States Geologic Survey (USGS). Shoemaker passionately believed that geology had a great role to play in lunar and planetary geology. The most immediate task was to provide more detailed maps to aid in landing site selection, first for robots and later for humans. The geological community skeptically received the remote reconnaissance he was doing on the Moon. Don Wilhelms, one member of Shoemaker's team, recalled giving a lecture at a French observatory in 1963 and explaining that you can tell the age of craters through visual inspection. The reaction to this claim was simple disbelief. "And that's been my experience through most of my career, especially in the sixties. It's become accepted now. There are a lot of people who now look at planets with this viewpoint. But in those days, it was like pulling teeth to get even a geologist to understand it" (Wilhelms 1987).

Provoked by the application of geology to the Moon and a formal instantiation of this practice within geology's most prominent institution, the USGS, several geologists resisted the burgeoning astrogeology narrative and attempted to reign in geology as a uniquely Earthly discipline. Kalvero Rankama of the University of Helsinki protested: "I, for one, am taking strong exception to the use of 'geology' in [planetary geology, lunar geology, and astrogeology]… Clearly, geology is restricted to the study of the

Earth and of terrestrial phenomena and does not apply to extraterrestrial bodies and processes" (1962, 519).[8] The retort to this, which came a few years later, was that geology is not about Earth, but earth. "It is the idea of the solidity, the stability of the land on which we can safely land after a travel through a more precarious medium, and it is the rock that composes this land." The analogy then stretched from early explorers who traveled through the seas to new land and astronaut explorers traveling through space to new, solid surfaces. "Geology will be the study of the place where they land" (Ronca 1965, 13).

After landing a man on the Moon, and after the astronauts received geologic training in large part due to the efforts of Shoemaker at the USGS, there was little hope for the dissenters to keep geology grounded on Earth. In a presidential address to the Geological Society of America in 1970, Morgan Davis began by declaring the past year "the most momentous year the geological profession has ever known. I refer, of course, to the lunar landing" (331). He used the opportunity to chastise those who sought to limit the scope of geology, urging his colleagues to embrace to study of the ocean floor, the Moon, and other planets. And by 1973, a retrospective of scientific work accomplished during the concluded Apollo program was careful to state, "This article attempts to evaluate the effect of the Apollo program on geology (using the term in its broadest sense)" (Smith and Steele 1973). Geology, successfully but perhaps a bit uncomfortably, was now a science applicable to the Earth, Moon, and in the near future hopefully Mars.

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[8] Rankama might perhaps be overly sensitive to the use of geological terms in other fields, as he ends his article with an admonishment of the petroleum engineer who has inappropriately "snatched" terms from petrologists and geochemists. In the early 1960s, geology appeared to be struggling with its boundaries, as echoed in a presidential address to the Geological Society of America delivered by M. King Hubbert (1963). Hubbert expressed discomfort with the disproportionate amount of geologists entering gainful employment in the petroleum industry, an industry he predicted was soon to decline and no longer be a source of employment for geologists.

The flourishing of the USGS's Astrogeology Branch helped legitimize geology as a multi-planetary science. In 1963, the branch moved from its original offices in Menlo Park, California (in the soon to be established Silicon Valley) to Flagstaff, Arizona. There, they had better access to telescopes and clearer seeing as they mapped the Moon. And, not insignificantly, it was near Meteor Crater. There, geologists had been doing fieldwork for some time to learn about impact geology as it might be applicable to the Moon. This same year, Shoemaker began training astronauts in lunar geology. Shoemaker asked Wilhelms to be the primary lunar geologist and work alongside more traditional geologists in training the astronauts.

An astrogeologial narrative suggested that, because of its grounding in geology, fieldwork was a necessary skill. To teach fighter pilots how to identify rocks and make sense of their lunar surroundings, the USGS ran mini-field schools for the astronauts. After all, as one member of the Astrogeology branch (who was not involved with astronaut training) put it, "fieldwork is the essence of geology, it really is. You know, you don't get any sense of the complexity of geology until you go out and try and do it" (Carr 1987). Shoemaker and his colleagues all received extensive fieldwork training in their geology educations and wished to impart this to the astronauts. Shoemaker wanted them to come out to Arizona, where the canyons and craters made ideal training grounds. He recalled his plan to "get scientist-astronauts away from their day to day involvement in the flight program and all the other activities the astronaut had, de-orbit them for awhile, get them on the ground, give them three months of really solid training – which is what it takes. You have to go out and do fieldwork to learn how to do fieldwork!" (Shoemaker 1988).

The aspiration behind astronaut training was not only to get them to see like geologists, but also to teach them how to compare what they saw on Earth to what they would see on the Moon. It was a move to place the terrestrial landscape on a different world. Donald Beattie, in his memoir *Taking Science to the Moon* writes, "on missions to the Moon some of the astronauts would comment on how much the Moon's surface looked like their memory of [their fieldwork sites]" (2001, 181).

Part way through the Apollo program, after the initial landings were accomplished and as the future missions promised to be more science driven, USGS astrogeologists decided that the analog sites they had been training at were not sufficient. They decided to craft their own, ideal lunar landscape. After carefully studying a region of the Moon photographed by the Lunar Orbiter, they precisely placed explosives and produced, to the extent possible, a facsimile of the lunar surface just outside of Flagstaff (182-183). Apollo training hugely influenced the ways in which the Moon and Earth were multiply exposed on each other's surface. These activities supported an argument that geologic analogies work in both ways: the Moon can be understood through a terrestrial landscape, but also that a landscape on Earth can come to stand for the Moon. Further, being in the field at such analog sites is not only a legitimate, but necessary way of knowing other planets.

Landscape Two was captured on a fieldwork training expedition. It looks like a messy, multiple interpretation of a landscape. In a scene of the shrubby desert with snow-capped mountains in the background, two men are encumbered by boxy backpacks with cameras strapped to their chest. They peer down at a mechanical scoop, inspecting a rock or soil sample that they might collect before returning to a minimalist buggy with a conspicuously large antenna attached. Looking at the picture now, we recognize familiar icons that tell us they are enacting the Moon on Earth. An astrogeology narrative that secures geology's utility in planetary science, which was by no means obvious or easily won, structures this landscape and brings dissonant images into harmony. It has also continued to be a powerful trope in contemporary planetary science and planetary geology, in which terrestrial fieldwork is understood as a proper tool for studying other planets.

Another motif unavoidable within space exploration rhetoric and central to Landscape Two is the imagination of the American west and the frontier. More than geologists, astronauts fancied themselves cowboys. They were not explorers setting sail at the behest of the crown. Instead, they imagined themselves setting out into the untamed wild of their own accord. A poster conceived by Larry Keith in 1984 illustrates the enduring notion of the cowboy astronaut. It is a drawing of an astronaut floating in space, with the traditional astronaut suit supplemented with a cowboy hat, boots, and a branding iron. The caption of the poster reads, "Texas – Still in the Frontier Business." Images like Figure 4.3 circulated during the Apollo era. In this picture, a geologist (not an astronaut) tests out an early space suit. To keep the desert sun off his head, he dons a cowboy hat, creating an iconic image of the cowboy astronaut as embodied by a geologist. Training in the American west intensified the association between frontier and space, and cowboy and astronaut.

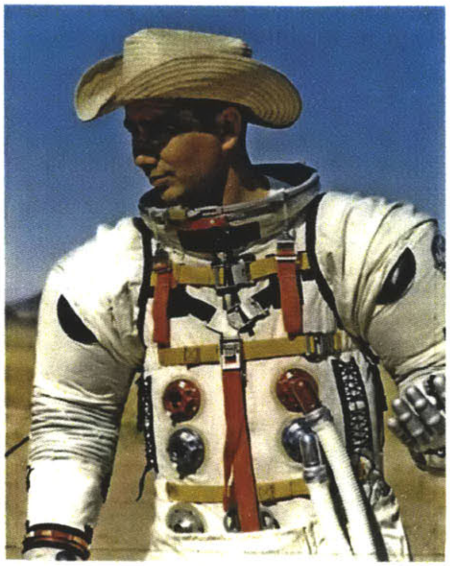

Figure 4.3: The Cowboy Astronaut. Geologist Joe O'Connor dons an early version of the Apollo spacesuit in the Hopi Buttes Volcanic Field within Territory of the Navajo Nation, Arizona, 1965. USGS Open-File Report 2005-1190, Figure 031a.

In American history, the frontier was imagined first as a physical manifestation and later as a mental one.[9] With the establishment of NASA and the goal of setting foot on the Moon, the mental and material frontiers were united.[10] Shoemaker, who found the frontier a compelling analogy for the growth of scientific research, recalled how this narrative ultimately unraveled:

> I tried to draw -- at the AAAS meeting -- an analogy between the early exploration of the American West and the Apollo program. The difference, of course, was the early exploration of the American West led to evolving, continuing, growing scientific

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[9] Fredrick Turner (1893) famously argued that the frontier shaped American notions of individuality and democracy. There is a significant literature produced by US historians revisiting, revising, and critiquing the Turner thesis. I will simply refer to Patricia Limerick's work (1988), both because she offers a nuanced history of the American West and because she has elsewhere (Limerick 1992) written against the use of the frontier metaphor in the space program. In 1945, Vannevar Bush opened up the mental frontier when he dubbed science "the endless frontier" (Bush 1945).

[10] De Groot shows how the frontier spirit animated NASA as early as the Mercury program. The first astronauts spoke of themselves as pioneers ready to explore the frontier of space. De Groot nicely suggests that, in the wake of the atomic bomb and the shattering of the romance of war, the press and public welcomed the resurrection of the fantastical frontier explorer (2006, 109). See also Parker (2009, 89-91) for a discussion on how capitalism intersects with the frontier narrative in the space program.

> enterprise. The Apollo program didn't. But at that stage it wasn't clear it was going to happen that way. I was trying to say what we wanted to do was just build on this early stage exploration and go on to a really deep, meaningful program of scientific exploration (Shoemaker 1988).

Even while the Apollo program was still going on, Shoemaker began speaking out against NASA's vision of exploration. He rightly diagnosed NASA as an organization of engineers, more interested in "can" than "why." After landing on the Moon, he did not think NASA should move quickly to Mars, the next target (Shoemaker 1969). Instead, the Moon should be refashioned as a scientific frontier and explored in that nature. To prove that a destination could be reached was not, for Shoemaker, justification in itself.

As Shoemaker seemed to have predicted, NASA lost its role as primary story spinner for the frontier narrative. Grassroots organizations like the Mars Society and commercial ventures of the early 2000s picked up the thread. In the late 1980s, the members of the Mars Underground began planning missions to Mars without a thoughtful answer as to why one might want to do such a thing. After Robert Zubrin began attending the Case for Mars workshops, he formulated a justification for Mars missions drawing heavily from Fredrick Turner's frontier thesis of the previous century. His thesis, "The Significance of the Martian Frontier," first appeared in *Ad Astra* in 1994, a magazine of the National Space Society, and later in various volumes published following Case for Mars workshops (1994, 1996, 2000a, 2000b). Zubrin does not pull any punches when he writes:

> The creation of a new frontier thus presents itself as America's and humanity's greatest social need... Without a frontier to grow in, not only American society, but the entire global civilization based upon Western enlightenment values of humanism, reason,

> science and progress will die. I believe that humanity's new frontier can only be on Mars (1994).

Because Mars is remote yet able to be settled, Zubrin's logic goes, it is the ideal frontier. Zubrin's narrative of the New World as frontier suggests that in creating distance between the Old and the New, settlers escaped the aristocracy and could pursue their dreams of democracy. Humanity needs Mars because it will provide a stage for improvisation in order to manufacture the next great development. This narrative notably lacks natives and slavery, bigotry and disease, oppression and poverty. It is a powerful story because of its simplicity and because it cleanly juxtaposes alien Mars with the familiar frontier.

Geology, the frontier, the cowboy, the explorer, the Earth and the Moon all come together in Landscape Two and are ordered by an astrogeological narrative. In this image, landscape and identity reinforce each other. The notion of the cowboy astronaut can make sense because of the western landscape. Doing geology on the Moon makes sense because astronauts train in the field on Earth. Geology might seem an odd addition to the "right stuff" arsenal, but geologists form their professional identities in landscapes not dissimilar to where astronaut training occurred. "If I were to describe a classical excellent field geologist," a planetary geologist offered to me in an interview, "it would be someone who is extremely physically tough and these are really explorer style people. You know, people who can walk all day and don't get tired or whine when their backpack gets heavier and heavier because you're filling it with rocks. And at night you cook around a fire and sleep in a tent and even if the weather's bad you go out anyway." It is this conception of the right stuff that informs fantasies of future Mars explorers.

While at MDRS, Carol and Larry told us about the Association of Mars Explorers. There are about 50 members and the founding document was written on a napkin at a dinner Carol and Larry attended in 2002. According to the scrawl on this napkin, "it is a forum for explorers of the Martian frontier, including the deserts, mountains, and poles to inspire, astonish, and inform their fellow explorers with tales of courage, bravery, and [...] discovery in the great frontiers of Mars or the Martian analog environments on the Earth" (Association of Mars Explorers). They swap these stories every other year at a dinner held during the Astrobiology Science Conference. Larry teasingly described these dinners as a classic British gentlemen's club, where they compare stories like 'and then I saw a lion THIS big.' Carol came to the defense of the club, saying it is more like the Explorer's Club, which emphasizes scientific work. What is striking about this association, and its founding statement, is that members are recruited based on both what they do and where they do it. The identities and landscapes central to this statement are part of a narrative that gained traction during Apollo training, is very much alive in the current activities at MDRS, and will only be resolved, so the story goes, when humans land on Mars.

Landscape 3: Finding Mars on Earth. An Areological Narrative.

Carol poses with a "concretion" at a potential drill site outside of Hanksville, Utah. Photo by the author.

On Mission Day 4, Mary Sue and Larry bid us and MDRS farewell. In the afternoon, Josh and Kevin would arrive, but Carol, Jhony, Susana and I would operate as a diminished crew that day. After an oatmeal breakfast to warm our bones following a cold night's sleep, the four of us locked up the hab (chaining the door closed) and spent the morning scouting more drill sites. We were looking at different locations today, avoiding the rocky strata and examining clay and sand deposits instead. We turned off the main road, driving beyond "Historic Giles," a ghost town that appeared to be fashioned as a tourist site. Though there were no dwelling structures, there were a few mannequins dressed as outlaws and a wooden sign that welcomed us to Blue Valley

Ranch and historic Old Giles Town of 1898. Another weathered post was engraved with a website to visit, but I discovered later that this website was also a ghost. Further down the road, another sign informed us that there were plots of land for sale. I looked out and saw desolation: a grey desert near a town that hosts a convenience store built into a mountain, a Chevron, and a burger shack. Carol saw something else. Over lunch later that day, she voiced a desire to buy land here. I asked if she would build it up. No, she responded with a headshake. She'd just like to have it.

We pulled over at a possible drill site along the side of the road. There was a fortress of Mancos shale, a mesa, sitting atop a dune of sandy debris. Unlike the reds and browns of the Morrison and Sumerville formations, these features were grey and tan; more lunar than Martian. Though the fine sand made it difficult to maneuver, we collected some soil samples. Carol and I implemented the collection and documentation procedure we developed that morning. After about an hour at this site, I was heading back to put our equipment away in the truck when I heard sounds of excitement coming from Carol and Susana behind me. I returned to see what they had discovered.

Scattered across the ground, a few meters from where we were collecting our samples, were hundreds of spherical rocks. Carol and Susana eagerly collected samples, forgetting about the procedure we worked on earlier and simply grabbing these rocks and putting them in whirl bags. Carol looked satisfied and excited, exclaiming that exploration is fun. I tried to join in the excitement – what are these rocks? They are concretions, I was simply told. I responded enthusiastically, asking what that means. Are they made of something special or do they indicate something unique? The only response I got was a shrug, and Carol and Susana went back to their frantic collecting.

After the initial wave of excitement died down and we were just standing around enjoying the site of the concretion field, I again asked why this find was so exhilarating. These are like the blueberries on Mars, Carol responded. Whereas the Apollo training taught astronauts to understand the Moon through the lens of Earth, an areological narrative was at work here that made sense of something on Earth by refracting it through knowledge of Mars.

Shortly after the Mars Rover named Opportunity landed on Mars, it set its electronic gaze on an outcrop of sedimentary rock near the rim of a crater. Sticking out of this rock were tiny globules, described by chief scientist Steve Squyres as resembling blueberries in a muffin. The description stuck, and the mystery of these blueberries occupied the science team for some time. Ultimately they concluded that these spheres were hematite-rich concretions, features formed when water carries dissolved minerals through softer rocks before settling within the rock. Eventually precipitates form in layers around the deposit, replacing the softer sediment with hard concretions. As wind erodes the softer material, the concretions end up littering the surface. Finding concretions on Mars was an exciting discovery indeed: the place Opportunity landed must once have been flowing with water (Squyres 2005).

Later in the day, we took a hike through Little Wild Horse Canyon. As we walked along the base of the canyon, Susana spotted little spheres nested in the walls of the Navajo Sandstone. Carol identified these also as concretions, and noted that they are even more analogous to Mars blueberries. She referred to an article published in *Nature* shortly after the blueberries were announced that mentioned these particular Utah concretions. In the June 17, 2004 issue of *Nature*, there is a letter and highlighted discussion in "News and Notes" on this topic. Through analogy between Mars and concretions found in Utah's Navajo Sandstone, the letter bolstered the link between hematite concretions and a watery past (Chan et al. 2004). The "News and Notes" piece, "On Earth, as it is on Mars?" prominently juxtaposes terrestrial and Martian concretions, asking in the caption of the image reproduced below (Figure 4.4), "Earth or Mars?"

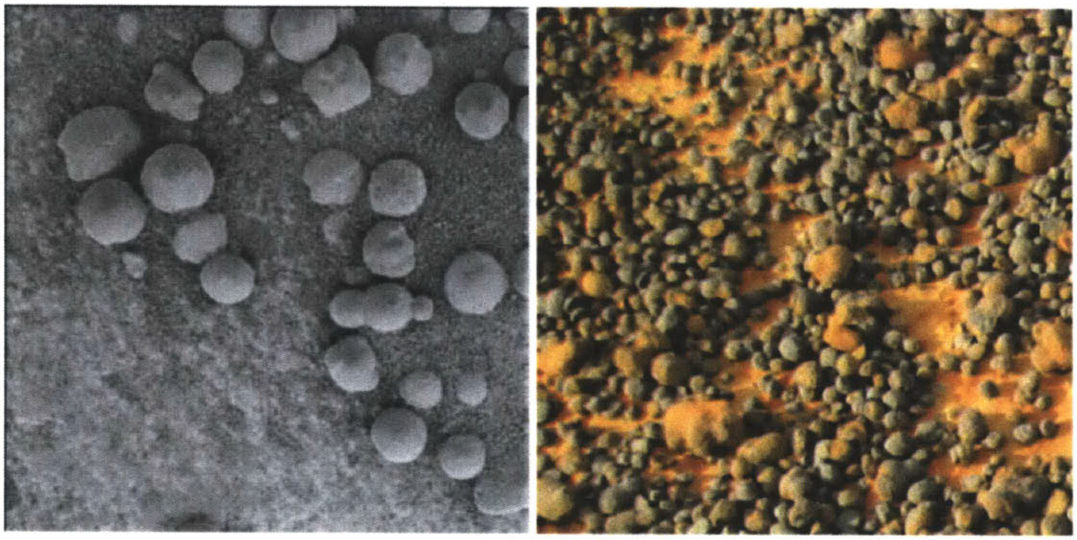

Figure 4.4: Martian and Terrestrial Concretions. Source: Catling (2004).

This case of concretions illustrates a complex trade between geologic and areological narratives and how they ultimately complement each other to add clarity to an otherwise confusing landscape. When Opportunity first spied the blueberries, multiple explanations were offered based on terrestrial geology. After a battery of tests, the team reached consensus that they were concretions. Articles like the one in *Nature* used geological findings to support that these were concretions and the attending fluvial implication. Years later, with the connection between blueberries and concretions secure, Carol is able to make sense of the Utah desert based on an areological narrative about concretions in the Martian desert.

At the site near Giles, Carol found a concretion nearly as big as her head. Even though the top had crumbled off, I asked if she wanted to pose with it. The image I captured, Landscape Three at the start of this section, is a double exposure of Utah geology and Martian areology. There is a clear story that relates these concretions to concretions elsewhere. The areological narrative in some ways operates in a different direction than the astrogeological narrative. Both suggest that landscapes in one place are tied to landscapes in another place. However, whereas the astrogeological narrative uses Earth to make sense of the Moon and other planets, Carol employed an areological narrative to make sense of Earth based on her knowledge of Mars. Finding concretions on Earth was an exciting discovery for my crew not because it confirmed that water once flowed here (there was a stream not far away), but because it was a symbol of Mars. It offered Carol, who knows far more about Martian geology than terrestrial geology, a new connection to the landscape. Though at analog sites such as MDRS, the conceit is that we are studying the Earth in order to better understand another place, in actuality when an areological narrative was available, we appreciated these terrestrial features because of our knowledge about Mars. The concretion field became a place-world, as Basso might say, not by invoking past geological or human events, but by invoking knowledge of the present; albeit the present of an entirely different place separated by the extremes of space.

It is not uncommon for planetary geologists to undertake terrestrial fieldwork, similar to the work we were engaged with at MDRS. At NASA Ames, I spoke with several planetary geologists for whom fieldwork informed their research. When I sat down with Jeff Moore, one of the first things we discussed was his training in geology. When I asked about his experience of field camp during his education, he made it clear that fieldwork was not just part of his training, but part of his current practice. To prove this, he stated that he just got back from the field two weeks ago. As he said this, he dropped a black spiral notebook that was sitting on his desk onto the table between us with a hearty thump. This, I took it, was his field notebook – a ubiquitous tool of the geologist and anthropologist alike.

He was working on a project about meandering rivers. On Earth, a meandering river forms where the river walls are reinforced with vegetation. On Mars, they have identified meandering rivers in satellite images. These "rivers" are not flowing with water today, but the pattern on the dry surface suggests this was the case in the past. Though it would be nice for astrobiologists to announce Martian meanders as proof of vegetation, Moore and his collaborators want to investigate alternative mechanisms for meanders. To think through this problem, they searched for an appropriate Earth analog – a river in a more desiccated landscape with scarce vegetation. This brought him to the Quinn River in the Black Rock Desert of Nevada. I wondered if while in the field he and his team ever imagined they were on Mars; did they ever think that they were directly studying Mars? "Sure," he responded. "I mean it was a topic of discussion." But they were always conscious of teasing out what in the landscape was purely terrestrial and what might be applicable elsewhere.

Moore, who finds the merging of the Martian and terrestrial landscapes to be a productive tool in his research, thinks that planetary science is at a disadvantage by the unwillingness by most people to go into the field "and see geology as it is." Another NASA planetary geologist, Lori Fenton, corroborates this view. She works on dune processes on Mars. When I spoke with her, she was in the process of organizing a workshop on planetary dunes. She was keen to organize a little field trip as part of the agenda, just to get the planetary people to see dunes "in real life." To "go out there, walk around the dunes for a couple hours. It doesn't take much, just to get some idea. OK, that's how tall they are, this is what little ripples look like, ok. Yes, that stuff actually happens." This kind of exposure, teaches one to see dunes in a different way. She also mentioned that she was taking her summer students to the Mojave for an orienting dune trip, "just to show them. There's nothing like seeing them and walking around on them. After you know a little bit about them... Suddenly you might go and walk on a dune and say oh, this is fun. But when you actually know what to look for, suddenly there's a lot more detail there than you ever thought."

Planetary scientists go on these fieldwork trips in an attempt to locate Mars in a place they can actually travel to. Fieldwork for geology and anthropology is grounded in a notion that "being there" is a valuable and telling experience. In Chapter Two, I discussed how astronomers often framed being at the observatory as important because it allowed them a direct, material connection with the telescopes and the data they were collecting. However, in practice, being at the observatory was most important because of the social relationships formed between researchers, teachers and students, and telescope operators. For fieldwork in planetary geology, being there is further complicated by the fact that the "there" they travel to on Earth is not the "there" they are actually seeking to understand. For being in the field to work, epistemologically speaking, scientists must persuasively argue that there is a *there* there that evokes Mars. My own experience in the field sometimes lagged behind those I was with. For example, Carol saw the concretion field as a "there" similar to Mars well before I did. While I was witnessing scientists at work in the Utah desert, Carol and Susana were already infusing that place with Mars. Our fields momentarily diverged.

Carol and other planetary geologists enter the field with more knowledge of areology than geology and consequently understand the terrestrial structures through the lens of Mars. At the same time, they expect that being at these structures will offer a new intimacy with the distant planet; an intimacy that "being there" affords. They are constantly using dunes, rivers, and concretions to draw links between distant worlds. It is this focus on specific features that transforms Mars from a planet into a landscape. Jeff Moore narrated his changing understanding of Mars. "You can't be much younger than I am," he began, "and remember what the Solar System was imagined to be before space crafts starting going there." He lived through the release of the first photographs of Mars in 1965. But it was not until he saw images of the surface and was able to identify craters and plains and volcanoes that he began to relate to Mars. "It literally changed my psychological disposition towards them. Before seeing them, before they became landscapes, they were astronomical objects. I could go out and look at them with my telescope. And now they are geologic landscapes that I look at with spacecraft images." When I asked if gas giants underwent a similar transformation and became places, he was clear to specify that while they are places, "they are not geological places" because without a surface there is no way to do geology on them. While Jupiter is pretty and he can appreciate it when looking through a telescope, he categorizes it more with the Sun than with the planets and satellites he studies. Moore returns again to Jupiter when describing why he finds planetary geology interesting. Jupiter's "timelessness makes it inherently less appealing, then, to be able to tell a story about the place. It used to do this and now it does that, etcetera." Without a landscape, Jupiter lacks a narrative.

Geologists are piecing together a narrative about Mars based on the shape of rivers, the rolling of craters, and the presence of anomalies like concretions. They cannot physically place themselves in the Martian landscape and thus seek out terrestrial landscapes to inhabit. This practice allows the planetary geologist to investigate the story she is crafting, and in doing so gives new meaning to the landscape at hand. The areological narrative draws attention to features that the geological narrative might miss.

As Susana, Jhony, and I piled back into the car and prepared to leave the concretion field, Carol took in this particular Utah landscape one more time. She sighed before exclaiming, "Really Beautiful. What *a place*!"

Landscape 4: Living and Working on Mars. A Science Fiction Narrative.

Carol, Susana, and Kevin, wearing simulated space suits, walk back to the MDRS hab after an afternoon of field tests. Photo by the author.

The landscapes so far discussed were images from the field. They captured double exposures of a single location over time (as with the geological narrative) and the blending of places removed in space, but existing in the same moment (the astrogeological and areological narratives). Our days were mostly spent in the field, navigating these multiple places. In the morning and evenings, we dwelt at the hab, and there, a different narrative ordered our practice. I call this the science fiction narrative. Utah and Mars come together at the hab in a different way then they do in the field. The Mars imagined near the hab is not the Mars of the present, but the Mars of the future. It is a vision of Mars shaped by popularizers and science fiction writers who have speculated on the nuance of life in a Martian colony. The hab becomes a place-world not because of remembrances of the past, but because of nostalgia for the future. I identify the hab as nostalgic precisely because of its many allusions to science fiction. As literary scholar Istvan Csicsery-Ronay, Jr. has suggested, one of science fiction's narrative aesthetics is the invocation of a "future past" (2008, 76). Sci-fi stories are written not as prophecies, but as remembrances of events yet to happen. For those familiar with the sci-fi genre, as most MDRS visitors are, they have the opportunity to weave their personal narrative into a familiar, though yet to happen, environment.

It was in the hab that I was much more likely to hear people proclaim the virtues (and hardships) of 'being on Mars.' "Ah Mars. I love looking out at Mars," Josh exclaimed one morning while he was making pancakes from Bisquik and powdered milk, gazing out the circular window onto the hill formation named Olympus Mons. Josh was perhaps most representative of a typical inhabitant of MDRS. He was tall and lanky, with long brown hair, often hidden under a bandana. He mostly wore black jeans and t-shirts, a mark of his involvement with technical theater during college. While at MDRS, Josh had to attend a virtual meeting of Students for the Exploration and Development of Space. SEDS has chapters at approximately 30 universities, and Josh was in his third year of serving as Chair for SEDS-USA. He had just finished up a degree at the University of Arizona in aerospace engineering, with minors in astronomy, physics, and planetary science, and before starting a masters program in Space Studies at the University of North Dakota, he was interning with Carol for a semester. Josh had also been to MDRS several times before, both as part of a different NASA affiliated crew and as part of the engineering crew that polishes up the hab at the beginning of the season. He felt a great deal of ownership over the hab, and spent much of his time at MDRS doing repair work – fixing the telescope in the Musk Observatory and maintaining the green water system that allowed us the luxury of a flush toilet.

In a crew with a healthy appreciation of science fiction, Josh's knowledge of the genre outshone us all. He read Heinlein during breaks and had heated discussions with Carol over whether Battlestar Galactica or Babylon 5 was the better show. His prowess of this genre spurred Carol to call him out as a true geek on more than one occasion. It is therefore Josh who I went to in order to decode the science fiction references of the hab. I asked about the meaning behind the flag that waved from the roof, a sequence of red, green, and blue rectangles. I found out that it is an homage to K. Stanley Robinson's trilogy *Red Mars, Green Mars, Blue Mars* and a general reflection of the ethos behind colonizing Mars.

Months after I returned from the hab, I sat down with Robinson's epic trilogy and was startled by the many connections between the beginning of *Red Mars*, when the architecture and operations of an early Mars settlement are being hashed out, and MDRS. The saga begins with the first 100 colonists journeying from Earth to Mars. Arkady is the ship's anarchist; insisting half way through the journey that they scrap the current architectural plans for the colony and remake one based on equality and the fusing of work and life. He puts forth his vision for living on Mars, the habitat should be circular or a geodesic dome; "As for the insides, perhaps mostly open. Everyone should have their rooms, sure, but these should be small. Set in the rim perhaps, and facing larger communal spaces… There. This is architectural grammar that would say 'All equal.'" (Robinson 1993, 80). Sure enough, MDRS is a cylindrical construction; the first floor is designated as the workspace, an unsegregated engineering and biology area. The second floor has rooms of equal size along the rim, opening up into the communal kitchen/living room/den/study.

I spent quite some time puzzling over why MDRS was round. This struck me as neither an efficient nor simple construction. A cylindrical construction began to make sense when considering how a habitat would be transported from Earth to Mars. During the 1984 Case for Mars conference, the attendees broke into small teams and considered mission and habitat architectures. The lander designed was shaped like the nose of a nuclear warhead. On the surface of Mars, the cylindrical body, lying along its length, would be outfitted as a living and working space (Chaikin 2008, 138-42). The main difference between this habitat and MDRS's is orientation.

Zubrin based the design of the hab on his proposed mission, Mars Direct. Mars Direct was a cheap way to get humans to Mars, and a concept that NASA showed great interest in when Zubrin (along with collaborator David Baker) first pitched it in the early 1990s. The Mars Society has overseen the construction of two habs (one in the Arctic in addition to MDRS), both similar and in compliance with the vision set forth in Mars Direct. The habs are 27 feet in diameter, as that is the maximum diameter the Lockheed Martin cylinder fabrication facility could produce (Zubrin 2004, 96). That these habs are constructed from a well-received vision and their dimensions are grounded in the constraint of Lockheed Martin's capabilities provides a connection between the present and a fantastical future. This present, however, is slowly moving in a different direction.

When humans actually do travel to Mars, it will not necessarily be on ships manufactured by Lokheed Martin but perhaps instead on platforms engineered by the growing commercial space flight industry. Regardless, that the hab is constructed from blue prints of the present industry supports the sci-fi trope of future history suggested by Csicsery-Ronay in which the present becomes a prehistory of the future.

The space suits that we occasionally donned were also directly out of Robinson's *Red Mars*. We put on the "fairly standard hard helmet, and locked it to the suit's neck ring; then shouldered into an airtank backpack, and linked its air tubes to [the] helmet" (128). Our helmets were fashioned out of garbage can lids and plexiglass; our backpacks contained a standard fan, which did little to infuse the stuffy helmet with fresh air. And though putting on the suit was a novelty and made us laugh, it rang familiar.

Landscape Four, at the start of this section, was captured towards the end of the mission. Most of the collection and testing tasks were accomplished, and Carol suggested it would be a good idea to test out the EVA suits. Susana and Kevin gleefully volunteered to suit up, and the three costumed explorers decided to test the dexterity of the suits by doing some soil sampling *in situ* (Figure 4.5). In Landscape Four, one can imagine an isolated habitat and the relief that returning to it would bring. One could finally scratch his or her nose, use the bathroom, and breathe deeply. The blue sky and an airplane's gaseous trail towards the top of the frame reminds the viewer that this is not Mars.

Figure 4.5: Simulating Working on Mars in Utah. Carol, Susana, and Kevin crouch around an instrument that tests the mineral properties of soil. Photo by the author.

This double exposure of place was emphasized during the first missions at the arctic Mars simulation. There, they often used an orange or red filter to suggest to the viewer that they are actually looking at a peopled Martian landscape. In a spectacular convergence of the imagined future and present experience, NASA's Pascal Lee (the original partner with Zubrin for the arctic Mars station) enacted a painting by space artist Pat Rawlings. *First Light (Exploration of the Noctis Labyrinthus canyon system on Mars)* was commissioned by NASA and depicts an astronaut repelling down the side of a cliff. After finding a suitable cliff near the arctic Mars station, he orchestrated a red-tinged photograph in which he repelled down the cliff in a simulated Mars Society space suit. As science writer William Fox observes, the Rawlings painting "was in itself an imagined re-creation of an event that has yet to happen in the future" (2006, 160). Thus, Lee's photograph is a present depiction of a future past. It is a photograph of a landscape waiting to be developed.

The science fiction narrative organizes these connections across time and space. It provides a framework already familiar to those at MDRS. For those saturated with the tales of Clarke and Bradburry, Dick and Burroughs, living for a couple of weeks in the hab is far from out of the ordinary; it is familiar. Just like the Utah desert made the most sense to Mars scientists once elements of Martian geology were present in the landscape, this cylindrical living space makes complete sense when viewed through the lens of science fiction. For those who have spent decades reading about future colonies on Mars, it is a joy to bring those elements into the present. In fact, for most of my crew it would seem that the hab and its sci-fi heritage were more familiar environs than the alien Utah desert.

Conclusion: A Utopian Narrative?

The landscapes of MDRS are informed by multiple ideas of temporality and spatiality. A geological narrative brings former iterations of the place into being, a areological narrative, built atop an astrogeological narrative, telegraphs the present of another already scientifically-investigated world, and a science fiction narrative imparts a vision of the future. If there is a single narrative that orders these juxtapositions of place and time, it is perhaps one of a scientifically driven, harmonious occupation of another planet. This is the foundation of perhaps a utopian story. How does the utopian narrative order the imaginations and materiality of MDRS?

Karl Mannheim (1929) suggested a binary relationship between ideology and utopia. Whereas an ideology maintains the status quo, utopia - as a system of ideas - works to change the status quo. Literary scholar Tom Moylan points out that this oversimplifies the relationship between ideology and utopia. For Moylan, utopia operates within an ideology, both supporting and challenging it (1986, 19). This was quite literally the case with the MDRS crew I joined. MDRS's mission is to pave the way for the human colonization of Mars. This is a utopian narrative borne out of a frustration with NASA's space exploration ideology, which has long stalled a human mission to Mars. And yet, the crew lead by Carol, populated by mostly NASA employees, represented an effort to make room for the utopian fantasy of MDRS within the NASA regime.

It is possible that the contradiction between the MDRS and NASA missions caused no problem in the minds of my crew because MDRS resonates with a utopia; a "no place" both in time and space. Being at MDRS offers an artifice of isolation as we are removed from our work and home and are without many of the trappings that structure our understandings of contemporary life. Each crew decides to what extent they want to enhance the feeling of MDRS being a no place. Cell phone reception was spotty, so most of us volunteered to leave our phones off for the mission to simulate a remove between MDRS and elsewhere. Though we had Internet access, the bandwidth was limited and forced us to adopt different usage habits. Crews are told that water is scarce and to conservatively shower at the hab. Our crew adopted an every third day shower routine, but I found out towards the end that one crewmember had been showering every day. Josh, on the other hand, sought a more "authentic" experience and opted to shower only once. We were simulating isolation, but was this a Mars outpost really a utopia?

Robert Markley explores the complex vision of utopia that Robinson puts forward in his Mars Trilogy (discussed briefly in the previous section).[11] At a broad level, Robinson classifies science fiction as "historical simulations" (quoted in Markley 2005, 355), meaning that science fiction does not *represent* experience but *simulates* the possible future of experience. Simulation does not imitate; it generates. Markley uses this distinction between representation and simulation, formulated by Steve Shaviro, to suggest that the "'utopian' possibilities of science fiction occupy a register of simulation: they give imaginative form to the desire to think beyond the contradictions of historical existence, and... beyond our location in time, culture, and geography" (356). MDRS, as a simulation, does just this. MDRS is a generative medium on which to speculate about future Martian experience. It is a material instantiation of a speculative future. It creates a history even as it simulates the future.[12]

The landscapes I have structured this chapter around certainly draw connections to different 'times, cultures, and geographies,' but these connections are not exclusively beyond the present. Instead of a utopian simulation, a no place entirely other, MDRS is very much of the current time, making connections to elsewhere and other times. Perhaps it is better thought of as a Foucauldian heterotopia (1967). The successful utopia is one that is entirely separate – surrounded by a moat or part of an undiscovered land. A

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[11] See also Jameson (2005) for a discussion on utopia and Robinson's trilogy.

[12] I would be remiss if I did not mention Jameson's formulation of utopia and science fiction and how it operates in some ways opposite to what Markley suggests. In writing about these literary genres, Jameson (1982) argues that in studying these works one comes to the ironic conclusion that they do not represent the future, but instead draw attention to our inability to conceive of utopia. They (unsurprisingly) illuminate the present moment as opposed to a past or future.

heterotopia, which Foucault contrasts to the imagined utopia, is somewhere that appears as no place, but is actually every place. Foucault's example *par excellence* is a boat: while it seems bounded, in practice it extends over the whole ocean and connects every port and every facet of human presence. For MDRS, these connections are made through a series of narratives. MDRS is *heterotropian.* The utopian narrative might appear as a master narrative, but it contains stories of geologic history, the ideal of fieldwork, the frontier and the American west, and scientific and speculative stories.

Whether the MDRS is imagined as a utopia, heterotopia, or heterotropia, living in such close quarters ultimately becomes dystopian – a realization of the different expectations at work in one place. One of my crew's most heated discussions happened after dinner one evening. We were sitting in the common space around a folding table surrounded by the remnants of missions past, which leave their mark in the form of mission badges, DVDs, books, posters, post-its, and make shift signs conveying tips on living in the hab. We started brainstorming ways to improve living. I observed that the clutter of the main area gave the hab a sense of hominess that welcomed modification. Jhony further suggested that to avoid users constantly altering the hab, the living space should be as sterile as possible. Josh, who has a deep affection for the quirkiness of the hab, leapt to defend the personality of the interior. Besides, he said, people will continue to behave as they have. We disagreed, suggesting that if the environment is clean and if directions are clear, people will comply.

This disagreement over the interior of the hab spoke to the different purposes we saw MDRS playing. Josh saw it as a retreat, a place to tinker with scientific goodies and imagine another way of life. That the hab was somewhat "hacked" together was not at odds with his vision. Jhony, on the other hand, imagined the hab as a machine with which to test equipment; the more standard and streamlined, the better. For Carol, MDRS is animated by both of these views. Having a place to fool around with the imagination of what it is like to be on Mars was a welcome departure from NASA work, but this also needed to be a place that was producing science and for this to be achieved, there needed to be a smooth organization behind the hab.

I began this chapter with my arrival, but I wish to conclude with the accounts of two other participants' departures from MDRS. The first comes from Sukrit, the undergraduate I worked with under Sara Seager while at MIT. He went to MDRS the season after me with a crew assembled from his summer experience at the NASA Academy. He did not know his crew very well beforehand, but told me how well they got along at the hab. They were all eager and excited to carry out a simulation of high fidelity. Sukrit told me that their crew decided to use the hab's Internet connection, but to disable all chat clients thus eliminating real time conversation with anyone not at MDRS. A few days in, they lifted their no Facebook ban, but kept its chat feature disabled. They turned off their cell phones and allowed themselves to create a little community for two weeks, cooking, cleaning and working together. It can be a shock to leave the hab at the end of the mission, to abandon the space suit and exit onto Utah soil as opposed to Martian terrain. Driving away from Hanksville, Sukrit recalled how surreal it was to turn back on his cell phone and watch as it accumulated bars and upgrade from 0G to 1G to 3G. Sukrit described an awareness of gradually becoming more connected. This was bittersweet, as with greater connection came greater distance between crewmembers. The story created by his community over the past two weeks was unraveling. People were being pulled back into their "real" lives.

The second account comes from anthropologist Kathryn Denning, who like myself was curious about the act of creating Mars on Earth. She traveled to MDRS the season before me, and wrote in her final crew report:[13]

> When we arrived here at MDRS last week, I was confounded by the contradictions of the place. I couldn't get my head around the disjunctions of the simulation exercise. I was equally astounded that the station sits upon an ancient sandy desert with almost no plants, and yet, nearby we found shells and fragments of trees that time has turned to stone. Now, as our rotation comes to a close, I find it all makes a strange kind of sense, for I've learned that the terrain we journey through here is known by many names, including "The Paradox Sea" (Denning 2009).

Denning, like most of us who spent time at the hab, ultimately found a logic by which to order the multiple exposures of place typified by MDRS.

My own logic comes from a reading of place through ideas of landscape and narrative. This allows me momentarily to hold steady the shifting process by which places are evoked and erased.

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[13] Denning graciously shared this text with me over an email exchange. Until recently, past crew reports were archived at the MDRS website, but these appear to no longer be available.

CONCLUSION
Placing Outer Space

How does the concept of "place" shape scientific practice? I sought to answer this question by attending not only to the physical places occupied by researchers, but more importantly by considering the places they cognitively and culturally create. I emphasized the salience of place by positioning it as a product, not a precursor, of scientific work. The planetary scientists with whom I interacted gain a greater understanding of what they study by transforming planets from *objects* to *places*. I suggest that the methods they employ to do so – visualizing, inhabiting, mapping, and narrating – are prominent in planetary science precisely because they foster place-making.

Why should planets be places? Why does imagining what it would be like to stand on these distant surfaces animate so much of the discussion and research? We understand strange, new things by relating them to what we know. Every moment of every day, we experience what it is like to be on planet Earth. Scientists translate this familiarity to other planets. Even when exoplanets are nothing like those in our Solar System, astronomers still discuss these strange worlds in relation to processes on Earth like weather and tides. The desire to find familiar exoplanets is most apparent in the search for an Earth-like exoplanet. In this pursuit, astronomers are seeking a "habitable" planet; one not necessarily teeming with life but a planet that potentially harbors places on its surface similar to those on Earth. Astronomers are not looking to find the alien in outer space, but hope instead to find a reflection of themselves.

In the Introduction, I promised to offer an account of how scientists understand places they have never been – how they make the strange familiar, to borrow an anthropological turn of phrase – through ways of seeing, embodying, and imagining. The motif of learning how to see was central to the first chapter, where I offered a glimpse at how leaders in the still coalescing field of exoplanet astronomy trained their students to see planets in stellar signals. Even when high-resolution pictures of a planet are available, as is the case with Mars, planetary scientists still need to cultivate particular way to see these images. They adopt geological ways of seeing in order to decode the visual evidence that marks the Martian surface, alluding to a dynamic past and present.

Techniques of embodiment can enrich planetary places elsewhere even while remaining on Earth. In Chapter Four, for example, I offered several vignettes to show how doing terrestrial fieldwork spins narratives that connect Earthly experiences to the Moon and Mars. Planetary scientists immerse themselves in evocative landscapes in order to enrich their understanding of a distant place. Even when not in an exotic location but in their offices, scientists leverage understandings of physicality to achieve a clearer sense of place. 3D models of Mars help them comprehend what it would be like to stand on the surface. They mentally embody another place so as to enhance a scientific claim.

The astronomical observatory also offers an experience of embodiment, but for different purposes. The observatory does not (necessarily) allow for physical intimacy with exoplanets, but nurtures social ties across the diverse network necessary for the complex and time intensive project of exoplanet detection. Inhabiting the observatory is necessary for astronomer Debra Fischer to locate a habitable planet.

Scientists structure ways of seeing and embodied experiences around an imagination of what might lie just beyond their bounds of perception. By way of conclusion, I wish to offer a final technique of place-making that indulges the fantastical imagination scientists have for the planets they study. Space artists, aided by scientists interpreting data for them, paint that which cannot be seen. Their work gives materiality to the scientific imagination that animates the study of worlds in our Solar System and beyond.

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A purple volcano spews orange lava from its craggy peak. Like a mountain stream, the lava braids down the ashen sides of the volcano and joins an ocean of molten rock. In the foreground, islands of solidified debris float in the lava sea. The hardened rock forms smooth, rolling surfaces. These features glimmer, reflecting the light of a distant star. The molten vista, dynamic and threatening, serves as a frame for the focus of the painting: an exoplanet. A gas giant, half in shadow, rises above the melting moon's surface. The atmosphere of the planet is filled with swirls of orange and white clouds reminiscent of Jupiter. But like Saturn, the planet is adorned with a system of rings, at a slight angle from the moon's horizon. A second and third planet, mere dots in the night sky, create a trail between this mammoth planet and its host star.

This is a painting of the planetary system 47 Ursae Majoris painted by space artist Lynette Cook in consultation with the astronomer who discovered it (see Figure C.1). In 2001, when only 70 exoplanets had been detected, Debra Fischer announced that there was a second planet in this system, known since 1996 to host at least one exoplanet. 2001 marked the first detection of a multi-planet system in which both planets had near circular orbits and were located at distances from their star on scale with our Solar System (Fischer et al. 2002). In other words, the 2001 discovery strengthened the possibility of there existing elsewhere a planetary system similar to our own. The detection of such a system propelled Fischer down the path that led her to focus her attention and telescope on Alpha Centauri in hopes of finding a habitable planet. The hope that such a planet exists is evident in Cook's painting of 47 Ursae Majoris. Lingering close to the star, hardly visible to the viewer, is a black speck representing where a rocky planet in the habitable zone might exist in this system.

The purpose of this painting is to showcase the exoplanet, not the moon whose existence is speculative. The moon is there to offer context for what would otherwise be a floating planet. Moons and satellite are often platforms from which to explore our relationship with a planet. Calvino's tale, which I related in the Introduction, illustrates how being stranded on the Moon allowed the narrator to better understand his connection to the Earth. Apollo astronauts were in the unique position to see and photograph a planetary globe unaffected by the billions of humans dwelling on its surface. At the same time, including the Moon's surface in the same frame as Earth's, as is the case with the famous *Earthrise* composition (also shown in Figure C.1), dispels any fear that the Earth is traveling alone through space. Moons are companions, playing a supporting role while allowing the host planet to be understood from a new perspective.

The convention of portraying a planet from a satellite was established before *Earthrise* and the Apollo missions. Chesley Bonestell pioneered the contemporary genre of "space art," especially as a medium for conveying scientific information about other worlds to a popular audience. In 1944, he brought several photo-realistic drawings of

Saturn, as seen from various moons, to *Life* magazine. They appeared in the May 29 issue, and the accompanying article proclaimed, "The pictures in color on the next two pages take you on [a] visit to the planet Saturn" (Anon. 1944, 78; see one of these frames in Figure C.1). The paintings brought the reader closer and closer to Saturn, treating him or her to a variety of ways to see and think about Saturn, as Bonestell hopped from moon to moon. Bonestell went on to be a prominent painter of other worlds, urging the collective American imagination to comprehend human space travel.

The compositions that show a planet from its moon offer a long view of the planet. It allows for a global view, but one that is still connected to a landscape legible as a world. Offering a view of a planet from a moon has a feeling similar to gazing at a city from the highest building or a nearby hill. During a first encounter, this vantage point allows one to take in the lay of the land. Looking at a planet from a moon begins the process by which a viewer can begin to understand the planet as a place despite the fact that he or she cannot physically go there. As science writer Wyn Wachhorst reflects, "What the microscope did for our perception of life, Bonestell did for the heavens, opening worlds within worlds, inviting adventure, converting those abstract points of light into real places" (1995, 13).

Figure C.1. Depictions of planets from moons. On the left is a painting by Chesley Bonestell printed in *Life* in 1944. The image is Saturn as seen from Titan. The middle frame is *Earthrise,* a photograph taken by the crew of Apollo 8 in 1968. On the right is Lynette Cook's interpretation of 47 Ursae Majoris c from 2001.

Planetary scientists use a wide range of techniques to gain a deeper understanding of their objects of study. In this dissertation, I focused on methods that bring a greater comprehension by fashioning planets as places. Expressing the placehood of planets to a popular audience is difficult to do through charts and numbers. To explain the role space art plays in this translation, prominent astronomer and space artist William Hartmann writes, "teamwork between scientists and artists will play a role in advancing a better view of our real place in the cosmos" (Hartmann 2002, 28). This notion of place in the cosmos is not concerned with our location in the universe. *Place* in this context is a measure of quality; of how the Earth is similar to or different from the other planets out there. Even if we have not yet found planets exactly like those around our Sun, astronomers assume satellites orbit most exoplanets. The space artist's compositions offer moonscapes as touchstones of familiarity when viewing these alien worlds. This suggests that we will increasingly understand our place in the universe by drawing connections between Earth and other worlds.

Since the era when Bonestell painted Saturn from its satellites, space agencies have launched dozens of human crafted satellites capable of sending back photographic postcards. An artist is no longer needed when depicting objects in our Solar System. However, in 1995 with the discovery of the first exoplanet, space art experienced a revival. Artists like Lynette Cook work with astronomers to depict scientifically accurate paintings for the public. I met with Cook at her home in the Bay Area while I was working at NASA Ames. We sat in her living room, where her walls were adorned with her art. There were several paintings[1] of exoplanets, often, like the one described above, with a rocky landscape of a moon in the foreground and a gas giant hanging in the sky. Another piece, titled *Cosmic Awakening*, featured a structure that looked like a radio telescope, but instead of a dish there was a flower with yellow and pink petals that contrasted with the dark sky. In place of the telescope dish's antenna, a stamen focused on a cloud of what appeared to be molecules hovering in the star field.

Cook was one of the first artists to paint exoplanets. She was then working at the Morrison Planetarium in San Francisco, and was acquainted with the scientist Frank Drake through both her work at the planetarium and some projects she had done for his place of work, the SETI institute. Drake is famous for the eponymous equation that predicts the number of civilizations the Milky Way galaxy might contain. He approached Cook to depict 51 Peg b, the first exoplanet known to orbit a Sun-like star.

When Geoff Marcy and Paul Butler, also of the Bay Area, began announcing dozens of exoplanets detected by their survey, Cook collaborated with them to produce artist interpretations for press releases and other public outreach needs. She described the process of painting an exoplanet. It begins with a meeting with the astronomer, where she is told the type of star the exoplanet orbits, the distance between the planet and star, and the mass of the planet. In one sense, Cook's work is the final stage of the planetary pipeline I introduced in Chapter One. I offered the pipeline as a way to think about how planets are transformed from objects into places. For the scientist, the place-making goal is gradually achieved through the process of cleaning and modeling data. By the time the

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[1] While Cook originally depicted exoplanets using airbrush techniques, she and most other space artists now use digital rendering packages such as "Bryce." When she took me on a tour of her studio, she brought me to her computer to show me where she composed exoplanets and then to her garage to show where she works on her fine art pieces.

astronomer has produced a light curve or radial velocity graph, he or she has a mental picture of how the planetary system behaves and what the surface might be like. Through conversations and journal articles, the community imagines various worlds contained in the data. An astronomer like Debra Fischer or Geoff Marcy then takes these ideas to Cook, who translates the conversations into an artistic representation. For those not trained in seeing light curves as planets, these paintings help the public imagine exoplanets as places.

Sometimes the astronomer instructs Cook just to depict the planet and its star, but she much prefers it when she has the liberty to include a moon. The exoplanets themselves, after all, are mostly gas giants and become tedious to reproduce. The moon is more interesting for Cook, especially because from the moon you can indicate attributes like temperature by including ice or pools of lava. For Cook, including these imagined moonscapes "tells the viewer what could be there."

When Cook paints moonscapes, she draws on familiar geological formations: snow-capped mountains, volcanoes, buttes, clouds, and craters. With these forms, her paintings suggest what being on the surface might be like. Further, they transform the portrait of an exoplanet into a landscape painting. This offers a familiar viewing experience. Elizabeth Kessler (2004; 2006), a scholar of visual culture, describes how even abstract images of the cosmos, like those taken of nebulae and galaxies with the Hubble Space Telescope, evoke a landscape aesthetic. She takes her cue from the press releases that accompany these images, which point out features that look like buttes and craggy mountaintops. In Kessler's analysis, this translates a colorful swirl of gasses into the language of American West landscape painting. Thus, images of "nebulae, galaxies, and star fields recall a well-established aesthetic tradition and in the process make these distant spacescapes familiar" (2004, 143).

Kessler compares the role of the space artist to that of Thomas Moran who, in the 19th Century, painted the Grand Canyon in spectacular form and color so that those back East could see the adventure that awaits out West. Cook confirmed that several artists in her community take seriously their work's connection to Moran and the Hudson River School. She herself dismissed this connection, insisting that she does not affiliate with a particular school of art aside from her training in science illustration. She did allow the comparison to the Hudson River School in so far as "space artists are showing worlds that the rest of society cannot see, that we cannot travel to." Her depictions bring exoplanets into the common vernacular: "It makes the distant worlds in our universe seem more real and close and more a part of our lives." As described in the case of the Mars Desert Research Station in Chapter Four, landscapes can simultaneously evoke different places. A familiar landscape offers an entry point from which to comprehend a place one has not yet explored.

However, there is still a palpable distance between the worlds she paints and the world we live in. In an article Cook wrote about the current state of space art for *Mercury,* a magazine of the Astronomical Society of the Pacific, she quotes a space artist who explains why exoplanets are not well-received by the art world in the same way Moran's paintings were: "Many people I have spoken to say they really love this work but wouldn't feel comfortable putting it over their living room couch. They think it is beautiful but don't understand it or know what to do with it. It seems so far removed from everyday life" (as quoted by Cook 2009, 20).

Even when presenting closer objects, the Moon and Mars, there is still a discomfort as to whether paintings and photographs of these objects have any place beyond the scientific arena and popular magazines. Do they actually symbolize something greater than a reflection of current scientific understandings? Is there a humanistic component to depicting moons and planets? William J. T. Mitchell (1998) observes that depictions of dinosaurs are mostly excluded from the art world because, while they are a symbol of modern*ity*, they do not appeal to modern*ism*, "an aesthetic of purity that rigorously excludes kitsch subject matter" (265). Further, as scientific illustrations, they seemed to lack an artistic imagination. Space art faces a similar stigma from the art world. In 1979, a gallery in New York City opened a show featuring NASA photographs from the Apollo and Viking missions. Gene Thornton, an art critic for the *New York Times* panned this exhibition suggesting that these were not works of art as there was not an intentioned artist standing behind the camera. Sometimes there was not even a human behind the camera. As their purpose was to "show earth-bound stay-at-homes what distant and inaccessible places look like," (1979, 27) even though they were phenomenal technological achievements, they did not belong in a gallery. Elliott Levinthal, producer of *Mars in 3D* as described in Chapter Three, took issue with this review and sent Thornton a letter to clarify that the photographs on display were something more than mere scientific documentation. He corrected Thornton's assumption that there was no human behind the camera, explaining how for Viking someone on the imaging team set up each shot. The photographs

> were the result of intense human interaction involving all the normal choices, scenes, framing, resolution, color, exposure, etc. Did it matter that our triggering cable was 100 million miles long and was electronic rather than mechanical? …I can assure you that

> humans were very much involved in the choices and moved by the landscape they were observing. Who can say why we were so fond of "Big Joe" on the horizon of lander one, or the drifts and dunes? The twilight, sunset and sunrise images could have served their scientific purpose with much less artistic formulations.[2]

Levinthal offered how these photographs allowed the scientist to become familiar with the landscape such that they had favorite locations that they chose to highlight in their documentation. Despite the intention that Levinthal tried to express, Thornton wrote back dismissively, sticking to his original point that the photographs nonetheless lacked *artistic* intention.[3] Mitchell offers examples of some artistic success the dinosaur has enjoyed with the postmodern art movement. Instead of using scientific illustration, several artists have embraced kitsch representations of dinosaurs and use these images of deep time to speak to the present and future. There are certainly examples of images of space being employed for similar purpose. The painter Scott Listfield, for example, paints an astronaut exploring the oddities of Earth's present. In some of his paintings, the astronaut, dressed in a Mylar spacesuit with a tinted helmet poses in front of the symbols of consumerism – a Pepsi sign or McDonald's golden arch. Space artists like Cook, however, pursue scientific realism and their work continues to be thought of more as illustration than art.

The exoplanet paintings do serve the same purpose highlighted by Thornton in that they offer a glimpse of "inaccessible places." Cook even remarked that several people have mistaken her work for photographs. "The nice part of [this mistake] is, they

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[2] NASA Ames History Office, NASA Ames Research Center. Moffett Field, California. PP04.02, Elliott C. Levinthal Viking Lander Imaging Science Team Papers, 1970-1980. 9 : 46. Letter from Levinthal to Gene Thornton. January 22, 1979.

[3] NASA Ames History Office, NASA Ames Research Center. Moffett Field, California. PP04.02, Elliott C. Levinthal Viking Lander Imaging Science Team Papers, 1970-1980. 9 : 46. Letter from Thornton to Levinthal. March 4, 1979.

wouldn't think these were photographs if they didn't feel already connected to them, you know? That these are real places!" As described in Chapter Three, there is a complex relationship between representation and reality when dealing to distant planets. Both with maps of Mars and exoplanet space art, representation goes beyond mimesis. For Mars, landscapes are rendered in an illusory three-dimensions in an attempt to evoke a reality. Cook paints in a photo-realist mode, even though direct imaging of these planets is technically infeasible. These techniques make the planets "real" through appeals to familiar modes of representation.

Space art, from Bonestell to Cook, crafts a scientific sense of place. As these works draw from the artist's experience of planetary dwelling - complete with mountains, rivers, and valleys - the worlds they produce feel familiar. They lead the viewer to consider our place in the universe as one made meaningful through Earth's resonance with other planets. That there are other structures in the universe that we can understand as *places* reshapes our thinking of Earth. It seems our planet is not unique and isolated, but exists in a galaxy filled with objects harboring familiar geographies. This is a cosmic view that informs the contemporary practice of planetary scientists and that space art is helping make accessible to the public. As notions of place populate the cosmos, outer space shifts from being perceived as an alien-ating void to a familiar landscape filled with destinations.

APPENDIX A
List of Interviews

All interviews were conducted by the author, digitally recorded, and transcribed.

Albrecht, Simon. November 10, 2009. Cambridge, MA.
Beyer, Ross. July 2, 2010. Mountain View, CA.
Broxton, Michael. June 29, 2010. Mountain View, CA.
Carter, Josh. November 6, 2009. Cambridge, MA.
Cook, Lynette. July 7, 2010. Daly City, CA.
Elkins-Tanton, Lindy. November 11, 2009. Cambridge, MA.
Fenton, Lori. June 28, 2010. Mountain View, CA.
Fischer, Debra. November 4, 2009. Cambridge, MA.
Gulick, Ginny. June 22, 2010. Mountain View, CA.
Madhusudan, Nikku. December 15, 2009. Cambridge, MA.
Moore, Jeff. June 16, 2010. Mountain View, CA.
Moratto, Zack. July 9, 2010. Mountain View, CA.
Nefian, Ara. July 1, 2010. Mountain View, CA.
Ranjan, Sukrit. February 21, 2010. Cambridge, MA.
Scharff, Ted. July 8, 2010. Mountain View, CA.
Seager, Sara. October 7, 2011. Cambridge, MA.
Winn, Josh. January 11, 2010. Cambridge, MA.

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