Life as-we-don't-know-it

Research repertoires and the emergence of astrobiology.

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PhD in Science, Technology and Innovation Studies

The University of Edinburgh

2018

Declaration

I declare that this thesis has been composed by myself and that the work presented is my own, except where explicitly indicated otherwise in the text. This work has no been submitted for any other degree or professional qualification.

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Abstract

This thesis presents an ethnographic study of the repertoires, sets of social and material practices, that scientists adopt to practice and promote the search for life in the universe, commonly known today under the disciplinary label of astrobiology. In particular, I take the expression "life *as-we-don't-know*-it" as an entry point to look into the role of non-knowledge as a cultural resource in the opening of new spheres of inquiry.

Throughout this thesis, I investigate the tensions and negotiations related to the definition of life, a central issue in astrobiology, and the way scientists are successfully shifting the boundaries of what is considered legitimate science to include the study of extra-terrestrial lifeforms. Unlike most previous work on the definition of life, this thesis does not formulate or support any definition and does not take a position on the question of to which disciplinary domain "life" legitimately belongs – on the contrary, it takes definitions and disciplines as social institutions with flexible boundaries.

To explore these issues, I engaged in a multi-sited ethnographic study that brought me to the different locations in which astrobiologists' activities take place, from conference venues to astronomical observatories, laboratories and field sites (such as underground caves and Icelandic volcanoes), following the lines of research that today form, at their intersections, the field of astrobiology.

Life "as-we-don't-know-it" soon emerged as a central theme in contemporary astrobiology. A commonly used phrase for extra-terrestrial and alien life, it summarizes and stands for the uncertainties and unknowns surrounding the definition of life and the design of life-detection experiments. These unknowns about life are not simply a void to be filled, but the result of a process of social construction, a collective achievement. This empirical account complements and challenges existing literature about scientific change and knowledge production by focusing on the construction of a collective agreement about not-knowing and its deployment as a specific research repertoire. The concept of repertoire is a useful thinking tool for the sociologist looking into astrobiology and its social dynamics because it does not describe change as fundamentally caused and shaped by theoretical developments. On the contrary, it both takes account of the material and institutional changes that accompany, ground or undermine the emergence of a research field and calls for consideration of the performative aspects of science.

I conclude by arguing that the agreement on what constitutes life – familiar and alien, Earthly or otherworldly – is an ongoing negotiation between astrobiologists' epistemic practices and what counts as a meaningful present and future for space exploration. This opens up a space for sociological inquiry about the particular social processes through which the emergence of astrobiology as a discipline requires collaborations to be established, allows for new interactions, and evokes previously unforeseen associations, thus constantly unsettling present imaginaries about the future.

Acknowledgments

I would like to express my most sincere gratitude to Jane Calvert and Alice Street for their insightfulness, patience and motivation. They have been examples of how to be excellent academics and amazing people in what has sometimes seemed a complicated environment to navigate. Their continuous support and positivity have been truly invaluable during my PhD, and will be even more so in the next steps of my career: you have set a very high standard of awesomeness for me to aspire to!

Thanks to my officemates (especially Mike Kattirtzi, Hung Nguyen, Chihwei Yeh, Daniel Thorpe, Sara Valencia and Sara Bea) and to the great STS community – what might have appeared to be random chats have in fact been an invaluable source of fun, inspiration and solace throughout this PhD journey. I would also like to express my appreciation and thanks to the Engineering Life group. A special thanks goes to Deborah Scott for her encouragement and for her example of enthusiasm and strength.

A huge thanks to my husband for the love and unconditional support. Thanks for keeping my feet on the ground and accepting when my head is in the clouds. Thanks for saying, after any casual chat about your day, your research, teaching, articles, experiments, measures, proposals and crystal marvels, "yeah, science is social". You have become, without even knowing it, a constructivist.

I cannot express with words how grateful I am for the support of my loving family. Thanks to my always fantastic mother for her example of strength and positivity; you have equipped me to face any challenge and embrace any adventure in life. My sister Sara has the amazing power of always cheering me up – she reminds me not to take myself (or anybody else) too seriously and that life is too good not to fully enjoy it.

A big thanks to "my tribe" – Tony, la Cicci, la Gabry, Baba, Nico, Tommy, Dina, Mario, Anna and Antonio – for their support and understanding, and for always showing me how to be the best version of myself.

Thanks to my friends in Italy for celebrating every time I spent a weekend home. I am also deeply indebted to Lucy and Fra for being amazing friends who have always made me feel at home in Edinburgh. I feel so lucky for being part of such an amazing group of women – all different, all very special.

Table of contents

Introduction

Life in a test tube: a mystery.
Life on Earth: a mystery.
Life on other worlds: a mystery.
The mysteries move closer together through
the immense shuttling of our thoughts,
our laboratory devices, our far-traveling rockets.

Ray Bradbury,
“A Serious Search for Weird Worlds”,
in *Life* (20/10/1960)

Learning astrobiology, unlearning life

“Are we alone in the Universe?” The bold white letters projected on the black screen light up the absorbed expressions of around 100 undergraduate students attending the first lecture of the Astrobiology course.[1] They come from a number of different departments of the University, the largest groups being biology and geosciences, but with significant numbers of astronomers and engineers. Sitting on the side of the very first row, I am the only non-scientist in the class, scribbling my notes as fast as I can so as not to miss any of the questions the lecturer is going through in his “introduction to astrobiology”. The presentation unfolds as an imaginary journey through time and space, starting from far away, from an ideal Archimedean point outside and above our galaxy. Huge as it might seem, the lecturer explains, the Milky Way is only the local neighbourhood in cosmic terms, one of the billions of galaxies scattered throughout the universe. The Sun sits on the periphery of this giant conglomerate of shining dots, in the outer area of the disk that orbits around the galactic centre. Neither our tiny planet nor the Sun can actually be seen from this far away. The image on the next slide brings us closer to the Earth and a

[1] The undergraduate course in Astrobiology (PHYS08051) was offered by the School of Physics and Astronomy at the University of Edinburgh.

landscape appears: not an Earthly one, but the rough sweep of grey lunar ground. Beyond the curved horizon pocked with craters, the Earth rises. Taken on Christmas Eve 1968 by the first Apollo crew orbiting the Moon, this picture has been considered one of the most influential photographs ever taken and has inspired environmental movements as well as peace campaigns (Cosgrove 1994; Jasanoff 2004; Poole 2010; Lazier 2011). Today, it serves a different function: creating a distance between the observer and the Earth. "[T]o understand life", summarizes the slide, "we need a cosmic perspective". The journey finally gets, if only temporarily, to the Earth, a very primitive one: a landscape of craters and volcanoes in which the black fumes emanating from the boiling calderas meet the thick uncanny clouds covering the sky. We are now invited to think about how life on Earth emerged. Despite being back on our planet, the artist's impression makes the observer think about it as an *alien* land, in which no signs of life are visible yet, but at the same time there is a suggestion that life's presence is emerging, somewhere, and will soon take over that alien landscape, turning it into what we are familiar with today. The next two slides, showing a layer of white clouds and the rocky Martian surface being crossed by the NASA Curiosity rover, invite us to wonder whether life is unique to Earth. The juxtaposition of the two surfaces tells a story of intangibility, the former because of its gaseous and impalpable state, the latter for its distance. Both visible and intangible, imagined but not physically experienced, they seem to suggest that beyond the Earth, there are plenty of landscapes that do not quite look like what we are used to, and invite us to think about what forms of life might inhabit them. Bouncing back, we conclude our journey with some future echoes: big radio-telescope dishes giving ear to imperceptible extra-terrestrial messages and an artist's impression of a lunar base encourage us to imagine the spread of human beings and artefacts to other worlds.

Structured as a collection of questions about life, the lecture was meant to introduce the neophytes to the fundamental themes of inquiry on which astrobiology is based, ranging from the process that led, more than four billion years ago, to the emergence of life on Earth, to the conditions under which simple cells – single instances of life – first aggregated in communities or larger multicellular organisms. It was about the physical and chemical limits to life's existence, the emergence of communication, technology and the future of humans and other-than-human beings – from animals to microbes and plants – on this planet or elsewhere in the cosmos. The presentation ended with the question that was assumed to summarize them all, and to which those who call themselves astrobiologists commit: "what is life?".

A new scientific revolution

Astrobiology is a relatively recent field of inquiry. Initially named *exobiology*, literally the study of life outside the Earth (Lederberg 1963:1126), the discipline has been included in space agencies' research agendas since the dawn of space exploration in the late 1950s. The field experienced many twists and turns, reaching a peak in popularity when, in the 1970s, the two Viking landers performed a series of life detection experiments on Mars, only to produce unclear data: the composition of the Martian surface was revealed to be so different from what scientists had expected that the apparently positive results could not be interpreted as evidence. In the wake of this failure to produce any definite result about the presence of life on Mars, exobiology was often accused of being a field of inquiry that "has yet to demonstrate that its subject matter exists!" (Simpson 1964:769) – and therefore, according to some, a discipline that did not have the status of a science at all. The search for extra-terrestrial life, in the following two decades, fell by the wayside. When, at the end of the 1990s, NASA funded the National Astrobiology Institute, the term 'exobiology' was partially discarded and a new one, in which the prefix *exo-* (outside) was replaced with *astro-*, was adopted[2] (Dick and Strick 2004). *Astro*biology redefined the scope of the discipline by including Earthly life among its objects of interest. What appeared to be a mere rephrasing was in fact due to – and at the same time contributed to drawing people into – a different way of studying and searching for life in the universe: to pursue the study of life in the cosmic context, astrobiologists become equipped with "at least one data point of the life that we know: life on Earth" (Cockell 2015:1).

Today, astrobiology is defined as:

> The study of the origins, evolution, distribution, and future of life in the universe. Astrobiology encompasses the search for habitable environments in our Solar System and on planets around other stars; the search for evidence of prebiotic chemistry or life on Solar System bodies such as Mars, Jupiter's moon Europa, and Saturn's moon Titan; and research into the origin, early evolution, and diversity of life on Earth. Astrobiologists address three fundamental questions: How does life

[2] The term astrobiology is now commonly used to refer to the study of life in the universe. There are still a few exceptions, nevertheless: in France, for example, the term "exobiologie" is still largely employed and the field is still often considered "fringe science" (personal communication, 03/05/2015).

> begin and evolve? Is there life elsewhere in the Universe? What is the future of life on Earth and beyond?[3]

Lynn Rothschild, professor of astrobiology at Stanford and one of the evolutionary biologists who has pioneered the field at NASA, describes astrobiology as a new scientific revolution, following those triggered by Nicolaus Copernicus and Charles Darwin. If the former displaced humankind from the centre of the universe, and the latter removed it from the pivotal position in the hierarchy of creation, astrobiology, she suggests, eventually combines them together to consider whether the emergence of life on Earth is a fortuitous accident or a necessity in the history of the universe.[4] Astrobiologists' ambition is eventually to overthrow the *paradigm*[5] of traditional biology by crafting a theory of life that is unbounded to Earthly idiosyncrasies, one that is "truly universal" (Des Marais *et al.* 2002:154).

In the years that followed that first introductory lesson to astrobiology, I engaged in an ethnographic study of the activities that allowed the astrobiology community to explore all the possible ways in which life elsewhere in the universe might not resemble what we are most familiar with here on Earth. According to the astrobiologists all the current definitions of life still miss the fundamental features in virtue of which something is considered alive, and thus need to be rewritten. "What is life?" might simply sound like a rhetorical question, but I soon came to realize that doubts, uncertainties and unknowns are part of the very ethos of astrobiology. The students, entering the classroom with various understandings of life that had been shaped by their participation in different communities (both scientific and mundane), left with no answers, as every Earth-bound understanding of life was unwoven, broken down into its components or reframed in scenarios in which it did not and could not make sense anymore. Necessarily Earthly – as no knowledge can be separated from the communities constructing and holding it – the discipline of astrobiology aims not to be Earth-centric and commits to theorizing on a cosmic scale.

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3 https://nai.nasa.gov/about/ [accessed 09/03/2017]

4 Lynn Rothschild, "Astrobiology and Space Exploration" course (a.a. 2009/2010) at Stanford University, lesson 3 (iTunes University).

5 Kuhn's vocabulary of revolutionary change in scientific thought (1962) is often employed quite explicitly by astrobiologists (and their philosopher friends) to describe their ambition.

In the last few decades, reflections on life have emerged as a central interest of scientists, philosophers, social scientists and lay public. Often nicknamed "the century of biology" [6], the 21st century has seen life becoming the focus of scientific and ethical concerns as a consequence of the development of new biotechnologies that allow previously unimaginable manipulation of living organisms. Cultured, engineered, synthetized and digitalized - "life," writes Stefan Helmreich,

> moves out of the domain of the given into the contingent, into quotation marks, appearing not as a thing-in-itself but as something in the making in discourse and practice. Life, becomes a trace of the scientific and cultural practices that have asked after it, a shadow of the biological and social theories meant to capture it (2011:674).

How to make sense of life, then, when its modes of existence and potentialities are so explicitly enmeshed in the fabric of the social? This question does not have a simple answer; on the contrary, it brings forth the awareness that life has never been something *in itself*, an abstract concept with no history, but is and has always been situated within historical and social coordinates. New fields of research and new biotechnologies emphasize and make explicit life's mutable but unavoidable cultural entanglements.

Among the new biosciences, life is at the very core of astrobiology too: it is the cornerstone of astrobiologists' concerns, their main hurdle and main goal at the same time. What is more, because astrobiologists' object of inquiry is still – at least partially – a speculative one, it lends itself to numerous different representations, and reminds us that the way *life* is framed depends on a series of choices, evaluations and judgments that gain more or less momentum within a scientific community. No straightforward appeal can be made to *reality*. As such, astrobiology provides fertile soil to look into the situated, diverse and shifting ways in which the concept of life is involved in social domains and, in turn, into the way the very concept of life shapes the social fabric into which it is built.

Each of us deploys, in everyday life, a number of ideas about "what counts as life" that, if not explicitly questioned, are simply taken for granted and thus experienced as *intuitive*; scientists interested in life in the cosmos, on the contrary, openly discuss and debate what life is and how to search for it elsewhere in the universe, so that, "at the end of the day", an astronomer concluded after a workshop, "thinking about life in the universe makes you realize how little we actually know". Their searches, she notes, can

[6] This quote is usually attributed to Craig Venter and Daniel Cohen (2004:73), but it has become very widespread.

only be built on “assumptions that are all based on the fact that *we exist here on Earth*” [7]. Her remarks are quite common among scientists who deal with the search for life on other planets. In public events and in informal conversation alike, when the ungrasped nature of life is mentioned, everybody nods and silently agrees. By looking for non-Earth-centric definitions of life, astrobiologists ground the awareness that the categories by which nature is catalogued, studied and known are bound to the human experience of them.

Defining life

In 1970, Carl Sagan proposed four categories to group the existing definitions of life.[8] The pattern he followed was to formulate a definition apparently identifying living systems, and then advance a number of counterexamples – objects or phenomena that did meet the characteristics listed, but which most people would *not* in fact consider “alive” – to show its insufficiency.

Thermodynamic definitions, for instance, describe a living system as one that takes in energy to create order locally (famous examples are Schrodinger’s (1944) and J.B.S. Haldane’s (1929) definitions of life). According to them, biological chemistry is identical to abiotioc chemistry, but living organisms operate with a speed and specificity directed at maintaining their stability in the face of externally increasing entropy. Carl Sagan proposed crystals as a counter-example: despite not being considered alive, they would meet the requirements of thermodynamic definitions as their growth produces a higher order compared to their external environment.

Biochemical definitions, on the other hand, are based on the presence of certain types of biomolecules. This category of definitions appears the most centred on Earthly life and might fail to discover non-terrestrial life that is not built out of Earthly life favoured molecules. Because every form of life on our planet shares the same molecular structure, counter-examples are usually found through thought experiments or *reductio ad*

[7] SETI meeting in Rome, 24/10/2017; emphasis added.

[8] Another interesting categorization of life definitions is based on the binary *vitalism/mechanism*. The latter includes all those understandings that equate life to complex machinery. The former assumes that "living organisms are fundamentally different from non-living entities because they contain some non-physical element or are governed by different principles than are inanimate things" (Bechtel and Richardson 1998). For an interesting collection of excerpts about the concept of life, see Bedau and Cleland (2010).

absurdum. "If we were to encounter Q, the Calamarain,[9] or any of these other conjectural entities", writes Steve Benner, one of the founding fathers of synthetic biology, with reference to particularly extravagant minor characters in the TV series *Star Trek*, "during a real, not conceptual, trek through the stars, we would be forced to concede that they do represent living systems, because they have the attributes that we value in living systems" (Benner 2010:1023). Science fiction plays, in this case, a fundamental role by providing examples of life that are conceivable even if imaginary.

A third group of definitions takes as the main characteristic of life its ability to consume and convert energy in order to move, grow, or reproduce. Fire, which consumes the material it burns and converts it into energy to grow and move, can be said to satisfy the criteria of *metabolic* definitions (Cockell 2015), thus providing one of the main counter-examples to it. The Viking life detection experiments (discussed in chapter 5) implicitly embedded this definition by looking for three different kinds of metabolism; despite the positive results obtained by at least one of them, the lack of organic chemicals on the Martian soil led the scientific community to declare that no form of life had been found, eventually prioritizing a biochemical definition of life instead (Benner 2010; Cleland and Chyba 2010).

The last group Carl Sagan identified, *genetic* definitions, are underpinned by the idea of evolution – i.e. the process by which variation in a population under certain environmental conditions results in the survival of the fittest organisms and the transmission of their traits to subsequent generations – as a fundamental characteristic of life. NASA's official definition, inspired by Carl Sagan and agreed upon in 1994 by a committee chaired by the microbiologist Gerald Joyce, falls under this category. Life, the definition states, is a "self-sustaining chemical system capable of Darwinian evolution" (Joyce *et al.* 1994:xi-xii). This characterization mirrors, quite effectively, some of the astrobiological contemporary inclinations: first of all, by mentioning Darwinian evolution, NASA acknowledges an antiteleological diversity of forms of life, and their dynamic relationship with their environments. The definition implicitly ties the concept of life to those of survival, change and reproduction, despite not mentioning or defining them. The word "system" acknowledges the existence of a number of parts that are

[9] Q and the Calamarain are minor characters in the TV series *Star Trek*. The former is a powerful and immortal entity that usually appeared in the form of a humanoid, the latter an intelligent, non-corporeal lifeform that existed as swirls of ionized gas. They are mentioned in this context as imaginary examples of life that would not be recognized as such according to biochemical definitions.

fundamental for the living being but might not be considered "alive" by themselves (Benner 2010). It also allows for the variety of forms of life that astrobiologists expect to find, as Darwinian evolution is essentially a process of divergence that, coupled with the variety of planetary environments being discovered within and outside the Solar System, would suggest that living organisms can respond in many different ways to the multitude of challenges they might encounter. Genetic definitions, nevertheless, are always accompanied by the warning that they are not definitive, and counter-examples might always be imagined, for instance computer software that acquires new information through feedback loops and can produce copies of itself (Mix 2015) . More importantly though, this definition and all its different articulations are not very useful for *detecting* life in the first place, as it is unclear how to test for evolution without targeting a living organism.

Looking for a definition of life, only to propose another counter-example that escapes it, is not a fruitless intellectual exercise. On the contrary, it is used to set the stage for astrobiology by making explicit the complexity of the issue. In this effort, scientists with different backgrounds and at different stages of their careers leave their comfort zones and try to establish a common foundation upon which further reflections on the way they should cast their gaze to the cosmos are built. The almost unavoidable conclusion reached is that there is no single definition that spells out effectively what life is and, at the same time, unambiguously excludes everything that is not alive (Sagan 1970; Chyba and MacDonald 1995).[10] It is often assumed that a second example of life is needed in order to turn Earthly definitions into general ones that take into consideration all the "universal" aspects of life.[11] "It is difficult", wrote Carl Sagan in 1970,

> to generalize from a single example, and in this respect the biologist is fundamentally handicapped as compared, say, to the chemist, or physicist, or geologist, or meteorologist, who now can study aspects of his discipline beyond the Earth. [..] In

[10] I consider this a simple characteristic of ostensive definitions, which are always bounded to previous experience and thus revisable in the future. The entrenchment of concepts and social interests is described in the famous example of the colour "grue" (Barnes 1976). Astrobiologists' discussion of the definition of "life" does not differ, beside the fact that they exploit the always revisable nature of definition to bring forth their interest in establishing a new field of study.

[11] The opposite approach, far less common, is adopted by those who claim that life simply cannot be defined and that a complete understanding of what constitutes the ensemble of processes we call "life" is beyond reach (see for example Cleland 2012, Machery 2012, and Oliver and Perry 2006 in Mix 2015). In contrast to the vast majority of astrobiologists – who argue that scientists might not be able to define life yet, but it is just a matter of time, because it is *essentially* out there – this latter group of authors looks at philosophical arguments for the limits of definitions themselves.

> this respect the possession of even a single example of extraterrestrial life, no matter how seemingly elementary in form or substance, would represent a fundamental revolution in biology (Sagan 1970:306).

In fact, despite their attempts to unpack definitions of life, most astrobiologists never stop being positivists: they think they will manage to find a definition of life that will eventually encapsulate its very essence. "[T]heories of life" from this perspective, "must be allowed to lose, to be disproved, until such a time as we find one worth agreeing upon" (Mix 2015:18). To guide the design of experiments to be built into the landers and orbiters sent into space, it is often suggested as a temporary solution that *operative definitions* ought to be adopted or that more than one kind of definition should be taken into consideration at the same time (Mix 2015). Today, therefore, the search for life in the universe is not restricted to a single line of research, but is articulated on multiple scales and across many disciplinary boundaries. Each of them makes use of different research practices and scientific narratives and is thus imbued with different understandings of life.

In this thesis, I look at astrobiology practices by grouping them according to five locales and five corresponding strategies of action (or what I will call *repertoires*, as suggested by Ankney and Leonelli, 2016) that share a number of features in terms of the kinds of research practices deployed and thus the way life is framed. It is in the comparing and contrasting of *what counts as life* on different scales, in different environmental conditions and through the lens of different instruments that make up the object of astrobiology – an object outlined by the uncertainties surrounding it. In the kaleidoscope of narratives and research practices ranging from exoplanets to Earthly extreme environments, a new agreement about *not knowing what life is* emerges. Most of astrobiologists' training, teaching, experimenting and theorizing are aimed at creating and transmitting this view, to enlarge the limits of life and blur the contours of previous explicit or implicit understandings and consequently bring to light new questions and new possibilities that fall in the realm of the not-yet-known.

Getting astrobiology off the ground

The foundation of the NASA astrobiology institute in 1998 inaugurated a decade of intense work defining the contours of the discipline and its proper forms of institutionalization. The writing of roadmaps in which the scope and direction of astrobiology were formalized (Horneck *et al.* 2016; Des Marais *et al.* 2008; Hays 2015) has shown the tension between the two main characteristics of the emerging field: the aspiration to the status of *discipline* and the nurturing of interdisciplinary research projects. On the one hand, interdisciplinarity has been one of astrobiology's characterizing features from the very beginning and is still considered one of its main strengths and weaknesses at the same time (Noack *et al.* 2015). The commitment to interdisciplinary research requires the formation of a community composed of people from different backgrounds and often maintaining different institutional affiliations as biologists, geologists, astronomers etc. On the other hand, astrobiologists are working toward the construction of a common agenda to encapsulate the variety of their research questions – which, nevertheless, have always been explicitly temporary and open to periodic renegotiations - under a single disciplinary label.

The aspiration to become a fully-fledged discipline and maintain an interdisciplinary nature[12] makes astrobiology a particularly interesting case to look at continuity and discontinuity in science. If we take it seriously, this seeming contradiction appears to be underpinned by two facts: first, scientific identities are not given once and for all; they evolve over time as a person's (or research group's) interests change and adapt to the financial, institutional and scientific situation. They also strongly depend on the immediate context, the audience one speaks to, the funding body one is applying to, the academic position one gets, the journals one submits articles to, the network of collaborations one establishes and so on. Of course, scientific identities seldom shift very radically, but many are the cases in which some of the competences gained by a person trained in a certain field are applied to another field, for example when a person trained in geology smoothly moves to palaeontology, geo-biology, planetary science and, finally astrobiology. Identities are not fixed, and neither are the methods one may adopt and the techniques one might learn to use (or indirectly use thanks to the competences acquired by other members of the same research group). In fact, studies of disciplinary identities often focus on disciplines as abstract entities, providing the basis for individuals' identification.[13] On the contrary, it is the embracing of a certain label by a more or less significant number of people that sustain the existence of a certain discipline. Every time I use the word "astrobiology", I mean the community of people who self-identify with the professional profile of the "astrobiologist", whatever they mean by it. The astrobiology community – like many other communities only recently coalesced under a single disciplinary label – can provide an interesting case to observe the ongoing negotiations

[12] In fact, this is not a unique condition. STS and many other disciplines share the same ambition.

[13] For an interesting discussion of the different theoretical approaches to the study of disciplines, see Krishnan 2009.

that take place where a heterogeneity of backgrounds, experimental methodologies and research questions is still manifest.

Secondly, astrobiology is often said to be *emerging*, a new discipline still at the stage of coalescing around new institutions and practices. The situation differs from country to country, but what remains unchanged is the emphasis put on its novelty, so that it is almost impossible for a sociologist of science to ignore the temporal dimension of its development. This thesis is not a history of astrobiology, but does take into consideration the historical dimension of what it means *to be an astrobiologist* and the changing ways in which instances of life (either Earthling or extra-terrestrial) are referred to.

“Very little”, claims James Strick, “has been said about how exobiology could crystallize so rapidly into a totally new, yet solid scientific discipline” (Strick 2004:132). At a historical level, this is partially true: very little has been written on exobiology’s earlier times, the circumstances under which it was established and its maturation as a research field along with its changes and reorganizations. From an STS point of view, however, Strick’s claim contains several elements that might impede a deeper understanding of astrobiologists’ present and past activities. First of all, it assumes that from a certain moment in time a discipline is fixed and stable, and a number of specific activities fall unambiguously under its umbrella. In fact, as has been discussed above, right after the period of time that Strick takes into consideration, exobiology went through an epistemic crisis that would only be overcome 20 years later with the rebranding of the study of life in the universe under a different name, astrobiology. On the other hand, the hallmarks of scientific recognition have always been an issue for researchers looking for extra-terrestrial lifeforms (not only exobiologists and astrobiologists, but also scientists and engineers looking for extra-terrestrial intelligence, as described in chapter 3) who have had to position themselves with respect to the broader scientific community, in the context of institutions like NASA and its changing politics, UFO hunters and so on (Blumberg 2003; Dick 1996; Garber 1999; Strick 2004). No discipline, I argue, “crystallizes”, but they are always evolving because they are actively enacted by people, framed by institutions and imagined across kaleidoscopic social landscapes.

During the many interviews and observations I have carried out over the past few years, I have had the opportunity and the challenge to introduce myself and my research project several times. More than once, I was asked what the hypothesis I was trying to test was. Needless to say, I did not have one; I tried to explain that ethnography is not meant to prove or disprove, but to give the researcher an insight into particular circumstances. Despite being aware that my methodology, to them, seemed not very useful in the best case, and definitely flawed in the worst, I started anticipating the question and explaining upfront that I had no hypothesis driving my observations and interview questions, but instead themes in which I was interested. During an interview with an astrobiologist based in a geology department, she laughed at my explanation, making the point that she took it for granted, as geologists do not have hypotheses to test either: they go into the field, observe what they are surrounded by and then try to describe how that complexity came about. They visualize lands and mountains as very viscous fluids, and they imagine their interaction with water, ice and wind as a dynamic process that continuously gives shape to what they see. A landscape is only a snapshot of the complex, ongoing dance of the elements.

From that moment on, I adopted that geological metaphor[14] to describe my work to other scientists I interviewed, trying to explain that I was looking at what might seem to be the rocky and crystallized institution of science in the same way a geologist looks at a mountain. Sometimes quite abruptly, other times at a very slow pace, change always occurs. This metaphor is useful today for thinking about change, about the coming into being of research fields and their objects. Disciplines do not crystalize in paradigms, or do so only with reference to the geological metaphor, in which crystals continuously, even if sometimes imperceptibly, grow and crack, mutate their structure and change their properties. Ethnography gives a snapshot of the present, but the present can be seen with the geologist's eyes. This thesis is therefore about the viscosity of science; it is about its dynamics, and the ongoing alignments or reframing of interests, methodologies, instruments and skills that slowly but incessantly make up disciplines.

Non-knowledge and research repertoires in astrobiology

From newspapers to funding proposals, scientists spend thousands of words describing what is not yet known. Contemporary cosmologists, for example, point to the fact that they only know the constituents of 4% of the universe; the rest is called "dark matter", a kind of substance still invisible to their hyper-technologized eyes (Lemonick 2013). The rainforest, in turn, has to be protected because of the huge biodiversity we still fall short of understanding; what makes it valuable, according to this kind of rhetoric, is the

[14] Levi-Strauss also explained his interest in anthropology, Marxism and psychoanalysis by referring to their common geological dimension. In all four cases, what initially appear to be "impenetrable phenomena", or "a seemingly incoherent mass", tum out to have an "order" which is "neither contingent nor arbitrary" (Kusch 1991:5).

"undescribed and unknown"[15] species that we still do not know, but will be able to learn about in the future (Costello, 2015) The agreement on what is unknown as foundational for future scientific developments is embedded in promises about the future, performed in daily decision-making processes and mobilized by scientists as a resource. Astrobiology, too, is bound to the commitment to non-knowledge – exemplified by the ensemble of theoretical approaches and research practices inscribed in the popular expression "life *as-we-don't-know-it"* - in becoming a standalone discipline. As such, it unveils the usually overlooked process of non-knowledge making around which communities might form.

Each chapter presents what Ankney and Leonelli call a *research repertoire*, an assemblage of "skills, behaviours, and material, social, and epistemic components that groups may use to practice certain kinds of science, and whose enactment affects the methods and results of research, including how groups practice and manage research and training" (2016:20). In doing so, I investigate the role of non-knowledge for the establishment and successful enactment of each research repertoire. The concept of repertoire is a useful thinking tool for the sociologist looking into astrobiology and its social dynamics because, compared to other accounts of scientific change, it does not frame change as primarily generated and shaped by theoretical developments. On the contrary, as Ankney and Leonelli suggest, it "takes account of administrative, material, technological, and institutional innovations that contribute to change and explicitly questions whether and how such innovations accompany, underpin, and/or undercut theoretical shifts" (2016:26). Research repertoires capture the pace of science in the tension between continuity and change in a way that goes beyond the dramatic fashion in which Kuhnian normal and revolutionary science follow one another. The concept does not hide all the practicalities and ambiguous positioning that scientists face in their everyday work, and it includes both the production of new models and novel strategies to support, organize and manage collaborative research. This opens up a space for sociological inquiry about the particular social processes through which disciplines require collaborations to be established, allow for new interactions and evoke previously unforeseen associations, and thus constantly unsettle present imaginaries of the future.

[15] Rainforest Conservation Fund, http://www.rainforestconservation.org/rainforest-primer/2-biodiversity/b-how-much-biodiversity-is-found-in-tropical-rainforests/

Research questions

This thesis traces the course of two entangled threads:

1. What is life in the context of astrobiology?

Life, like any other concept, is contingent and sustained by collective agreement. As I describe in the following chapters, astrobiologists, by focusing their research on contexts that extend the range of possibilities of life beyond Earth, actively challenge traditional definitions of life (as well as those of related concepts such as environment, humanness and cosmos). Some sub-questions that allow me to explore these ideas in more detail are:

- How do astrobiologists talk about life? What narratives, metaphors and analogies do they use to make sense of it?
- How do they redefine the concept of life when bringing it into play in relation to unexplored contexts, such as other planets, and unmapped subjects, such as imagined extra-terrestrial civilizations?
- How do they support the definitions they adopt and, at the same time, how do they call into question those that are discarded?

To approach life as a socially constructed concept, I situate it within the framework of astrobiology as an emerging field of inquiry with its own specific epistemic practices and social arrangements. Accordingly, the second research question is:

2. How has astrobiology emerged as a legitimate field of inquiry?

My concern is to explore and map the field of astrobiology and the relationships of continuity and disruption with other relevant disciplines. Some sub-questions that help articulate my research are:

- How do astrobiologists build knowledge about life as it could be elsewhere?
- Which instruments, practices and narratives do they make use of?
- What skills and competences are astrobiologists required to possess? How are these acquired or made use of in specific contexts?
- How do astrobiologists make sense of possible extra-terrestrial signals or bio-signatures as evidence of life? How do they construct them with their instruments?

Overview

The following chapters try to find answers to these questions by retracing the imaginary journey of my first astrobiology lecture, starting from outer space and moving closer and closer to the Earth and to present times. Each chapter describes a repertoire associated with a particular *topos* (a Greek term that means both a physical place and a method for developing arguments); the depths of the universe, exoplanets and the outer solar system, Mars, the laboratory and extreme environments are all places by means of which astrobiologists tell stories about life. They also offer practical ways to tackle the issue of institutionally and materially arranging a new field of research.

Like other kinds of scientific epic, the *voyage* has a long tradition as a narrative device to concede disunity in science while, at the same time, attempting to work toward the construction of the "whole of knowledge" (Zakariya 2016:3). Alexander von Humboldt, the famous 18th century explorer, titled his lifework about "everything that is in nature" *Cosmos* and structured it based on his travels around the globe. Carl Sagan's famous series of documentaries titled *Cosmos, a Personal Voyage*[16] echoed Humboldt's literary style by embarking on a voyage of exploration through space. Recent academic literature about alien life and alien worlds, such as Stefan Helmreich's *Alien Ocean. A Voyage into Microbial Seas* and Lisa Messeri's *Placing Outer Space* have adopted the voyage as a narrative device as well.

I decided, nevertheless, to reverse what is often considered the traditional order of the journey, and, instead of leaving the depth of the cosmos to the final chapter of my thesis, I designated it as my starting point for an intellectual voyage that will bring the reader back to Earth and its multifarious constellation of extreme environments, where astrobiologists try to expand their knowledge about the limits of life.

Despite committing myself to the investigation of life as a particular object of scientific research, I would like to emphasize, from the very beginning, that neither Earthly nor extra-terrestrial life is (or has ever been) a single and coherent ontological entity. "Instead of a simple *is*," writes Michelle Murphy, practices "are made possible by *ands*. Objects are constituted through their manifold material relationships, and these relationships have different histories" (Murphy 2006:12). I will thus be asking: what are life's *ands*? What did its historical relations make possible? Extra-terrestrial life is a multiplicity that can be disassembled, arranged and rearranged in manifold ways in

[16] The series of documentaries he co-authored and hosted was broadcast in 1980 and remained, for an entire decade, the most widely watched series in the history of American public television.

historically situated contexts. Repertoires may overlap and contradict each other, or have varying intensities, durations and stabilities. Each chapter[17] explores a research scenario in which understandings of life are embedded in specific research practices, narratives, institutions, skills and epistemic arrangements and further unpacks the different ways in which life is thought about, but none in particular will effectively represent astrobiology as such. It is precisely these intertwined trajectories and sets of repertoires that astrobiology eventually emerges

Structure of the chapters:

- *From microbes to mathematicians*

I will start off from as far away as possible, in the depths of the galaxy, where SETI (an acronym for Search for Extra-Terrestrial Intelligence) researchers look for artificial signals from technologically advanced civilizations. In the first chapter I will look into the way the register of "probability" has made the question "are we alone in the universe?" *scientific* within the framework of SETI research. SETI emerged in the early 1960s, and its trajectory has run parallel and diverged from the search for single-celled extra-terrestrial life multiple times and in many different ways. SETI provides an excellent case to focus on boundary-work in its two main dimensions: between science and non-science, and between different disciplines. SETI and astrobiology have often built on each other, with each representing its own identity with respect to its counterpart. This chapter looks into the divergent ideas of life brought about by SETI (which framed it in mathematical and probabilistic terms) and astrobiology (explored in the following chapters). Juxtaposing the two can help foreground the idea that the way life is defined scientifically has to be understood within its broader context.

- *Building habitable worlds*

In the next chapter, I follow the provocation offered by Brother Guy Consolmagno, Jesuit Priest and astronomer, of making the effort of "asking the right question" within its historical and social context. Nowadays, solving the problem of whether a planet is

[17] Each chapter could have been a thesis on its own, and I strongly hope that they will become, one day, other people's objects of interest. Each chapter leaves many questions unanswered and perhaps unasked. Nevertheless, by means of this structure, I hope to be able to address properly the two main questions to which I committed myself: "what is life in astrobiology?" and "how has astrobiology emerged as a legitimate field of inquiry?"

habitable depends on the criteria of what makes a scientific question *right.* Habitability contributes to the building of an interdisciplinary community by providing a grey zone that offers the opportunity for different methodologies, interests and expectations to co-exist. At the same time, as an analytical tool, it allows astrobiologists to rethink life as an environmental process, shaped by and at the same time shaping the environment. Exoplanets (*i.e.* planets belonging to other planetary systems) and the celestial bodies of the outer Solar System (not only the planets, but also satellites such as Europa, Enceladus and Titan, just to mention the ones that attract broader interest) are the main focus of this chapter. Despite being very different objects of inquiry, the investigation of which is mediated by very different instruments and tools of analysis, they are all studied through the lens of *habitability* and its multiple implications.

- *"The life on Mars roller-coaster"*

In the previous chapters, I build my way up to asking what makes a certain question "scientific" and what it means to ask "the right question" in science. In parallel, I show how the concept of life was thought of in statistical terms during the 1960s and 1970s, and introduce contemporary thinking about habitability, which makes life a process within a dynamic environment. This chapter looks at the parallel emergence of astrobiology as a discipline and the determination of what would constitute valid evidence for life, or a *biosignature,* in the contexts of the exploration of Mars. The Red Planet has constituted, in the last century and a half, the very lynchpin on which the entire discipline of astrobiology has been developed. Two episodes in which controversies about whether life on Mars had been found or not, Schiaparelli's maps of the Martian canals (late 19th century), and the Viking experiments (1970s), are the core of this chapter. I look into what counted as valid and legitimate evidence of life at the time of these episodes, and the way astrobiologists use these episodes today to present astrobiology as scientific compared to its forerunners.

- *"Alien life, right under our noses"*

In the following chapter I explore the emergence of the shadow biosphere hypothesis and look into the way that re-opening black-boxes can contribute to the creation of new spheres of inquiry. All life on Earth shares the same ancestor, the most primitive form of life that arose, in still unknown circumstances, more than 3.5 billion years ago. At least, this is what is commonly assumed. Astrobiologists have revisited this assumption and advanced the hypothesis of the existence of a shadow biosphere on Earth, addressing the possibility that life emerged on our planet more than once, giving rise to a parallel tree of life whose instances, being different at the molecular level to the kind of life we are used to, remain hidden from view. "Traditional" biology uses a number of techniques to study, visualize and understand the microbial world, but such technologies have been developed on the basis of the kind of life with which we are familiar. Would they enable scientists to detect life as-we-don't-know-it, either on Earth or beyond? At the laboratory bench, the black-boxing of tools to visualize and tame microbial life as-we-know-it might prevent the detection of other kinds of life, if they exist.

The hypothesis of a shadow biosphere is a theoretical exercise that poses a methodological question, inviting scientists to unpack the black-box of life and wonder how to recognize whether instruments work properly if they claim to lack a general theory of life. And how can we design experiments that can detect life as-we-don't-know-it? This chapter further explores the issue of what constitutes a biosignature by looking into the issues implied in revealing and recognizing alien life.

- *Despiciendo, suspicio*

To answer these last two questions, astrobiologists move outside the lab and engage in fieldwork. Astrobiologists' fieldwork began in the late 1990s with the study of "extreme" environments, which have had a *relativizing* function: they make Earth a little more alien and other planets a little more familiar. These environments are imagined as analogue field-sites, or places resembling, somehow, other space environments and therefore offering the opportunity to study those unreachable places by proxy. This chapter is built around two field-sites – caves in Sardinia and lava flows in Iceland – to discuss how space-analogues are established and maintained, and the different but overlapping analogies that come to constitute them. In the field, uncertainty becomes part of the collective experience and astrobiologists become more comfortable with both the unpredictability of the research and the idea that "they recognize life when they encounter it", one of the few operative definitions of life on which most of them agree.

- *Conclusion*

By looking into the emergence of astrobiology as a discipline, quickly gaining momentum and becoming a priority for space agencies all around the world, this thesis aims to make sense of the contextual horizon within which uncertainties about life are created, agreed upon and made functional for the institutionalization of astrobiology as a legitimate and authoritative branch of science. I advocate closer attention to the mechanisms through which non-knowledge is created, agreed upon and maintained. The uncertainty about *what life is* – encapsulated in the expression *life as-we-don't-know-it* – is the central in every repertoire astrobiologists embrace to practice and promote their discipline.

The epilogue offers a reflection on what is at stake in different understandings of aliens – others *par excellence.* I briefly discuss Jan Van der Straet's illustration of Amerigo Vespucci's arrival in the New World and his first encounter with the Indian "America", and, moving from Michel De Certeaux's discussion of the power relations inscribed in the encounters of the two bodies, I claim that the way alien life is studied and astrobiology is practised today are not neutral: because they build narratives about life in space through different kinds of embodiment, they shape the ethics of humanity's future in space.

Chapter 1

Methodology

Following the scientists: multi-sited ethnography as a research approach

Astrobiology as a scientific field is constituted by heterogeneous communities of scientists and engineers that are not bound to a single space of knowledge production. People based at different universities or institutions cluster in associations and networks that are often virtual and delocalized. Astrobiology in particular is characterized by the existence of virtual institutions (for example the NASA Astrobiology Institute and the UK Centre of Astrobiology), whose activities do not usually take place through face-to-face interaction, but by means of e-mail correspondence, periodic gatherings and long-distance collaborations. What is more, scientists – not only astrobiologists – are often in motion: in the early stages of their careers in particular, researchers often change institutions, so experiences, training and backgrounds are often shared by people who then relocate to different sites. Even those who have already found a certain professional stability contribute to the creation of temporary sites of gathering and action, such as conferences and workshops, which disappear when the community leaves. Because of the levels of mobility of the subjects I observed, bounding my ethnography to one single physical space (such as one laboratory) would have probably provided a fragmented insight into the larger set of activities astrobiologists' engage with. To explore the complex ecologies of people and knowledge, artefacts and metaphors that constitute the field of astrobiology I adopted what George Marcus calls multi-sited ethnography. As

Marcus (1995) puts it, “multi-sited research is designed around chains, paths, threads, conjunctions or juxtapositions of locations in which the ethnographer establishes some form of literal, physical presence, with an explicit, posited logic of association or connection among sites that in fact defines the argument of the ethnography” (p.105). This research methodology was proposed by the American anthropologist in the mid-1980s to account for the social dynamics that escaped the single local site and has given its best results in the ethnographic study of science and technology (see for example Ong and Collier eds., 2008). This approach seemed more apt given the mobile and fluid nature of the scientific community. Traditional ethnography (roughly identifiable with the set of practices codified by Bronislaw Malinowski in 1922 in his seminal work *Argonauts of the Western Pacific*) is based on the idea of a focused, sustained, intensive presence within a bounded community. This prolonged engagement is meant to progressively provide the ethnographer with the social actors' perspective, the *native's point of view* (Geertz, 1974), from which to observe the entire spectrum of social facts constituting a certain way of life. From the very beginning of my research, however, I realized that scientific communities (like many other contemporary social aggregates) do not lend themselves to this kind of approach: no PhD student or senior scientist could account for his or her own scientific activities without making copious references to an extended network of people, fieldtrips, conferences and to the work done by other groups. Becoming *native* in this context required that I become part of such a network of relationships which could not have been mapped before fieldwork, but as a function of fieldwork itself (Marcus 2005). What is more, multi-sited ethnography is well-suited to an approach to individuals as subjects in the process of becoming. As Marcus puts it:

> The habit or impulse of multi-sited research is to see subjects as differently constituted, as not products of essential units of difference only, but to see them in development— displaced, recombined, hybrid in the once popular idiom, alternatively imagined. Such research pushes beyond the situated subject of ethnography toward the system of relations which define them [...] In contemporary settings, what is shared is the perception that local realities are produced elsewhere, through dispersed relations and agencies, generating a multi-sited imaginary, one that is practical for the subject, and that is a found design of a mobile ethnography for the anthropologist. (Marcus 2005:7)

Every time I use the phrase “scientific community” in this thesis, I mean the network of people that – temporarily or with a certain continuity – identified themselves with the label "astrobiologist". In the semi-structured interviews that I carried with some of the people I met during my research journey, I asked whether they would call them self an astrobiologist and why. I received many different answers, whose variety and depth was often revealing.

Other ethnographic approaches could have provided useful insights but were not chosen for practical reasons. For example, it would have been fascinating to follow the trajectory of a single object, from research design, to sample collection in the field, manipulation in the laboratory, interpretation of the results, writing of one or more articles and presentation in a journal article[18]. I did not adopt this approach for both theoretical and practical reasons. First, the length of this process would have been extremely hard to predict, and thus hard to fit into my PhD research schedule (which provided a little more than a year of data collection in total) – moreover, had the process not finished on time (or if it was suspended, postponed or cancelled for whatever reason), I would not have completed my research project. This approach, nevertheless, might be interesting for a follow-up study of one specific object and its social and technical construction. Secondly, I accessed the field through two main avenues: an academic course for undergraduate students and a European conference. In both contexts, astrobiology was described as an interdisciplinary field including multiple research trajectories – and I came to realize that following only one of them at that stage would have been rather limiting.

In general terms, the study of science as a social and cultural phenomenon cannot but consider the many dimensions that constitute it. This is why I decided to draw on the concept of repertoire, which is based on the idea that scientific change is due to the strategic arrangement of institutional, financial, historical, practical and epistemological elements. A multi-sited approach allowed the study of the different layers of action of the many actors and their interrelatedness.

It is important to consider that the research plan initially designed was preparatory without being deterministic. This openness to what I would encounter in the field was not simply a necessity, but a research attitude that characterizes ethnography and makes it a distinctive approach (Fortun 2009:171). Several steps of the research process were tailored to the development of my own understanding of both astrobiology and STS and adapted to the circumstances that I encountered in the different sites I visited. Indeed, this openness required constant negotiation for access to the different sites of

[18] An excellent example of this kind of approach is Annemarie Mol's *The Body Multiple*, where she follows the construction of atherosclerosis during the journey of diagnosis and treatment.

investigation and the arrangement of meetings and interviews over the entire period of data collection. This proved, at times, more than challenging. For instance when, despite a long stay in San Francisco, I did not manage to make observations at NASA Ames. I managed, nevertheless, to adjust my research plan and make up for this by planning a large number of interviews with some of the many astrobiologists working in the area and attending a large number of relevant conferences and events. Another major limitation of this approach was the difficulty of deciding which events and sites were relevant and which ones were not, with the risk of spending significant amounts of time going down blind alleys. This assessment was not made once and for all; on the contrary, what was of interest had to be negotiated and renegotiated over time.

The sites I visited and observed include:

- The laboratories and offices of the UK Centre for Astrobiology, based at the University of Edinburgh
- The SETI lab at the University of California, Berkeley
- The Medicina Radio Telescope facility in Italy
- The Geology Department at the University of Bologna, Italy
- A number of national and international conferences and workshops:
    - EANA 2014: annual European Astrobiology Network Association conference, Edinburgh.
    - AbGradE 2014: the Astrobiology Graduate conference Europe, Edinburgh.
    - Building Habitable Worlds workshops, in 2013 (Edinburgh), 2015 (Glasgow), 2017 (Edinburgh).
    - GESE (Geobiology in Space Exploration) 2015: workshop in Iglesias, Italy (including oral presentations, field trips to Is Zuddas, Su Mannau and Su Zurfuru, and a final round table aimed at the writing of a Roadmap)
    - "Biosignatures and the Search for Life on Mars" summer school 4-16 July 2016, co-organized by the Nordic Network of Astrobiology, the European Astrobiology Campus, and the EU COST Action "Origins and Evolution of Life on Earth and in the Universe" - Iceland (which included lessons and field trips to Kerlingarfjöll hot spring area, Barðabunga lava field, Námaskarð geothermal area, Krafla volcanic area, the Mars analogue landscapes at Askja, the Myvatn area with the Skútustaðir pseudocraters and the Hverfjall cinder cone)
    - Scottish Planetary Network Meeting 2017, in Edinburgh.

- SETI meetings in Paris (March 2015), Milan (June 2017) and Rome (October 2017).

The following is a list of locations I had the chance to visit for my interviews (even if I did not have the chance to carry out any extensive observation there):

- The Vatican Observatory in Albano Laziale, IT (2015).
- Arizona State University, US (2016)
- University of S. Andrews, UK (2015)
- SETI Institute in Mountain View, US (2015-16)

Some of these sites were permanent, others temporary; in each of them, nevertheless, I could observe significant moments in the practice of astrobiological research.
In what follows, both the initial research plan and its several adjustments are specified and explained.

Choice of methods and data collection

The adoption of a multi-sited ethnographic approach required that ethnographic observation was integrated with other data collection methods such as unstructured or semi-structured interviews and the analysis of written and visual documents (Arksey and Knight 1999:33). The triangulation of these methods was aimed at achieving a more complete and complex understanding of the fields under investigation (Jick 1983).
The data collection process was articulated in the following steps:

- *Interface ethnography: participation in conferences and attendance at an astrobiology class.*

From September to November 2013, I audited an astrobiology class at the University of Edinburgh. Thanks to the course, I gained the background knowledge that allowed me to "interpret, understand and respond" (Arksey and Knight 1999:40) and to hold an informed conversation about astrobiology (Arksey and Knight 1999:123). The course also gave me an idea of the broad range of topics with which astrobiologists deal, and what kind of claims are considered foundational. This kind of introduction to astrobiology is a mix of outreach and training: it has the double aim of getting people interested in astrobiology while also teaching them the notions on which the discipline is based. What is more, I became acquainted with several researchers involved in astrobiology in my home university and I had the chance to let them know about my interests. The following steps of my fieldwork, such as interviews and observations, were possible thanks to the initial help of those gatekeepers, people I relied on for access to the fields described below.

Other gatherings, such as symposia, workshops and conferences, are what Blaikie calls social episodes, "social interactions that are limited in time and space, such as social gatherings of various kind" (2000:164), which are regarded as a primary means by which networks among social actors are created, collaborations are negotiated and knowledge is disclosed, institutionalized and problematized (Gomm 2008). Some of these events provided, very early in my PhD, an insight into contexts where access was, at that time, harder to obtain, providing opportunities for what Ortner calls interface ethnography, "events in which the closed institution presents itself to 'the public'" (2010:211). I attended and observed, for example, the European Astrobiology Graduate Conference (AbGradE) and the European Astrobiology Network Conference (EANA), held in Edinburgh in September 2015, the annual Building Habitable World workshop (described in chapter 2) and monthly astrobiology seminars. No video recording equipment was used during the observations, and the data were collected through systematic fieldnotes, which were written as soon as possible after the observations.

- *Unstructured or semi-structured interviews*

The second stage of data collection involved a small number of in-depth, loosely structured interviews, with the aim of becoming acquainted with the particular fields in which my informants moved. Interviews with the key informants followed the opening-the-locks pattern, which is characteristic of a situation in which the interviewer "is somewhat naïve about the matter at hand but is pretty sure the conversational partner is well informed" (Rubin and Rubin 2005:144). I carried out, in a second phase, a series of semi-structured interviews (see Appendix IV). Interviewees were selected according to so-called theoretical sampling – a technique that allows decisions to be made progressively throughout the analytic process in order to achieve a more complete grasp of topics of interest – and snowball sampling, i.e. contacts with interviewees made through natural social networks, by asking people to identify other members of their community who might provide significant insights.

The interviewees were invited to talk about their perceptions, knowledge, intentions, purposes, values etc. (Arksey and Knight 1999; Mason 2002). The semi-structured interviews conformed to an interview template (see Appendix III), whose primary aim was to make the conversations exhaustive and fluid. This template was always adopted with flexibility with regard to both the order of the conversation and topics discussed. Follow-up questions were necessary to understand the interviewees' ways of articulating answers in their own terms and to follow the thread of the conversation when it unfolded in novel and unexpected ways (Rubin and Rubin 2005:136). The interview guide initially had a second aim: being aware of the challenges of interviewing someone in a language that is not native to me, I found it useful to have my questions prepared in advance. Spontaneity and the ability to make on-the-spot decisions about how to further develop the conversation (Mason 2002:68) could have been at times reduced by linguistic issues. In addition, English was not the only "language" I needed to handle: the scientific jargon presented, initially, the same challenges. Articulating the main questions beforehand was a useful way to have some "conversational guides" (Rubin and Rubin 2005:147) and keep on "interviewing effectively" (Arksey and Knight 1999:38) when I felt bewildered by the conversational exchange.

Interviews were digitally recorded with permission (see Appendix II) and archived in mp3 format. They were transcribed and analysed with NVivo software, which was used to generate categories and index the information collected. Verbatim transcription (i.e. the exact reproduction of the words used originally) helped to provide an account of the interview that was as accurate as possible. Nevertheless, I acknowledge the impossibility of fully representing in textual form what was communicated during a speech act (McLellan, MacQueen and Neidig 2003:65). Interpretative and analytical decisions were necessary throughout the transcription process, and thus constituted the first step of data reduction. As Kevale argues, transcripts "are not the rock bottom data of interview research, [but] are artificial constructions from an oral to written mode of communication" (1996:163). For this reason, commentaries with reflections and annotations were attached to the transcript both to remark on the things that were not properly accounted for by the text itself, for example when something was said with particular zeal, disinterest or irony (Mason 2002:77), and as a tool to rethink and develop further the interview guide.

A number of interviews I carried out for this project aimed to complement the observations I had made on SETI research at the Medicina Radio Astronomical Observatory in 2013. My interest in SETI predated this PhD research and somehow inaugurated this research journey. Medicina is a small village in the countryside near Bologna, and has hosted a radio-telescope facility since the early 1960s. Among the many observations undertaken with the two radio telescopes, a 32m dish and a T-shaped array with a collecting area of more than 30,000m^2, the Medicina Observatory has engaged with SETI since 1998, when Stelio Montebugnoli, at the time director of the facility, founded SETI Italia. Over a little less than a year, I had the chance to help, once a week, with the data storage, and scout for signals in their waterfall plots collected several years before. I stopped spending time at the radio-telescope when I moved to Edinburgh for my MSc, but I always remained in touch with the SETI community. The opportunity to deepen my interest occurred during my visit to UC Berkeley, which happened a few months after the local SETI group received important financial support from the Russian entrepreneur Yuri Millner. The two experiences, together with the many encounters with SETI people during astrobiology events and gatherings, became the first chapter of this thesis.

- *Observation and participant observation*

During the interviews, it became clear that part of what I was interested in could not easily be verbalized. In particular, my questions about laboratory activities could hardly be articulated in a way that satisfied my interlocutors. More than once, they ended up inviting me for a laboratory tour to see in person the instruments used and the activities undertaken on a daily basis. Very often, though, these tours were intended to give me a quick glance of the laboratory, moved by the certainty that this would suffice to show me how "nature speaks" in the lab. For my research, nevertheless, I asked permission to spend time in the laboratory and observe, together with the instruments and samples, the scientists' activities, decision-making, evaluation, experiment design etc.

Observations of situated activities constituted the most precious method of data collection that came to integrate the understanding I gained at conferences, lectures and interviews. All these discursive activities overlap in complex ways with the practical activities carried out by astrobiologists, often using different narratives and involving different normative judgments. My observations were carried out in natural social settings (Atkinson and Hammersley 1994), comprehending social actors' interactions and everyday research activities, and placing emphasis on the micro-social and the ways meanings were attributed by the social actors to both their and other people's actions and to the production and reproduction of patterns, structures and institutions (Blaikie 2000:164). I did my best to become involved in the world in which my informants lived when doing science, which was constituted by activities such as laboratory meetings, observations, experiments etc. "The fieldwork goal", wrote Sharon Traweek in her pioneering work on particle physicists' culture, "is to find out what the community takes to be knowledge, sensible action, and morality, as well as how its members account for unpredictable information, disturbing actions and troubling motives" (1988:8).

The time I spent in the laboratory was split between the first year of my PhD and the second half of my second year. On both occasions, my fieldwork was mainly based at the

UK Centre for Astrobiology in Edinburgh (hereafter UKCA) where the PhD students and the post-docs agreed that I could be in the laboratory in the morning, a strategy I adopted so that people could be free to opt out whenever they wished. In the lab, each person had an individual project; their experiments often used different techniques in the lab and also necessitated collaboration with different groups within or outside the university. Weekly laboratory meetings served as chances for updates and brainstorming about each person's project.

Spending time in the laboratory made me realize how disruptive my presence was for the astrobiologists' routine. First of all, their laborious routine often happens in silence; each person concentrates on an individual task. The conversations going on in the laboratory, with very few exceptions, were often about the practicalities of the equipment (where to find glassware, how to properly store samples according to the safety rules) or random issues (birthdays, news, puppies and so on). Most of the time, the chatting was unrelated to their research topics. What is more, my physical presence in such a small space was not ignorable. When the laboratory was occupied by more than a couple of people working at their benches, I had to spend most of my time moving around, trying not to be in the way. There are many kinds of invisibilities within the laboratory framework, and I realized that if nature does not speak by itself in the lab, but requires scientists' expertise in performing experiments and their authority for the interpretation of the results, then science also does not speak by itself, but requires the presence, sometimes disruptive, of the social scientist with her questions, curiosity, inadequacies (for example how to open the door, how many times shall I change the gloves, how close to the samples could I stand) and awkwardness.

During the time I spent in the laboratory, I realized that there was another side of the astrobiology activities I could not overlook: fieldwork activities. I therefore decided to participate in fieldtrips as part of my own fieldwork.

- *Fieldwork*

The importance of the field experience for astrobiologists, and therefore the relevance of attending it on my part, was perhaps the most unexpected stage of my data collection process. Astrobiologists plan fieldtrips far in advance and, most importantly, try to optimize resources by inviting other scientists if the logistics allow. Fieldtrips to so-called "extreme environments", such as the Dry Valleys in Antarctica, the Andes or Hawaii, are also quite expensive. Given my limited timeframe and the financial constraints, I chose to participate in fieldtrips that were organized as part of larger formative experiences such as workshops and summer schools.

In May 2015, I participated in the second Geomicrobiology for Space Exploration (GESE) topical team workshop, held in Inglesias, a mining town in Sardinia, Italy. The workshop, titled "Extraterrestrial Subsurface Exploration and Geomicrobiology", aimed to encourage the development of a new interdisciplinary community focused on the study of possible uses and implications of mineral-microbe interactions in subsurface environments. The location, Iglesias, was chosen in function of the three sites we visited during the fieldtrips: two caves, Su Mannau and Is Zuddas, and an old mine, Su Zurfuru.

The following year, I attended an Astrobiology Summer School titled “Biosignatures and the Search for Life on Mars”, which took place in Iceland in July 2016. The summer school was co-organized by the European Astrobiology Campus, the Nordic Network of Astrobiology (institutions from Sweden, Denmark, Finland, Norway, Iceland, Estonia, Lithuania and the US participate) and the COST Action “Origins and Evolution of Life in the Universe”. We were 39 students in total, at very different career stages – from master’s students to postdocs – and from different countries – 13 from the US, 24 from Europe, 1 from China and 1 from Brazil. The first week of lessons was followed by group activities in the field.

My observations were recorded in the form of fieldnotes and supplemented with pictures and sketches (which are often used by geologists during their observations and therefore seemed a rich way to convey movements and actions in the landscape in visual and synthetic form). The written texts reported the experience in the most accurate way possible, including both descriptions and first impressions with regard to the positioning in the field, intentional and serendipitous circumstances, first thoughts, inconsistencies and uncertainties. Quick notes were written on paper (a notebook is often more accessible and discrete than a laptop) as soon as possible, but without intruding into and affecting those observational contexts in which it might seem inappropriate or make people feel uncomfortable (Emerson *et al.* 1995). All fieldnotes were later re-written and digitalized, but were not coded with NVivo. They were, nevertheless, an important source of information for the development of the codes I used to analyse the materials gathered with NVivo.

- *Visual and written document analysis*

SETI and astrobiology have been framed in different social contexts and, as previously described, reached their peaks of popularity in different decades. For this reason, I consider the history of both SETI and astrobiology as a fundamental first step to understanding their present. In order to do so, I draw not only on interviews in which I asked social actors to recollect the past, but also on the analysis of written and visual documents such as documentaries, press kits etc. (Rose 2000; Bryman 2012). Visual and written documents also played an important part in achieving an understanding of the present.

Scientists, either working in academia or employed by space agencies and research institutions, spend significant amounts of their time reading and writing papers published in academic journals. As part of my ethnography, I felt the need to get to know the scientific literature that astrobiologists consider foundational to what they do. These documents can be read at many different levels beyond the explicit intent of the authors: for example, the authorship of articles records a trace of the collaborations that made the research possible and thus provides an indication of the networks people were part of over their careers. It was also very interesting to note the presence of certain key words, such as “biosignature”, “habitability” or “interstellar messaging”, and their frequency variance through time, which provided a hint about the way phenomena and problems fade in and out of view. What is more, articles are often explicit about the significance of their work and situate their contribution within the broader disciplinary landscape. Articles were normally stored and annotated with Mendeley, but excerpts of particular significance were uploaded into NVivo and coded as written documents.

I also checked, weekly, a list of institutional websites, blogs and journals (listed in the “primary sources” section of the bibliography). The most significant articles and pictures were saved and imported into NVivo.

Images used in PowerPoint presentations and in leaflets advertising conferences, workshops and various events constituted a source of data as well. Logos of projects, scientific missions and organizations often provided a summary, conveyed in symbolic form, of what the group identity was shaped around, what was considered meaningful or unique and what the group considered worthy of being communicated. These images collected during fieldwork were scanned or photographed and imported into NVivo, where I coded them with the same nodes[19] I used for the interview transcripts and other textual data.

The spatial context in which the interviews took place also presented a number of elements of interest (such as paintings hung on the walls, to-do lists sketched on blackboards and quotations or comics displayed in the offices), as both visual documents and possible prompts for conversations. Attention to these details has not been neglected and they were often recorded in the fieldnotes. The narratives used by these visual documents was compared and contrasted with the language used by astrobiologists and SETI researchers during interviews and observations.
I only rarely collected materials from public outreach events or articles published by journalists in magazines and newspapers as I found that the narratives used and the communication style adopted by the media were often disapproved of by the astrobiologists themselves (this phenomenon was especially noteworthy for SETI, since often what becomes big in the news is in fact considered trivial or misleading by the SETI scientists, see for example Bartels 2018).

More interesting were those documents which might have appeared to be completely *alien* to the scientists' work but then proved to be widely discussed and sometimes appreciated. Science-fiction novels and movies[20] are an example of this category of texts and images. These were hard to identify as direct questions asked during interviews often produced vague and short answers given with a mix of embarrassment and (perhaps affected) indifference. Only once I started spending some free-time with the astrobiologists (such as during lunch-breaks and evenings at conferences, workshops and the summer-school) could I appreciate the extent to which science-fiction, movies and art were part of their imaginary. These moments provided interesting insights and were recorded in my extensive fieldnotes.

The use of NVivo was helpful to maintain a certain coherence of themes among the wide variety of materials I collected. The nodes I used changed and evolved over time, informed by the insights I gained during participant and non-participant observation,

[19] In NVivo, a node is a collection of references about a specific theme or case. References are gathered by 'coding' sources to a node.

[20] Three perhaps obvious examples come to mind: the *Mars Trilogy* by Kim Stanley Robinson, *The Martian*, by Andy Weir (and the movie inspired by the novel, directed by Ridley Scott) and, mostly for the more senior generation, *Star Trek.*

and at the same time provided prompts I followed during my research. The documents and transcripts coded in NVivo and my extensive fieldnotes informed each other and the two bodies of heterogeneous materials completed each other in the writing of this thesis.

Positioning in the field

The fields of SETI and astrobiology are interdisciplinary in nature. The extent of their interdisciplinarity results, sometimes, in engagement with social sciences and humanities as integral part of the disciplines themselves. Nevertheless, the two cases are different, and I had to take their specificities into consideration when negotiating access and positioning myself in the field.

SETI has traditionally been very open to social scientists' participation: the annual SETI symposia, for example, always includes a section dedicated to "SETI and Society". Since SETI researchers acknowledge the significance of a potential discovery, they are keen to address issues that go beyond a merely technological debate. Anthropologists, cognitive psychologists and theologians have been involved in the discussion of issues such as inter-species communication, risk assessment and management, social "impact" of a potential discovery and the appropriateness of engaging in active signal broadcasts (the so-called METI, acronym for Messaging Extra-Terrestrial Intelligence). Humanities and social science researchers taking part in the enterprise are regarded as conferring higher status on the research, ratifying its potential revolutionary outcome and constructing narratives that legitimize, boost and regulate expectations. On the other hand, SETI suffers from a longstanding lack of funding. Many of the people taking part in SETI conferences, workshops and meetings do not have the possibility of actively engaging in research; many people thus shift their interest to hypothesis-making, evaluating possible (or sometimes far-fetched) scenarios and speculating on what might be the best strategy to intercept an extra-terrestrial signal coming from outer space. Deciding what to look for becomes as important as the search in itself; therefore, people bringing a theoretical contribution are considered to be as "active" as those who are actually engaged in the research. In the conferences and gatherings I attended, I was only very rarely the only social scientist among the SETI researchers, and our contributions were always warmly invited. Nevertheless, what I often found myself invited to do was more than observe and understand (which were my primary aims): I was expected to take part in SETI as such, and "assess the societal impact of an ETI detection".[21] The risk

[21] MR, astrobiologist and ethicist, interview, 30/09/2015

of doing this was not only becoming overly involved and losing the methodological distance that allows clear critical thinking (Denning 2011:672), but also becoming involved in an endeavour with which I was not comfortable: I found both the idea of "assessing" something that had not happened yet and the concept of a one-way "impact" of technoscience on society somehow troublesome. I thus made my best effort to explain that my goal, in this project, was to provide a deep account of the way life is defined and looked for in SETI and astrobiology in order to understand better how the production of scientific knowledge works and the many entangled ways through which science and society are mutually shaped. Rather than speculating on life-out-there, my primary aim has been to reflect on life-down-here.

Astrobiologists, in contrast, define themselves as very down-to-Earth, only reluctantly engaging in broad speculations about far-future scenarios. In these circumstances, the opposite was sometimes the case: I was at times seen as an outsider whose gaze was imposed upon them, not one of them. Especially at the very beginning, I approached my gatekeepers as a student, thus establishing a student/professor relationship that was difficult to change. During the data collection and analysis I kept in mind the impossibility of "separat[ing] the interview from the social interaction in which it was produced" (Mason 2002:65), and I acknowledge the limits of such a hierarchical relationship when it comes to talking about personal thoughts, feelings and actions (Arksey and Knight 1999:32). Most often, however, my concerns were largely unfounded, and thanks to my informants' enthusiasm when talking about their work, vividness was achieved by the narration of iconic moments and anecdotes when, even if not explicitly, they responded "not just intellectually but also emotionally" (Rubin and Rubin 2005:131-2). When participating in fieldtrips in particular, the disciplinary barriers were often blurred and I could share moments of true friendship with the people I spent time with. When this happened, I felt like I had the opportunity, and also the ethical duty, to share something more about the goals of my research project. I realized, perhaps not so surprisingly, that they were not as interested or upset as I imagined. Paradoxically, the sense of distance and outsider-ness that I felt at the beginning (and that I still occasionally feel) among astrobiologists made my presence and participation in their activities less prescribed, and thus I felt freer to negotiate a position within the group in a way that better suited me and my informants.

Ethical issues

My research presented no reasonably foreseeable ethical risks, as it did not deal with sensitive topics or illegal practices, did not involve vulnerable groups and could not adversely affect participants (the project was thus considered Level 1 in the Research Ethics Approval form). Nevertheless, some of my questions and observations might have involved the disclosure of scientific information and thus required a high level of confidentiality. A leaflet (Appendix I) was prepared and sent in advance of interviews and observations to explain to my informants the nature and purpose of the research (Blaikie 2000:31).

Because I recorded the conversations, I had my interviewees fill out and sign a consent form (provided in Appendix II), where they were asked questions about confidentiality and anonymity (Arksey and Knight 1999:132). Many of them consented to be identified with their real names due to their habitual role as spokespersons for their institutions. I nevertheless decided to anonymize my informants when possible in order to protect the identity of those who did not want to be recognizable.

Chapter 2

Theoretical framework

This chapter presents the theoretical framework that informed the research and the writing of this thesis. The following four sections present the bodies of literature with which I have engaged in relation to my thesis: life, astrobiology, science as culture and agnotology. My ambition is not to cover all the literature on these themes exhaustively; instead, I aim to put into dialogue the authors and works that guided or challenged my research.

Placing life back into history

The concept of life can be approached in many different ways and made the object of scrutiny from different perspectives. The most common path of inquiry, undertaken by philosophers and scientists alike, is to try to pin it down and grasp its *essence*. Both groups try to encapsulate life somehow, even if using different approaches. “Together”, write Bedau and Cleland, “contemporary philosophy and science hold forth the promise of finding a satisfactory answer to the age-old question of the nature of life” (2010:xix). I do not embark here on the same enterprise: the aim of this research is not to propose or promote a particular definition of life, nor to discard any of them. On the contrary, I am interested in the way astrobiologists agree on a way of approaching life that is characterized by the acknowledgment that *we*[22] *do not know what life is*.

In the last century, forms of life have been put under scrutiny by scientists as well as historians, philosophers, anthropologists and sociologists, and investigated in its manifold instances, but rarely made object of reflection in itself, as if *life* – as opposed to its instances – was thought of as a timeless concept. In *The Order of Things,* Michel Foucault questioned this very idea and tried to show the deeply historical character of life. "Historians want to write histories of biology in the eighteenth century," he writes,

> but they do not realize that biology did not exist then, and that the pattern of knowledge that has been familiar to us for a hundred and fifty years is not valid for previous periods. And that, if biology was unknown, there was a very simple reason for it: that life itself did not exist. All that existed was living beings, which were viewed through a grid of knowledge constituted by *natural history* (Foucault 1970:139).

According to the French sociologist, it was only in the 18th century that natural philosophy went through a major change that established the conditions of possibility for present-day biology. In the first half of the century, Linnaean taxonomy, which classified the objects of nature into three kingdoms – minerals, plants and animals – laid the foundation of the modern biological scheme of binomial nomenclature. Living beings constituted one class, or rather several classes, in the series of all the things in the world, and so speaking of life was to speak about "one character – in the taxonomic sense of that word – in the universal distribution of beings" (Foucault 1970:160). Life was thus a mere category of classification, and the work of the naturalist was to order the objects of the world according to their visible structure. Only a few decades later, according to Foucault, the effort to turn the study of living beings into a science matching the prestige of the physical sciences transformed natural philosophers' efforts to collect and classify diversity into the study of *form*, called "morphology", and *function*, "physiology". The experiments and analysis of the French zoologist Georges Cuvier and his contemporaries were aimed towards understanding the internal organic structure of living beings. They revolutionized the science of classification by moving it from the hands of those who studied nature in the wild and bringing it into the controlled space of the laboratory or

[22] "We" stands, in astrobiological discourse, for the scientific community and, by extension, everyone else. Mirroring the idea that the exploration of space is an enterprise in the name of the entirety of humanity, astrobiologists promote a sort of scientific ecumenicalism.

dissection room, the new loci in which science was performed (Bowler and Morus 2005). As a new and fundamental category of knowledge, life produced new scientific objects and new methodologies of knowledge production (Foucault 1970:252).

In 2007, the University of California at Berkeley organized an interdisciplinary conference whose title asked the participants “what’s left of life?”, thus calling into question what, after 150 years, remained of Foucauldian life-itself (Helmreich 2011b:675). The question invited the participants to reflect not only on limits, possibilities and reconfigurations but also on the new loci of scientific knowledge and technological intervention. “The theoretical object of biology”, writes Stefan Helmreich, “is today in transformation, if not dissolution. Proliferating reproductive technologies, along with genomic reshuffling of bio-matter in such practices as cloning, have unwound the facts of life” (Helmreich 2011b:671). These rearrangements do not depend solely on new technological capabilities and the acquisition of new knowledge, but they are inscribed in new practices, mirrored by new biopolitics and multiplied as the disciplines dealing with life and its instantiations proliferate and cross disciplinary boundaries. As mentioned in the introduction, new biosciences reveal an essential condition of life as a scientific object: its being entrenched in the very social fabric that produces it.

The concept of life has gone through a multitude of revisions, adaptations and rearrangements during the last century, mirroring the different scientific frameworks within which it has been explored and their broader socio-cultural settings. The field of astrobiology offers a fertile soil to consider some of the issues raised above from a new and mostly unexplored perspective.

Instead of looking for a more exhaustive account of life that includes contemporary technoscientific developments, I am looking at the people that create these accounts, and I consider the concept itself to be generated through their interactions. I will move from the simple but meaningful consideration that attention to nature does not simply determine how to account for it: different cultures and disciplines have put different inherited concepts and labels into use. Barnes, Bloor and Henry’s assumption is that every inherited system of classification of kinds is learned by ostension, which they define as “any act whereby a direct association is directly displayed or shown or pointed out between an empirical event or state of affairs and a word or term of a language” (1996:41). Interestingly, despite ostension being indefinite, terms are eventually successfully taught, in the sense that each learner eventually becomes as competent as everybody else in her community in identifying which objects can be considered instances of a certain kind term, and thus in drawing what they call *similarity relations.*

> Ostensive learning is itself a social process. The learner is taught how to grasp things by other people, not by the thing[s] themselves, which remain silent and unconcerned. The right way to grasp things is established as convention in the tradition, and is transmitted in a social relationship involving trust in the teacher and acknowledgement of his or her cognitive authority. Which right way is taught will depend upon the tradition in which the learner is embedded […] each tradition orients us to experience in its own way (1996:54).

Beyond and above the explicit research into a definition of life, there are the many unproblematic uses of the term in everyday practice, which implicitly assume "what it counts as being *the same thing"* (1996:54). Science, in this respect, does not differ from any other field of knowledge. In science, nevertheless, different instances of a kind term (life, in this case) are pointed to in different ways: through a microscope, a spectroscope, coloured patches on rocky surfaces etc. – the relationships of similarity are therefore different, despite being referred to by what Barnes, Bloor and Henry called the same word-world relationships.

For this specific case study, it is interesting to put some emphasis on the fact that, because of the nature of ostensive learning, "future use of conventions or classification is underdetermined and indeterminate; it will emerge as we decide how to develop the analogy between the finite number of our existing examples of things and the indefinite number of things we shall encounter in the future" (1996:54). It is this indeterminacy that makes examples and counterexamples of life part of the training in becoming competent users of the term "life" in the cosmic context. Collective judgments, "negotiated on the basis of a range of more or less compatible individual perceptual intuitions" (1996:56), establish whether the use of a kind term is correct and the act of classification is performed successfully. Every time a kind term is applied, the object to which it is applied is added to the existing similarity relation, and thus changes that relation. Importantly, the interdependence of different acts of classification is a way of describing a form of interdependence between people.

Situating space science on Earth

"An Anthropologist on Mars" (1995) is the title of a book by the neurologist and writer Oliver Sacks, a collection of seven essays about the paradoxical role of mental conditions that both alienate and give new means of expression to the seven protagonists. The book has nothing to do with either anthropology or space, but the juxtaposition of the two words "anthropology" and "Mars" conveys a sense of impossibility that is familiar to the social studies of space sciences as well. Despite the large number of historical studies related to the field of astronomy (for example Kuhn 1962; Biagioli 1993; Azzolini 2013) from the 16th to the 19th century, and 20th and 21st century rocketry (McDougall 1985), anthropologists and sociologists of science have seemed more reluctant than other scholars to engage with the study of contemporary outer space related disciplines, as if the attention to the material practices that has characterized sociological and anthropological studies of scientific disciplines would not have been possible in these contexts. In fact, knowledge about outer space cannot help but be imbued with the Earthly logics of power and knowledge-making, as no knowledge can be detached from the social dimensions of its production and transmission.

It is only in the last 15 years that interest in the social dimensions of outer space has increased and is now becoming the focus of growing attention. In 2007, Fraser MacDonald, a cultural geographer interested in the history of rocketry, noticed the slowness with which contemporary human geography, as well as other social sciences, has "explore[d] the myriad connections that tie social life on Earth to the celestial realm" (MacDonald 2007:592), and advocated for a critical geography of outer space. Against the perception that the application of geographical approaches to other-than-Earthly places could be an esoteric enterprise, MacDonald provided a number of examples to show how outer-Earth had already been a sphere of human endeavour for several decades, yet still lay outside the "orbit of geography" (2007:593). From the increasing proximity of the Low Earth Orbit, reached almost weekly by satellites and spacecraft, to the everyday life reconfiguration that space-based technologies have made ordinary, such as the Global Positioning System (GPS), "our everyday lives", MacDonald argued, "already extend to the outer-Earth in ways that we entirely take for granted" (2007:594). This interest in space, he suggested, does not mark a rupture with the previous scholarship, but is a continuation and extension of the very same enterprise. First of all, outer space locales have and shape geographies: while space might seem an undifferentiated void that makes movement possible in any desired direction, the planetary bodies' gravitational pull imposes the use of particular paths or stationary points, so "natural" lines of travel extend from the terrestrial environment into the universe, making different orbits more suitable to "different astro-political purposes" (2007:599). Secondly, if one considers the relationship between knowing a place and exerting domination over it, a phenomenon entirely familiar to geographers, another element of continuity between Earth and space becomes apparent: space has (Earthly) politics. If space exploration, from its earliest origins to the present day, has been about familiar terrestrial and ideological struggles, MacDonald argues that "through space exploration we are forging new subjectivities and new forms of sociality here on earth" (2007:594), which in turn shape present logics of power and construct future alternatives. For its novel, far-reaching and critical approach to the study of space as an arena of human logics, Fraser MacDonald's paper still remains a cornerstone for every scholar approaching this theme.

At the beginning of the paper, MacDonald quotes one of the few exceptions to this apparent lack of down-to-Earth interest in outer space research: Peter Redfield's *Space in the Tropics* (2000). From the outset, Redfield wonders whether "it matter[s] where things happen? Or more precisely, what might it reveal that different things happen in the same place?" (2000:xiv). By exploring the shifting role of French Guiana from penal colony to satellite launch site, the anthropologist looks at the superimposition and entanglements between narratives of colonialism and the ESA Arianne space programme. By tying outer space practices to regional politics, Redfield makes the case that "outer space reflects a practical shadow of empire" (Redfield 2002:795; see also Redfield 2000) and thus carries the traces of previous forms of inequalities.

But If Redfield highlighted situated and Earthly logics of space activities, Stefan Helmreich, ten years later, showed how alienness informs understandings of the ocean's depths. Both Redfield and Helmreich play with unexpected connections between the local and the global: in French Guiana, space activities reconfigure local narratives about cross-ocean connections of power, while in Helmreich's work the local is dissolved in webs of meaning that cut across scales.

Helmreich's monograph branches off from the single site inquiry and embarks on a voyage across the webs of meaning in which the several lifeforms dwelling the depth of the oceans become meaningful for human forms of life. From marine biology to genomics, encompassing discussions about speculative forms of capital, race and nation, Helmreich's ethnography provides a compelling illustration of the way the sea is visualized, thanks to the mediation of technological devices, as teaming with microbial lifeforms that challenge longstanding definitions of life and show how contingent and contested their production is. In the closing chapter, Helmreich looks into the mobilization of extremophiles, microbes living in extreme environments (including, but not limited to, the deep ocean floor) in order to imagine life on other planets, thus collapsing the abyss and outer space as zones of alien biology. The concept of the alien proliferates and shifts as one tracks the long networks connecting lifeforms in, on and with the sea, and plays a central part in Helmreich's exploration of the making and unmaking of binaries such as same and other, intimate and foreign, Earthly and otherworldly. "The figure of the alien materializes", the author contends, "when uncertainty overtakes scientific confidence about how to fit newly described life forms into existing classifications or taxonomies, when the significance of these life forms for forms of life [...] becomes difficult to determine or predict" (2009:16). Importantly, the webs of meanings Helmreich describes are not simply made, but constantly reconfigured and mobilized to produce new universes of possibility.

There is, then, another element that Oliver Sacks' stories and the cultural studies of outer space share: the ambivalent role of otherness, a never-solved tension that allows new possibilities. The theme, already developed in Helmreich's work (2006), becomes the very core of Deborah Battaglia's edited volume *E.T. Culture: Anthropology in Outer Space* (2005), the aim of which is to take seriously the communities centred around a shared belief in alien beings and UFO sightings and their effect on popular and expressive culture. The relationship with the alien is seen as a projection of human needs and desires. Through the exploration of the various forms of visitation – including alien beings, alien technologies and uncanny visions – narrated by their informants, the authors engage with the primary concepts underpinning anthropological research: host and visitor, home and away, subjectivity and objectivity. Battaglia, together with David Valentine and Valerie Olson (2012), built on her work by engaging with other groups of people whose daily practices are aimed at making this encounter, even if under completely different premises, possible: cosmonauts (Battaglia 2012), astronomers (Hoeppe 2012) and colonizers-to-be (Valentine 2012). They suggest that extreme has become a signifier "securely attached to the problem of what humans, human practices, and human environments have become and are becoming, while simultaneously pointing to that which is to come" (Valentine, Olson and Battaglia 2012:1008). They argue that the extreme embodies a tension between defining a limit and opening new horizons, thus working as a mediating trope that brings limits and horizons into relation in complex and often unexpected ways. These works, addressing different processes of knowledge production and human imagination directed beyond Earth's atmosphere, show how outer space is first and foremost a realm of/for human sociality.

These studies, by emphasizing the Earthly logics embedded in outer space imagination and the new possibilities of expression offered by the establishment of new social relationships orbiting around space issues, ushered in a new wave of sociological interest in outer space. Very interesting examples are Janet Vertesi's *Seeing Like a Rover*

(2015) and Lisa Messeri's *Placing Outer Space* (2016), both dealing with place-making practices and the instruments that mediate and facilitate the understanding of those places, from the rover's kaleidoscopic cameras to the telescope lenses and the analogue field-site experience. Both works draw on several years of fieldwork among scientists at NASA and in other institutions. The former reveals the complicated set of practices that the team behind the Mars Exploration Rovers Spirit and Opportunity have to undertake in order to create the visual representations of the Martian landscape with which we are all familiar. The daily negotiations of the plan for the next sol (the Martian day), the programming of long-term scientific objectives and the processing, manipulation, interpretation and circulation of data provide an insight into science in action behind NASA's curtains. Ultimately, the author shows that every picture of Mars is not just a simple representation of the Red Planet, but portrays the whole Rover team as well. Messeri's *Placing Outer Space* looks into the place-making practices that turn the void of space into a place punctuated with worlds that can be known and explored. Messeri engages with different sides of exoplanetary research, trying to figure out the different strategies through which astronomers and planetary scientists envision distant planets as places. Place, in Messeri's work, is not a given but a social construction that passes through the sites of knowledge production she visits.

In 2015, Lisa Messeri joined forces with Valerie Olson to take up the baton from Fraser MacDonald in advocating the need for a growing sensibility for outer space in the context of the Anthropocene. By examining the emerging rhetorical topology of the Anthropocene, both a geological term and an environmental analytic, the two authors show how contemporary planetary narratives based on the inner/outer dichotomy in fact obfuscate the understandings of Earth's broader planet-scaled environmental relations that once informed contemporary environmental thinking. Messeri and Olson suggest that Anthropocenic theorizations can productively incorporate inclusive ways of thinking about environments that matter, and keep the Anthropocene "connected to its spatial absences and physical others, including those that are non-anthropos in the extreme" (2015:28).

Repertoires of change

The recent – and perhaps not yet complete – emergence of astrobiology as a legitimate field of inquiry shows two parallel kinds of boundary-work: first of all, astrobiologists and their forerunners have progressively turned "alien life", with its many resonances in pop culture and literature (Battaglia 2005; Crossley 2011), into an object of scientific investigation, thus claiming authority over themes salient in many other realms. Secondly, astrobiologists have had to position themselves within the broader scientific community and organize their field on both the social and the epistemological level. To do so, they have had to persuade peers and their funding bodies that there is a difference between the previous speculative (and thus non-scientific) ways of looking into the question of humanity's place in the cosmos and their own empirical scientific enterprise.

The problem of demarcating science from other kinds of knowledge dates back to Karl Popper, who held that scientific claims must be formulated in such a way that they could be falsified, i.e. tested empirically and eventually disproved (1963). Historians, philosophers and sociologists of science have looked very deeply into what "being scientific" means, coming to different, often contrasting, conclusions (for example Carnap 1952 [1928]; Merton 1973; Popper 1963). According to Barnes, Bloor and Henry, the drawing of the boundary between science and non-science has to be understood as a contingent social activity. In their words,

> What is to count as either of these things will be a matter of agreement, and it will be revisable. In so far as these concepts are used, these instances of use will be matters of fact to be understood in relation to the contingencies of particular historical situations. Similarly, the boundaries between scientific disciplines and specialities will be contingent accomplishments originating in specific situations and liable to revision as these situations change. (Barnes, Bloor and Henry 1996:140)

Scientists make and protect the boundaries of science both to avoid unwelcome additions to whatever may diminish science's reputation and to include the study of those objects which come to be considered within the realm of proper scientific investigation. To be adequately understood, the application of demarcation criteria has to be situated within its historical context and considered as a contingent social action (Barnes, Bloor and Henry 1996:142). In this thesis, I adopt the constructivist approach, which argues that "no demarcation principles work universally and that separation of science from other knowledge-producing activities is […] a contextually contingent and interests-driven pragmatic accomplishment drawing selectively on inconsistent and ambiguous attributes" (Gieryn 1995:393). Instead of trying to figure out whether astrobiology *is* scientific, I will try to follow the tensions and negotiations among scientists, lay public and other interested parties.

Thomas Kuhn's *The Structure of Scientific Revolutions*, published in 1962, paved the way for a new mode of writing the history of science: different "networks of commitments

– conceptual, theoretical, instrumental, and methodological" (Kuhn 1962:42), which he called *paradigms,* followed one another, each being able to explain what the previous one had already explained, and something more. Paradigms, at least in the hard sciences,[23] were incommensurable;[24] "when paradigms change, the world itself changes with them" (Kuhn 1962:111). A shift of paradigm was described by Kuhn as a gestalt shift: the same lines can give form to different objects, and once the shift has happened, it is extremely hard, if not impossible, to go back to the previous one. "After a revolution", Kuhn argued, "scientists work in a different world" (1962:135). At least in Kuhn's early work, incommensurability is both semantic – words are used with different meanings – and material – theories are literally incommensurable "as instruments providing the measurements for the one are inapt for the other" (Hacking 1992:56).

In the late 1990s, out of the so-called "laboratory studies", Karin Knorr Cetina moved beyond Kuhn's paradigms by associating the practice of science to that of culture, thus coining the phrase *epistemic cultures*, which she defined as "the amalgam of arrangements and mechanisms – bonded through affinity, necessity and historical coincidence – which, in a given field, make up how we know what we know" (1999:1). Knorr Cetina suggested that science is in fact divided into cultures of knowledge, each reflecting a diverse array of practices and preferences. Despite internal disciplinary homogeneity, science includes many different epistemic cultures, which constitute and are sustained by "distinctive traditions of teamwork and publication, specific epistemic strategies, different meanings of the empirical, and distinctive notions of reality as it was dealt with by the science" (Knorr-Cetina and Reichmann 2015:874). Moving beyond the mere reference to a generic scientific method, Knorr Cetina emphasized the many facets of science, not just with reference to the variety of methodologies used, but also with respect to how the world is accessed and constructed (Knorr-Cetina and Reichmann 2015).

Comparing science to culture is not devoid of consequences. In the 1970s and 1980s, sociologists, anthropologists and feminists began to study scientific communities as "tribes", "cultures" and "power networks". For many writers in the sociology of science as well as for many feminist critics, science was no longer the purely cognitive, socially disinterested and gender-neutral rational enterprise that had often been presented by

[23] This was what, according to Kuhn, distinguished "hard" from "soft" sciences: in the latter, more than one paradigm might be in place at the same time.

[24] Kuhn redefined incommensurability many times in his lifelong career. For insights into the way the concept changed, see Sankey (1993).

traditional philosophies of science. On the contrary, science started to be understood as one social culture (or bundle of cultures) that can be studied with methods known from sociology and anthropology. Knowledge plays, in this cultural form, a foundational role, as the scientific community – the science tribe – is defined by the adherence to a certain way of producing knowledge and a certain body of knowledge; the two cannot be disentangled.

However, recognizing that science is a cultural entity can open up as many issues as it tries to solve. Anthropologists (among other scholars) have defined culture in numerous ways, from a stable and self-contained whole made up of coherent patterns, beliefs and symbols to a more contemporary approach in which culture is seen as a porous set of intersecting practices. The social studies of science, despite having broadly embraced the idea of science as a cultural entity, have not always kept pace with it. Knorr Cetina, for example, admits that her concept of epistemic culture is resistant to change. Bounded by disciplinary institutionalization, epistemic cultures seem to be self-sufficient and not in conflict with each other. In new and emerging fields, nevertheless, the situation might be less straightforward.

Astrobiology, for example, is often talked about as an emerging discipline whose scientific community is still in formation, and whose methodologies, instruments and protocols are still being negotiated. Yet the creation of an epistemic space in which astrobiologists' questions would make sense, and be worthy of the social, economic and institutional effort that the development of a research programme requires, escapes in many ways both the Kuhnian framework of revolutions and change that astrobiologists use so often, and Knorr Cetina's more pragmatic but too rigid concept of epistemic culture. First of all, the interest and attitudes toward the search for life elsewhere have gone through ups and downs of optimism and disillusion, and attempts to answer the question "are we alone in the universe?" have taken many forms, from the search for intelligent signals in the form of radio waves to the search for an origin of alien life on Earth. These different questions have been neither completely overlapping nor always separated, but they have functioned as resources that scientists can employ selectively and strategically. The kaleidoscopic introduction to astrobiology that opened this thesis is an example of the way they can be combined, but this was not the only possible narrative, despite being the most popular at the time I entered the field. Secondly, scientists' choices to embrace or turn away from some or all of these questions are not only rooted in scientific motives, but involve a number of pragmatic choices and normative assessments that make sense only when considered within their social context: funding availability, institutional support, career choices etc. have determined the tying and twisting of the resources available in ways that make sense in each particular historical, cultural, political and economic situation. Last but not least, different modes of "doing science" (roughly identifiable with epistemic cultures) have been employed at the same time to foster strategically scientists' interests or encourage communication and collaboration with different communities. One might, for example, participate in a fieldtrip and act as a geologist, publish the findings in a microbiology journal and then advocate one's interests as deeply astrobiological when applying for funding. As noted by Ankeny and Leonelli, in emerging interdisciplinary contexts "researchers can and do move between different approaches and models of work, depending on circumstances, including making smaller-scale changes and using more than one approach simultaneously" (2016:19).

Ankeny and Leonelli have used the term *repertoire*, defined as the "assemblages of skills, behaviours, and material, social, and epistemic components that groups may use to practice certain kinds of science, and whose enactment affects the methods and results of research, including how groups practice and manage research and training" (2016:20) as a useful thinking tool to explore and make sense of this complexity, made up of expertise, knowledge-making and practical considerations in a situated manner.

The word "repertoire" comes from the Latin *repertorium*, a word used to address the works performed by an artist, the abilities and skills needed for these performances and also the unique characteristics of each specific enactment. Today, the word maintains these associations and refers to both what is regularly performed and the skills that a person habitually uses. For Ankney and Leonelli, the performative dimension of a repertoire is connected to the idea that it can be enacted by different groups. Like in a music performance, a repertoire is not reproduced identically in every circumstance, but variations and local specificities are part and parcel of what makes a performance successful; in each instantiation, a performance has to be both recognizable and original.

The concept of repertoire had previously been used in the studies of culture to explore continuities and discontinuities inherent to processes of cultural change. The most noteworthy example is anthropologist Ann Swidler's suggestion that "a culture is not a unified system that pushes action in a consistent direction [...] it is more like a "tool kit", or repertoire from which actors select differing pieces for constructing lines of action" (1986:277). People, she suggests, do not select actions one at a time as straightforwardly instrumental to given aims. On the contrary, they build chains of action starting from at least some "pre-fabricated links". Culture, she claims, influences action through the arrangement of those pre-existing links. Even in science, therefore, technological and material practices are inevitably borrowed from other disciplines, adapted to different goals, or rejected as insufficient or misleading. Each of these practical decisions and judgments establishes the kind of knowledge or non-knowledge to which a discipline commits, who is considered knowledgeable, which promises deserve credit, which challenges have to be tackled and which new tools and concepts are needed. They also enable the elaboration of "strategies for coordinating and managing" (Ankeny and Leonelli 2016:20) both the social structure and the know-how characterizing all these components. These practical decisions come from a strategic recombination of past and present resources that create new possibilities for the future. Following Swidler, the term "strategy" is not used in this thesis in the conventional sense of a plan intentionally contrived to a certain end, but as a "general way of organizing action that might allow one to reach several different life goals" (1986:277).

My use of the concept of repertoire is more similar to the one proposed by Ankeny and Leonelli, but takes into consideration the continuities and discontinuities inherent in the processes of change that Swidler's work emphasizes. I will not, therefore, claim that skills, attitudes, models of work and all the other components that come to constitute the repertoires adopted by astrobiologists are unique and exclusive to those very repertoires. On the contrary, they are usefully deployed exactly because they are *not* unique, but allow communication and exchange with other fields. They are, nevertheless, arranged in ways that give them more or less prominence and it is this arrangement that is unique and characterizes each repertoire. For example, the fact that scientists still do not know what life is (an idea whose role in astrobiology is central in this thesis) is not unique to astrobiology. Most biologists would probably agree with this claim, but would not usually consider it at the very core of what they do on a daily basis and would not mention it at the outset when defining their discipline. They would probably admit to it only if pushed in that direction, and probably with some reluctance. The same can be said for some of the skills I will talk about in the next chapters: doing fieldwork, for example, is not exclusive to astrobiology, but it is common in many other kinds of research. However, selecting certain kinds of sites and treating fieldwork as providing the necessary experience to recognize life on other planets is indeed quite a specific attitude. In other words, the single elements of a repertoire - the material, social, epistemic and practical resources that constitute it – are not unique. It is their relationship and mutual strengthening that makes them so.

As well as emphasizing Swidler's emphasis on change and continuity, the concept of repertoire I make use of in this thesis departs from Ankeny and Leonelli's for another reason: despite their definition of repertoires as sets of resources including both material and theoretical elements, the examples they offer tend to overlook theoretical components. They do so in order to emphasise one of the features of their approach to scientific change: the fact that change is *not* driven by theory. This is one of the original elements that distinguishes it from Kuhnian accounts of change. This emphasis, nevertheless, makes their concept of repertoire almost devoid of theory, as a mere institutional organization fostering collaborations and research. In this thesis, on the contrary, I have tried to move beyond this rigid distinction by describing the unavoidable entanglements of theory and practice, and thus the impossibility of making one of them prevalent over the other.

In the empirical chapters, I look into the more or less successful deployment of scientific repertoires, focusing on the commitment to porous boundaries and the production of non-knowledge to look at the process of disciplinary formation. Disciplines and fields of research are not inscribed into nature. As with any other system of classifications, disciplinary boundaries are the outcome of the social arrangement in which they are created and deployed. As such, they depend on precise historical coordinates and are subject to crossing, revisions and negotiations. Typologies can also co-exist, so that different scientific disciplines and systems of knowledge can deal with different constructions of the same "object" (nutrition, for example, can be appreciated from either a physiological, a legal or a religious perspective with different consequences), or be contested (Gieryn 1983). A discipline is both an intellectual and a practical arrangement: it is a specific form of social organization of the production and reproduction of knowledge. It faces, within precise historical coordinates, a series of challenges: finding economic resources to support people's activities; agreeing on the proper means of communication; negotiating norms of conduct and conventions of discourse; regulating the inclusion or exclusion of practitioners; recognizing merit and status for its members; and securing external legitimacy (Turner 2017; Hackett *et al.* 2017).

Ethnographies of non-knowledge

By exploring the practices deployed by astrobiologists to answer the question "what is life?", I have come to appreciate their commitment to the expression *life as we-don't-*

know-it. In this expression, the epistemic and the ontological dimensions of alien life overlap: being *other* and *not being known* coincide. What might seem a mere catchphrase is in fact very meaningful in terms of what is produced by astrobiologists' practices and why. The juxtaposition of the many research fields, techniques and narratives about Earthly and extra-terrestrial life eventually contributes to the creation of unknowns.

With a few excellent exceptions,[25] sociologists of science have only very rarely taken into consideration the social processes though which, within a scientific community, non-knowledge, uncertainty, ignorance and doubt are created, the status they acquire and the possibilities of action that they might open (McGoey 2009, 2012; Street 2011). It is easy to imagine that this could be due to the fact that ignorance is often simply described as a void to be filled[26] and uncertainty as a form of incompleteness of information. To a certain extent, the history of sociology of science itself might have also contributed to reinforcing this tendency to overlook non-knowledge claims.

Although until the early 1970s, only errors and mistakes in science were believed to have social causes, in the following years, historians and philosophers became keen to explain both "true" and "false" – successful and unsuccessful – knowledge claims, with the same type of explanation. Truth came to be considered the outcome of a social process, not an explanatory resource (Barnes 1992; Barnes, Bloor and Henry 1996). The process of knowledge production became the very core of the new sociology of science, and looking into scientific ignorance and non-knowledge might therefore have appeared to be a step back (Croissant 2014). Despite refusing a narrative of progress describing science as the accumulation of knowledge, sociologists of science had mostly described science in terms of the production of knowledge and the overcoming of moments of uncertainty. Attention to relationships of power, both between the scientific community and the lay public and within the scientific community itself, has shown that science not only produces knowledge, but also establishes how things can be known, and who can know what. In the distribution of these social roles, nevertheless, it is not only established what is known, but also what is *unknown.* Non-knowledge claims are constitutive of the scientific endeavour, and the same analytical

[25] A major exception is the extended literature on risk evaluation (for an overview, see Beck 1992; Giddens 1998).

[26] As noted by Smithson (1985), this claim is often implicit; Smithson mentions Moore and Tumin (1949) as a rare example of explicit description of ignorance as the lack or distortion of "true" knowledge.

tools used to explore the processes of knowledge production offer insight into the complementary shaping of non-knowledge claims (Smithson 1985).

Authors such as Abbott (2010), Smithson (1985) and Proctor (2008) have proposed typologies to describe how many kinds of non-knowledge – so to speak – exist, how they are put in place and their function. In *Agnotology*, Proctor proposes a threefold classification to question "the *naturalness* of ignorance, its causes and its distribution" (Proctor 2008:3). The author describes the first kind of ignorance as a *native state* or resource; scientists, he claims, think about ignorance as a "great place to be from." In his words,

> Ignorance is seen as a resource, or at least a spur or challenge or prompt: ignorance is needed to keep the wheels of science turning. New ignorance must forever be rustled up to feed the insatiable appetite of science. [...] This regenerative power of ignorance makes the scientific enterprise sustainable. We need ignorance to fuel our knowledge engines. (Proctor 2008:4).

Proctor distinguishes this type of ignorance from other instances such as the maintenance of military secrecy or the tobacco industry's attempts to cast doubt on the effects of smoking, which he describes as a *strategic ploy* or an active construct, as "something that is made, maintained, and manipulated by means of certain arts and sciences" (Proctor 2008:8).[27] Nevertheless, as Smithson recognizes, ignorance is always socially constructed, even when it is described as a native state – the original condition of infancy or a void to be occupied by knowledge. "Ignorance" he claims, "is a social creation, like knowledge. Indeed, we cannot even talk about particular instances of ignorance without referring to the standpoint of some group or individual" (Smithson 2007:6). Ignorance, like knowledge, is thus always socially constructed and negotiated.

In joining those who advocate paying more attention to the social production of unknowns and their strategic deployment, I recall McGoey's suggestion to resist the tendency to value knowledge over non-knowledge, "to assume that the procurement of more knowledge is linked in an automatic or a linear fashion to the attainment of more social or political power" (McGoey 2012:1). As Mair, Kelly and High claim, the anthropological approach to non-knowledge considers ignorance as a phenomenon with its own history, practices and effects, and remains open to the possibility that people attribute a particular value to their ignorance and actively work to maintain it. As they

[27] On the production of doubt by the tobacco industry, see Michaels (2008) and Oreskes and Conway (2010); on military secrecy, see Galison 2010.

recognize, ignorance is not simply the absence of knowledge, but also a "substantive historical phenomenon that in each particular case might incorporate certain knowledge, logics, ethics, emotions, and social relationships" (2012:3). Ignorance, they claim, has a substance of its own. An ethnography of ignorance, therefore, requires attention to the "production, out of the infinite sea of things that people happen not to know, of culturally recognized and elaborated units, fields, and modes of ignorance" (2012:16).

A number of terms referring to claims about what is unknown can be found in the literature. In this thesis, I have preferred the verb *not-knowing* and the nouns *non-knowledge* and *unknown* to emphasize the connection to knowledge and the same social nature.[28] I follow Matthias Gross's suggestion to adopt the term *non-knowledge* as a literal translation of the German *Nichtwissen*, indicating "a type of knowledge where the limits and the borders of knowing are taken into account for future planning and action" (Gross 2007:749). I prefer these terms to the term *ignorance* as the latter shares the same root of the verb *to ignore,* whilst the kind of claims I am taking into consideration are not ignored at all: they are formulated, agreed upon and explicitly used for specific purposes.[29] At the same time, I think that bounding my argument to what is *ignored* would imply that scientists are taking into consideration something that was previously neglected but has always been "out there". On the contrary, I contend that *unknowns* are socially constructed (Dilley and Kirsch 1977:15). In using *non-knowledge* and *unknown*, I nevertheless resist further typologies as I am intrigued by the plasticity of those non-knowledge claims; rather than encapsulating them in a few categories, I prefer to attend to their specificities and contingencies, and thus I will make use, at times, of other words with slightly different connotations such as *indeterminacy, vagueness, uncertainty, unreliability, unpredictability* etc.

As we shall see in this thesis, the non-knowledge that astrobiologists produce about life is not simply a threat to science; it is also generative and performative at the same time, as it creates a demand for the settlement of the uncertainty it perpetuates and substantiates the epistemic power of those who advanced a position of uncertainty (McGoey 2009). Eventually, I claim that, in astrobiology, unknowns are aimed at creating and maintaining the status of scientific discipline and, at the same time, disrupting the prominence of traditional Earth-bound biology.

[28] In other words, a non-knowledge claim is a claim that takes the form of "we understand and agree on the fact that we do not know X".

[29] I often use the term *uncertainty*, but with its common sense meaning, without any reference to the broad literature on uncertainty and risk assessment.

Chapter 3

From Microbes to Mathematicians
The Search for Extra-Terrestrial Intelligence

"I was a disembodied, wandering view-point."
— Olaf Stapledon, *Star Maker*

SETI and the boundaries of science

It was 1975, and a young woman named Jill Tarter[30] had just finished her PhD in Astronomy at UC Berkeley. With a background in engineering, Dr. Tarter had been studying a new category of sub-stellar objects for which she coined the phrase "brown dwarf" (Tarter 2013). Too faint to be seen with optical telescopes, their detection was dependent on infrared astronomical techniques, whose data analysis required, at the time, the use of a PDP-8/S, one of the first computers that would fit on a desk. Because of the rapid turnover of hardware, some obsolete and disused PDP-8/S were donated to the Hat Creek Radio Observatory, a radio astronomy facility in a remote valley 300 miles northeast of San Francisco, to elaborate the data collected in the search for what is commonly referred to as "extra-terrestrial intelligence"(Tarter 2006), a phenomenon possibly even more elusive than the faintest brown dwarf.

A few months after the end of her doctorate, Jill was asked to use her programming skills at the service of this SETI project to help program the computers donated by her department. The Hat Creek Observatory was the gathering space for those working on

[30] Jill Tarter is not only a leading scientist, but also an iconic character in the SETI community; any effort to anonymize her would be in vain.

the so-called "Project Cyclops" (Oliver and Billingham 1971), a long proposal written a few years earlier by Bernard Oliver, head of the R&D department at Hewlett-Packard Corporation, and John Billingham, head of the Biotechnology Division at NASA Ames Research Centre. The document proposed the design of a telescope array to survey the sky in search of artificial radio signals beamed to Earth. "I read that document from cover to cover", Tarter recollected,

> it took about one day and a half and I didn't sleep and I was really excited… I was excited by the fact that for millennia we've been asking to priests and philosophers, and other people we thought were wise, "what is the answer? Is there anybody out there?" And suddenly I realized that in that 20th century, we suddenly had some tools that would allow the scientists and the engineers to try and answer that question on the basis of what that is, rather than on somebody's belief system. And I just thought "aaaw, spectacular!", so here I am, it's the right time, I have the right skills, I have an engineering background, I just got a, you know, an astrophysics PhD, and I can do this. Um, I said, absolutely, I am in.[31]

Jill's enthusiastic account of her first reaction to the ambitious proposal in my interview with her reveals something interesting about the attitude toward the search for extra-terrestrial life and its status at that particular time: Jill's description of SETI portrays it as a rephrasing, in scientific terms, of questions that used to be the domain of "priests and philosophers", which she antithetically placed in opposition to scientists and engineers. Despite being a niche project, she did not doubt its scientific status. Over the 40 years since Jill's first involvement with SETI, people have had different, often contrasting, opinions about whether the search for extra-terrestrial intelligence falls within the realm of *legitimate* and *worthy* scientific investigation (Garber 1999).

In the same period of time as my meeting with Jill Tarter, in January 2016, at the heart of the Berkeley campus, a large room in the recently restored Astronomy department building was being refurbished in order to be designated as a new SETI lab. One of the largest SETI groups in the world has been based at UC Berkeley for almost four decades. After a period of changing fortune, the group of astronomers and engineers was finally back in full swing thanks to a generous donation by Yuri Millner, a Russian billionaire funding SETI research for a $100 million ten-year project named Breakthrough Listen.[32]

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31 Jill Tarter, interview 04/12/2015.

32 More details about the Breakthrough projects can be found at http://breakthroughinitiatives.org/initiative/1 (last accessed 05/07/2018).

> We, you know, want to…to conduct the best SETI programme ever, we wanna see SETI [coming into] its own as a *bona fide* scientific inquiry. We want every university in the world to mean to have a SETI person you know, there, in their astronomy department. We wanna kind of take SETI from being sort of…kind of fringe esoteric kind of cabalistic little thing to a mainstream part of observational astrophysics and astrobiology. That's the goal. And I hope we get there.[33]

In the words of the centre director, SETI is indeed recognized as a scientific inquiry by those who take part in it, but the quotation also shows the need to make its status similarly recognizable by those who come from outside the ranks of SETI itself. His uncertainty does not refer to the general public, who have often shown a sympathetic and supportive attitude, but to the sceptical gaze of those he would expect to be peers and colleagues (Ćirković 2013), those scientists approaching SETI for the first time from cognate fields, too often putting up resistance to SETI's inclusion in research pursued in academic settings.

In my account of the shifting status of the search for extra-terrestrial signals, I will not focus on discoveries or theoretical shifts – in fact, no discovery of extra-terrestrial life has ever been made. Instead I will show how a series of practical rearrangements articulated and re-articulated SETI research in historically situated framework which proved to be more or less successful.

Over the decades that separate Dr. Tarter's enthusiastic reaction to SETI and Yuri Millner's generous donation, SETI underwent several ups and downs. In this chapter, I retrace some of the phases of SETI's history and discuss what can be considered the first successful research repertoire on which SETI – and more generally the search for life elsewhere in the universe – was built for several decades: the so-called Drake Equation. In doing so, I point to the historical context in which SETI managed to acquire a certain scientific authority as a research project. I claim that the emergence of a new object of scientific inquiry, extra-terrestrial life, and of a new field of research, SETI, are due to the successful creation of a temporary community which included people from many different backgrounds by means of the Drake Equation. The formula framed extra-terrestrial life in a mathematically informed manner and shaped the research on an institutional and epistemological level simultaneously. The Drake Equation alignment proved to be successful for certain amount of time, and then its odds changed. Some of

33 AS, SETI astronomer, interview 24/02/2016.

the people involved in SETI research changed institutions to continue what they were doing, others simply disengaged with the research project and moved on with their more mainstream research. No *Gestalt* shift was actually produced by the Drake equation, and many scientists who jumped on the bandwagon of SETI abandoned it with equal ease. But SETI did not fade away disappearing forever: many scientists kept on working on it and SETI remained a resource to be used in other research enterprises and a reference point against which boundary work was conducted.

One might wonder why SETI is being discussed at the beginning of a thesis about astrobiology. It is because a study of the unfolding of SETI provides a valuable position to think about the historical trajectory of the search for life in the universe and points to the historical situatedness of any research repertoire. The success of the Drake Equation in making a certain scientific enterprise relevant was not due to any theoretical development: nothing new had been discovered. The Drake equation simply put into use a set of resources that were already available and made a coherent strategy out of them. But I also want to suggest that no set of resources is necessary or obvious given the research question at hand; both SETI and astrobiology try to answer the question "are we alone in the universe?", but they phrase the enterprise in different terms, deploy different instruments, skills and theories, appeal to different communities and are articulated in different institutional settings. They are therefore to be understood as discrete – sometimes diverging, sometimes overlapping - arrangements of resources whose legitimacy and authority has to be continually negotiated within specific social coordinates.

The beginning of SETI

Inquiry into the existence of extra-terrestrial life is not a recent idea; speculations have taken many different forms according to historical and cultural circumstances. The debate over the plurality of worlds is only one of many examples (Brake 2006; Drake 1982). At the end of the 19th century, both Guglielmo Marconi and Nicola Tesla registered signals they could not explain with natural phenomena, and they suspected they might be due to alien communications. The news made it into popular magazines, but none of the surmises was ever considered a scientific claim. Despite the lively discussions about interplanetary communication in amateur radio literature, according to NASA historian Stephen Dick, SETI's "time had not yet come" (Dick 1996:414). It was only in the second half of the 20th century that the attitude changed, as later recognized by John Billingham and Bernard Oliver:

> It is only recently that speculation about the existence of intelligent extra-terrestrial life has turned into serious scientific study. As recently as 40 years ago, almost all scientists, speaking *ex cathedra,* would have argued that life, if not unique to earth, was at least exceedingly rare. The last 15 years have brought about an almost complete change of opinion. Today a large segment of the scientific community is willing to accept the belief that life is common in the universe and indeed that many civilizations have existed and still exist in our Galaxy, and that many may be more advanced than our own. Indeed, the debate is now concerned primarily with how best to discover these civilizations rather than with the plausibility of their existence. (Oliver and Billingham 1971:3).

The two authors of the ambitious Project Cyclopes recognized the change in attitude that had happened over the course of the previous decade and thus wondered, "[w]hat is it that gives us such faith, and the audacity to suggest such an undertaking? What has caused such a reversal of conventional scientific thought over the last few years?" (ibid). This is the same question I would like to ask in this chapter. What made the search for extra-terrestrial life – interpreted as a search for artificial signals – come to be perceived and embraced as a legitimate research enterprise over the course of the last few decades? And also, when did these conditions and resources misalign?

The origin of contemporary SETI dates back to 1959, when Giuseppe Cocconi and Philip Morrison, two particle physicists from Cornell University, published a paper titled "Searching for Interstellar Communications" in the prestigious journal *Nature*. The two-page article presents an idea they had been developing for several years during their theoretical work on gamma rays at the Cornell synchrotron. Considering the capacity of the radiation beam produced during their experiments to reach distances of the order of the galaxy, they envisaged the possibility that these frequencies could be used for interstellar communications. Aware of the large amount of energy required to generate gamma rays, they proposed that radio waves, having the same properties but requiring a much more modest amount of energy to be produced, might be used instead. "What set Professors Morrison and Cocconi apart", according to the press of the time, "was that they had thought their philosophy through, applied it specifically to the physical theories and to the state of the art in instrumentation of the immediate present, and emerged with a course of action." (*Saturday Review* 1960). The way Cocconi and Morrison formulated their proposed research design followed the particle physics experiment pattern: the planning of a series of trials and observations to detect something that had been predicted in theory. Still quoted today by SETI scientists all around the world, the closing sentence of the article for the first time phrased research effort in terms of *probability of success*: “the probability of success is difficult to estimate, but if we never search the chance of success is zero” (Cocconi and Morrison 1959:846).

In the following year, Frank Drake, astronomer at the National Radio Astronomical Observatory at Green Bank, West Virginia, conducted the first SETI observations (Shuch 2011). The project was named *Ozma* after "the queen of the imaginary land of Oz – a place very far away, difficult to reach, and populated by exotic beings" (Drake, in Struve 1960:22). In both Cocconi and Morrison’s article and Drake’s research, the 1420 MHz emission line, the wavelength of the radiation emitted naturally by interstellar hydrogen, was suggested as an appropriate choice to communicate with galactic neighbours. The decision was mostly based on the practical limitations of the search: the emission of waves in the radio portion of the microwave spectrum requires a relatively moderate amount of energy; and both interstellar dust and the Earth’s atmosphere are transparent to radio waves, which can therefore pass through regions that would be completely opaque to visible light and also be searched from telescopes on the ground with continuity. Last but not least, hydrogen is the most common element in the universe and therefore, in Cocconi’s and Morrison’s words, “it is reasonable to expect that sensitive receivers for this frequency will be made at an early stage of the development of radio astronomy” (Cocconi and Morrison 1959:846). In my interview with Frank Drake, he elaborated:

> Very few astronomers thought there was life in space. […] when I was a young astronomer, it was a very bad thing to believe in life in space, it was a taboo subject. When I started talking about it, the only reason why I got a way around it is that the director of our observatory at that time – this was Green Bank – was Otto Struve. He was considered the world's greatest optical astronomer. He happened to be one of the few astronomers that thought there was life in space […] and he was also renowned, nobody dared consider him evil for that. So I proposed to him to look for signals, and he was like "yeah, great!" ahahah, that's how it all got started.[34]

In the early 1960s, the search for extra-terrestrial intelligence had been first formulated within a scientific framework. The vocabulary they used could be

[34] Frank Drake, interview 27/02/2016.

evaluated as scientific hypotheses and thus started being treated as such. What is more, those who took responsibility for these hypotheses were already popular within their scientific field and lent to SETI the credibility they had already secured in their own careers. Nevertheless, up to this moment, the search for artificial signals was nothing more than an individual experiment. Certainly, Giuseppe Cocconi and Philip Morrison on the one side and Frank Drake on the other came to their conclusions independently and thus demonstrated at least the presence of an interest in the issue of extra-terrestrial life, and the availability of a certain technology to be deployed. But their speculations would have remained individual intuitions without the creation of a community with whom to share them, not unlike Marconi's and Tesla's claims only few decades before. It is only with the Drake Equation that a repertoire available to and reproducible by others was created.

The Drake Equation: the plausibility argument

The following year, Frank Drake organized the first SETI meeting at the Green Bank Observatory (Shuch 2011). The group gathered by the astronomer reflected the breadth of expertise he considered necessary to the enterprise: the small group included astronomers, physicists, biochemists, a linguist and electrical engineers[35] (Dick 1996:427). To summarize the agenda, or to "compress a large amount of *ignorance* into small space" (Billingham and Oliver 1971:26, emphasis added), Frank Drake devised a concise way of quantifying the possibilities of making a contact with an intelligent extra-terrestrial civilization, the so-called Drake Equation:

[35] The group was composed of Otto Struve and his former student Su-Shu Huang, whose work predicted that the number of habitable planets around other stars was large; Giuseppe Cocconi, Philip Morrison and Frank Drake himself; Carl Sagan, a young astronomer who became, in the following decade, the strongest advocate of SETI on the public and political stage; Melvin Calvin, a prominent biochemist supporting the idea that the origin of life was a common and even inevitable step in planetary evolution, who was awarded the Nobel Prize for his work on the chemical pathways of photosynthesis during the meeting; John C. Lilly, a dolphin researcher whose work was adopted as emblematic of the spirit of the meeting, so they started calling themselves "the order of the dolphin"; Bernard M. Oliver and Dana W. Atchley, both electrical engineers; and J. P. T. Pearman, biologist of the National Academy.

$$N = R^* \times f_p \times n_e \times f_l \times f_i \times f_c \times L$$

N	number of communicating civilizations in the galaxy
R^*	rate of star formation
f_p	fraction of stars with planets
n_e	number of planets per star with environments suitable for life
f_l	fraction of suitable planets on which life developed
f_i	fraction of those life-bearing planets on which intelligence evolved
f_c	fraction of cultures that were communicative over interstellar distances
L	lifetime of communicative civilizations

The equation was not meant to be solved, but to express in mathematical terms the agenda of the meeting and the forms of expertise gathered in the room. The equation, in Drake's words,

> was a way of organizing the meeting. I thought we should organize the meeting and categorize topics and establish themes for various sessions at the meeting and that caused me simply to think about what we needed to discuss and how these things were related. And it was easy to see that they were in the way that is described by the equation.[36]

The equation, not unlike the astrobiological imaginary journey through space outlined in the introduction, is a zooming-in movement whose focus moves from the immensity of the galaxy to the very specific forms of life and intelligence emerging on the planets offering suitable conditions. The terms of the equation also mirrored the expertise of those attending the meeting: the first terms (R^* and f_p) represented the variables whose estimation would be pursued by astronomers; the following terms (n_e, f_l and f_i), regarding the possibility and actual emergence of life, were within the realm of evolutionary and micro-biology; and the last terms (f_c and L) were meant to be informed by linguistic and socio-historical sensibilities. When multiplied, they would give an estimate of the possibilities of making contact with another civilization[37] in the galaxy that was capable of radio communication.

[36] Frank Drake, interview 27/02/2016.

[37] "Civilization" is an actors' category; it is broadly used to indicate the population of a planet capable, on the whole, of broadcasting radio signals for communication purposes. This ideal is

The last term, L, the average lifetime of technologically advanced civilizations, allowed SETI practitioners to turn society into a numerical factor – at least in theory (Maccone 2013) – and to include it in an argument articulated thanks to the semantic field of *probability*. On the other hand, it presupposes that those societies which, during their history, become capable of producing and using a technological apparatus will eventually end up destroying themselves by means of the very tools they have developed. During the Cold War, this was more than just a feature of dystopian science-fiction novels; the fear of a nuclear war that would eventually bring humanity to an end constituted a part of everyday experience and is understood as the very fuel powering the space race bold enterprises (Wolfe 2002). In this context, the feeling of empowerment given by science and technology was counterbalanced by the fear they would ultimately bring humankind to an end. "Think about it", suggests Jill Tarter,

> if we detect a signal, we could learn about *their* past and the possibility of *our* future. Successful detection means that, on average, technologies last for a long time. Understanding that it is possible to find solutions to our terrestrial problems and to become a very old civilization, because someone else has managed to do just that, is hugely important! Knowing that there can be a future may motivate us to achieve it. (Tarter, in Major 2012)

In an era of uncertainties and ambiguous relationships with science and technology, SETI found in the Drake Equation a successful repertoire not only for its ability to phrase its research in terms that were compatible with the institutional organization of science, but also by deploying a rhetoric that coherently situated the research within the broader historical context. The last term of the Drake Equation (L) was the real unknown quantity, to be extrapolated by determining the others. Contact with an extra-terrestrial civilization boded well for the future of humankind.

The mathematical language of probability, or what came to be called a "plausibility argument" by Bernard Oliver and John Billingham in their Project Cyclopes (1971:5), came to constitute SETI's specific way of framing their enterprise, providing a specific vocabulary and, at the same time, determining the range of possibilities of what could be

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highly technocentric: the decision-making process and the content of the message itself are imagined to be strictly connected to the use of mathematic and rigorous logic, which are often thought of as *universal.*

said and done. The following excerpts are only two of the numerous examples that could have been chosen:

> "Are there intelligent living beings on any of the many billions of planets?" Opinions may differ. An intrinsically improbable single event may become highly probable if the number of events is very great. (Struve 1960:23).

And also:

> We are in the position of a man who has bought a lottery ticket, not knowing what kind of lottery it is. It may be a great international sweepstakes with odds of 10 million to one against anyone winning. Or it may be a neighbourhood raffle where chances of winning are high (Morrison, in Bradbury 1960:118).

The use of mathematics, also embedded in the choice of a privileged frequency (the 1420 MHz hydrogen line), and the technicalities of radio astronomy allowed scientists to draw a boundary around the scientific community, which they situated against both religion and pseudoscientific movements, thus legitimizing their work and giving a scientific basis to its promises. Frank Drake explains:

> [Mathematics] gave the subject some credibility, because radio SETI from day one was based on real numbers: what signal strength we detected; is that plausible? Is that reasonable? It was not just "we have got no idea, but let's look", we could say a signal of this strength can be detected from Earth, which was true even in the 1960s. So it had a…it really sounded scientific, and more and more people got into it.[38]

SETI researchers have often described the Drake Equation as a *paradigm* (for example in Vakoch and Dowd 2015:6). In fact, the enterprise was far less totalizing, leaving room for other ways of searching for extra-terrestrial life and other kinds of research upon which, often, SETI scientists built their own academic careers, with very few exceptions. SETI can be better understood as a shared interest that oriented scientists and engineers toward broad collaborations. Sometimes they actually had the chance to work together in the same physical space or institution, but most of the time scientists would put their different skills and training to use for SETI, whilst maintaining a "comfortable primary identity"[39] in a different research field. The rise of a new object of

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[38] Frank Drake, interview 27/02/2016.

[39] IS, SETI astronomer, interview 24/02/2016.

research, artificial signals, and the use of radio telescopes to detect them built on antecedent and co-existing discourses and technologies but articulated them in a different way.

The Drake Equation and its mathematical framing of life in the universe could be described as a *research repertoire* for several reasons: it draws a precise boundary around the object of inquiry, it attributes legitimacy and authority to a certain way of searching for extra-terrestrial life, it enrols several disciplines but establishes the primacy of certain techniques over all possible alternatives, it could be performed by different groups and yet maintain a coherence, and it also made itself relevant to the troubled Cold War context.

The Drake Equation and the *probability argument* underlying its interpretation constituted, for a long time, a very strong argument in favour of SETI research, as the estimates of N were often optimistically oriented toward a strong presence of space-faring planets (see for example Sagan 1980). Despite the fact that only one of the terms was actually agreed upon at the time, i.e. the number of stars in the galaxy, this number was so enormous (around 100 billion) that all other factors could have even been relatively low and still guarantee the presence of a significant number of extra-terrestrial civilizations broadcasting radio waves across the galaxy. One factor, in particular, is worth noting: the estimate of f_l, or the fraction of planets with habitable conditions in which life actually emerges, was often considered to be 1 (Mash 1993), meaning that SETI researchers at that time assumed that every time conditions are favourable, life eventually originates. This was to be challenged in the following decades, first within the framework of exobiology and later by astrobiology.

Changing the odds

In the early 1990s, SETI experienced a climax in financial support from NASA and a sudden drop that forced its rearrangement into two different, and somewhat opposed, directions: on the 12th of October 1992, the 500th anniversary of Columbus' arrival in the Americas after his three-month journey across the Atlantic Ocean, a ten-year SETI programme was launched as a celebration of human exploration (Garber 1999). The programme, nevertheless, had a short life. After only one year, Senator Richard Bryan (R-NV) launched a last-minute amendment which was supported by the entire Congress, bringing NASA's SETI programme to a premature end. "Not a single Martian", he mockingly claimed, “has said 'Take me to your leader,' and not a single flying saucer has applied for F.A.A. approval” (in Dick 2001:230).

Historian Stephen J. Garber claimed that a number of political factors concurred at the expense of the most ambitious SETI project ever attempted. NASA, he suggests, had already fought other battles to support the building of new infrastructure, such as the International Space Station and the Hubble telescope, and the agency was left with little political ammunition to defend the small programme (Garber 1999:10). The multidisciplinary character of SETI, which had made its research efforts more robust in the last few decades, became in this situation a weakness in terms of support from Congress and when the new Clinton administration looked for budget cuts, SETI seemed to be an easy target. Garber’s excellent description stresses the fact that the SETI programme suffered politically because it could not guarantee any major short-term results and describes it as a “surprising and *unreasonable* decision for all informed parties [who] agreed that the SETI programme constituted worthwhile, valid science” (Garber 1999:3, emphasis added). Garber privileged what a few decades ago would have been called an *externalist* explanation, ascribing what the author sees as wrong decisions to factors not having to do with science. To balance out Garber’s explanation, I do not want to move to the opposite side of the dichotomy and propose an *internalist* explanation. On the contrary, thanks to the concept of repertoire, I would like to move beyond this distinction and integrate Garber’s account by exploring why SETI had ceased to be ‘valid enough’ to be funded by NASA. In fact, during the previous decade, NASA’s SETI programme had already gone through very different phases: support had been withdrawn and restored more than once, and the efficiency of the Drake Equation as a repertoire started vacillating, as exemplified by the debate between Ernst Mayer and Carl Sagan, two prominent figures who gave voice to opposite perspectives and very distinct ways of estimating the *probability* of success.

In the mid-1970s, the so-called Fermi Paradox – “if the universe is teeming with aliens… where is everybody?” (Jones 1985) – formulated more than 20 years earlier by the Italian physicist who gave this conundrum its name, Enrico Fermi, was brought back to the fore. By the end of the 1980s, the main question the critics of SETI had been asking was whether the search for artificial radio signals was worth taxpayers’ money if the probability of success was so small. After many years of attempted observations, the problem had become how to justify the “eerie silence” (Davies 2010). The debate between Sagan, an astronomer, and Ernst Mayr, a biologist, represents the two antagonistic positions (Mayr and Sagan 1996).[40] Sagan referred to the probability framework established by the Drake Equation and the last claim of Cocconi and Morrison's article: the length of a comprehensive search, he claimed, was very hard to predict. "Anytime we dip a glass into the ocean and we come up with water but no fish" Sagan explained, "for somebody this is like saying 'hey, the ocean is empty of life'... but it's false. We've barely scratched the surface". This promise of empiricism had, for a long time, had the power to move even SETI's most resolute opponents to a neutral position (Gary Coulter, in Garber 1999). From this perspective, denying the possible existence of extra-terrestrial civilizations seems to be as non-scientific as the blind belief in their existence. The only way *not* to contradict the scientific method is to perform the experiments: "let's just run the experiment and find it out", claimed an active SETI advocate I interviewed, "the only thing that has to do with science is to run the experiment".[41]

In turn, Mayr accepted the fact that the probability of the existence of intelligent life somewhere else in the universe might not be nil – despite suggesting an estimate of the equation factors that was far less optimistic. Since the possibility of success was so small, he argued that the research might not be worth the money required. The biologist added that SETI researchers' optimism was due to astronomers' and engineers' tendency to underestimate the complexity of the origin and evolution of life, which he believed to be a well-established feature of a biologist's sensitivity. Sagan's final reply accuses (even if in very subtle terms) Mayr of holding a narrow-minded view, comparable to those who did not want to believe in the Copernican heliocentric system because they insisted on the Earth being at the centre of the universe.

What I find very interesting about this debate, other than the emergence of themes that will recur with greater frequency in astrobiology, is that the statistical discourse of SETI centred on the idea of "probability", both of life emerging and of SETI people succeeding, was so powerful that Mayr could not move on any other ground. He had to stick to this narrative, despite using it against SETI itself. He went through the Drake Equation factors and came to the conclusion that SETI was unlikely to succeed and therefore, if detection was so improbable, the research itself was not worthy. This way of thinking, quite widespread by the time NASA's SETI programme was cancelled, partially constituted a reason for Congress' about-face.

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[40] The debate originally appeared in the *Planetary Society's Bioastronomy News*, beginning with Vol.7, No.3, 1995.

[41] JG, entrepreneur and SETI advocate, interview 16/02/2016.

This kind of reasoning was rooted in a specific position on what was the goal of the research that was funded by governmental agencies: the fact that this funding was granted on the occasion of the 500th anniversary of Columbus' arrival in the "New World" – the "first encounter" *par excellence* in US rhetoric, tells us a lot about the symbolic and political value that SETI was charged with. The debate between Sagan and Mayr in the late 70s had exemplified a first fissure between SETI scientists and those tackling the problem of the origin of life (see chapter 6) who were attributing a different interpretation to f_l – the fraction of planets on which life emerges, given the right conditions. At that time, the positions were simply made explicit. Two decades later, when the Sen. Bryan speech took place, biology was becoming the prevailing research enterprise of the era, thanks to its promise to unveil the "secret of life" with the help of big science projects such as the Human Genome Project, which had started only two years before, in 1990.

The lack of results became an essential factor in the assessment of how to distribute funding. Not only did SETI's research question not offer an immediate response, but there was no interest in phrasing it a different way. The Drake Equation stopped being an efficient repertoire in that historical and social context and in relation to other repertoires which started gaining momentum and proving more successful in driving research efforts, in both theoretical and practical terms.

In the contemporary search for extra-terrestrial life, the Drake Equation represents a much less powerful tool, even if it is nowadays possible to estimate the value of the first three terms (number of stars in the Milky Way, average of planets for every star, fraction of planets in the so-called habitable zone) and even if the numbers seem to be highly encouraging (see for example Petigura, Howard and Marcy 2013). Biologists and astrobiologists have also deepened their knowledge about life, or – in their words – they have realized the extent of their ignorance about it.[42] Carl Sagan optimistically estimated that "under very general cosmic conditions, the molecules of life are readily made and spontaneously self-assemble".[43] This whole set of assumptions is nowadays problematized by many disciplines: the origin of life has turned out to be more complex and puzzling than previously imagined, and the factors of the Drake Equation

[42] 2014 NASA Astrobiology Strategic Plan (http://dps.aas.org/news/2014-nasa-astrobiology-strategic-plan).

[43] *Cosmos, a Personal Voyage*, episode II, minute 37:45 (https://www.youtube.com/watch?v=XJMh_QoKTEE&list=PL474A7F1BA0FCEF8C).

summarized as “biotechnological factors” are nowadays broken down into a myriad of possibilities whose determination is far beyond our reach.

Space exploration, considered in the 1960s and 1970s as the ultimate future for humans in space (see for example Clarke 1968), soon stumbled into technical obstacles and socio-political resistances that have not yet been overcome. At the end of the century, Sagan’s invitation to swim in the cosmic ocean was no longer so appealing, and after a quick dipping of toes, space agencies all around the planet decided to move back to the much safer beach.

During the 1980s, under ever-growing pressures, NASA appointed Sally Ride, the first American female astronaut, to chair a committee in charge of drafting a new list of priorities for the new decade’s space programme. The first point they listed was what they called “Mission to Planet Earth” (McCurdy 2011). “The most significant achievement of that lunar voyage”, said Norman Cousin, American journalist and pacifist, “was not that man set foot on the moon, but that he set eye on Earth” (Cousins 1976). In 1991, the Cold War came to an end and space missions progressively lost a significant fraction of their funding. Their charm was also partially lost (Benjamin 2003). Every manned mission to other celestial bodies has been postponed to an unspecified future, and the probes sent far into outer space many decades ago have already reached the outer boundaries of the Solar System, sending back to us pictures of planet Earth from a cosmic distance we nowadays doubt humans will ever reach (Poole 2008:183). The outer atmosphere might have become the new human limit, as other threats to the planet, such as global warming, draught and hunger, seem likely to obscure for a long time the ambitions of going into outer space, urging us instead to pay attention to Earthly problems. This set of claims has been challenged, in the last few years, by public and private commitments to send humans to Mars in the near future.

From the moment Senator Bryan’s amendment was approved, SETI came to be considered “the four letter S word that you couldn't say at NASA headquarters anymore”.[44] Researchers moved, therefore, in two very different directions, mirroring the attitude of the two major groups who had been able to perform SETI research continually for a long period of time: the SETI Institute, and what is today called SETI Research Centre at Berkeley. All the other groups in the world either are affiliated to these two or have only sporadic interest in the field.

[44] EK and Jill Tarter, interviews.

When NASA ended the SETI programme, most of the scientists involved moved next door, to the SETI Institute, which had been in place since the late 1980s as a way of optimizing the funding received and avoiding university overheads. "If we hadn't had the Institute already there", Jill Tarter explained to me, "it might just have stopped, and it might have been too much of a barrier. But the Institute was in place, we could go and get to the right intergovernmental exchange to get our equipment loaned to the SETI Institute permanently, receivers to go to Arecibo and places like that… We were able to scramble".[45] Jill Tarter and her colleagues started looking for private support for their enterprise; over the years, they began the ambitious construction of a radio telescope array completely dedicated to SETI. The Allen Telescope Array, today composed of 42 dishes out of the 350 originally planned, was largely funded by Paul Allen, co-founder of Microsoft, and built at the Hat Creek Observatory in California.

A few years earlier, on the other side of San Francisco Bay, the SETI Research Centre at Berkeley started the development of a spectrometer called SERENDIP, acronym for "Search for Extraterrestrial Radio Emissions from Nearby Developed Intelligent Populations", in the late 1970s. As the acronym suggests, the spectrometer was designed to "piggy-back" on other ongoing radio telescope observations, and possibly make a fortunate discovery without following a precise rationale for the observations. The investment in the instrument turned out to be an excellent strategy for facing the constant lack of *ad hoc* funding, as no specific hardware or observation time was required, and it also challenged the arbitrary assumption that the 1420 MHz line would be chosen as the most appropriate frequency to communicate with other receiving civilizations somewhere else in the galaxy (Lampton *et al.* 1992; Siemion *et al.* 2011). Since the development of the first version, the instrument has been collecting data from the Arecibo radio telescope in Puerto Rico, the Green Bank Telescope in West Virginia and other facilities all around the world. The Medicina Radio Observatory is one of them (Montebugnoli *et al.* 2006).

The oblique lines

The first time I set foot in the radio-astronomical station at Medicina, long before I started my PhD, I didn't have the faintest idea what a radio wave was. I drove for almost

[45] Jill Tarter interview 04/12/2015.

an hour on the *trasversale* freeway, an asphalted straight line that cuts through the Po valley, before reaching the fertile countryside surrounding Bologna. I turned onto a narrow lane with an entrance hidden behind a small parabola, suggesting that visitors were on the right path for the radio-astronomical station. In the distance, the antennae of the big North Cross, a radio-telescope composed of an array of smaller elements aligned with the cardinal points, appeared not much taller than the leafy maize stalks that covered the fields separating the radio astronomical station from the small community of Medicina. Along the lane, a number of signals informed guests and tourists that they were accessing a radio-quiet area, warning them to switch off any device that might interfere with the functioning of the massive and extremely sensitive instruments. I immediately stopped my car, wondering which parts of it were using radio waves…the radio, obviously. And the GPS, maybe. And the phone? I turned it off, anyway. How could one be silent on a frequency that cannot be listened to? The cicadas were chirping incessantly, and I was not sure whether I should move the car again, afraid of breaking a silence I could not hear. Once inside the station, Stelio, at that time director of the facility, explained to me that no device should actually work on a radio-astronomical bandwidth, since they are protected by international agreements.[46] Some malfunctioning devices could emit on a frequency that was being observed by the radio telescopes, but specialized engineers were able to detect what was emitted artificially and isolate it from what constituted a naturally produced radio wave.

During our first conversation, I asked Stelio whether there was something I could do to participate in their activities. Stelio was enthusiastic and offered me a desk and a computer to go through the plots that the SERENDIP instrument installed in Medicina had collected for years and archive them in a more systematic way.

My desk in Medicina was located on the first floor, in a long and narrow room that had previously been used by students and interns working on short projects at the observatory when the Northern Cross, the main radio-telescope of the facility, still attracted numerous engineers and astronomers from academia. Stelio and Germano, his right-hand man, moved an old computer to the empty desk and cleaned the space of old hardware and scratch paper scattered everywhere. A window ran for the entire length of the wall facing the antennas; when sitting in front of the old computer, looking beyond the black screen dotted with white and pink signals coming from space, I could see the iron parabolas half hidden in the fog and surrounded by vast fields of corn and

[46] European regulations can be found at https://www.craf.eu (last accessed 04/07/2018).

wheat, and hear the sound of the wind passing through the thousands of metres of wire constituting the receivers' surfaces.

The time I spent in Medicina was often very solitary, with the exception of the lunch breaks, which were always deeply social moments. The long table where everybody had lunch at 1pm was placed in the big common room at the entrance. The handful of scientists and engineers permanently based at the facility totalled 15 staff members;[47] most of them had been born and raised in the area, and had dreamed about working there since they were kids. The vast majority of the personnel based at the observatory were engineers taking care of the precious hardware, designing new software and processing the requests of observations from astronomers all around Europe. During the lunch breaks, we talked about the news and whatever was on television. Very often, someone would make a joke about the aliens Stelio, Germano and I were looking for, but nobody – including Stelio and Germano – ever asked me whether I had found any. I spent most of my days at the Observatory scrolling down the long plots and zooming in on lines of dots. What I had to look for, Stelio explained to me on the very first day, was an oblique line. This was for two reasons: first of all, natural radio signals, which are emitted by a number of sources in the galaxy, were never on a single frequency, and therefore produced a sort of cloud of dots concentrated in the middle region. Artificial signals, on the contrary, might be on a single frequency and thus be plotted on a straight line on the graphs I was going through. The graphs in fact had plenty of straight lines due to artificial signals, not produced by aliens but originating from the human technologies by which we were surrounded. Most of them were easily recognizable, as they maintained the same frequency over time and were therefore perfectly vertical on the plot. On the contrary, the source of a signal from a different stellar system would move at a very high speed relative to the receiver on Earth, and would therefore shift in frequency because of the so-called Doppler Effect, the same thing – Stelio explained to me – that makes ambulances sound different as they move. What I was looking for was therefore a monochromatic signal shifting in frequency over time – put more simply, an oblique line. Stelio was not very confident that an algorithm would spot them with the same efficiency as the human eye. There was no way of telling in advance how skewed the line would be, and how many dots would compose it – it might well be indicated by three dots aligned but distant from each other. Recognizing such a pattern would require a huge amount of time and computer power. Stelio, an electrical engineer and

[47] Only one of them was female.

life-long radio amateur, was very confident that, as a human, my pattern recognition skills would defeat, if not in speed, at least in efficiency, those of the machinery available. I have never been very sure that was in fact the case, and people from other SETI groups have often laughed at the story.

The SETI data were stored in a tall pile of CDs containing hundreds of files each. During the time I spent there, I managed to go through two of them that contained plots from 1998. Finding the first oblique line was extremely exciting. A short but neat line was crossing the black screen, from the bottom left almost to the centre of the diagram. I jumped on my chair, and zoomed in and out for a couple of minutes. I took a piece of paper and placed it on the screen to make sure the dots were indeed aligned. They were.

To my amazement, Germano was not as surprised as I was. He congratulated me for the good work and told me to store the file on a different folder called "interesting signals" and take a note of the details: name of the file, day, times (when it started and when it stopped) and frequencies. After a few weeks, the folder contained a dozen files. One day I looked at a series of plots in which a signal would appear over and over again. With less excitement but full of curiosity, I went to Stelio's office and, using the excuse of a coffee break and some random conversation, I told him I found a signal that seemed to be quite persistent, the frequency was around 1575 MHz. "Oh", he said, "that's the GPS satellites frequency. Ignore them". Satellites produce the same kind of signals as they transmit on radio frequencies and orbit around Earth at a very high speed, which produces a remarkable Doppler Effect on the signals emitted.

Several months after I left Bologna and stopped going to Medicina on a regular basis, Germano sent me an email saying that he and Stelio had checked the "interesting signals" folder, and found two signals that they actually considered *really* interesting; they wanted to show them during a SETI conference as soon as they had the chance, and they wanted me to be among the authors of the talk. He attached the picture of two signals, which I actually remembered very well: the two sinusoids were in the 1420MHz region, the famous hydrogen line. It was several months before I heard further news. By that time, I had become familiar with the acronym RFI, shorthand for Radio Frequency Interferences, and I was very far from surprised when the signal presented did not arouse any enthusiasm at the conference.

In the past few decades, instruments have become exponentially more sensitive than they used to be in the 1960s and 1970s when SETI started. The rationale for the search has not changed much, one of the astronomers and programmers of the SETI group at Berkeley admitted, but what has definitely changed is the sensitivity of the instruments and the amount of data being collected.[48] The pipeline of data processing consists of a series of cycles in which the interesting signals selected from the algorithm are compared to possible interferences, or RFI, and once identified as such are deleted from the list. The following interview excerpt describes the long and intricate process through which, after a large number of potential extra-terrestrial signals are identified, interfaces are filtered out until very few signals – or none at all – are left:

> So you make a score for every candidate [signal] and... Basically you make a score for every point on the sky, and *that score is the probability* that the signals you see there are not noise. So things that are artificial get very high scores, and thing[s] that look like noise get very low scores, and then...but all RFI is artificial, so it gets high score. So you basically...if you decide something's an RFI, all the signals that are in that part of that sky at the frequency you think it's RFI, you mark them all as RFI, and then they don't get included in the further round. That's the process. And the big problem is that it just takes RFI and background noise, and stores them in a database. Now, there's two types of signals in that database right now that we're sure of: one it's interference from human intelligence, 'cause we have a lot of radios on the planet, satellites in orbit around the Earth etc., they all generate radio waves, they end up in our database. The other signal that we have is random noise. Our thresholds are low enough that just random thermal processes in the amplifiers can actually show up in the signal...and maybe there's also an ET, or maybe there's ten ETs! ... I don't know! So, the next step in the pipeline...we have to sift after all those signals now and remove the ones that are from interference, RFIs is the acronym for that. Then we look for everything that has come from the same spot in the sky at two different times, at about the same frequency.[49]

[48] EK, SETI engineer, interview 24/02/2016.

[49] EK, interview 24/02/2016. I decided not to paraphrase EK's own words on the explanation of the process he contributed to designing as I found the entanglement of the uncertainties revelatory.

Three points, and their interconnectedness, are striking: the first is that the sky has become a field of probability, in which every pixel is a number quantifying the non-impossibility that a signal comes from that precise spot in space. I am using the adjective "non-impossible" as opposed to possible in order to highlight the double negation: each signal is first labelled as non-noise, and then as non-interference when it becomes of some interest. The huge matrix full of numbers represents a universe in which there is no room left for empty spaces, for the abyssal void constituting the interstellar medium. Second, both terrestrial and purported extra-terrestrial signals score high on the probability scale because they are artificial and therefore share the features that distinguish them from naturally emitted radio waves. In the matrix, they are therefore virtually indistinguishable. Each signal with a high score in the database has to be checked against all the possible sources of RFI their system has identified – which by no means corresponds to all the possible sources, only the ones of which SETI programmers are aware. Each signal goes through this two-step process multiple times, initially automatically, and then under the expert eye of astronomers and programmers. Third, it is only when something that has not been sifted out as background noise or identified as RFI appears to have been observed more than once in the same spot in the sky, it enters a new list of signals to be re-observed once telescope time is available, which might happen – according to the availability of funding – every few months or once a year.[50] All the signals that have been recorded only once enter a grey zone. At this stage, only a few hundred signals out of the petabytes of data recorded are left. But even among them, SETI people hardly ever see what they call a "wow!" signal.

> We see so many things all the time, there are things that I...that we've seen that I really have no idea where it came from, but also I have no reason to expect it's extra-terrestrial. On one day, on one time we saw pulses of all bunch of periods: one spot on the sky, the power was almost constant, the frequency kept going up, and then it disappeared, never seen it again. And yeah, it could have been someone's cell phone.[51]

[50] The SETI Institute adopts a different strategy: because they do not piggy-back on other observations, but instead conduct SETI-oriented observations, they always make use of two telescopes located at different positions on the planet, at the same time. This gives them the possibility of identifying RFI on the spot (because of the differential Doppler effect); if the signal observed is confirmed not to have terrestrial origins, the coordinates are immediately passed to all the other radio-telescopes to be observed independently.

[51] EK, interview, 24/02/2016.

The silent sky of the 1960s and 1970s has nowadays become a noisy radio field, filled up with terrestrial chatter and random noise amplified by powerful technologies.

> Given enough data you start finding things that pass your threshold, and you'd find that they are still all RFI, and as you keep sort of iterating on these strict thresholds for what you determined to be like interesting or non-interesting source, like what is RFI or not RFI depending on labelling scheme, you have to start adopting pretty arbitrary and difficult to justify thresholds, um…so I felt like SETI experiments now are running into that problem, and um...it's a really difficult problem. Because those simple thresholds are not enough to identify truly interesting signals from the huge diversity of confounding RFI.[52]

The difficulty of recognizing where an artificial signal is actually coming from has transformed the language of probability into that of *indeterminacy*. Those signals *could* be ET, but *most likely they are not*. If an Earth source cannot be identified, a simpler explanation would be to attribute it to a natural and still unknown radio source, of which the universe seems to have plenty.

The statistical framework SETI has been built on shows, in these examples, the other side of the coin. Probability includes, admits and needs uncertainty. But uncertainty takes a different form when considered on an individual or a collective level. On the latter, i.e. SETI as a research programme, resting on the myriad of worlds that might be out there and all the possible outcomes of other evolutionary trees, it is indeed a promising narrative that supports the perpetuation of research that can only cover a tiny proportion of the places from – and ways in – which our extra-terrestrial neighbours might want to communicate with us. On the individual level (i.e. the single observation that might or might not contain the coveted signal), the opposite is the case; the statistics are not very encouraging, and the chances are that what looks like an ET signal is yet another RFI, or worse, what is labelled and discarded as an RFI is in fact the signal for which SETI researchers were looking.

In fact, humankind still wonders if we are alone in the universe, but mostly in a different fashion. In 1998, NASA inaugurated the National Astrobiology Institute, devoted to the "study of the origin, evolution, distribution, and future of life on Earth and in the Universe" (Blumberg 2003:456). According to Garber,

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[52] IS, interview, 24/02/2016. He was explaining why he was trying to introduce AI into SETI data elaboration.

astrobiology has clearly come into its own as an accepted scientific field of study supported by the government, while SETI research had had to fly under the radar [...] Somehow it seems that SETI remains tainted by the congressional politics of the early 1990s, while astrobiology has enjoyed a much higher public profile. Overall, since 1993, scientists have managed to perform some smaller scale SETI research. Simultaneously, astrobiology has experienced tremendous growth and acceptance as a scientific discipline (Garber 1999:47).

The picture might nevertheless be more complex than this. SETI and astrobiology did not just take two different directions; they keep on building on each other and articulating themselves on a set of resources that can be strategically opposed or aligned. The SETI Institute, for example, found itself in a very good position for presenting the two kinds of research as inherently connected. Its institutional structure, originally designed according to the principles of the Drake Equation, seemed very suitable for hosting a centre for astrobiology (funded in 1998 and later dedicated to Carl Sagan), and was considered by NASA contractors the best business model of which they could take advantage to maximize their funding. Jill Tarter, who served as director of the centre until she retired in 2012, reacted enthusiastically when I explained to her my interest in the way astrobiologists and SETI people articulate definitions of life.

> The 21st century was gonna be the century of biology, ok? And so I think this is a bold claim, but I don't think it's bold enough, I think what's so fantastic about the 21st century, is that it's gonna be the century of biology of life on Earth *and beyond*, right? So…I think that is just incredibly opportune time to be talking about the things you're talking about. Um, yeah…we're gonna learn things that we didn't expect; we – I hope! – we're gonna get a second genesis somewhere, so that we can begin to pull apart what's necessary for life and what's just contingent, and we may even find mathematicians as well as microbes out there.[53]

The discovery of the exoplanets has ushered in a new era of collaboration between SETI and astrobiology, paving the way for new synergistic co-operations. The new SETI observations, planned thanks to the generous support of the Breakthrough Foundation, are mostly targeting promising exoplanets (Isaacson *et al.* 2017; Worden *et al.* 2017).

One of the main achievements in astrobiology is the realization of the extent of life's resilience, and SETI adopts this awareness to suggest that the odds might still be in their

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[53] Jill Tarter, interview 04/12/2015.

favour.[54] On the other hand, SETI is nowadays sometimes presented as a very special case of astrobiology itself (rather than astrobiology belonging to the factors constituting SETI research). Astrobiologists use SETI to catch the attention of the public.[55] More often, they highlight what they hold to be the essential difference between the two: they say that while SETI researchers can only hope to have adopted the best strategy, astrobiology is an experimental discipline; by means of rovers, satellites and analogue fields on Earth, they can take their object of study to make it visible and manipulable.

Conclusion

In this chapter, I explored the entangled historical roots of SETI and exobiology (later called astrobiology). In particular, the chapter has focused on the establishment of a repertoire for SETI and its changing fortunes. During the 1960s and 1970s, and in somehow different conformations up to the present day, scientists and engineers have coalesced around the Drake Equation, which the famous American physicist Freeman Dyson called "the orthodox view" for the search of alien life as early as 1966.[56] The equation proved to be a powerful tool both on the epistemological and the institutional level. Born as a means of setting the agenda of the first meeting, it became a way to align the interests of different communities, arrange new institutions and set out a discourse that would articulate SETI in a mathematical language. Probability became the main strategy for promoting both the existence of life elsewhere in the universe and the success of SETI research. I have shown how, nevertheless, the Drake Equation failed to provide a durable successful narrative over time. SETI researchers exploited, with different degrees of success, the tension between probability and indeterminacy to make an argument in favour of their research assumptions.

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54 For example, AS's talk, SETI-day conference, Milan 11/05/2016.

55 "Talking about searching for microbes on Mars, nobody...so for the public is not different than saying that we're searching from deuterium on Mars, because they don't relate to microbes any more than they relate to deuterium, but they relate to intelligent aliens", CMK interview, 09/10/2015.

56 Alternative views include that advocated by Freeman Dyson himself, suggesting that the search should aim for the detection of mass energy-harvesting technologies around stars, and the Soviet view, which was more focused on the issue of communication and interpretation of a possible message.

This chapter has also shown how divergent ideas of life were brought forward by the two fields; their juxtaposition is meant to foreground the idea that the way life is defined scientifically has to be understood within its broader context. SETI researchers envisioned the forms of life with which they aimed to connect as disembodied, intelligent and technologically advanced collectives.

In the following chapter, I look further into how astrobiology – phrasing the question "are we alone in the universe?" through different research repertoires - had started gaining legitimacy, authority and popularity for the same reasons SETI was losing them. Repertoires are evolving entities, they are useful precisely because the resources available can be mobilized or not, and they are deployable to different "ends".

Chapter **4**

Building Habitable Worlds

Interdisciplinarity and life as a planetary phenomenon

ALL THESE WORLDS ARE YOURS – EXCEPT EUROPA.
ATTEMPT NO LANDINGS THERE.

Arthur C. Clarke (1982) *2010: Odyssey Two*

Trappist-1

On the 22nd of February 2017, NASA held a press release to announce the discovery of Trappist-1,[57] the first planetary system known to have several – probably seven – Earth-size planets, three of which were estimated to be in the so-called *habitable zone* (Gillon *et al.* 2017). The planetary system took its name after the Belgian telescope that first observed it, TRAPPIST, a backronym[58] standing for TRAnsiting Planets and PlanetesImals Small Telescope, located at La Silla Observatory in the Chilean mountains. After the first three planets, the closest to the star, were discovered by the Belgian group in 2015 (Gillon *et al.* 2016), other telescopes all over the globe (and in orbit around it) were pointed toward this system in the hope that more detailed observations would reveal the other system's components, if they existed. In less than a year, NASA's Spitzer Space Telescope

[57] The press release video is available on the NASA YouTube channel at https://www.youtube.com/watch?v=v5Xr-WkW5JM.

[58] The acronym was deliberately formed from a phrase whose initial letters spell out the name of a beer traditionally brewed in Trappist monasteries, considered one of the most renowned Belgian products.

granted the astronomers' wishes. The press conference was to announce publicly that Trappist-1 might be the Solar System twin for which everyone had been (and still is) looking.

I watched the press conference broadcast on the NASA web channel from the small museum in the Geology department at the University of Edinburgh. The room housing crystals, rocks and fossils hosted, for the day, the poster session of the first Scottish Planetary Network Meeting, a gathering immediately following a workshop titled Building Habitable Worlds. I was right in front of the screen when the livestream started, chatting with a Dutch student who had authored a poster about genetically engineered lettuce for astronauts complaining about the lack of crunchy food in space.[59] On the other side of the screen, inside the small NASA studio, the principal investigators of the five teams that collaborated on the observations sat on stools behind a small white desk with a NASA logo. The scientists were interviewed by the host one by one, and their answers illustrated with artistic representations of the exoplanets.

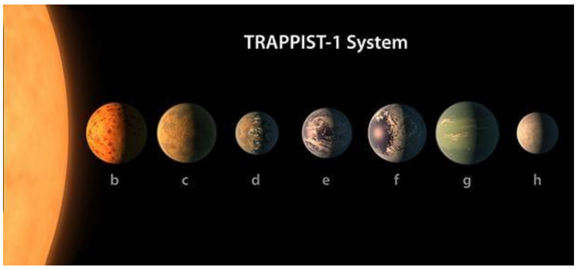

Figure 1 This artist's concept shows what the TRAPPIST-1 planetary system may look like, based on available data about the planets' diameters, masses and distances from the host star, as of February 2018. Credits: NASA/JPL-Caltech

Despite the many differences between the Sun and Trappist-a, a small and dim star, the planets orbiting around them were regarded as possibly very similar. Nikole Lewis, astronomer at the Space Science Institute in Baltimore, moved around a model of the system on a large touchscreen. She zoomed in on every planet in turn, from the closest to the star. Each planet's artist representation was juxtaposed to a picture of the Earth to show how similar they might be. The vivid colours clearly conveyed ideas about what their surfaces and atmospheres might look like, but, at the present, were no more than surmises. "Now, we don't know much about the planets", admitted Nikole Lewis' colleague Sara Seager, a planetary scientist based at the Centre for Exoplanets and Habitability at MIT, "we know, as we heard earlier, the masses and sizes and how much radiation is falling on them and their orbits. So for now we just speculate, and for that, the Trappist-1 system has really captured our imagination."[60]

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[59] Indeed, food preferences and design of comfort for long-term dwelling in space are part of making a place *habitable.*

[60] Trappist-1 press release, minute 13:25.

A number of elements contributed to making this system special in scientists' eyes. As already mentioned, Trappist-1 was the system with the largest number of known planets; three out of the seven planets' orbits seemed to lie within the so-called habitable zone. Furthermore, for the first time, masses and radii were measured with relative precision and inferences were made about the planets' composition. Last but not least, given the relatively short distance from the Earth, they were considered excellent targets for the new generation of telescopes. The NASA administrator for the science mission directorate situated their excitement within the broader picture of exoplanet hunting:

> The discovery gives us a hint that finding a second Earth is not just a matter of "if," but "when." Scientists believe actually that around every star there could be one planet, take three, take five, take seven...and you can just imagine how many worlds are out there that have a shot to becoming a habitable ecosystem that we could explore. And what we really have in this story is a major step forward towards answering one of these very questions that are at the heart of so many of our philosophers of what we are thinking about when we are by ourselves and that basically is – are we alone out there?[61]

Leaning on the synthetic lettuce poster, I was totally absorbed by the video stream. The video was of a decent quality – the organizers had really made an effort to improvise the projection of the press conference announced less than 24 hours earlier – but the audio was not the best. When I turned around to comment on the fact that – finally! – I would not be the only one grateful for the subtitles, I noticed with a bit of disappointment that nobody was watching the screen but me. I thought it would have been a great (despite unplanned) opportunity to participate in an event of some relevance for the astrobiologists at the meeting, but that definitely did not seem to be the case: everyone else in the room was happily drinking wine and chatting with colleagues, surely not about Trappist-1. When one of the PhD students with whom I was more familiar passed by, I stopped him to ask the reasons for the rampant indifference. Wouldn't it be interesting if any of the planets of this nearby system were habitable and maybe inhabited? He shrugged his shoulders: "we cannot go there, we'll never know!" For a meeting immediately following a workshop called *Building Habitable Worlds*, this seemed to me quite a surprising claim.

On the following day, the news made it to the cover of the prestigious journal *Nature,* and Google designed a doodle displaying a jubilant Earth celebrating when, on the other

[61] Trappist-1 press release.

side of the telescope, a bunch of chubby planets waved hello. The discovery of the Trappist-1 system was indeed welcomed as a big step forward in the search of a "temperate, Earth-size planet" (Gillon *et al.* 2017) – a habitable world.

Habitability has not always been part of the way people, whether astronomers or laypeople, think about planets. It is only very recently that the assessment of the habitability of different celestial bodies (either exoplanets or other planets and moons of the Solar System) has become a primary concern for astrobiology communities (Voytek 2016). The quest for habitability becomes more interesting when one starts looking into what astrobiologists and planetary scientists actually mean with "habitable". Habitability turns out to be a set of sometimes very diverse research questions about the presence of life on planets, which can be investigated with different techniques, defined in different terms and assessed according to different standards or different scales (from a sand grain to an entire planet). The search for habitability is the second repertoire I would like to explore in this thesis. As we shall see in the chapter, this repertoire is characterized by a flexibility which, on the one hand, allows people with different backgrounds and skills to adopt it and adapt each "performance" of the repertoire to his or her needs and opportunities. The concept of habitability and its various understandings provide a space in which tensions between different approaches can be performed but not necessarily resolved.[62] On the other hand, it also provides a shared goal and thus a sense of unity for those who adopt it.

In the following pages, I look into the uses and community-building practices connected to the term *habitability,* a concept not simply shaped by different disciplinary practices, but in turn also shaping the emerging astrobiology community.

Planets out of reach

The Solar System is often described as being constituted of two main kinds of planet (each including in turn planets with many diverse characteristics): small rocky planets, like Earth and Mars, and gas giants, such as Jupiter and Neptune. At least around the Sun,

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[62] In "The Problem with Pluto", Lisa Messeri (2010) makes a similar claim about the term "planet" when analysing the controversy about Pluto that ended up with the formulation of the category of dwarf planet. In her case, however, the imprecision about the definition of the term planet was perceived as a problem by the astronomy community. The controversy ended with a claim of authority by a group of astronomers over the other members of their scientific community and, most importantly, over the lay public. In the case discussed here, in contrast, habitability is valuable precisely because it is vague. Its vagueness helps scientists build an interdisciplinary community and maintain the interest of the public. Instead of constraining its meaning and thus privileging some interests over others, scientists happily bridge its many connotations and work toward community-building.

the gas giants – Jupiter, Saturn, Uranus and Neptune – populate the outermost part of the system. All of them, despite their very different characteristics, are several times larger than Earth, and mainly constituted by hydrogen and helium. Because of their high mass, these giant planets imprisoned a huge cloud of debris in the early stage of their formation, which coalesced into a number of small and rocky satellites. Most of these satellites have been studied, in the last few decades, by means of spacecraft – Voyager, Galileo, Cassini and Huygens just to name a few – undergoing long journeys toward the edges of the Solar System. Thanks to the data collected, some of these satellites, such as Europa, Enceladus and Titan, have recently become a primary interest for astrobiologists and planetary scientists (McKay *et al.* 2011; Porco 2017).

Perhaps even bigger is the interest attracted by the discovery of so-called exoplanets, literally "planets outside" the Solar System. Back in the 1980s and early 1990s, the idea of observing planets orbiting around another star was considered much beyond the technological capabilities of the time. Describing the emergence of this research field, an astronomer told me:

> I remember being a kid and people were like "we will never find exoplanets". [When the first exoplanet was detected, it made an] enormous impression on me and now I teach first year [students], and this has been their entire life, there have always been exoplanets.[63]

What might seem today a straightforward observation, the fact that stars other than the Sun have planets too, was in fact a huge technological challenge until a couple of decades ago. In a popular metaphor, the quandary was described as observing a mosquito flying around a light tower in California by an observer placed in Moscow. Despite the fact that the universe (or at least our galaxy) was expected to have plenty of planets orbiting around other stars, astronomers did not know how likely their existence actually was (Goldberg 1985). The Solar System might have been an exception.

The first exoplanet, whose official name is 51 Peg b, was discovered in 1995 by Michel Mayor and Didier Queloz (Mayor and Queloz 1995), two astronomers based at the University of Geneva, due to a method called "radial velocity". By detecting tiny changes in the frequency of a star's luminosity, astronomers can infer the presence of one or more planets dragging the star around their common centre of gravity. This technique allows astronomers to infer the planet's mass and periodicity (how long it takes to complete an

[63] BB, astronomer, interview 22/07/2015.

orbit). Among the number of planets discovered, the vast majority are more massive then Jupiter. Astronomers, nevertheless, confidently consider this a bias of the technique itself: the smaller the planet, the harder to detect the star's wobbling. Another technique can be used to obviate this issue, the so-called "transit method", which involves observing the dimming of the star's luminosity as the planet passes in front of it. The transit technique is much more sensitive to smaller planets, giving information on their diameter and, again, their periodicity. This technique, nevertheless, also creates a bias in the population of planets discovered, as it requires their orbits to be on the same plane as the observer. The closer the planet to the star, the more likely the orbit to fall within the stellar disk, so the exoplanets observed with this method tend to be very close to their host star. Until recently, observations could not confirm whether the Earth was an outlier in the statistical distribution of planets. This, nevertheless, went against the astronomers' expectation that the universe is "full of worlds to be inhabited", and so the search went (and still goes) on, in the hope that the improvement of the two techniques might fill the gaps and find the long-awaited twin of Earth.

The moons of the outer Solar System, and the recently discovered exoplanets, are indeed very different celestial bodies. Coupling them in this chapter is a somewhat arbitrary choice that I have made for a number of reasons. First, despite their distances from Earth being very different, they are all still considered beyond human reach: while a manned mission to Mars seems to be only a matter of will (developing the technologies is possible but too expensive), a manned human mission to the outer Solar System would require new technologies that are neither available nor close to being developed. Exposure to a high level of radiation for a prolonged time, storing or producing the food necessary for the space crew for the entire journey, preventing irreparable changes to the human body and metabolism and solving medical emergencies are only a few of the challenges posed by such a trip. Even if a huge effort was made in this direction, at the present it is difficult for engineers even to imagine how one could reach the outer Solar System in less than a lifetime.

Of course, there are also huge differences, and the scientific trajectory of the study of these entities will probably sensibly differ in the future. In a few years, the moons of the outer Solar System might be explored with landers, pictures may be taken and perhaps they too will be within reach using state-of-the-art technology (Fletcher 2018; Wright and Oman-Reagan 2018). When that happens, they will probably become closer and closer to Mars in the way people think about them. This difference in expectations actually makes moons such as Europa and Enceladus more interesting to the astrobiologists who foresee the possibility of a sample return mission (Sandford 2011). Astronomers, on the other hand, are much more intrigued by the promise of a cascade of new and more detailed data to feed their computer models of exoplanetary systems, thanks to the new generations of telescopes that will begin their service in the next few years.

At the present time, the most interesting similarity that still draws exoplanets and the celestial bodies populating the outer Solar System together is the fact that their habitability is still to be assessed. Assessing habitability is not only a problem of making more precise measurements, but also involves building a community that considers this a primary goal: the right question to be asked.

Asking "the right question"

As agreed in an earlier email, I arrived at Albano Laziale by train, then walked for a couple of miles through a botanical garden leading to the historical centre of the small town, in the Roman countryside. I was told that getting to the Vatican Observatory would not be hard, but I had to hold my phone to check the map over and over again to avoid getting lost. Traditionally hosted in Castel Gandolfo, the Pope's summer residence, the institution moved in 2009 to a more efficient (for those who do not have to rely on public transportation) and sober location in an old convent in Albano Laziale. I finally arrived at a front door in a short building that delimits one side of a square. When I rang the bell, Brother Guy Consolmagno[64] came to the entrance to welcome me, and led me through the complicated maze of corridors to his office. I had already tried to talk to Brother Guy before, but despite his friendliness, his wandering life made it hard to arrange an appointment with him. What might appear to be quite an unusual career – Catholic priest and astrobiology professor – brings him to Arizona for six months a year, to the Roman countryside for the other six months, and to barren lands in search for meteorites every now and then (Impey 2010; Consolmagno 2000). Since he became a Jesuit priest at the Vatican Observatory, he has been working on meteorites, but what brought me to knock on his door was another interest of his, dating back to his PhD times at MIT. When I told Brother Guy that I was intrigued by the way Europa and Enceladus had become objects of interest in astrobiology, a large smile showed behind his thick grey beard.

[64] I decided not to anonymize him in order to give him very well-deserved credit, not just for this hypothesis about life on Europa, but also for his insightfulness.

Europa was discovered by Galileo Galilei in 1610 together with the other so-called Galilean moons – Io, Europa, Ganymede and Callisto, named after the lovers of the god Zeus, or Jupiter in the Roman mythology – due to the first observations performed with a spyglass, the antecedent of the telescope, put together by Galileo himself (Helden 1974). The observation of their position was a cornerstone in the overcoming of the Aristotelean cosmos in favour of the Copernican model. The interest, nevertheless, did not go much further, according to Brother Guy, for several centuries. Even in the 19th century, when instruments already allowed the measurement of both the masses and radiuses of the other celestial bodies of the Solar System, "nobody", Brother Guy told me after a long pause, "bothered calculating the densities. Because in the 19th century, as you know, the question of astronomy was 'where are things located?' not 'what are things?'"[65] Then he asked me whether I had ever read *On the Planets*, published in the second half of the 19th century by one of his predecessors at the head of the Vatican Observatory, Angelo Secchi. I felt a little ignorant and I shook my head. Brother Guy invited me to the small library on the other side of the floor.

For centuries – he explained while walking down the corridor – the mass, radius and albedo of many planets and moons were known in what is still considered today a good approximation, but "the first person who really fights to determine not *where* the planets and stars are, but *what* the planets and the stars are was Angelo Secchi". Brother Guy pushed one of the shutters of the several anonymous bookshelves full of white boxes protecting the old leather-covered books from the damage of time. While I wondered what treasures might have be hidden within those walls, he pulled one of the boxes out, removed an old book from its case and started reading aloud:

> The science dealing with celestial bodies is composed of two distinct parts: the first, and principal, is the one that determines the laws describing their movements behind the precise measurements of the apparent positions; the second, which is accessory, regards their physical properties and their external structure. The first is more important and difficult; it takes more time to be perfected and it has all the merits for the results that deserve the glory of modern science. Its study, nevertheless, can only be afforded by a few privileged intellectuals, who need to train through long and difficult study, and to the majority leaves nothing but admiration for what they cannot understand. The second, on the contrary, is more delightful and

[65] Guy Consolmagno, interview 21/06/2015.

> more accessible even to those who only have mediocre scientific notions, and it can give a better idea of the universe in a way that is within everyone's reach.[66]

Describing the position and movement of a planet, Angelo Secchi seems to suggest, is the true essence of the discipline of astronomy; what he was about to do (describing planets as *places*), on the contrary, was a mere recreation for less educated people. If planets were relevant only in terms of their positioning, even less interest was raised by the Galilean satellites, whose features remained overlooked for several centuries after their discovery. Even in Secchi's time, more than 200 years later, the few notions available had never been double-checked and were simply copied from one work to the next.

During his time at MIT in the 1970s, Brother Guy worked on the first computer models simulating the interactions between Jupiter and its satellites in order to follow up his supervisor's intuition that underneath the layer of ice constituting Europa's surface there might be an ocean of liquid water maintained by so-called tidal heating, the push and pull of the Jovian system's gravity. "For all the wrong reasons", he claimed once back in his office, "I came to the right conclusion and I confirmed its presence".[67] Still laughing, Brother Guy stood up to grab a typewritten volume on the small shelf above his desk, his master's thesis written in 1975. He looked for the appendix and then read aloud:

> Giving the temperatures of the interiors, and especially of the silicate layers through which liquid will be percolating, the possibility exists of simple organic chemistry taking place involving either methane from the ice or carbon in the silicate phase. However, we stop short of postulating life forms in these mantles; we leave such to others more experienced than ourselves in such speculations. (Consolmagno 1975).

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66 "*La scienza dei corpi celesti ha due parti ben distinte: la prima e principale e' quella che determina le leggi dei loro movimenti dietro le misure precise delle posizioni apparenti; la seconda e accessoria riguarda le loro proprieta' fisiche e la loro strutture esteriore. La prima e' la piu' importante e difficile, quella che piu' tempo dimanda per perfezionarsi, e ad essa spettano tutti que' risultati che meritamente formano la gloria della moderna scienza. Il suo studio pero' trovasi alla portata di pochi intelletti privilegiati, i quali vi si devono preparare con lunghi e difficili studi, ed ai piu' non lascia che l'ammirazione di cio' che non intendono. La seconda invece e' piu' dilettevole e piu' accessibile anche a chi e' fornito di mediocri cognizioni scientifiche, ed e' quella che meglio puo' far concepire una idea dell'universo in maniera adattata alla portata commune".*

67 Guy Consolmagno, interview, 21/06/2015.

"So", he added, "I was not the first one to predict life in these oceans, but the first one *not* to predict it!"[68] As far as he knows, this was the first time that the possible existence of life in the outer Solar System appeared in print in any kind of scientific publication. This idea, nevertheless, did not echo much in the scientific community at that time:[69]

> I showed up at the Jupiter conference and presented this work there, and Carl Sagan was the host and the chair of that session, and before my talk I mentioned that "maybe there's even life there" and he goes "it's gonna to be dark in those oceans, there's no sunlight, you can't have life without sunlight" and I go "grrr" […] and so I didn't mention that.[70]

The short chat with Carl Sagan, one of the most famous astronomers of his time and an eager advocate of the search for extra-terrestrial life, relegated Brother Guy's hunch into oblivion for a few more years before Europa was brought back to the fore as one of the most intriguing celestial bodies for astrobiologists in search of a habitable world in the Solar System.

Brother Guy did not mean to tell me a story of *progress*: what he wanted to emphasize was that planets have been thought about in many different ways, along with the kind of life that might exist on them. What counts as "the right question" depends on what he called "the sociology of the science": *what* the relevant issues to be addressed are and *how* to address them are a sociological matter.[71] Angelo Secchi's division of astronomy into two different fields investigating planets as different kinds of bodies – either abstract points in the sky moving according to gravitational laws, or material places whose landscapes can be imagined and described – mirrored the different social statuses of those who studied them. The two understandings could not merge because their practitioners were not meant to mingle either. Carl Sagan's dismissal of Brother Consolmagno's hypothesis, however, instead mirrored the lack of a common ground between biology and planetary science at that time. The glacial and dark waters under the icy crust of Europa were not imagined as offering any suitable habitat for life. It was only after the Earth's subsurface and the ocean depths were explored and described with

[68] Guy Consolmagno, interview 21/06/2015.
[69] On the contrary, it greatly appealed to the science-fiction writer Arthur C. Clarke, who based *2010: Odyssey Two* on this idea. Brother Guy talked extensively about the intersections between science and science fiction and the way the latter "makes things thinkable".
[70] Guy Consolmagno, interview 21/06/2015.
[71] Guy Consolmagno, interview 21/06/2015.

a common vocabulary that the connection was made and the hypothesis of the existence of life under Europa's subsurface ocean could become conceivable (Impey 2010).

This quick sketch of the changing perception of planets over the last two centuries, briefly reconstructed thanks to the conversation with Brother Guy Consolmagno, shows how what we take for granted today might not have been obvious in the past. As scientific objects, planets – which we today think of as far-away places – used to be thought of as abstract points moving in a finite space. Many shifts have occurred to reach our present understanding; among other things, the association between the interest in space exploration and the discovery of life in places previously considered unhospitable for life laid the foundations for the concept of habitability. The idea that planets are places that might be habitable requires a series of concepts, practices and communities to be mutually attuned. If this social work is not done, what might seem, from our perspective, an interesting or perhaps the *most* interesting problem to be tackled, can simply fall into the void and be ignored as unimportant. It is only when a viable path of action is provided, that the question becomes *the right one* to be asked.

Habitabilities and interdisciplinarity

In *Placing Outer Space,* Messeri calls *planetary imagination* the "holistic conception that scientists have of the planets they study" (2016:12). She does not point to a singular imaginary, but a set of articulations of planets as places that span narrating, mapping and visualizing. Messeri focuses on the place-making techniques that enable planetary scientists to bridge the experiential gap between scales "by reconnecting [planets] with the concept of place" (2016:11). By exploring the practices connected to "habitability", she looks at the way *inhabitation* is articulated by planetary scientists in order to explore the interrelatedness between the promise of inhabiting other planets in the future and the present situatedness of scientific research as astronomers inhabit geographically situated locales or virtually distributed networks.

In my experience among the community of astrobiologists, habitability is indeed articulated in these dimensions, but its multiplicity expands even further: habitability might have to do with microbes on a sand grain, entire planets, their oceans or atmospheres or an imaginary disk floating around a star. Habitabilities are embedded in the different techniques used to assess them, which in turn shape what kinds of places planets are and what kind of life ought to be found on them.

It is important to notice that habitability is not a concept exclusively used by astrobiologists. On the contrary, it is available to other groups and communities not interested in the search of life. What makes it interesting is how astrobiologists use it strategically and as part of a practical arrangement (articulated in conferences, papers, visual representations and so on) that are specifically targeted to the search for life and shape the way it is pursued.

There are contexts in which different types of habitability and different ways of conceptualizing the kinds of worlds that might be found out there can confront each other and allow a multiplicity that strengthens – rather than weakens – the social and epistemic configuration of the astrobiology community. Astrobiology is defined, and indeed practised, as a deeply interdisciplinary field: the prefix *astro-* and the term *biology* delimit a broad spectrum of specialities that cut across many different scales and include disciplines such as organic chemistry, geology, planetary science etc. and many of their subfields. I will not make a list of all the specialities that are somehow involved in astrobiology research projects (many will be mentioned and described in this thesis), but I would like to emphasize that NASA's definition of astrobiology places interdisciplinarity at the very core of the enterprise,[72] and indeed the fast-growing scientific community explicitly puts a lot of effort into addressing issues of jargon translation, cooperation, funding allocation (Noack *et al.* 2015; Race *et al.* 2012) etc. Disciplinary territories merge, overlap and cross each other all the time, providing the conditions for creative recombination of data, expertise and ideas (Hackett *et al.* 2017) and giving rise to a complex topography which, nevertheless, is often unproblematically recognized as a discipline in itself.

In the following four sections, I spell out different understandings of planets as habitable places and the research practices to which they are connected. First, I focus on the so-called *habitable zone*, an imaginary disk around the star in which the temperature might allow for liquid water to exist. I then move to the search for *Earth-like planets* orbiting other, not necessarily Sun-like, stars and the exploration of extreme *habitats* on Earth and the "weird" forms of life that thrive in them to stretch the imaginary of extra-terrestrial life to planets that are very different from the Earth. Lastly, I look at the way astrobiologists relate to exoplanets as places to be, one day, *inhabited*. Interrogating instruments with these forms of habitability in mind provides

[72] "This interdisciplinary field", reads the NASA Astrobiology Institute website, "requires a comprehensive, integrated understanding of biological, geological, planetary, and cosmic phenomena." https://nai.nasa.gov/about/, last accessed 18/08/2017.

the astrobiology community with a grey area in which tensions are allowed and can be debated without necessarily being solved. It is important to note that wondering whether a certain Solar System body or exoplanet is habitable should not be considered a *controversy,* as it does not aim to achieve closure. On the contrary, habitability purposefully allows multiplicity.

The habitable zone

On the cover of the prestigious journal *Nature*, Trappist-1 is a bunch of marbles on a glossy dark surface similar to an induction stovetop. At the centre, the star is represented as an incandescent sphere, while the planets are marbles randomly positioned on concentric orbits. The shiny smooth surface is covered with water, which evaporates close to the star, crystallizes on the bottom of the page – in what represents the periphery of the system – and forms small patches of liquid water somewhere halfway. The image reconciles the two main features that made the system so remarkable to astronomers' eyes. First of all, "three of these planets", writes the NASA website, "are firmly located in the habitable zone, the area around the parent star where a rocky planet is most likely to have liquid water" (NASA Press Release, 22/02/2017).[73] The term *habitable*, indicating a temperate zone favourable to human inhabitation, percolated into space exploration from 19th century human geography, perhaps in parallel with other metaphors dripping with colonial resonances (Messeri 2016). The idea of a circumstellar habitable zone was first discussed in the late 1950s. The driving question, according to the astronomer Su-Shu Huang, was "[i]s there any way of knowing which kinds of stars favour the existence of life on their planets? The question," he confidently claimed, "can be reasonably answered […] with our present knowledge" (Huang 1959:397). In the 1960s, the canvas of the galaxy was filled with stars; these were being observed with spectroscopes providing astronomers with the temperature and mass of each star, which in turn could be translated into the star's stage of development. According to Huang, the circumstellar habitable zone was a disk within which the planet would receive a certain amount of radiation that allowed water to exist in a liquid state.

Figure 2 Nature 542, 23 February 2017.

73 https://www.nasa.gov/press-release/nasa-telescope-reveals-largest-batch-of-earth-size-habitable-zone-planets-around, last accessed 17/08/2017.

The habitable zone was thus initially made out of a hypothetical range within which the planetary orbit might fall, and where there was the possibility of life evolving through time.

Defining a habitable zone was a means to talk about life on other systems without need of actual planets. In fact, once the necessary premise that the hypothetical planet's atmosphere was "Earth-like" – i.e. mainly composed of N_2, H_2O and CO_2[74] – was made, the planets could be simplified as abstract punctiform entities. The orbits of planets, rather than the planets themselves, were the primary focus of interest. Habitable zones are indeed modelled in two dimensions (Kasting, Whitmire and Reynolds 1993) and today, due to the advent of computer algorithms, the parameters (stellar type and age of the star) can be set by even the most novice astronomer to return the radiuses of the circumferences delimiting a flat circumstellar disk.[75] Within the range delimited by the disk, water can exist in a liquid state on the surface of a *generic* rocky planet.

The way to calculate the value of its inner and outer edge remained an object of many different interpretations, and the opinions about the extension of the habitable zone differ, as they depend on multiple factors. Those who tend to make more conservative estimates (see, for example, Ward and Brownlee 2000) sometimes call it the "Goldilocks zone", from the famous English fairy tale in which Goldilocks chooses to eat the bowl of porridge that is *just right*, not too hot and not too cold (Riddle 2014). This echoes the Earth, which orbits around the Sun at *just the right distance*.

> Our closest neighbors in space provide sobering examples of what happens to planets close to, but not within, the HZ [habitable zone]. Closer to the sun than the HZ, a planet gets too hot. Venus is an example. The surface of this neighbor is nearly hot enough to glow. If Venus ever had an ocean, it has long since evaporated and been totally lost to space. Outside of the HZ, temperatures are too low. Mars, for example, is frozen to depths of many kilometers below its surface. If Earth were moved outward (or if the sun reduced its energy output), Earth's atmosphere would cool to a point where the planet would become ice-covered. Eventually, carbon dioxide would freeze to form reflective clouds of "dry ice" particles, and ultimately, CO_2 would freeze on the polar caps. (Ward and Brownlee 2000:18).

[74] Nitrogen and oxygen are today the main compounds forming the Earth's atmosphere; carbon dioxide was its main component in the early stages of Earth evolution and still plays a very important role for life on Earth as it constitutes a main source of carbon in the carbon cycle.

[75] The Habitable Zone Gallery (hzgallery.org) website provides information about the extension of the habitable zone of many known stars and where their planets' orbits fall.

According to the supporters of this estimate, the Earth is not only unique in the Solar System, but possibly exceptional among all the other stellar systems as well.

In the 1960s, Su-Shu Huang, the astronomer who coined the expression "habitable zone", expressed a preference for stars with a long and smooth life, such as M type stars, because – as mentioned in the previous chapter – the only indication of alien life, at that time, was considered to be the detection of an artificial signal, requiring technological capabilities thought to be the outcome of a long and successful "biological evolution" (Huang 1959:397). When the definition of the habitable zone was reformulated by linking it with the presence of liquid water as the solvent allowing an efficient interaction of organic molecules, a different kind of life was favoured:

> We ourselves are more interested in determining if life can evolve on other planets than we are in colonizing them, so we will use the presence of liquid water as our habitability criterion […] recognizing that not all planets in this region would make suitable homes for humans (Kasting, Whitmire and Reynolds 1993:108).

Water was identified as the key factor for life to exist in the universe and a perfect solvent for organic molecules, i.e. molecules mainly formed by carbon atoms that are capable of multiple kinds of intramolecular bonds and therefore able to form very long chains of atoms making possible greater complexity. Life here is a chemical concept or, in other words, the capacity of a long chain of molecules to engage in complex reactions, such as DNA replication and reproduction.

Earth-like planets

On the other hand, what made Trappist-1 of great interest was its closeness to the Earth (*only* 40 light years away), which made it the perfect target for the next generation of telescopes that will start to characterize the atmospheres of exoplanets in late 2018. "With the James Webb [Space Telescope]", Sara Seager said during the press conference, "we'll be able to study the atmospheres and we will try to assess the greenhouse gas content which will help us understand the surface temperature of the planets."[76]

The first step toward the characterization of the planetary conditions was taken when, in the luckiest cases, both the transit and the Doppler shift methodologies could be applied and information about planets' masses, diameters and distances from their stars obtained. These pieces of information give some hint to planets' compositions: whether they are gas giants or small rocky planets like the Earth. Similarly to what

[76] NASA Trappist-1 press release.

happened with the outer Solar System moons, hypotheses about Trappist-1 planets conditions were made through a series of inferences based on estimated mass and diameter. Of each exoplanet, belonging to Trappist-1 or any other system, very little else is known so far. Even the colourful representations of the planets were based on the comparison between "both the masses and the radii of these habitable-zone-type earth-size planets".[77] The next generation of telescopes, mainly the James Webb Space Telescope and TESS (standing for Transiting Exoplanets Survey Satellite), will look at the spectrum of the radiation from the star that has passed through an exoplanet's atmosphere before reaching the Earth. Transit spectroscopy uses the same principle as the transit method to detect exoplanets, but while the latter only detects the dimming of the star's luminosity when a planet transits in front of it, the new James Webb Space Telescope will be able to detect tiny changes in the stars' spectra due to the radiation that is filtered by the planet's atmosphere during transit. The portion of radiation absorbed by the atmosphere itself will give an indication of its composition. Scientists hope to figure out whether some of the target planets have an atmosphere that resembles the Earth's (as opposed to that of Venus, for example, whose extremely high surface temperature cannot be explained by the distance from the star alone) and possibly detect so-called *biosignatures,*[78] "any measurable property of a planetary object, […] that suggests that life was or is present" (McKay *et al.* 2002:625).

If the habitable zone discussed in the previous section is a two-dimensional concept, here planets become bodies composed of a spherical surface surrounded by an atmosphere; the two mutually influence each other, and life will shape both. The idea that the presence of life would entirely change a planet dates back to the 1960s, when James Lovelock, working at NASA to design a method to detect the presence of life on Mars, suggested looking at the planet's energy imbalance: the atmosphere carries traces of life in the form of co-presence of gases that would otherwise be unstable, such as oxygen and methane, both produced by biotic processes (Lovelock 1965). This version of habitability does not simply couple life and place, but also changes the factors of the equation: life becomes a planetary phenomenon, changing the conditions of the entire planet.[79]

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[77] NASA Trappist-1 press release.

[78] What would constitute a reliable biosignature is still an open question; see chapter 5.

[79] Earth itself might come to be understood in different ways when framed this way: based on his research on life detection experiments on Mars, James Lovelock was struck by the differences in their atmospheric composition which, according to him, were evidence of Earth's livelihood. Following up on these studies, Lovelock formulated the famous Gaia Hypothesis, suggesting that

Habitats

When astrobiologists are asked what the most interesting place is *in terms of habitability*, most of them reply, with almost no hesitation, Europa or Enceladus. The two icy moons, nevertheless, lie far beyond what used to be considered the Sun's habitable zone. In an article titled "Expanding the Habitable Zone", published in 1999, right after the foundation of the NASA Astrobiology Institute, Gretchen Vogel wrote that:

> New finds on Earth, such as colonies of bacteria deep underground, have suggested that organisms can thrive even if sealed off from the sun, by living on chemical rather than solar energy. And discoveries in space, such as a possible subsurface ocean on Jupiter's moon Europa, have opened up any number of odd corners of the universe as possible wellspring of life. (Vogel 1999:70).

From 1995 to 2003, Galileo, a spacecraft designed and launched by NASA to orbit Jupiter and its satellites, underwent a long voyage in the outer Solar System. It returned to the Earth pictures that reinforced the hypothesis that under Europa's icy surface there was an ocean of liquid water. A few decades earlier, life had been discovered in the bottom of the ocean and then in caves and deep underground. Here, habitability indicates the possibility of existence of what is sometimes called "weird life" or, most commonly, life "in extreme environments" (National Research Council 2007). It took years for the study of extremophiles, organisms thriving in extreme conditions, to percolate to space sciences, but once the connection was made, the two phenomena could no longer be decoupled and astrobiology started increasing in popularity (Greenspoon, in Impey 2010).

Most of the environments considered extreme on Earth are hard to reach. Scientists explore them by means of long and tough expeditions (more on this in chapter 7), submarines, drills and so on. What they all look for is the hidden and often unpredictable presence of liquid water and living beings that have adapted to their inhospitable conditions. Water, in fact, can be transient or geographically precisely located.

When planets are seen through the lens of extreme environments as very specific habitats, it no longer makes sense to talk or look for habitability as a planetary phenomenon. Habitability comes in different degrees and varies in time. A planet is not

biological and abiotic components form, on Earth, a complex interacting system that can be understood as a single organism (Lovelock and Margulis 1974).

a homogeneous sphere anymore; it might be barren on the surface and yet potentially host life under its subsurface, or have thrived with life a long time ago and now be deserted because of changed conditions. Life, then, is not seen as a planetary and timeless phenomenon, but might well be located in special places that are more profitable for microorganisms, whether dormant, transient, fossilized or just about to take over (Cockell *et al.* 2016).

Inhabitation

When talking about what the discovery of the Trappist-1 system would bring about, one of the astronomers taking part in the NASA press conference enthusiastically showed the latest creation of the fictional Exoplanets Travel Bureau, a tongue-in-check vintage postcard, saying:

> We have a new travel poster […] and if you see here it's captured scientifically accurately the…you know, how on one of the planets you could see all the other planets in the sky. Now, historically in exoplanets in the kind of brief history of the last 20 years, when there's one, there's more. And so that's why I'm so excited to be here today to share it with you. Because, with this amazing system, we know that there must be many more potentially life bearing worlds out there, just waiting to be found (Trappist-1 press conference).

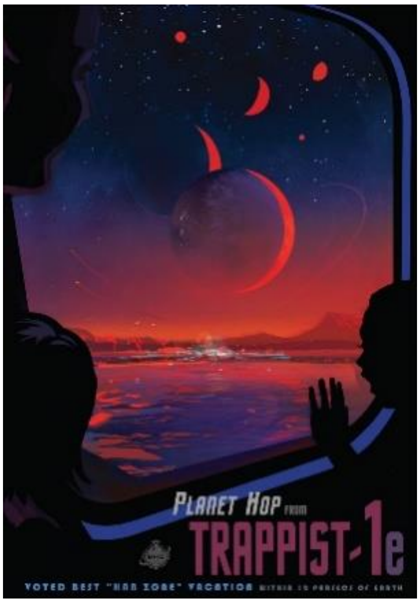

Figure 3 Postcard NASA/JPL

The series includes items from the most interesting and promising exoplanets, and also other bodies of the Solar System such as Europa, Titan etc., alluding to humans travelling to these far-off places. The artwork, combining 1930s and 1940s National Parks poster visual aesthetics and a dose of science-fiction whimsy, evokes both nostalgia and awe for the future.[80] The postcards often portray family trips and romantic jaunts, advocating a dimension of space that is not only dedicated to science

80 https://www.mnn.com/earth-matters/space/blogs/nasa-promotes-exoplanet-vacations-with-retro-posters

or business, but for everyone's enjoyment. Tourism, here, is a form of temporary human inhabitation. Artists' impressions, nevertheless, cover a much wider spectrum of envisioned futures; they do not merely travel far beyond the scientific community but also go much deeper within it.

Here, I am treating visual representation as a form of practice that informs a certain way of constructing prospects of inhabitation. These paintings, in fact, are the outcome of an intense collaboration between the artist and the scientist, very much like a graph is produced due to a collaboration of people that combines their knowledge, intentions and representational skills. Pascal Lee, astrobiologist and artist, writes on his website:

Figure 4 Pascal Lee, Mars Mobility Systems, Painting depicting a human mission to Valles Marineris on Mars and the use of a pressurized rover and all-terrain vehicles (ATVs) as surface mobility systems. (Acrylic on board, 9 x 11.5 inches, 2004).

> I strive for realism, scientific and technical, in most of my drawings and paintings. I attempt to create visions as they would appear to a human explorer on site. I allow the scenes depicted to be imaginary, but endeavor to make their representation realistic, as if actually experienced. My goal is to transport the viewer to another world, to make him/her a front row witness to a unique moment in space and time.[81]

Artists' representations evoke the human inhabitation of space through the idea that postcards physical move from a place to another and acquire their meaning and value not for their mere visual content, but once they are manipulated by the traveller and travel themselves from their place of origin to the receiver's hands.

Representing human presence is a performative act: on the one hand, it is a way of visually showing something that has not happened yet, "making things thinkable"[82] by paying attention to both the details and the flavour that each possible future must have. On the other hand, the excitement takes the form of a self-fulfilling prophecy: the more attention from the public and the scientific community these representations catch, the more effort people and institutions put into pursuing them (Borup *et al.* 2006). Visual

[81] http://www.pascallee.net/artwork/ (last accessed 01/08/2018).

[82] Guy Consolmagno, interview 21/06/2015.

representations of possible futures, then, are entangled in complex relationships with the present.

Building habitable worlds

Every other year, the UK Centre for Astrobiology organizes a one-day workshop titled "Building Habitable Worlds". The workshop is formally aimed at early career researchers, but in practice almost nobody is excluded: from undergraduates up to any stage of career, as long as one has some interest in looking at extra-terrestrial life through the lens of science (whatever this is taken to mean) – me included. "The fact that you are interested in these things makes you an astrobiologist"[83] is repeated at the end of the workshop. The gathering of people from different backgrounds brings under the same roof many different ways of studying life and planets. Habitability provides astrobiologists with a common vocabulary to speak about very different things: the places they study are very different places, and so are the lives for which they are searching.

After the presentation of each attendee's research in a five-minute pitch session, the afternoon is dedicated to group work, making the move from the compilation of mental maps about some of the "hot themes" in astrobiology. Small groups of people randomly gather around the five tables distributed throughout the large seminar room. Each table is covered with a white piece of paper in which a major theme is written in capital letters: exoplanets, Mars, Habitability, origin of life, biosignatures. Despite the fact that all the attendees have an interest in astrobiological themes, for the majority of them this is the first time they have actually engaged in this kind of conversation with colleagues from other disciplines. At almost every table, someone happens to write down on the mental map the word "life" – often followed by a question mark. Someone else wonders what the chances are of finding life:

> "We don't even know what life is..." claims a PhD student in astronomy. "What do you mean?! We do know", quickly replies the biologist. "Do we? What is it, then?" "Well, we know that life has the capacity to metabolize, grow, react to the surrounding environment and reproduce", "and what if life does not evolve? Or does not reproduce…or just reacts in a way that we do not understand as a reaction at all? I know it might seem absurd, but once a professor of mine wondered whether a planet or a neutron star are alive. We might simply not be able to detect their liveliness".

83 Private conversation.

> Silence, the astronomer laughs, a little embarrassed. I nod as I feel like I have already heard different versions of this conversation so many times before. "I never thought about that", says the biologist. She takes the marker and draws a zig-zag line on the definition, and then she highlights the question mark after the word "life". "Anything can be habitable then" (from fieldnotes).

The uncertainty about "what life is" is learnt and performed over and over again. At the end of the workshop, every participant will go back to his or her own university, to a lab bench to put samples of extremophiles under a microscope, to a telescope whose data will be plotted as dots on a Cartesian graph, to computer simulations fed with numbers and returning images of colourful worlds, to different ways of telling, representing, imagining and making habitable worlds visible and assessable. They will, after all, ask different questions, but use the same world, slowly coming to engage with the constitution of a new scientific community.

The status of planet is not given once and for all. In 2006, the Astronomical Union redefined the term "planet" (and consequently all the cognate terms used to classify celestial objects) after a long and controversial debate about whether Pluto could be considered a planet or not. In "The Problem with Pluto", Lisa Messeri (2010) claims that the planet "means different things in different contexts, which is why, left undefined, it served as part of a contact language between groups" (Messeri 2010:206). In her analysis of the controversy about Pluto that ended with the formulation of the category of "dwarf planet", the imprecision over the definition of the term "planet" was perceived as a problem by the astronomy community. The controversy ended with a claim of authority by a group of astronomers over the other members of their scientific community and, most importantly, over the lay public. This closure rests upon social dynamics involving authority, interests and tradition. In this chapter's case, on the contrary, habitability is valuable precisely because it is vague: its vagueness helps scientists build an interdisciplinary community and maintain the interest of the public. Instead of constraining its meaning and thus privileging some interests over others, scientists happily bridge its many connotations and work toward community-building.

Defining habitability in a single way would not only be partial and unmindful of its being made in a variety of research practices, but it would also miss what makes habitability "the *right* question", to paraphrase brother Consolmagno. Astrobiologists, despite being aware of the different ways in which habitability is achieved, and often commenting on the unsatisfactory ways in which habitability is defined in the scientific literature, do not look for closure, for one of the possible ways of doing it to prevail over the others. On the contrary, habitability is a grey zone that allows for the coexistence of different narratives about life and planets, different understandings of life associated with different understanding of places. It is *right* not because it is certain or undebated, or even *true*. It is right because it allows the community to coalesce, to coordinate different ways of world-making, phrasing different interests and sensibilities with the same vocabulary.

Chapter 5

"The life on Mars roller-coaster"

Biosignatures, evidence and uncertainty in Martian environments

"All philosophy is based on two things only: curiosity and poor eyesight ... The trouble is, we want to know more than we can see. [...] True [natural] philosophers spend a lifetime not believing what they do see, and theorizing on what they don't see"

(Bernard le Bovier de Fontenelle, *Conversations on the Plurality of Worlds*, 1686).

Narrating Mars

Every time I entered Charles Cockell's office, I was struck by the paintings hung on the walls between the tall shelves packed with books and printed articles. Adorned with wooden frames, a number of oils on canvas showed images of people and machineries deployed in what could probably be described as space *exploration* and *colonization*[84], mainly of Mars. Against the red and brown brush strokes giving texture to the landscapes, splashes of white depicted astronauts, instruments and, just above the horizon, futuristic shelters. Despite the un-Earthly scenes, the expressions portrayed on the characters' faces were human: one could see pride and enthusiasm, but also exertion and a mix of curiosity and caution. Charles Cockell had personally commissioned all the paintings adorning his office: he would describe to the artist the scene he would like to have painted and then wait to receive the first sketches, on which he would later give feedback both about the general inclination of the scene and the correctness of the scientific details. The scenes were surely not real, but aimed to seem at least plausible in a not-too-far future. In the following years, I found out that several of the

[84] I use the words "exploration" and "colonization" somehow reluctantly. They are *actor categories,* very often used by astrobiologists and space entrepreneurs, but I have often wondered what the consequences of the use of these two words are and whether there are alternatives.

astrobiologists I met paint and draw their favourite astrobiological subjects, often Mars, or the extreme environments used as Martian analogues. Their paintings have rich narratives: they depict landscapes, settlements and human activities. These images, nevertheless, are only one of the types of representation at the very interface between imagination and scientific research. In the last few years, for instance, a wealth of images of the Martian surface shot by landers and rovers quickly travelled on social media; the sophisticated system of lenses and sensors constituting Curiosity's "eye" have captured beautiful postcard-like landscapes and taken "selfies" of the rover crossing the Martian surface. Even if every bit of information collected and sent back to Earth is a precious commodity for the mission control engineers and scientists, Janet Vertesi observed that a significant portion of the rover's time and energy is dedicated to the production of images to be circulated among the scientific community and the general public (2004:42-3). This is just one of countless examples, from the recent "Journey to Mars" project – a step-by-step plan that set forth a number of missions, unmanned and manned, to the red planet – to the ESA training of astronauts for future Mars exploration aimed at *in situ* search for evidence of extant or extinct life (see chapter 7). They all point to the red planet as a central resource in space exploration and, in particular, in the astrobiology agenda. Interestingly, Mars as a *topos* has served as a valuable resource in many different repertoires connected to space exploration and to many different versions of space colonization. Elon Musk's interest in Mars as a back-up for the Earth's entire biosphere is one of many possible examples. Not being exclusive to astrobiology is, nevertheless, what makes Mars valuable as a resource by providing continuities, ties and overlaps with other communities and interests. From a sociological perspective, I explore how the history of the scientific exploration of Mars is told and deployed as a resource in the repertoire built around the search of biosignatures, which includes a larger set of theoretical and practical resources (as we shall see in the following chapters).

This chapter will show how the expectations about the presence of life on Mars and the development of astrobiology have often run on parallel trajectories, and neither of them can be accounted for as a smooth and linear processes; on the contrary, one of my interviewees described the search for life on Mars as a "roller-coaster"[85] of enthusiasm and disappointment, of discoveries and withdrawal, of optimism and disillusion. As

the astronomer Paul Davies claimed, even in the mid-20th century,

[85] PL (planetary scientist and amateur painter), interview 22/02/2016.

> to profess belief in extra-terrestrial life of any sort, let alone intelligent life, […] was tantamount to scientific suicide. One might as well have expressed a belief in fairies. What, then, has changed? Why is it now scientifically respectable to search for life beyond Earth? (Davies 2011:625).

Comparing this claim to the current popularity of astrobiology is indeed quite striking, but describing this development as a linear shift from "philosophical speculation" to scientific discipline would be misleading.

If the last century opened with a wave of enthusiasm about the possibility of Mars being inhabited, the first missions to the Red Planet returned discouraging results followed by a new rise of curiosity triggered by the Viking missions. In the aftermath of Viking and as a consequence of a long controversy about the correct way to interpret the life detection experiment results, the search for life on Mars remained dormant for the following two decades until a series of events again boosted interest in life in the universe. It was only at the end of the 1990s that the discipline was renamed astrobiology and the first Astrobiology Institute was funded by NASA, followed by many other institutions dedicated to the search for extra-terrestrial life in other countries. It is only in the last decade that astrobiology has accumulated significant amounts of funding, publications and people involved in research projects (Weinzierl 2018) and the search for life in the universe has been brought back to the fore (Voytek 2016). In the words of one of my interviewees:

> CMK: Now it's very popular, astrobiology and the search for life, everybody is doing it!
> VM: Really? Do you mean here in the US?
> CMK: It has become... even in Europe, a lot of planetary missions are tied to the search for life. Rosetta,[86] why we're going there? "To understand the origin of life". […] The root of the motivation, they keep coming back to life and the origin of life and that's, it's widespread, it's not just a US phenomenon: all the missions, planetary missions are focusing on search for life, the Japanese also. So it has become a background for why we're going out in the Solar System and it's even now the background for why we're looking for extrasolar planets life, so…even

[86] Rosetta approached the comet 67P/Churyumov-Gerasimenko between January and May 2014 and its lander Philae landed on it on the 12th of November of the same year. The mission was coordinated by ESA.

astronomers and people who aren't astrobiologists point at astrobiology to justify their work, so it's truly quite popular. [87]

By drawing on astrobiologists' own accounts, I follow on the narratives deployed by astrobiologists to account for two episodes in which life on Mars was imagined and searched for in ways that were later made objects of criticism: Schiaparelli's description of the Martian "canals" and the Viking life detection experiments. In looking at the role these stories play in defining the present status of astrobiology, what counts as proper astrobiological practice and what place it occupies in the scientific landscape, I claim that accounting for the past can serve as valuable resource for gaining legitimacy and tracing a threshold that characterizes astrobiology as "scientific" when compared to its forerunners. In other words, the accounts given today by astrobiologists of these episodes are meant to position their enterprise with respect to the past. On the one side, they emphasise the continuity with historical events and figures, making references to them as part of a shared trajectory toward the exploration of Mars. On the other side, if Mars has been an object of interest since time immemorial, long before the word "astrobiology" was coined and attributed the status of a scientific enterprise, astrobiologists claim that the way the study it today is inherently different.

The anecdotes I take into consideration in this chapter are meant

to pass on a particular sensitivity to two crucial issues: the taken-for-granted assumptions about what life elsewhere might look like and the possibility that impartial interpretation of the data collected is inhibited by biases and hopes. These are the pillars of one of the most pervasive repertoires astrobiologists engage with: the definition and search for biosignatures. According to David McKay, a biosignature is "any measurable property of a planetary object, its atmosphere, its oceans, its geologic formations, or its samples that suggests that life was or is present" or, in other words, the "fingerprint of life" (McKay *et al.* 2002:625). According to Stefan Helmreich, biosignatures are Peircean *indices*, or indirect representations; they are traces, like smoke seen from afar indicating the presence of a fire. Like an individual's signature, they are the paradoxical reproduction of "irreproducible authenticity" (Helmreich 2006:73). Biosignatures are characterized by this tension: torn between defining and detecting, they mirror and at the same time shape astrobiology's concept of life as becomes definitionally unstable (*ibid*).

[87] CMK (astrobiologist at NASA Ames Research Centre), interview 09/10/2015.

In this chapter I take into consideration the development of the concept of biosignature in relation to Mars exploration and the emergence of astrobiology as a legitimate field of scientific inquiry. By looking at the search for biosignatures as a repertoire adopted by astrobiologists, I will show how the history of interpretation of Martian observations and the institutional history of astrobiology as a discipline are inherently intertwined.

Mapping the Red Planet

On the rooftop of the old Jesuit College in Milan, overlooking a quiet botanical garden, a large dome covers one of the most sophisticated telescopes of that time. It is 1877, and Giovanni Schiaparelli, director of the Brera Astronomical Observatory, is ready to observe the planet Mars during one of its closest oppositions.[88] The observations resulted in the production of a series of maps - reviewed and refined over time - in which Schiaparelli reported the observations of a number of straight *canali* crossing the surface of the Red Planet, forming a vast network from pole to pole.

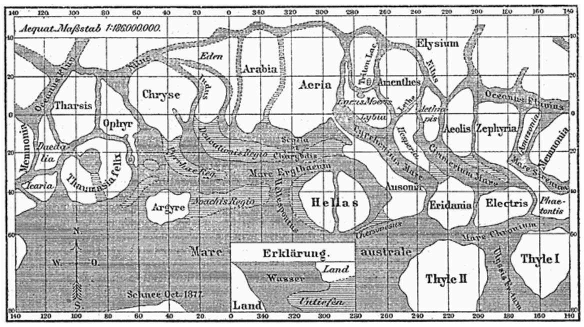

Figure 5. 1877 map of Mars by Giovanni Schiaparelli.

The Italian astronomer was not the only one observing Mars and drawing areological maps; his graphical representations, nevertheless, differed from his contemporaries' more nuanced and naturalistic works in the use of straight lines and sharp contrasts[89] (Lane 2005). Where other astronomers could see no more than unresolved shades, Schiaparelli transformed his detailed notes taken during the long nights of observation into firm shapes on the map. The *canali* obtained had no curves or bends and did not change in width; they were, in Schiaparelli's words, "depressions in the soil that are not very deep, extended in a straight direction for thousands of miles" (Schiaparelli 1877).

Schiaparelli's maps attracted some criticism at first, as many astronomers claimed not to have been able to repeat his exceptional observations and see the canals. Very soon,

[88] An opposition occurs when Mars, Earth and the Sun line up in space. It is the time of their orbits when Earth and Mars are closest. Oppositions happen every 26 months, but because orbits are elliptical, some oppositions bring the planets closer than others.

[89] Another difference was the novel place-name system inspired by the classic Mediterranean world.

nevertheless, the strong scientific authority of the Italian astronomer accorded to the maps and to the apparent greater precision of its drawings a similar level of visual authority. The complexity of the waterways network, together with the highly geometrical pattern they formed and their presumed gargantuan size, made many astronomers think of artificial origins. Schiaparelli neither encouraged nor resisted this interpretation, which, he claimed, "involves no impossibility". In fact, in his *La Vita sul Pianeta Marte* (1895), he indulged in the idea of "the absence of rain on Mars" and hypothesized that the canals were "probably the main mechanism by which the water (and with it organic life) can spread on the dry surface of the planet."

In 1894, the issue triggered the interest of Percival Lowell, a Harvard-educated Brahmin from Boston. Lowell spent his youth travelling to the Far East, especially to Japan and Korea, and publishing books on Oriental religions, languages and cultures. Once back in his home country, he was elected a fellow of the American Academy of Arts and Sciences and, after reading the popular book *Le Planete Mars* by Camille Flammarion, he decided to dedicate himself to the observation of the Red Planet. In the mid-1890s he spent time and resources on the foundation of an astronomical observatory in Flagstaff, a small town at an altitude above 2,100 metres in northern Arizona, where he could enjoy clear skies for most of the year and little environmental pollution. In the following years, Lowell did not simply repeat Schiaparelli's observations, but enriched the maps with new details and became the most zealous advocate of artificial origins of the *canals.* Lowell translated the word *canali* into the English "canals", implying the artificial nature of the Martian waterways, instead of the perhaps less controversial "channels". "Every opposition has added to the assurance that the canals are artificial; both by disclosing their peculiarities better and better and by removing generic doubts as to the planet's habitability" (1908). He wrote:

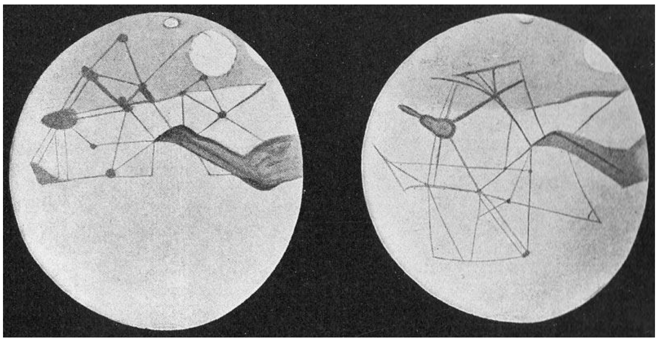

Figure 6 Martian Canals depicted by Percival Lowell. (Source: Wikicommons)

> The aspect of the lines is enough to put to rest all the theories of purely natural causation that have so far been advanced to account for them. This negation is to be found in the supernaturally regular appearance of the system, upon three distinct counts: first, the straightness of the lines; second, their individually uniform width;

> and third, their systematic radiation from special points. On the first two counts we observe that the lines exceed in regularity any ordinary regularity of purely natural contrivance. Physical processes never, so far as we know, end in producing perfectly regular results.

Percival Lowell saw in the canals proof that Mars was inhabited by a resilient civilization, resisting the progressive desiccation of their planet[90] by means of a global irrigation system they had constructed (Crossley 2011). Despite the scarce agreement with which Lowell's theories were met in the scientific community, his description of Mars greatly influenced the public imaginary.

Mars mania

According to Lane, "the formative early claims about Mars's possible habitability were presented in the quintessential geographical format – the map." The map, she continues, "was the foundation on which truth claims about Mars were built and the primary medium by which knowledge about Mars was communicated" (2005:478). The adoption of cartographic conventions in the representation of the Red Planet allowed for a number of conceptual shifts; first of all, astronomers started paying closer attention to the conditions under which the observations were performed and therefore started going to remote locations where they could enjoy clearer atmospheric conditions, such as Lowell's observatory on the top of a mesa in dry northern Arizona. So important were their travels outside the major metropolitan centres to ensure their instruments could perform appropriately and thus legitimize their observations that astronomers adopted the language of field sciences of that time, such as geography and botany, in their publications. Percival Lowell's contribution to the Martian map at once drew on the geographical discourse and emphasized it. Mars astronomers adopted the prevailing attitude of the field sciences "that a landscape had to be seen to be understood" (Lane

[90] According to the Nebular hypothesis of stellar system formation, in fact, all planets will eventually dry out – Mars was thus seen as a dying planet. In *The Evolution of Worlds* (chapter 7, "Death of a World"), Percival Lowell wrote that "Everything around us on this Earth we see is subject to one inevitable cycle of birth, growth, decay. Nothing that begins but comes at last to end. Not less is this true of the Earth as a whole and of each of its sister planets. […] The same inevitable end, in default of others, is now overtaking the planetary group. Its approach is stamped on the face of Mars. There we see a world dying of exhaustion. The signs of it are legible in the markings we descry. How long before its work is done, we ignore. But that it is a matter of time only, our study of the laws of the inexorable lead us to conclude. Mars has been spared the fate of Mercury and Venus to perish by this other form of planetary death".

2005:493). Being able to see by oneself and actively to contribute to the characterization of Martian features, as opposed to relying on someone else's reports, became the seal of scientific authority; as a consequence, those who wanted to disprove the existence of the canals or simply reduce the detail of the maps were accused of not having "the kind of eye needed for the detection of planetary detail" (Lowell 1905:92) and not making any contribution to the discipline. On the contrary, only those who could add new features to the areological canal networks were considered the maps' most trustable interpreters. A second consequence was the increasing attribution of Earth-like features to the Red Planet: despite the insistence on the differences between Mars and Earth, Earthly landscapes were often used as analogies to explain the Martian features, for example by saying that the periodic melting of the polar caps had, on Mars, the same fertilizing function that the annual Nile floods had in ancient Egypt (Gregory, in Lane 2005) This new view of Mars as a geographical world was indeed contestable, but imaginable and fascinating at the same time.

At the beginning of the 1900s, the canals were proven to be an optical illusion, but the so-called Mars mania was already underway, and what Stephen Dick called Lowell's second legacy, i.e. people's confidence in the presence of life on the Red Planet, lasted well into the 1930s. The spread of belief among the public that Mars was inhabited is testified by the panic triggered in October 1938 by the radio version of H. G. Wells' novel *The War of the Worlds*. The audience, terrified by what they did not know was only a radio drama, poured out into the streets in fear of a Martian invasion.[91] It was in this climate of strong expectations for the possibility of Mars hosting some form of life - ranging from the very optimistic scenario in which complex organisms could be found to the more sober idea of seasonally variable spots of vegetation - that the space race era began in the mid-1950s and the first missions to Mars were designed.

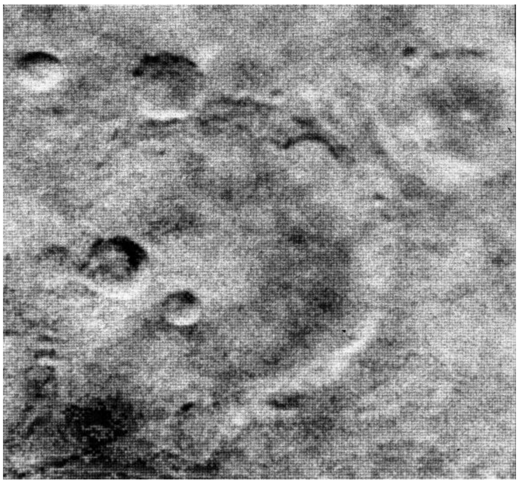
Figure 6. Mariner 4 Image NASA/JPA

[91] As Stefan Helmreich (2006) notes, there is an interesting reversal here: if in *The War of the Worlds*, the Martians were eventually defeated by the Earth's microbes, now there is a broad agreement that, if Martians exist, they might in fact *be* microbes (see also Wolfe 2002).

Mariner 4 was the first spacecraft to photograph Mars from a closer distance; around a fifth of the surface of the planet was photographed, but "nearly all the interesting features were missed" (Snyder 1979:8487) and Mars appeared as a flat deserted land covered in impact craters. "Mars", wrote the popular science fiction writer Arthur C. Clarke, "was a cosmic fossil like the Moon – no, not even a fossil, because it could never have known life. The depressing image of a cratered, desiccated wilderness was about as far removed from the Lowell-Burroughs fantasy as it was possible to get" (Clarke in Crossley 2011, note 35). By the beginning of the following decade, the pictures taken by Mariners 6 and 9 had covered the entire surface and thus enriched the first impression with a wealth of new geological traits, "a profusion of geological features, a kind of geological exuberance, which the Earth lacks" (Viking Press Kit 1975:24). In the "new Mars" (Hartmann and Raper 1974), the word "canal" was definitively deleted from the areological vocabulary: one of the major canals, Agathodaemon, was found to coincide roughly with what is now called Valles Marineris, and a few others were identifiable as corresponding to geological features that later appeared in pictures, but the vast majority of them could be associated neither with topographic nor albedo features. They appeared, on the contrary, "to be largely self-generated by the visual observers of the canal school, and stand as monuments to the imprecision of the human eye-brain-hand system under difficult observing conditions" (Sagan and Fox 1975), optical illusions projected on an intricate distant surface.

Schiaparelli's and Lowell's maps of Mars signified an era in which the Red Planet was assumed to be so similar to the Earth as to mirror Earthly political, economic, social and engineering dynamics. Astrobiologists today blame them for overlooking any other alternative explanation that made sense of the same visual inputs – in this case, an optical illusion – and jump to the conclusion that better fit their hopes. The two astronomers, nevertheless, could not be said to lack zeal and rigour; in their time, in fact, their maps were shared with the community, agreed upon and supported. Their misplaced optimism serves today's astrobiologists, reminding them what *not* to do when interpreting their experiment results.

Almost 100 years after the opposition used by Schiaparelli to craft his map of the Martian *canali*, NASA moved a step further in the exploration of the Red Planet. The so-called Viking mission, consisting of two twin spacecraft composed of an orbiter and a lander, was explicitly designed to search for life on our planetary neighbour's surface. Due to the pictures sent back to Earth from the Mariners, the Lowellian legacy had already faded out, together with the expectation of finding a complex civilization struggling to survive their planet's desiccation. Hopes were instead placed on simple microbial lifeforms, which could have evolved to adapt the harsh – and still partially unknown – Martian conditions. The possibility of actually finding forms of life on Mars, avowed the press kit released before the probes' launches, "makes the exploration of Mars the most important objective of planetary exploration for many decades to come" (Viking press kit 1975:3).

Figure 7. Viking press kit cover page NASA

Launched in late summer 1975, both spacecraft entered Martian orbit after several months of space travel. Once revolving around the planet, the orbiters' precise mapping provided mission control on Earth with information for choosing the landing site, which was eventually fixed as Chryse Plantitia (from the Greek "Golden Plain),[92] a flat region, where the lander arrived successfully on the 20th of July 1976.

[92] Viking 1 landed on the 20th of July, a couple of weeks later than desired. Mission control had hoped to land on Mars on the 4th of July 1976, the second centenary of the Declaration of Independence. Space exploration has always gone hand in hand with nationalistic ideals.

Each lander carried, among other instruments, the so-called biology package: a set of three experiments that aimed to test for the presence of living organisms. The instruments had been designed, selected and further developed in the previous decade; scientists agreed on the fact that "the best 'search' strategy for life on Mars under these circumstances", in the words of the scientific leader of the Viking Biology Investigation, Harold Klein, "would entail [...] a large number of 'life detection' experiments based on differing assumptions about the nature of Martian biota" (1976:274). However, because of the engineering constraints that a planetary mission required, only three experiments were chosen – each investigating a different physiological mechanism (Gold 1972). What they had in common was the focus on the detection of metabolic activities within small samples of Martian soil. The so-called gas exchange experiment aimed to detect the production of gases as metabolic by-product under the assumption that living organisms would be stimulated by the presence of water moisture, and the "pyrolytic release" experiment assumed that organisms on Mars would assimilate gases into organic matter and thus measure the release of volatile organics during the heating of the sample after an incubation period. The third experiment, called "labelled release", tested the hypothesis that Martian microbes would eat simple organic compounds, decompose them and produce gases as end product.[93] A week after the landing, Viking 1 started its biology experiments, and positive results started coming through very quickly. In particular, the labelled release experiment registered a peak in CO_2 when nutrient broth was added to the sample (while the control sample did not register any fluctuation), a result that was at first glance consistent with the biological positives as run on Earth. "However", Richard Young continued, "it quickly became evident that the chemical nature of the Mars surface material was quite different from anything known on Earth" (1978:502).

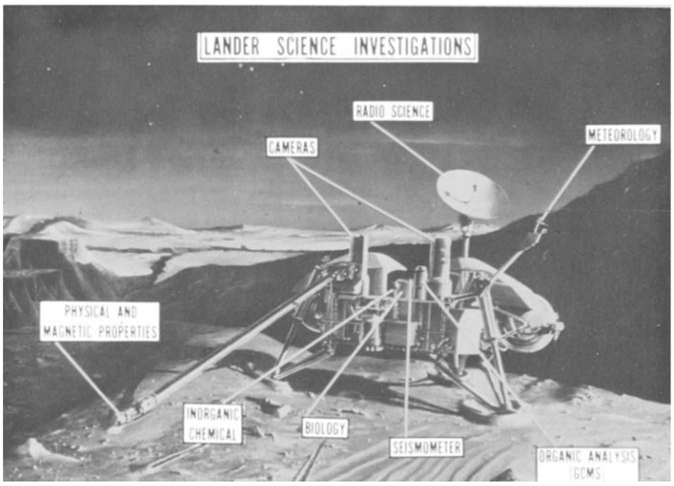

Figure 8. Viking Lander, instruments. From Harold Klein (1976)

[93] A detailed description of the three biology experiments and the other instruments carried by the Viking lander can be found in Klein, Lederberg and Rich (1972). Historian Stephen Dick also dedicates a chapter to the missions on Mars in the late 1960s and early 1970s (Dick 1996).

The excitement about the positive results was immediately offset by what was later described as "probably the most surprising single discovery of the mission": the instrument designed to analyse the soil composition, the gas-chromatograph mass-spectrometer, detected "absolutely no trace of organic constituents" (Snyder 1979:8508). All the above-mentioned hypotheses about ways to test for the presence of life were based on a more general assumption: the fact that Mars was *similar* to the Earth, at least approximately. Similarity is always arbitrary, but the absence of simple organic molecules (which had been detected in many other celestial bodies) revealed the Red Planet from a completely different perspective. After the Viking missions, the Martian soil could be generally characterized as an iron-rich clay, "but no single sample of terrestrial material fits the observed concentrations of the elements" (Snyder 1979:8508). The lack of organics unhinged this very basic assumption and made all the data collected hard to interpret.

Reports of the first runs of the Viking biology experiments were released after a few weeks, and from the very first provisional analysis of the data, the scientists who had designed the experiments found themselves in an ambiguous position: "According to the criteria set before launch", wrote Carl Sagan in 1977, "the results of the first run of [the labelled release] experiment[94] were positive [and] consistent with the existence of life on Mars, but many scientists are properly cautious in their interpretation of this evidence" (Sagan *et al.* 1977:26-7). In the following years, the procedures, the data collected, and their possible interpretations were vigorously discussed[95] (Dick 1996; Sagan *et al.* 1977; Young 1978). The debate on the results lasted for several years, and the reports that appeared in the scientific literature clearly evidence the lack of agreement on what the data collected actually evidenced. The following quotations exemplify the ongoing negotiation on the correct interpretation of the results.

> Considerable *debate* and much ground-based research ensued, and the following conclusions have been *reached by most participants* […] Most scientists *do not feel that* the Viking data are indicative of life on Mars […] Ground-based laboratory studies *tend to support the conclusion* that a chemical explanation *is more tenable* […] At the same time, many scientists think that the results *do not rule out* the possibility

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[94] The labelled release experiment was meant to detect metabolic processes occurring in life-favourable conditions.

[95] Some of the scientists involved in the experiment design are still debating its validity; for example, Gilbert Levin still claims that NASA's Viking missions found microbial life on Mars (https://www.youtube.com/watch?v=jqiq3iCUAhM).

> of life on Mars. They *believe it is not reasonable* to extrapolate to the entire planet from evidence obtained at two very localized sites. (Young 1978:503, emphasis added).

And also:

> [In the Pyrolitic Release experiment], as in the "Labeled Release" experiment, it is possible, although by no means demonstrated, that non-biological chemistry of an unfamiliar sort might also account for these results. Mr Sagan concluded by saying that the experimental results of the search for life on Mars are *mixed, enigmatic, puzzling and exciting, but certainly not definite*. There are data which may indicate microbiology on the planet or an exotic non-biological chemistry (Sagan, Horowiz and Murray 1977, emphasis added).

Interestingly, instead of being presented as *knowledge* obtained from the mission, the interpretations still held their status as opinion and beliefs that were more or less shared by the groups participating in the research. The debate lasted several years, and the scientists involved took different positions not only on how to interpret the results but also on what the lack of results did *not* imply. Many of them highlighted that the two locations might not have been indicative of the entire planet, others that Mars might have been inhabited in the past or still host microbial communities under the surface. From the end of the 1970s, the exobiology community found itself in a difficult position.

In the introduction to the Viking Symposium held in 1972, a few years before the mission was launched, Thomas Gold expressed his hope that "the level of enthusiasm and encouragement will persist over the intervening years, both within NASA, within government circles, and in Congress, so that the program can go ahead smoothly. This enthusiasm", he continued, "is dependent in turn on the support given by a significant portion of the scientific community" (1972). Gold admitted that Mars exploration was not able to proceed in isolation from the rest of the society, but required the support of the public and the public administration. The lack of results inhibited this enthusiasm, and, together with a financial crisis culminating in the 1980s, led to a change of direction in space exploration. The lack of agreement about the Viking results would keep scientists busy for two more decades, but, at the same time, deprived the ambitious exobiology programme of confidence. The lack of epistemic authority, or what one of my interviewees called "Viking Syndrome", would affect the search for extra-terrestrial life until the end of the 1990s. At the end of an article discussing the Viking controversial results, Snyder very realistically foresaw the next unmanned mission on Mars to be planned for the end of the 1980s, or probably the 1990s, and he hoped for a "quantum jump" in terms of understanding the Red Planet (Snyder 1979:8515). Interestingly, Snyder listed the goals of Mars scientific exploration and placed the study of the conditions for the existence of biology at the very end. This is not indicative, as there was not a hierarchy of priority, but clearly geology was about to become a driving force in the rising "comparative planetology" (Young 1978:502).

The Viking age ended with the decline of exobiology's epistemic authority, not only due to inner dissent about the result, but also because of the incredibly expensive failure to produce any kind of knowledge about life on Mars at all. Not only were scientists left with no answers, but the question marks about Mars had increased exponentially: what they had assumed to be similar to Earth – at least the composition of the soil and the basic conditions for performing experiments that had always given reliable results on Earth – in fact was hugely different and unexpected. It would take 20 more years to figure out what was so different and how this might have affected the Viking's life detection package. In the meanwhile, the discipline went through a refashioning that made it into present day "astrobiology". One of the fundamental precepts that astrobiologists share is to question all previous assumptions about what life elsewhere might look like. This form of non-knowledge is foundational and is learnt and transmitted through examples such as Viking.

From exo- to astro-biology

In this section, I move on to the last decade of the 20th century, when a number of events, people and circumstances offered the chance for the search for life in the universe to coalesce under a single disciplinary label again. This field in formation cannot be entirely attributed to new scientific discoveries and available technologies, or to the changing institutional frameworks that facilitated the assembling of people and funding. On the contrary, institutional and epistemic changes went hand-in-hand and provided each other with available options for further development. Eventually, what counted as valid evidence of life in contemporary astrobiology was the outcome of an epistemological and institutional refashioning. This refashioning both set astrobiology on a line of continuity with its forerunners and, nevertheless, marked a turning point. Astrobiologists capitalize on this tension by referring to the past to define, by contrast, what counts as *good* astrobiology today.

If Viking resulted in a sense of depression at NASA (Rothschild, in Imprey 2010:94; Baross, in Imprey 2010:194), the 1990s offered the opportunity for the latent interest in life in space to come to the fore again. A series of announcements, all made within less than a decade, are credited for the change in mood within and outside the scientific community, thus offering a favourable combination of circumstances for what would be a turning point in the history of the discipline.

The first ground-breaking announcement came from two Swiss astronomers, Michel Mayor and Dider Queloz, who observed the first extrasolar planet, Peg-51.[96] The discovery confirmed what many astronomers had already expected: the fact that planets were not unique to the Sun and their absence from the catalogues of astronomical objects was simply due to the insufficient sensibility of the technology available. Once the instruments were perfected, astronomers hoped to find many more of them. In fact, this large planet orbiting its star at a very close distance did not resemble any known celestial body and did not fit with any prior theory of planetary system formation. In the following few years, these so-called "Hot Jupiters" turned out to be very common in the cosmic neighbourhood, and theoretical research on the formation of planets thrived. Both the feeling of an imminent discovery of an Earth twin and curiosity about the diversity of the planet population sparked researchers' interest and the security of research funding.

If extra-solar Hot Jupiters intrigued the exoplanet astronomer community, the satellites of the more familiar Jupiter were just about to surprise planetary scientists for their unanticipated variety of geological features. The Galileo spacecraft, launched in 1987, reached Jupiter's orbit and began its data collection in 1995. As already seen in the previous chapter, the data broadcast back to Earth radically changed the image of the outer Solar System as a stable and dull place, and, in particular, supported the hypothesis of the presence of a liquid ocean under the icy crust of Europa, the smallest of the four Galilean moons.

Another element usually considered to have played a major role in this phase is the detection of new ecosystems in unexpected places, such as the dark and deep ocean floor, where complex communities of microorganisms were thriving around so-called hydrothermal vents. These sites, collected under the name of "extreme environments", came to constitute an important cornerstone in astrobiological research (chapter 7).

In 1996, it was the turn of a meteorite called ALH84001 to capture media attention. As its alphanumeric name encodes, ALH84001 was found in 1984 in the far western icefield of Allan Hills, and, since it was immediately recognized as the most unusual rock

[96] Orbiting around a Sun-type star some 50 light years away, Peg-51 can be found in the Pegasus constellation. The planet was later dubbed Bellerophon, the Greek mythological figure that rides Pegasus, the winged horse.

collected, it was the first Antarctic meteorite to be processed from that field season.[97] Petrological and mineralogical analysis revealed the rock to be one of the oldest Martian meteorites ever found, formed more than four billion years ago. David McKay and his team at JPL analysed one of the sections of the rock and identified a number of tubular shapes that they associated with the fossilized remains of primitive microorganisms formed on the Red Planet before being thrown on a several-million-mile journey to Earth. "Although there are alternative explanations for each of these phenomena taken individually," they asserted in an article published in *Science* in 1996, "when they are considered collectively, particularly in view of their spatial association, we conclude that they are evidence for primitive life on early Mars." (McKay *et al.* 1996:929).

The news had such a powerful impact that President Bill Clinton was urged to comment on the discovery, which he defined as potentially "one of the most stunning insights into our universe that science has ever uncovered." Leveraging the *Americanness* of the research (in terms of personnel, funding and attitude), the President guaranteed, despite the "tough financial times", all the support needed for NASA scientists to confirm the discovery and to "search for further evidence of life on Mars". Continuing and succeeding in space exploration was linked, as many times before during the space race, to matters of national pride. In his final remarks, President Clinton promised an official summit to discuss the future of the American space programme. After more than two decades, ALH84001 managed to bring back to the Congress table the option and opportunity to support the search for life[98].

Considering these events as crucial to triggering public interest would perhaps be too simplistic. More likely, it was the latent interest that made them so big in the news and so significant for the astrobiology scientific community, who often refer to them to account for the rise in interest and funding that started in the second half of the 1990s. In fact, according to Chris McKay, there was also an absence that signposted the end of the decade: the accomplishment of the Human Genome Project left scientists' quest for the "secret of life" unanswered, thus making room for other ways of investigating what life was about.

Despite the magnitude attributed to these events, astrobiology had to be formulated "in the world of politics" (Hubbard 2008) to become a fully-fledged part of NASA's (and

[97] Roberta Score, in Mars Meteorite Compendium 2003 (https://curator.jsc.nasa.gov/antmet/mmc/84001.pdf).

[98] The entire press release is available at (https://www.youtube.com/watch?v=pHhZQWAtWyQ)

then of other space agencies') agenda. In fact, the 1990s did not seem to offer the best starting conditions: in fiscal year 1993,[99] NASA underwent a major re-evaluation to reduce the agency's costs.[100] The proposed realignment of roles and missions envisaged that each centre would assume unique leadership on a few focused and very specialized areas and thus redundant competences distributed among different locations were to be optimized by relocating or discharging a large number of personnel (Bugos 2000). "The luxury, and perhaps the wisdom, of overlapping roles at the Field Centers," stated the report, "is no longer an option" (Wisniesk 1995, in Dick and Strick 2004). According to the recommendations, Ames – characterized by a broad range of activities, including exobiology - was to hold onto the lead for Aerodynamics and Aviation Human Factors, but lost its programme Earth Sciences to Goddard Space Centre (and in Planetary Sciences, to the Jet Propulsion Laboratory, in Pasadena (Bugos 2000)). It was under the threat of a profound administrative upheaval at NASA Ames Research Centre that the young discipline began to reinvent itself.

According to NASA historians Steven Dick and James Strick, Ames personnel "resisted the drastic implications and urged a new strategy" (2004:203). After a series of internal meetings and consultations, encouraged and chaired by France Cordova, at that time NASA chief scientist, a common strategy "to argue that the manifold activities at Ames were not a weakness but a strength, that interdisciplinary research was more important, indeed more productive, than fencing research within traditional disciplinary boxes" (ibid) was agreed upon. The Ames management turned interdisciplinary[101] into its centre's main strength in order to focus on a new single research topic: life in the universe. Instead of what was supposed to be a going-out-of-business plan to reduce its

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[99] The Zero Base Review started in 1995, a month before the discovery of the first exoplanet, and more than a year before David McKay's ALH84001 presupposed discovery. The moment of transition, nevertheless, lasted several years.

[100] NASA's response to the President's request to all agencies in the Federal Government to identify savings in their five-year fiscal year (FY) 1996 budget request to accommodate his proposed middle-class tax cut. (Dear Colleagues letter, 30/05/1995, by Wesley T. Huntress (https://solarnews.nso.edu/1995/06_95.html#1).

[101] Dick and Strick 2004:203-204. Such a strategy was not new; Harper recalled that it was part of the philosophy enunciated by John Billingham in connection with the NASA SETI programme he had headed at Ames beginning in the 1970s: "Billingham was always convinced, and convinced me, that if you attempt to understand life in the universe then you have to have all of the pieces – life on the cosmic scale, the planetary scale, the organism scale, and the volition or the purpose or the intelligence piece of it that manages evolution if it wants to do so. Those pieces were so powerful and important, both as a scientific discipline and for what it offers to humanity, offers to the future of my kids, that it would be wrong to break up that unique capability."

scope drastically, a new "Life in the Universe" plan was presented to the NASA headquarters. A number of people supported this idea by engaging with it both intellectually and financially until NASA's headquarters embraced the idea too. In the following year, with the 1996 NASA Strategic Plan as the enabling document that gave Ames the astrobiology mission, NASA went about building the discipline in several ways (Dick and Strick 2004).

The first "important exercise in consensus building", in Dick and Strick's words, beyond the centre walls occurred in September 1996, when Ames hosted the first Astrobiology Workshop,[102] gathering people from all around the space agency, academia and the private sector. The stated goal of this first meeting was to stimulate cross-disciplinary thinking and new ideas for research, which eventually coalesced in the creation of the NASA Astrobiology Institute, a virtual institution embodying this multidisciplinary approach to the study of life in the universe and promoting collaborations between academic institutions, research laboratories and NASA centres across the US and partnerships with research institutions from all over the world.[103]

The word "astrobiology[104]" was suggested by Wesley Huntress, at the time associate administrator for space science, to designate the "study of the living universe" (Huntress 1995) by putting together programmes that already existed at Ames, such as exobiology, admittedly weakened in the disappointing aftermath of Viking, Earth science and space science. Essential to the process of building a new research programme was defining what *astrobiology* was.

Putting together a definition of astrobiology that would include its main goals and objectives was an ongoing process that required a number of meetings and workshops heavily promoted and sustained by NASA, an effort that culminated in 1998 with the

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102 The final report of the workshop can be found at https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19970025374.pdf

103 The list of the teams that have taken part in the different rounds of CAN (co-operative Agreement Notice) can be found at https://nai.nasa.gov/teams/

104 According to Dick and Strick (chapter 9 note 5), outside NASA the word *astrobiology* actually predates Joshua Lederberg's coining of the term *exobiology* in 1961. For example, Laurence J. Lafleur of Brooklyn College in New York City, who wrote an article entitled "Astrobiology" in Leaflet No. 143 (January 1941) of the Astronomical Society of the Pacific (Lafleur 1941, in Blumberg 2003). The context of the paper indicates that the word was in use prior to the publication. The American astronomer Otto Struve pondered the use of *astrobiology* to apply to the broad study of life beyond Earth in 1955. However, until 1995 the *exobiology* terminology was used almost exclusively among biologists, while *bioastronomy* was used among astronomers.

See also https://arxiv.org/ftp/arxiv/papers/1207/1207.1491.pdf creation of the first Astrobiology Roadmap, which defined astrobiology as the "study of the origin, evolution, distribution, and destiny of life in the universe", a field encompassing "multiple scientific disciplines and space technologies to address some of the most profound questions of humankind" (Morrison 2001:3). As Lynn Harper at Ames put it:

> The sea change between exobiology and astrobiology was the inclusion of Earth sciences and life sciences as part of the portfolio. Conceptually, exobiology had always recognized them, but practically it didn't develop them within that programme umbrella. Astrobiology pulled them in hard and made some conceptual advances based on the synergies between Earth sciences and space sciences or Earth sciences and life sciences that had never occurred before. (in Dick and Strick 2004:206)

If the previous *exo*biology was the study of life elsewhere (the prefix *exo-* means "outside"), the new *astro*biology was meant to start from "the one data point of life that we know: life on Earth" (Cockell 2015:1). By including Earthly life among its object of interest, astrobiology could resist one of the major critiques that affected exobiology during its early stages: being a science that "has yet to demonstrate that its subject matter exists!" (Simpson 1964:254). The adoption of the new term astrobiology also made the field "respectable" again (Grinspoon, in Impey 2010:179), restoring enthusiasm and legitimacy to the field after almost two decades. Emerging out of the tumultuous experience of the "zero-based review" and the 20 years of stagnation of exobiology research, the refashioning of the disciplinary label embedded the social nature of the epistemic change occurring at the end of the 1990s.

Back to Mars

The 1990s saw the recovery of the missions to Mars, after a period of slowdown that had lasted almost two decades. After the global mapping was completed by Mars Global Surveyor, the first spacecraft orbiting Mars after the Viking missions, a new model of exploration was set out by the rover called – symbolically – Pathfinder. The spacecraft, consisting of a lander and a small wheeled rover, carried a series of scientific instruments to analyse the Martian rock and soil composition, geology, climate and atmosphere. The motto driving NASA's research was "follow the water": not artificial canals, but grooves created by the flowing of liquid water in a remote past. Water counted as both a geological force that shaped the environment and the *conditio sine qua non* of life on Earth, providing a bridge between geological evidence and biological sensibility. Mars was seen within a geological framework as an evolving environment, whose age could be studied by moving the rover up and down the craters, ridges, valleys and mountain tops (Vertesi 2014).

Many successful missions have landed and crossed the Martian surface since then, and, together with the rise of astrobiology, brought the quest for life on Mars back to the fore again, this time split into two different research objects (whose discovery would lead to two very different scenarios): extant and extinct life. Most planetary scientists believe that Mars has been very different throughout its history, and a few billion years ago it offered "better" conditions than Earth. On the other hand, all the studies about life in extreme environments (more on this in chapter 5) emphasize the resilience of life, which spreads and evolves to survive. It is then hypothesized that if life existed, it might still survive today in niches where liquid water is still present, such as underground or beneath the polar caps. NASA and ESA prioritize, for their future missions on Mars, one or the other approach.

ESA, for example, is preparing for ExoMars, a mission equipped with a drill, which will dig up to two metres below the surface of the Red Planet to collect samples for *in loco* analysis. NASA has recently developed a step-by-step plan for a sample return mission instead, which they tend to consider the only certain way to assess biosignatures and to improve the chances of correctly recognizing traces of life.

"A warning from the past"

Robert Crossley's *Imagining Mars* opens with the question: "Of what value is the history of an error?" He refers to the many episodes, such as Schiaparelli's mapping of Martian *canali*, as well as the Viking mission results interpretation, that are often narrated by astrobiologists themselves as key moments in which those who made the observations were misled by their biases and presumptions about life. Today, Giovanni Schiaparelli and Percival Lowell are often mentioned in the history of the search for life on Mars as figures standing at the very edge between speculations and observations. In fact, both Schiaparelli and Lowell spent hundreds of nights under their observatory domes, pointing their telescopes at Mars, taking very detailed notes about what they had seen and maintaining correspondence with other astronomers around the globe.[105] If one

[105] At the Brera Observatory Archive are kept more than 20,000 letters and tens of logbooks. Some of this material is available on the INAF archive website (http://www.archivistorici.inaf.it/schiaparelli.php); see also *Mars* by Percival Lowell (1895). The details of the observations are listed in the preface (p.v-vi).

could follow this controversy with their contemporaries' eyes, they would probably agree on the fact that both those who endorsed the Martian canals hypothesis and those who opposed it could not decide whose instruments worked properly based only on disagreement between their observations. Harry Collins called this kind of not so rare conundrum "experimenter's regress", a loop of dependency between theory and evidence (Collins 1985). From a historical perspective, Schiaparelli and Lowell might not have been as naïve as astrobiologists think today. From an STS perspective, nevertheless, astrobiologists' recounting of this episode as an example of a methodological fallacy can be read as a contribution to the building of a particular normative attitude about what constitutes proper astrobiological practice today. "Asymmetrical accounting for error", Mulkay and Gilbert suggest, "is a device by means of which scientists make their actions appear to exemplify the traditional conception of scientific rationality and, thereby, foster the commonly accepted image of science" (1982:166). Through making explicit which implicit norm had been transgressed, astronomers moved to their advantage the boundary between what is considered scientific and what is not, marking the transformation of the interest on Martian life from "its previous philosophical underpinnings to its present day status as a branch of science" (Cockell 2016:8). These kinds of examples are relevant because they are repeated with a certain consistency to the point of almost becoming myths of origin for the discipline[106].

Natalie Cabrol, director of the astrobiology section at the SETI Institute, for example, places them at an epistemological turning point:

> While the scientific foundation for a living universe was established in the 16th century with the Copernican revolution, the nature of advanced civilizations remained the domain of philosophers and fiction writers for a few more centuries. The latter populated the Universe and our psyche with beings and worlds that were no more than idyllic or nightmarish versions of ourselves, our society, and our biosphere. By the end of the 19th century, the advent of new technologies opened a different epistemological chapter […]. At that point, the quest for alien civilizations started to transition from a justifiable belief to a technology-based endeavour: […] Schiaparelli described channels – *canali*, in Italian – on Mars that later, Lowell (1906) erroneously claimed were artificial canals constructed by Martians. (Cabrol 2016:2).

[106] For an interesting analysis of science as storytelling and the relation between scientific knowledge and myth, see Nasser Zakaryia 2017.

According to Natalie Cabrol, what did not allow the early observations of Mars to rest on a solid foundation was the tendency of thinkers to engage in an activity which would today be more similar to those of the science fiction writer, projecting on other planetary surfaces the mere products of imagination. A similar warning came from Carl Sagan in the aftermath of Viking:

> There is a long tradition of scientific fable about the planet Mars. [...] Lowell recognized, as we still do today, that [Schiaparelli's] "canals" were a product of intelligent life. The only dispute concerns which side of the telescope the intelligence was on. Mr. Sagan pointed out that it is clear that intelligence was on our side, that the canals were an artefact of the human imagination[107] (Sagan, Horowitz and Murray 1977:22).

Schiaparelli and Lowell, despite their use of sophisticated telescopes, are often considered as incapable of completely detaching themselves from earlier "philosophical speculations", as if the astronomers' eyes were in fact looking into a mirror instead of a telescope and as a result flattening the exuberant diversity of forms of life expected today into mere "versions of ourselves". In retracing astrobiologists' "philosophical" ancestry, Charles Cockell draws two lessons for his contemporaries to be learnt from Schiapparelli's and Lowell's observations:

> First, we would have to wait for the space age and the direct and close-up observation of planetary bodies to truly force astrobiology into an empirical era and, second, [Lowell's] quotes are a warning from the past. The desire to believe in alien life should not trump empirical observation. Life should always be the last explanation after all non-biological explanation have been exhausted.

According to present-day astrobiologists, both Schiaparelli and Lowell did not make enough effort to find other possible explanations for the unusual features they came to consider canals. They refer to the ideal sceptical attitude that scientists are invited to maintain towards others' and, more importantly, their own theories. The "canal debate", claimed Carl Sagan,

[107] Interestingly, Lowell seemed to be much more aware of a potential bias in the observations than astrobiologists usually admit. In *Mars* he claimed "Fashion is as potent here as elsewhere. [...] A few years ago, it was fashion not to see them, and nobody did, except Schiaparelli. Now the fashion has begun to set the other way, and we are beginning to have presented suspiciously accurate fac-similes of Schiaparelli's observations." (Lowell 1895:206).

> is important because it indicates that there are strong psychological predispositions which condition our search for life elsewhere. [...] These predispositions run both ways: there are some who deeply want to believe, regardless of their evidence, that there is life. And there are others who deeply want to believe the opposite, also regardless of the evidence. Thus it is often necessary to disentangle actual scientific argument from discussion based on emotions. Such predispositions, however, may not be entirely detrimental since they have helped motivate believers and disbelievers alike to support extensive exploration (Sagan *et al.* 1977:22).

In blaming Schiaparelli and Lowell for reaching undue conclusions, Sagan actually fought a battle on two fronts: on the one hand, his aim was to establish a standard that could guarantee astrobiologists' *objectivity*, defined in this case as resistance to the tendency to interpret evidence in the most desirable way – "exceptional claims require exceptional evidence" has become Sagan's most celebrated motto.[108] On the other hand, nevertheless, Sagan did not forget to emphasize that those who adopt the opposite attitude, a mere dismissal of astrobiological interest, commit the same methodological blunder. The unremitting questioning of whether there is life elsewhere is thus advocated as the golden mean, the proper scientific attitude.

If Schiaparelli's and Lowell's confident interpretation of optical illusions as evidence of a complex landscape architecture invites continuous questioning of *interpretations*, Viking's ambiguous results serve as an archetypal example of how *not* to deal with geocentric *assumptions*. Again, quotations will be used to illustrate the pattern used by astrobiologists to describe how Viking constituted a watershed in the discipline's attitude.

> I am a very big fan of the Viking mission, because they produced a lot of data. But the biology – now looking with 40 years of perspective – was misguided…but it was not "misguided", they didn't even know better. That's the best they could do with the knowledge of the time, but that's the kind of issue we still face today. We need to

[108] Accordingly, almost every astrobiologist I interviewed would claim to maintain a neutral attitude toward the existence of life elsewhere in the universe. The conversation often took a similar twist: when I challenged them on the fact that if they dedicated their career to the search for extra-terrestrial forms of life it was probably because, at the very least, they "really hoped" to find them, they would answer that not finding any other form of life in the entire universe would probably be even more exceptional. In saying this, they both reinforced their struggle to appear neutral and naturalized the idea of a universe filled with other forms of life.

make assumptions about what we're looking for, and when it comes to life, our assumptions are very slippery.[109]

The life detection experiments on Viking were all invalidated by the lack of organics, the presence of which was the very postulate on which they had been designed. The unexpected soil composition, together with all the atmospheric and geological data collected, provided geologists, mineralogists and planetary scientists with important material to work on for many more years. As one of my interviewees explained, geologists have had a huge advantage in taking part in space missions and in the process of instrument selection:

> I don't know if others told you that, but the field is very much dominated by geologists these days, you can see it in every mission that goes to Mars. They're geology-oriented, and a lot of this comes from Viking, and that's a debate that is very interesting, because one of the problems of the "life versus no-life" question or "should we search for it? How we search for it?" and all this stuff is that a biologist have a disadvantage when it comes to doing space science, a disadvantage with respect to the geologist. Geology is very easy: you just land and start shooting, and you get data. It's impossible not to get data if you're a geologist doing planetary science. Whereas, if you're looking for life, […] evidence disappears very easily, it degrades, and so […] when you come to proposing a mission […] your approach is, um, is rated with equal weight as a geologist, who just want to look at rocks. And managers and administrators, they don't care about science, honestly, they care about results, they care about investments and returns. So when they look to proposals, [one] is guaranteed [to bring] useful results – obviously interesting results, no question – and the other has a good chance that it does not produce anything after spending 500 million dollars. So I think that's a barrier that is very hard to break through, for any life detection mission[110].

Geology, first of all, seemed a better fit with the criteria on which missions are assessed. However, there was another reason: on the biological side, "everything is based on what we know" of life, clearly from Earth. In Jill Tarter's words:

> Viking lander had a life detection experiment, right? That was really the first, I think, um, and […] most of the community doesn't think that those experiments worked and in fact there is one very important lesson about what to look for, and the

[109] AD, astrobiologist at the SETI Institute, personal communication.

[110] AD, astrobiologist at the SETI Institute, personal communication.

> fact that we build experiments on the Viking that would work pretty well on Earth, but we are going to an alien planet, and who knew about perchlorate, or hydrogen peroxide and all of the active stuff in the Martian soil. Um…so we were a little naive, let's say it that way. Um, and now we're getting, we're still, we only know what we know but at least we're trying to be less, you know, blinkered, and try to think about other possibilities.[111]

The puzzle in which exobiologists were trapped was heuristic. What they would look for and how they would do it were objects of debate and discernment: "the design of life-detection experiments to be performed […] by spacecraft landers depends on decisions about what life is, and what observations will count as evidence for its detection" (Cleland and Chyba 2007:372). How would it be possible to produce astrobiological knowledge without being trapped between the necessity of defining life and the attempts to detect it?

[111] JT, interview.

Chapter **6**

"Alien life, right under our noses"

revealing and recognizing alien life on Earth

"Come now, I will tell you (and do you preserve my story, when you have heard it) about those ways of enquiry which are alone conceivable. [...] You can neither know what is not (for it is impossible) nor tell of it, for the same thing is for conceiving as is for being"

(Parmenides, fragments 4 and 5, translated by A.H.Coxon 2009)

"A different way of being alive"

GFAJ-1 is a potato-shaped microbe that, for a few weeks in 2010, shook the foundations of biology. Found within a series of water and mud samples collected by the NASA-funded scientist Felisa Wolfe-Simon on the shores of Mono Lake, a body of water on the eastern slopes of the Sierra Nevada mountain range, the microbe had been transferred to a US Geological Survey lab and cultured within an arsenic-rich and phosphorous-depleted growth medium. It is commonly believed that every living thing uses six fundamental elements (carbon, hydrogen, nitrogen, oxygen, sulphur and phosphorus, known as CHNOPS) to build its most fundamental molecules. According to Wolfe-Simon and her team, the observations performed in the laboratory showed that, if necessary, GFAJ-1 could substitute for the phosphorus used in molecules such as DNA and ATP with arsenic (Wolfe-Simon *et al.* 2011). In other words, this microbe seemed able to do something no other known organism could do: switch one of the so-called building blocks of life with another molecule, arsenic, a poisonous element for any other living being. The discovery was presented as so exceptional as to demand textbooks be re-written, because it would suggest, in Wolfe-Simon's words, "*a different way to be alive*. And if that were true," she added, "what else might we be able to replace? And if you can replace it, could it be evolved completely independently?" (Wolfe-Simon 2010).

The release of Wolfe-Simon's paper was met with harsh criticism from fellow scientists; several biologists declared the article "shameful" for its poor science, (Redfield 2010) and in a few months a number of formal and informal publications described what they considered valid evidence to disprove Wolfe-Simon's findings. The lack of traces of arsenic in the GFAJ-1's DNA and a high preference for phosphorus constituted, according to the critics, "just the last nail in the coffin" (Cressey 2012) of arsenic-based biology. Wolfe-Simon replied to the many critiques by politely welcoming the new experimental results as a direct consequence of her study; according to her, the series of follow-ups "represents the kind of careful study that really helps the community", but, she pointed out, these works "do not necessarily rule out an entirely novel mechanism" and "there's still a lot of interesting *open* questions." (ibid). The exchange deployed many terms and expressions related to the "opening/closure" semantic domain; where biologists could see "relatively definitive refutations"(Borhani in Hayden 2012) of the discovery, Wolfe-Simon saw the possibility to "*crack open* the door" (Wolfe-Simon 2010) to a new epistemic space[112] filled with unanswered questions and unknowns.

In this chapter, I do not attempt to document the *closure* of this controversy. On the contrary, I want to emphasize the active, performative and situated movements of *opening* achieved by means of future-oriented claims about what is still unknown, as well as the agreement of astrobiologists on the potential unreliability of the laboratory devices on which biology has traditionally been based. The identification of microbes (either Earthly or extra-terrestrial) involves both *revealing* (i.e. making visible, perceptible) and *recognizing* (determining similarities and differences and discerning what is what). It is often assumed that these two tasks, in practice, simply overlap in the use of laboratory devices. This chapter problematizes the straightforwardness of this assumption: when going through the challenges of detecting life as-we-don't-know-it, revealing and recognizing have to be disjoined and can be put into question. It is the potential impossibility of successfully completing either of these tasks upon which astrobiologists eventually agree.

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[112] By epistemic space I mean a space of knowledge-making, which can be either a new research question within a traditional discipline or a new research discipline altogether, depending on the extension of the new space of knowledge production obtained by certain actors. On the opening of new spheres of inquiry, see Rheinberger 1997 and Hackett 2005.

As astrobiologists would adamantly admit, they could not do any science without the resources they find in the laboratory: instruments and concepts provide them with the basic framework within which (and sometimes in opposition to) their own specific narrative can be built. Laboratories are, nevertheless, contested places at the same time. This might not emerge on a daily basis, but there are particular situations in which the black-boxes onto which they usually rely are re-opened and problematized.

The shadow biosphere hypothesis provides a repertoire that astrobiologists occasionally embrace and sustain to position their discipline in the wider scientific community, justify the necessity of their research (on the basis of the knowledge gaps that other disciplines have overlooked), and support a certain approach to the knowability of life. On a practical level, the shadow biosphere hypothesis can be deployed as a set of resources to think out of the (black) box and, most importantly, facilitate networks, alliances, and collaborations to move beyond what astrobiologists consider *Earth-bound* biology.

Building a black-box for microbial life

In the 1860s, a young chemist, Louis Pasteur, engaged in a long and controversial debate with the naturalist Felix Pouchet, who was then 60 years old, over the existence of spontaneous generation[113] i.e. the possibility that living systems could self-assemble from non-living material. Pasteur opposed the long-established doctrine of *heterogenesis*[114] to so-called *biogenesis*, asserting that all living organisms come from other living organisms. What started as a rather polite and friendly exchange of letters on their respective experiments shortly became such a relevant dispute that the French *Académie des Sciences* appointed two commissions, the first in 1862 and the second just two years later, to settle the debate and award a prize "to him who, by well conducted experiments, throws new light on the question of so-called spontaneous generation." (Farley and Geison 1974:181).

Due to a series of experiments, Pasteur convinced the commissions that the microorganisms formed in Pouchet's flasks during his tests were not proof of

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[113] As Farley (1972) noted, the generic use of the expression "spontaneous generation" tends to collapse two issues that in some periods in history were considered quite distinct: abiogenesis, the possibility that life arises from non-life, and heterogenesis, the theory that an organism does not emerge from identical parents.

[114] The particular case of spontaneous generation according to which living microorganisms can self-assemble from other organic material but without the need for identical parents (Farley 1972).

spontaneous generation but the result of a number of blunders in their preparation. Germs, therefore, could not form inside properly sterilized flasks; when they appeared, it was simply because they were somehow introduced as a contaminant. The controversy has been remembered as a paradigmatic instance of the new experimental method (Roll-Hansen 1979:273), leading to the consolidation of one of the most fundamental assumptions on which contemporary microbiology is based: the fact that we know whether we have seen microbes or not.

During the unfolding of the debate, in fact, things appeared much more complex. As Latour noted, the controversy was not simply about the spontaneous generation of microscopic living creatures in the laboratory, but about the very *possibility* of demonstrating it (Latour 1996:527). The debate was not just on whose theory was right, but on the proper methodology and instruments that would make the microbial realm visible, investigable and understandable beyond doubt. Retrospectively, one might describe the resolution of the spontaneous generation debate by saying that the correct experimental method decided who the winner of the controversy was. The description of a contemporary of Pasteur and Pouchet would probably turn the causal relation around and say that the winner was he who could convince the commission that his method was the correct one.[115] The material apparatus, constituted by flasks with different shapes, microscopes, sterilization techniques and so on, became the very basis on which experimental biology took shape. Pasteur managed to convince the commission that his sterilizing techniques were more reliable than those adopted by Pouchet, and thus he could tame the microbes within his apparatus. This is the important point: if they did not see any microbes, it was because there were none, as opposed to Pouchet's experiments, in which failure to see microbes in the supposedly sterilized instruments came to be considered as an illusion. Microbial life was perceptible and tameable – and thus knowable – within Pasteur's laboratory, with all the instruments and disciplinary practices included. Once the appropriateness of Pasteur's methodology and the functioning of the laboratory as a visibility device were tied together and slowly made

[115] In fact, Pouchet withdrew from the controversy as he was convinced that the entire commission was already biased against materialism and Darwinian evolution and thus they favoured Pasteur's germ theory. According to him, the belief in one of the two theories had already determined whose methodology was then considered correct (Farley and Geison 1974). Pouchet's sympathizers would probably phrase the last sentence as "the winner of the controversy was he who could convince the community that his method was the correct one with the help of a theory that already fitted with their prior beliefs". This is what Harry Collins called "experimenter's regress", the circular process about the validation of a theory and the judgment about whether an experiment has been performed successfully (1985).

invisible, the spontaneous generation debate came to an end and the claim that no living organism could emerge without identical parents acquired the authority of a scientific *fact*.

In the opening of his *Science in Action*, Bruno Latour (1987) introduces the reader to the mythological figure of Janus Bifrons, the two-headed deity borrowed from Ancient Roman folklore. Janus is represented with both a young and a mature face, each speaking for science at a different stage of its unfolding: *science in the making* and *ready-made science*. While *science in the making* is uncertain, involving many people at work, harsh competition and provisional decisions, *ready-made science* is certain, cold and unproblematic. When science is in the making, concepts and devices are questioned, deconstructed and reassembled; when science is ready-made, on the contrary, the complex chain of social relationships and alliances that made it possible are hidden from view. The achievement of this latter stage is what Bruno Latour called a black-box: the functioning of an artefact, either a technological device or a scientific concept, comes to be accepted and then taken for granted. All the elements that used to be questioned and reassembled, at this stage, flawlessly work as a whole (Latour 1987). Because looking into the artefact's complex internal functioning becomes unnecessary and inconvenient, black-boxes are first of all practical achievements that make communication more efficient and simplify usage, thus defining a shared paradigm for practitioners. Black-boxes are not intended to exclude ways of thinking or experimenting, but in hiding the complex chain of decisions that came to constitute them, they also prevent change. This is why, when science is *made*, opening a black-box becomes, according to Latour, an almost impossible task. This is what makes Janus, as a narrative device, necessary: "the impossible task of opening the black box is made feasible (if not easy) by moving in time and space until one finds the controversial topic on which scientists and engineers are busy at work" (Latour 1987:4). The narrative device serves the sociologist well in accounting for the dynamics of science through scientists' own words; Janus is not committed to any representation that a scientist (or technologist) herself would not support in a particular moment in time.

However, even though the scientific community came to agree on this new set of interconnected instruments and concepts whose social nature slowly came to be forgotten, the question of how life emerges did not disappear, but instead changed the scientific domain and was presented under different guises, such as the so-called problem of the "origin of life".

To make sense of science, we could easily imagine a third face for Janus who borrows the voice of those scientists talking about the future of their fields or the emergence of new realms of inquiry. Looking at the future, future Janus would make promises about the fulfilment of the gaps still present in science and the grasp of what is still unknown (Borup *et al.* 2006). By looking at the role of the so-called "shadow biosphere" hypothesis in contemporary astrobiology, this chapter explores how artefacts (including the entangled life of concepts and devices) are put into question in scientific discourse and everyday practices. I claim that emerging fields of inquiry presuppose one or more claims about what is still unknown, which must be agreed upon to legitimate the research and create new epistemic spaces. As a consequence, I propose that we should rethink the black-box metaphor to include more fluid, flexible and locally contingent movements of closure and reopening. By borrowing from astrobiologists' interest in the "shadow biosphere", I advocate paying closer attention to the ways in which claims about what is unknown are socially constructed and organized.

If the closure of the spontaneous generation debate seems to suggest that life simply does not originate from non-living matter, the inevitable observation of the existence of life on Earth presents a conundrum. In the second half of the 20th century, interest in the question of how life could possibly originate from abiotic molecules could not be encapsulated under a single disciplinary label. Among the different approaches adopted, such as evolutionary microbiology, synthetic biology and so on, one particular way of looking at the problem connected the study of the origin of life on Earth to the search for extra-terrestrial life elsewhere in the universe (Dick 1996; Messeri 2016). As already described in previous chapters, the field of astrobiology is still in the process of being defined and institutionalized (Des Marais *et al.* 2008), but its legitimacy and sustainability are often linked to the questions "how likely is life to emerge elsewhere? What conditions are required for it to self-assemble from non-living matter?" (see chapter 3). The Viking mission press kit, released in 1976 on the occasion of the launches of the first landers equipped with life detection experiments to be performed on the Martian surface (see chapter 5), expressed this uncertainty:

> Science cannot calculate the *probability* of encountering extraterrestrial life on this solar system and in other solar systems on the basis of this evidence.[116] We cannot

[116] The evidence to which the press kit refers is the claim that "our Galaxy contains 100 billion stars, many of which are surrounded by families of planets, according to the best astronomical

> tell conclusively by laboratory studies or theoretical reasoning whether the evolution of life is *vanishingly improbable* or *quite likely*. (Viking Press Kit 1975:2).

With respect to this issue, the situation has not changed much at the time of writing, and there still seems to be no way of estimating how likely the emergence of life is according to the current state of science.

With very few people holding a position in between, the vast majority of those involved in the debate are divided into two factions. Those who support the so-called "cosmic imperative" position claim that life will promptly arise as soon as the conditions are favourable.[117] Carl Sagan, astronomer and spokesperson for exobiology and SETI between the 1960s and the end of the 1980s, was notoriously a great supporter of this position and managed to make it very popular. In 1995, Christian de Duve rearticulated it in a book titled *Vital Dust* (paraphrasing Sagan's motto "we are all stardust") in which he suggests the view that "life is an obligatory manifestation of matter, written into the fabric of the universe" (de Duve 2011:620). Other authors, such as Francis Crick and Stephen Jay Gould, claim that the emergence of life cannot be but the outcome of such an improbable chain of events that it might have happened only once in the history of the universe. The problem lies in the interpretation of what is translated in the factor f_l of the Drake Equation, a fraction. If the probability of life emerging is taken to be more than zero, all the recent discoveries of exoplanets become encouraging and the detection of a second example of life seems to be right around the corner. On the other hand, if chances are considered close to zero, the same huge number of exoplanets becomes meaningless, as it would be neutralized when multiplied by zero. There seems to be no way of estimating this in advance.

What most scientists would agree on is that finding a second example of life would tip the balance in favour of a higher probability of the emergence of life (Davies 2011). The Viking press kit continued by saying that "we can only estimate the probability by looking around us for signs of extra-terrestrial life; the nearest reasonable planet on which to look is Mars" (Viking Press Kit 1975:2). In this respect, on the contrary, the situation has

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evidence. In studying these stars with telescopes, man has been able to verify that the basic chemicals of which Earth is composed are found throughout the universe." (Viking Press Kit 1975:1).

117 In fact, given the scale of the other factors, to have a significant probability of finding extra-terrestrial lifeforms, it does not matter whether f_l (to call it by the corresponding term in the Drake Equation) is very close to one or not, as long as it is more than zero. The question then moves to that of which conditions are appropriate for life, but this seems to be less of a problem given the huge number of planets that have been recently discovered.

changed dramatically; after the Viking missions returned ambiguous results (Sagan, Horowitz and Murray 1977; Young 1976), no space agency has ever performed life detection experiments on Mars (or on any other extra-terrestrial surface) again.

In the early 2000s, however, a number of scientists came up with a hypothesis that could serve as a test of the two positions without relying on the detection of lifeforms on the Red Planet. When the hope of finding a second example of life on Mars was fading away, a group of scientists started looking for it on Earth. They set out by noting the common assumption that all life on Earth shares the same ancestor: the most primitive form of life that arose, in still-unknown circumstances, more than 3.5 billion years ago. All living beings on this planet, even if on different branches, are believed to belong to the same tree of life. However, using the premise that life is quite likely to emerge as soon as the conditions are favourable, a group of scientists came up with the hypothesis that on Earth – the only place where we know with certainty that the conditions of life are all fulfilled – life might have originated more than once. This alternative origin of life would have given rise to a different tree of life – or maybe a number of them – which might look nothing like the tree of life we are used to, the tree of "standard" life, or life *as-we-know-it*. The microbiologist Shelly Copley and the philosopher Carol Cleland coined the phrase "shadow microbes" to name this parallel ecology, which, they suggest, could have been completely overlooked by traditional biology (Cleland and Copley 2005).

> Life as we know it on Earth today shares a number of fundamental characteristics at the molecular level. […] However, it is also clear that some of the molecular building blocks of proteins and nucleic acids could have been different. Indeed, it is an open question as to whether all life (wherever it may be found) is constructed of proteins and nucleic acids. This question is difficult to answer outside the context of a general theory of living systems, something that we currently lack. […] The detection of even modestly different life forms poses a tremendous challenge (Cleland 2007:166).

Because of these unusual features, Cleland and Copley suggest, microbiologists might never have noticed these still unknown microbes, which might have gone on to evolve their own independent, interlocking ecological system or to become adapted to environments that are less hospitable to familiar microbial life. In fact, if these forms of life are fundamentally different from the life we are used to and able to interact with, the tools present in the laboratory might not be able to detect it or recognize it.

In 2006, Paul Davies, an astrophysicist and self-defined "armchair astrobiologist",[118] organized a workshop dedicated to "the question of how we might identify an ancient, or even extant, hidden biosphere of alien organisms".[119] The use of the word "alien", here as in other contexts, aims to echo its Latin root *alius,* meaning "other" or "stranger". Chris McKay, one of the participants of the workshop and a planetary scientist at NASA Ames Research Centre, commented (on a different occasion) that astrobiologists are not simply looking for life on other worlds, but for "something that is not on this tree of life, an alien. When I was a kid," he continues,

> an alien was defined geographically: if you were from Mars, you were an alien; if you're an alien, you're from another planet. But now we define it biochemically…you can be on Earth, living right in the back-yard, and be an alien if you don't map on this tree of life. [Among the other questions], this would also tell us if life is common in the universe. If life started here in our Solar System twice, independently, that would be strong evidence that life is common.(McKay 2013, min.3.10).

The workshop's aim was to figure out ways to look for the microbial heir of a second genesis; after describing the ways in which instruments and understandings of terrestrial life might fall short in grasping *life as-we-don't-know-it*, they suggested keeping an eye open for anomalies[120] such as signs of metabolism in conditions where life *as-we-know-it* would not be able to survive (for example at high temperature, low water availability etc.). Felisa Wolfe-Simon was among the workshop attendees, and her research at Mono Lake (whose description opens this chapter) was inspired by these conversations (Wolfe-Simon, Davies and Anbar 2009). In a short documentary shot

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118 Paul Davies, personal communication 08/02/2016.

119 Workshop announcement, at https://beyond.asu.edu/workshop/tree-or-forest-searching-alternative-forms-life-earth

120 Davies' and colleagues' use of the word "anomaly" (Davies *et al.* 2009) makes explicit reference to Kuhn's *Structure of Scientific Revolutions* (1962). They identify its potential discovery with the acceptance of a new paradigm, a new theoretical and material framework within which to conceive questions and experiments about the nature of microorganisms on Earth and in the universe. Kuhn's work was used by astrobiologists as an instrument to show the social and conventional dimension of biological knowledge, that which is "taught in textbooks" – nevertheless they struggle to escape the logic of progress: as already noted somewhere else, if contemporary biology is only partial, future astrobiology, they claim, will indeed be "universal" (Dick 1996).

during one of her fieldtrips to Mono Lake, Wolfe-Simon summarized the rationale behind her work:

> I've come to one of the most unusual places, an alien environment here on Earth to look for life as we don't know it. If there is a different kind of life here on Earth, our current methods would never see it. Why? Because we only know how to look for the life we do know. So if there is a shadow biosphere, if there is an alternative kind of life, even here on Earth, we would never see it. In fact, it could be all around us. (Wolfe-Simon, 2010)

Mono Lake was taken as an example of a site that could harbour the vestiges of a shadow biosphere and a place to look for anomalies, such as microbes that could grow in conditions that would otherwise be lethal.

Despite this broad-minded thinking, the workshop organizers very pragmatically admitted that dedicating time and resources to such risky research could be inadvisable. "You cannot get a PhD out of something that doesn't work. So if you're trying to culture some sort of bacteria or some sort of microbe in the lab…and it won't grow, your first thought is 'I'd better find something else, I'd better do a different experiment and find a different microbe'".[121] Being a good microbiologist, and thus obtaining a doctorate or having your research funded, means making use of and aligning with a series of precepts and techniques accepted as foundations of empirical biology. The evaluation of the outcome of an experiment (and whether the experiment itself counts as successful) is based on compliance with them.[122]

At the same time, astrobiology "rests on the popular hypothesis that life emerges readily in Earth-like conditions" (Davies 2011:624), a principle in contrast with what is observed within laboratory walls. Life's promptness refers here to geological timescales, which surely do not correspond to the quick pace of laboratory daily activities. But still, despite the many efforts to recreate the conditions favourable to the self-organization of living organisms from their so-called "primordial soup", or "building blocks", nobody has been able to make life from scratch yet, or observe this process happening (Benner 2010). Thinking about the possibility that some forms of life might live undisturbed and unseen requires astrobiologists to unpack the controversies

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121 Davies, personal communication, 08/02/2016. The reception of Wolfe-Simon's work provides an example of the perils implied in the commitment to such an out-of-the-(black)-box research theme.

122 For a broader overview of microbiologists' "epistemic culture", see Knorr-Cetina (1999).

that Pasteur and his colleagues had already closed: those of sterilization, culture and the possibility of determining whether those techniques were performed successfully. Once they are reopened, the impossibility of life self-assembling, spontaneously emerging out of non-life, is put into question and thus biology is made partial, local and biased by Earthly idiosyncrasies. Being a good astrobiologist – and making astrobiology a respectable discipline in the first place – requires that scientists learn how to question the rigidity of these claims and the very instruments on which these incompatible principles are inscribed.

Uncertain laboratories, emerging sciences: making microbes invisible again

When I asked astrobiologists what their laboratories looked like, I was often told that they resembled any other microbiology lab but that all the activities were performed with a "context" in mind. To figure out what this context might consist of, I spent many mornings strolling around an astrobiology laboratory, wearing a white coat, scribbling notes and making drawings on a small and worn notebook. I was not the only one jotting down notes on the experiments that were being performed: everyone had to take careful note of all the samples, codes, repetitions and steps of the experiments, without which their laborious work would not be of any use.

Sitting on the stool in front of the microscope, one day, one of the senior PhD students in Astrobiology was looking at his microbial samples. The act of "looking" is more troublesome than one can imagine. First of all, the microbes he was interested in did not come from a commercial strain; they were not purchased from an online catalogue and delivered to the laboratory but collected on a field site instead, in some environment presenting characteristics of interest as *analogue* to other planetary places (see chapter 7). Right after collection, the samples were stored in plastic bags, placed in a backpack and then carried to the laboratory, where the microbes could be separated from the other components of the sample. Extracting microbes from a soil sample requires a complex process of crushing, dissolving, blending and centrifuging. Once separated, they can be transferred on to agar plates and cultured in different conditions for several days to monitor their responses. After waiting for an established time, the cells were coloured with a fluorescent dye, making them glow under the microscope in infrared light.

A few experiments and measurements can be done at this stage, the most elementary of which is simply counting. Leaning on the microscope ocular, the young researcher was zooming in on random spots of the slide he had carefully prepared, and counting the cells lightened in every spot to estimate their growth or ratio of survival. "How many cells are there?" I asked. "Not that many of them", he said, and then he explained that most of them had probably died, at least those that we know. However, that thin piece of glass might have plenty of cells of a shadow biosphere, he added, that he simply could not see or recognize – "… alien life right under our noses". His younger colleague, pipetting on the nearby bench, turned his head around and asked what he was talking about. "It's just a hypothesis, but it makes you wonder"[123].

Microbes cannot be seen with the naked eye; their detection and recognition is mediated by a multitude of instruments that make them visible and manipulable. The microscope, for example, allows the researcher to exercise her sensing capabilities across scales with the mediation of lenses, lights, dyes, calibrations etc. Each of these devices is a black-box connected to all the others, which come to constitute a microbiology lab. These techniques, when thought about in relation to the hypothesis of the existence of an independent biosphere, have to be reopened:

> There is an obvious circularity here. Organisms are analyzed via chemical probes that are carefully customized to respond to life as we know it. These techniques might well fail to respond appropriately to a different biochemistry. If shadow life is confined to the microbial realm, it is entirely possible that it has been overlooked. (Davies *et al.* 2009:247).

Under the lens of a microscope, the single cells might not be visible, as fluorescent microscopy can only identify cells containing a gene or protein complementary to the probe being used. On the contrary, they might be visible (if they contain sites where the dye can actually attach or with traditional optical microscopes) but not recognizable, as the morphology of microbes (i.e. their shape and physical characteristics) provides little insight into their phylogenetic classification or metabolic capabilities. As Cleland and Copley put it, "we are unlikely to be able to distinguish between normal life and alternative life *just by looking*" (2005:168).

Cell culture is also used to make microbes visible by encouraging them to grow into large communities. Biologists spend a significant part of their time taking care of them, following protocols for "optimal" growth. However, biologists adamantly confess that only a small portion – less than 1%, according to Pace (1997) – of the huge microbial diversity found in the field can be cultured in the lab, often for unknown reasons. The identity of most of the microbes refusing to survive and duplicate within a petri dish remain unknown, "shrugged aside as *uncooperative*" (Davies *et al.* 2009:247). Shadow

[123] From fieldnotes.

lifeforms might require conditions that astrobiologists do not expect, for example unusual chemical elements, extreme temperatures, a different barometric pressure etc., putting into perspective adjectives such as "standard", "normal", or "optimal".

Another important technique to identify unculturable components of microbial communities is Polymerase Chain Reaction (PCR), which allows for the amplification of a segment of DNA across several orders of magnitude. However, PCR might not be serviceable for different forms of life, as the process requires "*universal* primers", which might in fact turn out to be very specific and contingent.

In Davies' and colleagues' words:

> This extensive ignorance raises the intriguing issue of how sure we can be that all microbial types have been identified. Might it be the case that the exploration of the biosphere is not complete? (Davies *et al.* 2009:421).

In so doing, they agree on what might be still in the shadow – unobserved and unacknowledged – and thus tweak instruments, concepts and procedure toward the creation of a new epistemic space in which new research questions can become relevant and be investigated.

Conclusion

Exploring the active questioning of otherwise widely-accepted black-boxes and borrowing astrobiologists' interest in the "shadow" might provide insight into the way new epistemic spaces are created. In examining non-knowledge through the lens of the word "shadow", I am not proposing a new metaphor, but a thinking tool that helps to make explicit the situatedness of what is unknown. "Shadow" does not refer to a property of something, but depends on its positioning and demands that questions be asked. First and foremost, shadow of what? What kind of black-boxed artefact do scientists want to open up, disassemble and put into question? As black-boxes are always interconnected and built upon each other, the opening of one requires a long process of unpacking that has to be followed in its intricacies and entanglements. Secondly, if a shadow is due to light, it is not simply a lack – something missing – but also assumes contours and object-like qualities. The relationship between shadow and light cannot disappear, as one defines (in its etymological sense of *de-finire*, "putting a limit around") the other. However, one can look at the ways their boundary is pulled and pushed, moved in different directions, never to disappear. Thirdly, what is in the shadow is indeed hidden, but only partially, and thus can be represented, imagined and used to justify research. Borrowing the idea of shadow, I thus intend to emphasize the contingent, active, performative and always social nature of the making of what is unknown.

Despite their reference to traditional biology – usually referred to as "textbook biology" (as in Davies *et al.* 2009:242) – as a paradigm to be overcome by astrobiology, explicitly highlighting the necessary attention to anomalies, astrobiologists' unpacking of black-boxes is indeed partial, as they keep capitalizing on the assumptions embedded in most of the black-boxes they question for other practical needs, for example publishing papers with data obtained in the laboratory (with all its "traditional" techniques), elaborating experiments and measurements and seeking collaborations with microbiologists, synthetic biologists and so on. Nevertheless, the uncertainties formulated about the possibility that those black-boxes might not work with life *as-we-don't-know-it* and the consequent tweaking of epistemic, practical and social components in order to address this purported unreliability has become, for astrobiologists, a successful repertoire. Indeed, as Ankeny and Leonelli emphasize, researchers can and do shift between different approaches and models of work, depending on circumstances; they can make use of biology's traditional black-boxes and, occasionally, embrace the shadow biosphere repertoire to unpack them and look into their functioning, give shape to new unknowns and deploy them strategically.

In fact, as mentioned above, very little research into the shadow biosphere hypothesis is today actively carried out in laboratories, possibly as a side effect of the harsh debacle that followed NASA's triumphant announcement. The shadow biosphere hypothesis, which became both well-known and infamous following Wolfe-Simon's GFAJ-1 article, did not fade: on the contrary, the possible existence of a shadow biosphere, even if seldom discussed in formal settings, is still brought up in informal talks and taken into consideration when debating whether anomalies should be discarded as failed experiments or investigated as possible insights into what "traditional" biology would fail to grasp.

Despite the debacle described in the opening of this chapter, it would be misleading to say that the GFAJ-1 case was not successful, at least in part. A number of laboratories tried to replicate Wolfe-Simon's experiments and look into the matter further and they used blogs to make the results immediately available. Although most microbiologists immediately attempted to re-close what Wolfe-Simon, Davies and others had tried to open up for scrutiny, for the astrobiology community the right to keep on looking for anomalies in an attempt to shed light on the unknown nature of alien life had proven to be a strategically deployable narrative. GFAJ-1 messed things up, created shadows, moved them around, and situated knowledge and non-knowledge in *space* (claiming that current theories about life might hold on this planet only) and *time* (renegotiating what was known, what was not-known, and the temporal horizon for them to become knowable). If astrobiology is gaining momentum, it is not only because of uncontroversial discoveries and widely accepted protocols, but also (and perhaps mainly) because of the articulation of what should not be taken for granted anymore[124].

This chapter analysed the shadow biosphere hypothesis as an entry point into some of the astrobiologists' implicit assumptions and concerns. This repertoire, in which skills, attitudes and epistemic, practical and social components are arranged in a strategic contraposition to what they consider traditional and "Earth-bound" biology, creates a discursive space in which they can share their perplexities, uncertainties and new possibilities of visualizing living beings and broadening the definition of life. In fact, these are not simply negligible and external motives in scientists' work but important sites for the creation of meaning. The possibility of arguing against the successful use of the instruments by means of which living organisms are known and made recognizable offers astrobiologists the opportunity to propose new sites and methodologies for life detection. The study of extreme environments and the attention to *in situ* dynamics and anomalies is an example (more on this in the next chapter). What is more, it reinforces the agreement on another significant non-knowledge claim that characterizes astrobiology: the fact that we *do not know* what life is.

This set of uncertainties and unknowns is, in a sense, the different *context* that astrobiologists have in mind when performing their daily work at the laboratory bench. By emphasizing its locality and idiosyncrasy, these unknowns contribute to the displacement of biology from the place it occupies in the scientific landscape, and offers a fertile terrain to advocate what astrobiologists propose as a more "universal" biology.

[124] The purported discovery of microfossils within ALH84001, a Martian meteorite found in Antarctica, is another example of this phenomenon. See for example Steele et al. (2000).

Chapter 7

Despiciendo, suspicio
The exploration of extreme environments as space analogues

Su Zurfuru

The breeze was warm and filled with the subtle aroma of the myrtle that in late spring punctuates the gentle slopes of the southern Sardinian hills. The bushes and short trees did not offer much of a shelter from the sun shining high in the clear sky, as they were constantly swept by the Mediterranean air currents. Earlier in the morning, we had been warned to wear heavy clothes as the mine temperature is significantly lower than the temperature outside; in the rocky darkness of the mine, it barely varies between winter and summer. The water, copiously dripping from the rocky walls, keeps the humidity high and covers the muddy floor, creating stagnant conditions that enable bacteria to recolonize what humans appropriated in the 1880s and then abandoned a century later. The Su Zurfuru (Sardinian dialect for "sulphur") mine had been depleted of lead, iron and fluorine over the decades, before being deserted along with the adjacent small village where miners used to live and process the raw materials extracted from the nearby deposits.[125]

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[125] A brief introduction to the history of the Su Zurfuru mine can be found at http://www.parcogeominerario.eu/images/files/pagina%20633(1).pdf (in Italian).

Our hiking boots were already sinking into the muddy soil just in front of the tunnel mouth, a regular opening excavated in the rock, almost completely covered in Mediterranean vegetation. Gabriele,[126] an experienced member of the local speleological team, started the engine of his Jeep, packed with scientists and their equipment, and slowly turned the car toward the entrance. The wheels plunged into the reddish water of a deep puddle as the car moved into the tunnel. A small wave preceded us, rippling the silky surface of the water lit by the car's headlamps. We moved onwards, deeper and deeper into the abandoned mine.

When the car stopped, we heard the voices of the group that had entered the mine before us. "Don't walk alone," Gabriele said with an affable smile, "it takes nothing to get lost here." Then he turned the car and drove back to the entrance to transport the last group of scientists still waiting outside. Somebody approached us, illuminating the space where we were standing with a cone of light from the top of her helmet. Laura, one of the organizers, joined our small group, showed us how to switch on the lamps on our hats and then led us to where the others were gathered, in a different tunnel, where the walls had been further excavated to form what was almost a chamber. There, John, a geologist from the University of Bologna, was casting his helmet lamp on a white and blue jelly substance formed around the groove excavated by the water gushing through a crack. He poked his finger into it. "This is *biology*," he claimed.

The visit to the Su Zurfuru mine was one of several fieldtrips that concluded the workshop organized by the Geo-Biology for Space Exploration (GESE) ESA topical team,[127] held in Sardinia (Italy) in spring 2015. The workshop aimed to encourage the development of a new interdisciplinary community focused on the study of the possible uses and implications of mineral-microbe interactions in subsurface environments. The workshop presentations were carried out in the auditorium of the local mining school, founded in 1871 in an attempt to improve the economy of a region still considered poor, but rich in raw materials.[128] Established during the decline of the extractive sector, the museum is located in multiple small rooms and arranged around different aspects of local mining life, and includes the 400m practice mine tunnel excavated by the students under the school and the nearby square. During the Second World War, the tunnel was

[126] All the people mentioned have been given pseudonyms.

[127] The workshop was titled "Extraterrestrial Subsurface Exploration and Geomicrobiology". The location, Iglesias, was chosen for its proximity to the three sites we visited during the fieldtrips: two caves, Su Mannau and Is Zuddas, and an old mine, Su Zurfuru. The vignette refers to the latter.

[128] http://www.asproni.it/index.php/sedi/50-breve-storia-dellistituto-minerario

used as an air raid shelter, infirmary and operating theatre, directly connected to the old hospital.[129] In more than purely economic terms, mining and survival in Iglesias were deeply interrelated. During the 1990s, almost all the mines in the district closed down, and today the mining industry has mostly disappeared. The old buildings and tunnels remain as ruins for industrial archaeologists, and attractions for the rampant tourist sector.

Figure 9. Su Zurfuru, picture taken by author.

There might seem to be an unbridgeable distance between the depth of a mine and the deep space where astrobiologists hope, one day, to find life. To understand how these *topoi* have become thinkable within the same astrobiological discourse, we need to disentangle the narratives[130] that are deployed by scientists when talking about and experiencing caves as Mars analogues.

The exploration of extreme environments as space analogues is the last repertoire I discuss in this thesis. By drawing on my ethnographic study of astrobiologists', geologists' and speleologists' fieldwork activities, I am looking into the use of *space analogues*, i.e. material settings – such as the Su Zurfuru mine, but also the Utha desert, the Antarctica Dry Valleys and the lava fields in Iceland – in which one or more analogies between Earth and outer space are embedded. In particular, I am focusing on the way the analogies through which these scenarios are turned into epistemic tools to investigate life in the universe are built, sustained and experience. I argue that it is the multiplicity and redundancy[131] of the analogies that imbue the field site that maintain its validity as a heuristic tool. Analogies between specific Earthly environments and their

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[129] http://www.sardegnacultura.it/j/v/253?s=22723&v=2&c=2487&c1=2128&visb=&t=1

[130] Messeri proposes *narrative* as a device that "unsettles landscapes as static images" and "structures both place and time as they manifest in landscape" (2016:31).

[131] The word "redundancy" is intended here with a meaning similar to the one the Oxford English Dictionary attributes to the engineering use of the word: "the deliberate duplication of parts in a system so that its function is not impaired in the event of a malfunction or failure" (http://www.oed.com/view/Entry/160537?redirectedFrom=redundancy#eid).

otherworldly counterparts are not a given; they are negotiated and made relevant through scientists' experience of them, which, at the same time, creates a dialogic space to envision, explore and negotiate tensions and alignments between alternative futures for space exploration.

During the time I spent with astrobiologists, working, talking and thinking through terrestrial analogues of Mars and other planetary environments, I came to realize that astrobiology is a discipline deeply infused with a sense of place (as also described in Messeri 2016): researchers, research practices and material settings mutually define each other. Analogue field sites are an example of what Thomas Gieryn defines as a "truth-spot", i.e. a place that "allows claims to escape place, to transcend its suffocating particulars; [to] achieve placelessness" (Gieryn 2002:113). All scientific knowledge claims, he argues, originate in some particular place – a laboratory, a field site, a farm etc. – but to become "truths", they need to become detached from the specific context in which they were made and become "universal", true everywhere and nowhere in particular. To become placeless, Gieryn explains, claims have to situate their origin in a place that contributes to their credibility and thus allows the transit from "here" to "everywhere". Truth-spots are *topoi* that make us "believe that claims from there are true everywhere, but each does it in a different way"(Gieryn 2002:114). By taking the conceptual efforts and scientific practices that turn Earthly environments into space analogues as the focus of this chapter, I investigate the process by which astrobiologists build and sustain the validity of extreme environment as space analogues, and, at the same time, the ways in which analogue field sites allow astrobiologists' knowledge (and non-knowledge) claims to be considered universal.

Despiciendo, suspicio

The hems of my jeans were still covered in dried mud from the morning walk deep into the abandoned mine; we all had a spare pair of shoes so we could change out of our soaked hiking boots, but I kept wearing the dirty trousers with a peculiar explorer's pride when the excursion was over. A few hours later, we were sitting around a table in a typical Sardinian *osteria*. "I liked your quote!" said Tim, one of the astrobiologists with whom I

Figure 10. Sample collection in Is Zuddas. Picture taken by author.

was sharing the table, commenting on the presentation of my work I had given the day before. I smiled gladly at the compliment. "What was it precisely?" "*Desipiciendo, suspicio*, or in looking down, I see upward".[132] The sibylline quote was painted at the entrance of Tycho Brahe's castle, erected in the 16th century on the Isle of Ven, where he retired from the Danish aristocracy to accomplish his own vocation: studying and measuring nature. Tycho Brahe's castle architecture mirrored his vision of the cosmos. The castle was divided into two symmetrical parts: the basement, where he would perform alchemical experiments, and the top floor, which housed his astronomy tools (Hannaway 1986). By trying to understand alchemy, the Earthly art of mastering nature's elements, Tycho was looking for a key to understand the heavens. The opposite was equally true; *suspiciendo, despicio*, or in "looking up, I see downward" was the equivalent counterpart. On a different island, several centuries later, astrobiologists were thinking about that quote and nodding enthusiastically in the sunshine of the warm Sardinian spring. But was their experience of the planet, imbued with a sense of vertical analogy between what is down here and up there, comparable at all?

Today, as in the past, a certain understanding of the cosmos is inscribed in what scientists believe to be the proper place to carry on their research. Nevertheless, Tycho's planet could hardly be more different from the one astrobiologists are inhabiting today. During the era of great revolutions in astronomical thinking, the place of the Earth was still under discussion, and figuring out whether it was a planet among others was a subject of great philosophical, religious and mathematical controversy (Kuhn 1962). Today, the pictures of the Earth taken by the Apollo astronauts from the Moon's orbit are pervasive, and since the 1970s, when thinkers and tinkerers adopted them as icons of a new "global environment", they have become part of our ordinary visual experience of the Earth as a planet (Jasanoff 2004; Lazier 2011; Poole 2010).

Less popular in the literature is the role played by other images, offspring of the same space technology but somehow polar opposites of them: since 1965, probes and rovers have populated the Martian landscape, sending back to their mission control pictures, diagrams and "postcards" (Vertesi 2014), enabling humans to imagine it as a surface on which, one day, they might actually stand, or – in the words of one of my interviewees – "exist as a person in that panorama"[133].

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[132] During the first day of the workshop, participants were invited to give presentations of their own specific field of research. I used this quotation during my presentation, titled *Exploring Laboratory and Field Practices in Astrobiology.*

[133] Personal communication, 17/06/2016.

The Earth as a planet and Mars as a landscape merged in scientific and popular imagination alike, providing the conditions of possibility for space analogue sites on Earth: observing an alien planet from the ground, through the rover's "eyes" – not from a vertiginous perspective of detachment, but from the body-like presence of the lander firmly set on the soil – created a number of what Hesse called "observable" similarities on which analogies are based (Hesse 1966). Experiencing such a landscape in person, even if through the mediation of the analogue field site, was thus just an extension and implementation of what these images already made conceptually possible.

As already mentioned, for several decades the discipline called *exobiology*, the study of extra-terrestrial life (Lederberg 1963), was accused of being a field of inquiry that "has yet to demonstrate that its subject matter exists!" (Simpson 1964), and therefore, according to some, a discipline that did not have the status of a science at all. When NASA funded the National Astrobiology Institute at the end of the 1990s, the term exobiology was partially discarded and a new one, in which the prefix *exo-* (outside) was replaced with *astro-*, was adopted (Dick and Strick 2005). What appeared to be just a mere rephrasing was in fact due to – and at the same time contributed to drawing people into – a different way of studying and searching for life in the cosmos, defining the discipline in a way that would also include Earthly life as an object of interest. To pursue the study of life in the cosmic context, astrobiologists become equipped with "at least one data point of the life that we know: life on Earth" (Cockell 2015:1).

Today, the use of extreme environments as space analogues shapes the design of space missions and the way the data collected during those missions are interpreted.[134] In fact, not every astrobiologist engages in long and adventurous fieldtrips: some of them focus on computer models and simulations, others on doing experiments in the laboratory with samples that other scientists collected in the field. Nevertheless, a growing portion of those who would call themselves astrobiologists have started engaging in fieldwork activities, and the resulting knowledge has been used to confirm the validity and legitimacy of what is done in other experimental spaces. Astrobiologists' engagement with extreme environments as analogue field sites thus informs the establishment of what constitutes astrobiological research today.

Among the many complex research trajectories within the field of astrobiology (Strick 2004; Dick and Strick 2005; Impey 2010), I would like to draw attention to the way *extreme*

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[134] Some good examples of this feedback process can be found in the *JGR-Biogeosciences* Special Issue "Field Investigations of Life in the Atacama Desert" 112 (2007).

environments and the microorganisms inhabiting them, called *extremophiles* (Rothschild and Mancinelli 2001), have captured much of astrobiologists' interest and research. Despite being considered very hostile to most multicellular organisms, these environments have revealed that they can host thriving ecologies of microbes. "The field," Helmreich and Paxson note, relies "on the promise of microbes as revelatory entities that might reveal life's universals with reference to unexpected particulars." (Paxson and Helmreich 2014:181). The term "extremophile", coined in the 1970s for food conservation research (Helmreich 2009:256), includes many different types of microbes: halophiles, or "salt lovers"; acidophiles and alkaliphiles, whose optimal growth is at low or high levels of pH; thermophiles, thriving at temperatures above 80°C; and so on. Extreme environments have become an object of intense scrutiny that help to understand how life behaves in circumstances previously considered hostile to life and that might be comparable, to a certain extent, to average conditions on other planets. In fact, "extreme" is an interesting term because it both reflects a deeply anthropocentric perspective about what constitutes a suitable environment for life and, at the same time, shifts this perspective by acknowledging the potential commonalities between Earthly and other planetary environments (Helmreich 2006; 2012). Because many of the microorganisms living in extreme environments are still unknown or very hard to culture in the laboratory under "standard conditions", the study of extremophiles has required astrobiologists to vacate their lab benches periodically to set foot (as well as hands, eyes and the rest of their bodies and instruments) on their chosen field sites.

Analogies and space analogues

Analogies are ubiquitous in science (Hofstadter and Sander 2013; Lakoff and Johnson 2013; Holyoak and Thagard 1995). It is common, not only among the lay public but for scientists as well, to think about gravitational waves in terms of *ripples in the fabric* of time, evolutionary phylogeny in terms of *branches of a tree* and light in term of *waves and particles,* to mention just a few examples. "Without models," Mary Hesse wrote in 1966, "theories cannot be genuinely predictive." The analogies between a model and the systems under study, she claimed, provide the only effective way to search and test for new hypotheses and expand the explanatory power of a theory. Similarities and differences between the two terms of an analogy are not fixed, but they are objects of testing and debate; in this very process lies the predictive power of analogical reasoning (Hesse 1966). Nancy Leys Stepan reminded us that scientific metaphors and analogies, unlike those used in narrative, do not have to be considered arbitrary or merely personal to count as valid epistemic tools. On the contrary, the simile (e.g. figure of speech in which the analogical comparison is made explicit, such as "light *is like* a wave") has to be agreed upon by a community to the point that the arbitrary and creative process bringing together the two terms of the analogy are hidden (e.g. "light *is* a wave"). "Nevertheless," Stepan writes, "because a metaphor or analogy[135] does not directly present a pre-existing nature, but instead helps *construct* that nature, the metaphor generates data that conform to it, and accommodates data that are in apparent contradiction to it, so that nature is seen via the metaphor and the metaphor becomes part of the logic of science itself"(Stepan 1986:274).

In their sociological analysis of scientific knowledge, Barnes, Bloor and Henry emphasize that, despite seeming obvious, the identification of analogies[136] in science as a contingent action is crucial. "When it is overlooked," they claim, "the result is typically a purely formal account of modelling, which fails to grasp its purposive and goal-oriented character, and hence how it comes to be recognized as successful or unsuccessful" (Barnes, Bloor and Henry 1996:108-9). No model is ever perfect, they admit, and this is what makes the agreement of what constitutes a *good enough* metaphor interesting to the sociologist. "A successful model", Barnes and Bloor suggest, "is a pragmatic accomplishment, something which those who evaluate it take to serve their purposes". Caves and mines in particular have proved to be fertile terrain for unpacking the set of related questions about the inherently cultural sources of scientific analogies (Battaglia ed. 2005), their role in creating forms of life and lifeforms (Helmreich 2012), their normative consequences (Olson 2012) and the ongoing process by which they are agreed upon .

Indeed, despite their being "extreme", no place on Earth is absolutely Mars-like (or Moon-like, or like any other body in the Solar System). Earth's atmosphere, soil composition, gravity and tectonic dynamics, just to mention a few features, are not the same as those on other planets. Especially important in the use of analogies is their "similarity-creating" capacity, involving the scientist in a selection of those aspects of reality that are compatible with the analogy itself, and the neglect of information about

[135] Simile, metaphor and analogy are all figures of speech in which two elements are juxtaposed and similarities are drawn between the two. The comparison, nevertheless, is made explicit in different degrees: a simile takes the form of "*a* is like *b*"; a metaphor takes the form of "*a* is *b*" and in the analogy the first term is completely hidden, so that talking about *b* induces the reader to refer to *a*.

[136] They use the term "modelling", which they generically define as the establishment of a link between two things – which might range from mathematical structures to verbalized systems – by means of resemblance or analogy (Barnes, Bloor and Henry 1996:107-9).

the human experience of the world that does not fit the similarity implied by the metaphor (Stepen 1986: 272).

A number of these extreme environments on Earth are today used as analogues of other outer space environments,[137] Mars in particular. These analogue sites are said to have characteristics that are *so* similar to the ones we would find on the Red Planet that they can be considered valid Mars analogues. But how *similar* is *similar enough*? There is no one single answer to this question. Each analogue field site has its own history of why, how and when it was selected, and its own stories about life to be told.[138]

Because analogies are not *found,* but *made* – and, at the same time, *making* what counts as valid and legitimate – in astrobiological practice, the investigation of their conditions of possibility cannot be conclusively settled. On the contrary, one can extend the principle of finitism to the making and use of analogue sites and the analogies embedded in them.[139] Space analogues raise continuous problems with correspondence and reconciliation between the features of the two settings coupled in the analogy. Every time an active member of a certain group (in this case, a member of the relevant scientific community) is presented with a case that might be considered a valid analogy, he or she will evaluate its characteristics in order to judge whether it counts as a valid and meaningful analogy to be investigated. If other scientists agree on the validity of this judgment, the hypothesis made out of the analogical argument might create the need to revise other pre-existing analogues, which may no longer be considered valid. Every time a new instance is evaluated, this judgment is repeated. Different analogies are thus not mutually independent, and might strengthen or question each other's validity. Determining what counts as similar or different, meaningful or negligible, is an ongoing process and thus its unfolding deserves close attention.

Three analogies between outer space and subsurface environments on Earth

Fieldwork is never a solitary experience: a small handful of scientists from a wide spectrum of disciplinary backgrounds join forces to understand multiple aspects of the

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137 The use of the word "environment" to designate other planetary surfaces is not to be taken for granted. Planets have not always been considered *places*, but what is considered the correct way of thinking about planets has changed over time. See for example Alexander *et al.* 2010 and Messeri 2010.

138 HS, interview 21/10/2015.

139 As above, I define *analogue sites* as material settings in which one or more analogies are embedded and *analogies* as correspondences between Earth and outer space.

environment and make them significant for reasoning about life beyond Earth. Very often, their collaborations are driven by logistics and the necessity of optimizing resources, as reaching remote and barely accessible sites requires laborious planning and preparation. Nevertheless, once in the field, their collaboration becomes part of the way science is done. Interaction among people with heterogeneous experience and expertise often leads to the mingling and intertwining of several analogies. During the GESE workshop, for example, caves and mines were seen as offering the following analogies to space exploration:

i. Caves and mines as microbial habitats.

The presence and activity of microorganisms underground became an object of interest in astrobiology when decades of data on the Martian soil and atmospheric composition led scientists to agree that today it is very unlikely to find either extant or traces of extinct forms of life on the surface of the Red Planet (see chapter 5). Because Mars' atmosphere is today about 100 times thinner than that shielding the Earth, the landscapes once shaped by rivers and lakes do not, at present, offer the conditions for liquid water – with the exception of the flowing brines saturated in perchlorates, highly oxidizing salts that only very rarely form on Earth. What is more, the amount of UV radiation passing through the thin atmosphere would constitute a severe threat to the stability of any organic compounds. Even if there was, once upon a time, life on Mars, astrobiologists think it would be very hard to find any trace of it left on the surface; nevertheless, based on observations of the way life behaves on Earth, they have considered the possibility that there might have been residue colonies hidden underground for much longer after the surface became uninhabitable, and that their traces might be better preserved (Cockell *et al.* 2013). Some astrobiologists have actually made the claim that microorganisms might still be there, adapted to a niche where UV radiation is lower and where there seem to be reservoirs of liquid water (Bandfield 2007).

Astrobiologists are thus interested in the cave as an environment in which most solar radiation is filtered out and in which microorganisms have lived undisturbed and isolated for thousands or millions of years. On Earth, these conditions are "extreme" (i.e. unusual and unfriendly from a human perspective, requiring microorganisms to adapt and develop efficient physiological mechanisms to survive), while on Mars they are seen as the last bulwark of refuge from even more hostile surface conditions. Despite what most microorganisms living on the Earth's surface would consider highly hostile conditions, caves are teeming with lifeforms capable of optimizing the resources available. If they can do this on Earth, why shouldn't they act the same way on Mars, astrobiologists wonder? This unexpected multitude of microorganisms adapted to the deep darkness of Earth's caves reinforces the hopes of many astrobiologists. They conceive them as instances of life's great capacity for survival, despite the darkness, isolation and lack of nutrients – conditions that might all be similar to those on the Martian subsurface. The differences, for example the copious presence of water that is indeed the primary force giving shape to caves on Earth, are considered negligible, and thus disappear into the background of what astrobiologists observe within the framework of the analogy.

ii. Caves and mines as human shelters.

In the early 2000s, for the first time, satellites orbiting Mars sent pictures of possible cave entrances back to Earth (Cushing 2012). Speleologists suggested these might be used as shelters in future human exploration of the Red Planet. Lava tubes, caves formed during volcanic eruptions, might offer a cost-effective solution to the danger of UV radiation exposure, which is one of the main obstacles that will have to be faced when planning the establishment of long-term settlements on Mars (Boston *et al.* 2004). From 2002 to 2004, NASA funded the Caves of Mars Project, as part of the Institute for Advanced Concepts,[140] to assess the best place to situate the research and habitation modules that a human mission to Mars would require. Microbiologists' and speleologists' interests have always been deeply rooted in understanding adaptive solutions that would allow microbes to thrive in caves. However, to investigate them, they had to develop a parallel speleological expertise: during the long expeditions bringing these teams to still-unexplored hollows, they lived inside caves for several days. In building up a network of people interested both in speleological themes and in the possibility of extending their technical and scientific expertise to space exploration, they traced a second relationship between exploring caves and inhabiting other planets.

iii. Caves as sites for astronaut training and exploration.

Sardinian caves have also been periodically populated by groups of astronauts for training purposes.[141] In 2011, ESA established a training programme called CAVES, an acronym of "Cooperative Adventure for Valuing and Exercising human behaviour and

[140] http://www.niac.usra.edu/

[141] http://www.esa.int/Our_Activities/Human_Spaceflight/Caves/

performance Skills". Every year, training takes place in a different cave; avoiding contamination and preserving the environment are among the imperatives of the training. The depth of the caves is chosen for its "dark and alien underground environment with *many analogies* to space".[142] The analogies here mentioned have nothing to do with microbes or UV radiation; they are relative to the astronauts' training needs. As one of the trainers describes:

> One of the terrestrial environments which best mimics a planetary world, such as the one on Mars, is without any doubt the cave: darkness, constant temperature, limited visibility, physical obstacles, strict safety rules, isolation, loss of temporal cognition, difficulty in supplying materials and food, the necessity of working in a team. If exploration and documentation tasks and scientific sampling and experiments are added to those factors, the similarity of a cave mission to an extraterrestrial one becomes even more striking. (Bessone 2013:321).

Since the beginning of the space programme, astronauts have been selected according to criteria that evaluate both technical skills and personal temperament. Because of the stressful conditions to which they will be continuously exposed during space missions, only those applicants who demonstrate a high tolerance to demanding endeavours are considered for selection. Yet, for training purposes, they have to be exposed to conditions that exceed their tolerance, which are very hard to simulate in a controlled environment that does not present any real danger. One of the strategies adopted is to bring small groups of them into unfamiliar contexts, where they feel uncomfortable, "where they have to *adapt*".[143]

During the six days of cave mission, the astronauts cannot be left idle, as this would be too inconsistent with the tight schedule of a space mission. For this purpose, ESA trainers ask the speleologists of the University of Bologna to provide a number of scientific goals that the trainees have to achieve once in the cave. Each year, the team is thus given a series of scientific projects that they need to learn how to carry out. The assignments usually take the form of collecting samples and specimens and making maps of the chambers that are still uncharted. What is at stake is not merely survival in a cave by following standardized safety procedures, but being able to apply them while *exploring*. The trainers' goal is to turn the engineers into explorers, teaching them how to become attuned to what is new and surprising, to step inside the unfamiliar, inhabiting

142 http://blogs.esa.int/caves/why-caves/ (emphasis added).

143 25/05/2015, private conversation.

– sensing and dwelling in – an isolated space, with no weather, daylight or night, alien and alienating.

Through the experience in these particular field sites in Sardinia, the scientists were involved in the production of these three analogies at the same time: they were thinking about the field sites we visited as isolated subsurface microbial habitats, as shelters protecting humans from the dangers of the Martian atmosphere and as isolated enclosed spaces that reproduce some of the features specific to space journeys. At the end of the workshop, a roadmap identifying future research directions, spanning from near-term use in the search for biosignatures to long-term planning of human exploration and settlement, suggested that "many of [the mineral-microbe interaction] processes have applications in human and robotic space exploration, and on the surface of the Moon and Mars where the surface regolith – the layer of unconsolidated solid material covering the bedrock of a planet – contains minerals and elements useful for life support systems and *in-situ* resource use" (Cousins *et al.* 2016). The three analogies, in the lived experience, overlapped and became, at times, almost indistinguishable.

Lisa Messeri describes analogues as the successful super-imposition of planetary and local. In the Mars simulation facility based in the Utah desert of which she gives an account, this overlapping carves out "a unique place to inhabit and consequently forge a novel connection to or understanding of another world" (Messeri 2016:25). The analogue is not just a simulation: the new way of thinking about outer space, both considered place-less and nevertheless deeply situated, is, according to Messeri, generative: "it creates a history even as it simulates the future"(Messeri 2016:67). In creating a geo-microbiological history of the Earth within the broader Solar System, it makes it possible to think about the future inhabitation of other planets. What Messeri calls the "double exposure" (Messeri 2016:30) of planetary and local can be, in fact, multiple exposure. By means of first-hand experience and group interaction, astrobiologists can quickly shift from one narrative to another and build up a shared vocabulary of *adaptation, isolation* and *exploration,* with which they can refer to all three analogies, making the shift between one and the following even more immediate. The analogue was redundant in that even when one narrative failed to convince those involved in the analogue-making activity, others could support the legitimacy of the field site as a space of knowledge production about extra-terrestrial environments. In abstract terms, the analogies drawn between a terrestrial cave and Mars might not have always been very strong or very obvious, but in the lived interaction the analogies were substantiated and tied together.

It is legitimate to wonder why astrobiologists do not avoid the field and instead safely remain in the ordered, simplified space of the laboratory. Another fieldtrip in which I participated might provide an answer. I claim that astrobiologists consider their epistemic power to be entrenched in their engagement with nature, their travels to the field and the way they somehow become part of it.

Welcome to Planet Mars: An exercise in astrobiological fieldwork practice

"Welcome to Planet Mars," read one of the panels at the Myvtan information centre in Iceland.[144] The small green building rose from a service area surrounded by a broad car park full of buses and off-road vehicles; a few well-equipped hikers were making a quick visit to the mini-market next door to buy provisions of water and instant food before returning to their explorations. The small information centre was no more than a cube of concrete, filled with a huge collection of leaflets and posters displaying Icelandic wonders and advertising tours. The astonishing natural landscapes sharply contrasted with the functional and minimalist Icelandic architecture. Next to the "Welcome to Planet Mars" board, other panels showed watercolour representations of the variety of birds and flowers populating the nearby wetlands and the rich diversity of lava concretions that can be found in the Myvtan area. Every year, thousands of tourists are attracted to this place because of its geological liveliness, producing a broad set of rare and stunning phenomena. On the opposite wall, books were displayed on a long shelf; one of them was titled "The Living Earth". The Earth, in Iceland, seems to be no less alive than plants and flowers and humans: less than 20 million years ago, a blink of an eye on a geological scale, Iceland was not a land at all. When the Mid-Atlantic Ridge, the fissure created by the drift of two large continental plates, met a hotspot moving east, a lively bubbling and bustling of the melted magma below the thin crust started to rise up to the surface, creating the ground where we were standing. Because of the high latitude, the volcanic magma often interacted with the glaciers that until a few thousand years ago covered the entire area. For astrobiologists, this constitutes a similarity to what might have happened on Mars almost 4 billion years ago, when the Red Planet still had a thicker atmosphere and a higher amount of water (probably in an icy state), before they were lost forever in outer space. Interestingly, during the Apollo programme, Iceland was used as an analogue of

[144] This field study was part of the 2016 Astrobiology Summer School titled "Biosignatures and the Search For Life on Mars", which was held in Iceland from the 4th to the 16th of July 2016. The school was co-organized by the Nordic Network of Astrobiology, the European Astrobiology Campus, and the EU COST Action "Origins and Evolution of Life on Earth and in the Universe".

the Moon for astronaut training purposes (Messeri 2014). Today, Iceland has stopped being the Moon, and has *become* Mars.

Once back on the bus, Wolf, the summer school organizer and a remarkable expert on everything concerning Iceland, told us that according to traditional beliefs, elves dwell in rocks, and people are strongly discouraged from removing or damaging them if they don't want to upset the householders. Other traditional mythologies involve trolls turning into rocks when hit by the sunlight. The same advice holds: don't move rocks if you don't want to upset the trolls, who are neither the smartest nor the kindest people on the island. In turn, for scientists, rocks are small pieces of that world that can be moved around, magnified, deconstructed into smaller components and tested. The group of people I was part of surely enraged the elves and trolls: for the following three days, we collected samples for an astrobiology exercise. As the information centre panel suggested, we were using Iceland as a Martian analogue.

For the practical exercise following a week of lessons about astrobiology, we were divided into four teams of around ten people each. The groupings had not been formed randomly: each group had at least a biologist and a geologist, who were informally responsible for training the other members of their teams in what would be considered proper practice in their disciplines. The organizers had equipped each group with a set of tools composed of a few pairs of sterile gloves, three or four masks, an equal amount of sterile spatulas and 14 falcon tubes. In the following three days we visited four or five sites (depending on weather and time availability), where we were allowed to collect a maximum of twelve soil samples to be analysed for the quantity of ATP, a molecule used by all forms of life on Earth to store energy, and thus used in this exercise as a proxy for the quantity of living molecules present in each sample. The exercise consisted of finding a good research question to be answered with what we had at our disposal (what had been provided, plus what we had with us and what we were able to find in the local shops). Clearly, we had been warned, this experiment would not work if searching for alien life: ATP, the molecule that mediates in the metabolic processes of storage and consumption of energy, is indispensable for Earthly life too. However, we were told, it is really difficult to imagine that the same mechanisms might have evolved independently. But this was not the point of the exercise. In fact, the way the practical part of the training was proposed raised a number of uncertainties and complaints about the scarce instruction we had been provided, but nothing more was added by the organizers.

The evening before we started visiting the field sites, we met in a small bungalow with our laptops and a copious amount of coffee in order to decide how to proceed. The first decision to be taken was where to start from. The brainstorming discussion often got stuck due to the many limitations – the small amount of samples we could collect, the small amount of tools we could use, the only measurement we had at our disposal and the scarce knowledge of the site we were to visit. We agreed to collect our samples in Holuhraun[145] lava field, in the Askja region. Because the erupting magma was rich in volatiles, the small bubbles coming out of the solidifying lava created a rough rubbly surface of broken lava blocks with very jagged sharp edges and a network of tiny porosities within the rocks. Microbes, we assumed, might have progressively migrated into these tiny vesicles, and we decided to figure out how deep within these rocks microbes were able to survive and colonize. Barbara, a geologist, was required to break pieces of rock with her invaluable geologist hammer at different depths (on the surface, 1cm deep and then 2cm, 3cm, 4cm and 5cm), and then crush each piece inside a sterile plastic bag before pouring the coarse grain into the falcon tube.

Figure 11. Sample collection in Holuhraun. Picture taken by author.

Once we arrived at Holuhraun, we started walking over the huge field of dark sharp volcanic rock. Because it was so recent, water and wind had not had enough time to smooth it, and walking on it not only required tracking boots, but also thick gloves to protect the palms when climbing. We walked a couple of hundred metres into the field to find an isolated spot to sample.

145 The huge eruption in Holuhraun lasted for 181 days. It began on the 31st of August 2014 and ended on the 27th of February 2015. The new lava field covers 85km^2.

Once we selected our *perfect* spot, Barbara started hitting the rock with precision. It took a while for the first chunk of rock to come off. The piece was a few centimetres – too big, so we had to change position and start over. The same problem happened again. At first, we simply decided to increase the depth of our sampling if breaking the rock into smaller pieces was not possible. Louth, the biologist of the group, carefully picked up the chunk and placed it inside the plastic bag for crushing, but as soon as Barbara started hammering it, the pointed and sharp sample tore the plastic bag and the tiny crumbs we were trying to collect fell on the ground. Keeping a safe distance so as not to contaminate the sampling site, we all started searching our backpacks to find a solution for this new problem. We decided to try to wrap the rock inside a paper tissue before smashing it inside the plastic bag, in the hope that the paper would soothe the stresses ripping the plastic apart. The quick fix seemed to work until we tried to pour the particulate into the falcon tube – the quantity we could obtain was well below the minimum required to perform the test and, what is more, pieces of paper had fallen into the small cylinder together with the sample, compromising the purity of the rock. We were running out of time, but because we still had 13 falcon tubes left, we decided to rearrange the experiment once back on the bus. Tired and frustrated, we gave up on Holuhraun and headed back to the meeting point where the various groups were gathering. Indeed, we had learnt a lesson.

Figure 12. Vulcanic rock field. Pictures taken by author.

"Collecting samples from such a hostile environment *is*, in fact, *doing astrobiology*"

Iceland did not simply represent a location geologically similar to Mars, but also an analogue in terms of the way we were to experience it: the challenges to which we were exposed were not very different from those that missions to Mars have to face. A rover on Mars, for example, crosses sites that are only roughly known in advance. Research questions continually change according to the unpredictable opportunities or challenges that a certain site presents, and they have to be answered using instruments that are limited compared to those available in the laboratory and chosen several years before the mission actually goes to work, when the spacecraft is projected and assembled.

During the summer school exercise, we were under the same conditions: first of all, we had learnt about the history of our sites during one of the lessons, but there were many practical details we simply could not even imagine until we found ourselves there in person; we had roughly known in advance what kind of question we wanted to answer, but the precise articulation of it was a mix of planning and improvisation; and last but not least, we had not chosen which test to perform based on the practicalities of the site and our research question, but vice versa: we decided where and what to sample based on the only measurement we were allowed to perform. This analogue exercise was meant to provide training for the *unpredictability* implied in space exploration.

To understand this tension – and why it must not be solved - we need to go back to the necessity for astrobiology to engage with the field, explicitly aiming to account for the complexity of nature, which cannot be reproduced by any means in the laboratory with its rigid boundaries, oversimplifications and standardization (Kohler 2002). It is very common to hear that astrobiologists are studying the only planet currently liable to experimental scrutiny "that harbours an experiment in evolution", Earth. It is precisely this encounter with the complexity and disorderliness of nature in which astrobiologists are interested: this encounter with the unknown and undisciplined that at once threatens their science and confers its epistemic power.

In describing what a space analogue is, one of the lecturers claimed that "analogue missions can be about science, technology or exploration". When I asked her to explain the difference between them, she pointed to the fact that engineers and scientists have different attitudes that have to be reconciled: while engineers need to solve problems of feasibility (very often related to the weight, size and functionality of instruments), scientists want to learn something from them. Exploring is about the habitats, logistics, psychology and physiology of the explorers themselves; it means taking into consideration all the practical and heuristic implications of "being there" and coping with the fear of contaminating samples, arranging equipment, facing the hardness of the rock and the sharpness of its surface, dealing with the quantity of material needed for an experiment we had not chosen, confronting fatigue and shortage of time, considering the passage of many people and animals other than us, documenting and mapping the sampling process so as not to forget or overlook important details and discussing and debating with the other members of the team on what to do next. "Because collecting samples from such a hostile environment", explained one of my interviewees, "*is*, in fact, *doing astrobiology*. Because it is tough, physically tiring for humans, that's it. Getting to such a remote place, the kind of place that presents you with difficult situations, enables you to think in *astrobiological terms*".[146] Exploration is about "being there" and embracing all the various interactions one comes to be entangled with. The field, which represents the renewed encounter with a nature not allowed within the strictly filtered boundaries of the laboratory, "is believed to harbour a surplus of multiplicity, abundance, and potentiality humans have not yet discovered or characterized."

The importance of "being in the field" is very familiar to the ethnographer, whose epistemic power is deeply bounded to his/her immersion in a certain way of life, and to the oxymoronic positioning of the participant observer, which, among other things, puts into perspective what is usually taken for granted. The ethnographer is also familiar with the awareness of modifying her/his very object of interest and the virtual impossibility of avoiding it, as he/she is an agent, exactly like any other person he/she relates to in the field; her/his presence, her/his being there, is never neutral. The ethnographer is also the inhabitant of two spaces: the field and the desk, exactly as the astrobiologist inhabits the lab and the field, with all their uncertainties and unpredictabilities. People and objects (samples or concepts) travel between these two spaces, which do not overlap, but always shape each other. In Strathern's words, sometimes ethnographers – like astrobiologists – inhabit both fields at the same time; "any ethnographic moment, which is a moment of knowledge or insight, denotes a relation between immersement and movement". In this very moment, "immersement yields to the often unlooked for. It yields precisely the facility and thus a method for 'finding' the unlooked-for" (1999:6), blurring for a moment the boundary separating same and other, Earthling and alien, known and knowable.

In Iceland, we had been trained not to know what to expect, and to prepare for the unpredictabilities of the field. The same happened in the Sardinian mine. Once we entered the tunnel, we were projected into an environment that most of us would describe as *really alien*, the closest thing possible to what each of us imagined standing on another planet would feel like. Being in there, within the mine, breathing the humid and sulphurous air and soaking one's boots in the mud, led to the overwhelming feeling of becoming part of the mine itself. In its darkness, moving our heads to shine the light where we wanted to look was not an instinctive gesture. Peripheral vision was completely inaccessible; what could be seen was always and only a sharp cone of light pointing straight ahead. The importance of bodily movement within the space we were occupying became apparent in a way that I had never realized before. Seeing was a

[146] BC, geologist and geomicrobiologist, interview 02/04/2015.

combination of the skilled art of pointing one's light in the right direction and involuntary movements, for example when stumbling on a rock and pointing the light downward, maybe to note the presence of something unexpected, standing out against the surrounding darkness. In fact, I gradually realized that the non-trivial combination of skilled observation and serendipity was an integral part of what made that fieldwork experience a valuable analogue for the search for life in space, perhaps the most fundamental one: when astrobiologists imagine what it takes to find life in an alien environment, they acknowledge that they should probably not expect to find exactly what they look for, but they rely on the idea, often repeated in formal and informal settings alike, that they will recognize life, despite the different forms it might take, once they encounter it. The possibility of unexpected findings is not unique to the field as opposed to the lab – even in the controlled and standardized space of the laboratory, people sometimes make unexpected breakthroughs. What fieldwork provides is the possibility of *purposefully* searching for the unforeseen and unforeseeable. This intuitive understanding on which scientists rely is not pre-scientific: the ability to recognize life is acquired by dealing with new situations in a similar way to those that one has already seen and experienced. Acquiring the sensitivity of judging whether a certain environment can become, in people's experience, a space analogue, how to make knowledge out of it, and how to reverse the analogies to interpret the data coming from space missions is part of becoming a skilled astrobiology practitioner. "Skills", Tim Ingold and Terhi Kurttila write, "are not properties of the individual body, but properties of the whole system of relations constituted by the presence of the agent in a richly structured environment" (Ingold and Kurttila 2000:183). The practitioner needs to be situated in the context of an "active engagement with his or her surroundings" (*ibid.*) to practise and develop these practical and always evolving skills. Through the analogue experience, astrobiologists are equipped with a toolkit of *exempla* that they can apply on Mars – through their rover-mediated presence, or maybe, one day, in person.

Unpredictability

At the end of a walk in Is Zuddas, a show cave whose first kilometre has been equipped with steel stairs and neon light to form a tourist attraction, we were told that the key to the gate securing the entrance had been lost and the gate could not be re-opened to let us out until someone came and fixed it. A group of us stopped and waited on a terrace a few metres below the cave mouth. We started jokingly talking about how we would survive in the cave for a long time: would we need to hunt bats, collect bugs, drink the

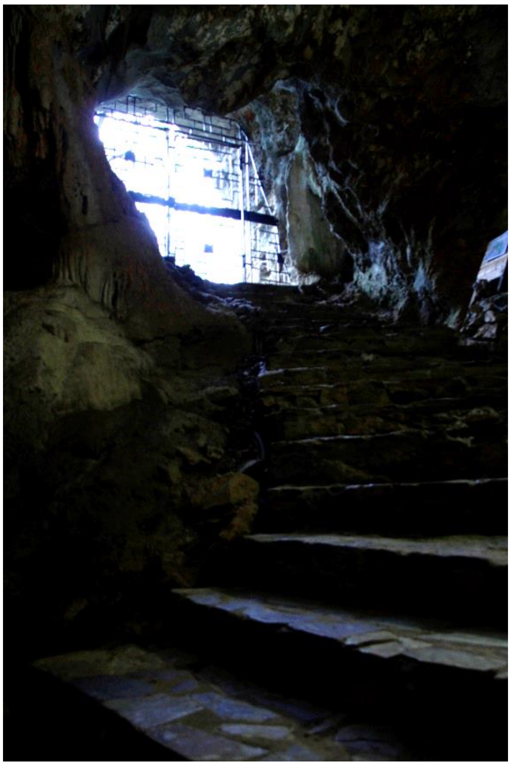
Figure 13. Is Zuddas cave entrance. Picture taken by author.

water dripping from the walls? Would our grandchildren evolve to see in the dark? Would we, like in Jules Verne's *Voyage to the Centre of the Earth*, discover prehistoric landscapes in the depths, moving in space and travelling in time? The expert guide looked at our faces and laughed. When astronauts come for their training, she always plays the same trick to see their reactions: after many days of isolation, how would they cope with the impossibility of getting outside, metaphorically returning to Earth? For us, the gate had always been open anyway; we exited the cave and started walking along the wide path under the shade of the trees. Some veteran speleologists chatted about the way leaving a cave makes the surface feel different and indeed very chaotic: the wind moves the leaves; birds tweet and insects fly and land on our clothes; the warm sun, high in the sky, suggests that it is time for lunch. I wonder whether we are back on Earth, or if we have travelled even further on a terraformed Mars. "This cannot be Mars," someone tells me, "too many mosquitoes. Who would want to put mosquitoes on Mars?!" The irony is that Earth is the only planet we know we can live on, but indeed what makes it feel unique are its many imperfections. I cannot help but think about the principles of finitism: while the first thesis states that the future applications of terms are open-ended, the last states that the applications of different kind terms are *not* independent of each other. The Su Zurfuru mine does not seem *abandoned* anymore, but repopulated and given new life by different communities of microbial miners and dwellers. However, even when stepping outside the analogue field site, the analogy still carries out its generative work: it has not only brought Mars a little closer, but also made the Earth surface and atmosphere unfamiliar and new.

Conclusion

Life *as-we-don't-know-it* within research repertoires

In this thesis, I have investigated the research repertoires astrobiologists embrace to practice and promote the emergence of their discipline. In particular, I have taken the concept of "life as-we-don't-know-it" as an entry point to investigate the strategic role of non-knowledge claims. I eventually argue that what is not-known is socially constructed and contribute to the opening of new spheres of inquiry.

In the first empirical chapter, I retraced the emergence and changing fortunes of SETI, the search for signals purposefully sent by alien "civilizations" with technologically sophisticated capabilities. The Drake Equation and the set of epistemic, social and practical components that it represented initially included microbial life as a mere transition in an inevitable chain of events, a factor (called "f_l" in the Drake Equation) whose estimation would contribute to the more general extrapolation of the total number of "technologically advanced civilizations" in the galaxy (or "N"). The Equation, formulated in 1961 to summarize the agenda of the first SETI meeting, described the enterprise using a mathematical register that both conferred it a sense of empirical soundness and inscribed it on the broader historical context. The Drake Equation represented a first repertoire that scientists adopted to answer the question "are we alone in the universe?", providing them with a series of research practices that could successfully fit the technological and institutional apparatus within which SETI was inscribed.

This chapter brought attention to the boundary-work performed both between science and non-science, by looking at the way alien life has become an object of scientific inquiry, and between different disciplines, by looking into the relationship between SETI and astrobiology. Over time, the relationship between SETI and astrobiology passed through different phases and, in the last few decades, SETI has often been described as part of the larger field of astrobiology, providing a special, but neither necessary nor always worthy, understanding of extra-terrestrial life.

In the following chapter, *Building habitable worlds,* I looked into the assessment of habitability, the planet's potential to provide environments hospitable to either endogenous or exogenous life. I described how the *flexibility* and *multiplicity* of this term made it what Brother Guy Consolmagno described as "the right question". Habitability benefits from not having a singular characterization: the habitable zone, the search for Earth-like planets, the study of habitats and imaginaries about inhabitation all contribute to the question of habitability. Its variability supports the organization and the management if the community that coalesces around this repertoire. By studying the potential for life on exoplanets and the bodies of the outer Solar System in terms of habitability, astrobiologists allow different imaginaries, objectives and research rationales to co-exist. At the same time, habitability aims to describe the relationship between living beings and environments and, because of the seemingly endless variety of environments that can be imagined, leaves the door open for a number of very different forms of inhabitation and inhabitants. It is in this kind of interdisciplinary debate that newcomers are first trained in questioning what life is. Overlaps and tensions are deployed as resources for an eventual agreement on not-knowing what counts as life.

The next chapter focused on Earth's neighbour, Mars, and the ways past observations are narrated in the present as a way to present the contemporary search for extra-terrestrial life within the astrobiology research framework as more "scientific" than its forerunners. Two episodes, in particular, are often recollected with this function: Schiaparelli's mapping of the canals, first interpreted as proof of the Martians' skilled engineering planning and then revealed as an optical illusion; and the Viking life detection experiments, which first returned what appeared to be positive results, then were reinterpreted in the light of new findings about the composition of the soil that eventually delegitimized the assumptions about life embedded in the experimental design. These anecdotes, recounted to discourage Earth-centric assumptions and biased interpretations in the search for life, have contributed to the establishment of another key concept in contemporary astrobiology: *biosignature*, or the "signature of life". This expression embeds uncertainties and anxieties connected to the search for life: how can life be revealed and when is evidence reliable?

The last two chapters unpacked these two issues: the *Shadow Biosphere* chapter problematized the *revealing* and the *recognizing* of microbes. The example of the shadow biosphere hypothesis, a parallel tree of life on Earth, questions – according to some - the reliability of laboratory devices that are built according to the principles of traditional biology and therefore potentially blind to other kinds of cellular structures. In the occasional adoption of the Shadow Biosphere repertoire – a set of attitudes, expertise and epistemic components to decouple and question the revealing and recognizing of microbes – astrobiology aims to promote the displacement of traditional biology and offer a more "universal" account of life. The unreliability of tools, concepts and standards elsewhere considered to be best practice allows for the creation of a new epistemic space that can be occupied by the emerging discipline.

The last chapter, I looked at the repertoire constituted by the study of the so-called space analogues, extreme environments that present characteristics that are considered similar to those that one could find on other planetary surfaces. Throughout the chapter, I discussed how space-analogues (and the different but overlapping analogies that constitute them) are socially established and sustained. Research trips to analogue fieldsites managed to attract the support of many institutional partners (e.g. space agencies, academic institutions, private companies), thus promoting broader participation in what was once considered a niche enterprise. Together with the practical and social organization of collaborative research, analogue field studies, by moving outside the laboratory walls, provide astrobiologists with a way to tackle the paradoxical condition of searching for the unexpected. In the field, uncertainty becomes part of the astrobiologists' research methodology, thus fostering the idea that they will "recognize life when they encounter it", one of the few operative definitions of life on which most of them agree.

Placing life back into history

In his excellent book, *Being Alive*, the anthropologist Tim Ingold writes:

> Every so often the media of the western world register a surge of excitement about the imminent prospect of discovering life on the planet Mars. [...] I am at a loss to know, however, what it is exactly that scientists hope or expect to find on the surface of the planet. Is life the kind of thing that might be left lying about in the Martian landscape? If so, how would we recognize it when we see it? Perhaps the answer might be that we would identify life on Mars in just the same way that we would identify it on our own earth. But I am not even sure how we would do that. What I am sure about, because we know it from ethnography, is that people do not always agree about what is alive and what is not, and that even when they do agree it might be for entirely different reasons (Ingold 2011:67).

Far from being as naïve as Tim Ingold portrays them, astrobiologists – as shown throughout this thesis – share most of his uncertainties: they also wonder how to identify life, either on Earth or on Mars, and they are aware too, because of their many interactions with scientists from different disciplines, that people see living processes in very different ways, and might reach the same conclusion for totally different reasons. They too wonder how to relate the existence of Martian forms of life with the landscapes by which their rovers and landers are surrounded and move across. They too explore the exchanges between living beings, the atmosphere, the land surface and the subsurface, aware that life is never "the kind of thing that might be left lying about" (*ibid.*), because life and environment actively shape each other in ways that – astrobiologists suspect – are perhaps too numerous to be grasped. They too are aware that even within their community, people do not always agree, and if they do so, it might be for entirely different reasons. What they all agree with is that "astrobiology is frustrated by the lack of a definition of Life. We don't really know what we are looking for", as it reads a slide posted on the internet as representative of an astrobiology conference. The concept of life is indeed central to the definition of the scope of astrobiology as a discipline; but, as shown in this thesis, defining life appears to be an almost impossible task. In fact, most of the explicit discussions about "what is life?" are actually exercises to deconstruct previous understandings of it and come up with a series of unknowns to be further explored, for example when at public astrobiology events the lack of a single and shared definition is mentioned and everybody nods and silently approves (see ch. 4); not knowing *what life is* is so foundational that it is taught in every astrobiology class and introductory lecture to which I have had access.[147] Throughout this thesis, I have looked into what life becomes within some of the repertoires that today form, at their intersections, the field of astrobiology.

The Drake Equation (ch. 3) assumes a linear evolution that includes all objects in the universe. Starting with the number of stars and planets, there seems to be a sense of continuity that progressively leads to more accomplished achievements, inexorably developed through the history of the universe (Maccone 2013). Sooner or later, it is assumed, all the living beings of the universe, independently of their biological structure, could ultimately develop technological capabilities and a mathematical understanding of the universe, before the entire civilization eventually becomes extinct. The possibility that this might happen at a different pace is envisioned, but it is still assumed that it will happen, every time in a similar order. In the introduction to Project Cyclopes, John Billingham and Bernard Oliver claim that:

> Regardless of the morphology of other intelligent beings, their microscopes, telescopes, communication systems, and power plants must have been at some time in their history, almost indistinguishable in working principles from ours. (Oliver and Billingham 1971:4).

Carl Sagan's famous claim that "we are star stuff" adds a shared starting point to SETI's linear understanding life: despite the different possible evolutionary trajectories, life starts from the same material and ends up with mathematicians and philosophers (Cabrol 2016; Tarter 2011). Abstract thought and its by-products, namely science, technology and the ability to express concepts in mathematical form, are considered universal; they are what a successful evolution would eventually reach, under any material conditions of possibility. "We wanna know their philosophy", one of the SETI researchers at Berkeley explained to me, "their physics, have they found a unified theory? Have they figured out an economic system that actually works? And the music, for me, it's mostly about the music. I am a musician!"[148] The plurality that forms of life might take moves completely in the background to give prominence to what is considered the ultimate outcome of evolution: scientific and technological progress and abstract thinking. SETI people are engineers and scientists looking for other engineers and scientists in the universe and their idea of life is not simply abstract, but goes hand in

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147 Either in person, such as in Charles Cockell's class, or online, as in the case of Lynn Rothschild's course in astrobiology at Stanford, available on YouTube.

148 EK, interview 24/02/2016. Music, in this context, seemed to echo the Platonic understanding of music as a form of mathematical thinking.

hand with SETI research practices, institutionalization and narratives: first of all, they looked for signals transmitted as radiowaves for practical reasons – waves could travel long distances and pass through the atmosphere – but the choice was supported by the idea that technology always goes through the same stages of development and therefore every civilization will develop radiotelescopes and a system of communication based on long waves sooner or later. The emphasis on civilization rather than on the single individual gives a sense of ecumenic unity which boosted the collective support: SETI – despite being an elite research project – seemed to be undertaken by the few for humanity sake. The engineers and mathematicians elected themselves as the legitimate representatives of this planet, the ones able to communicate. Another element that shows the entangled nature of what appears an abstract position about life and the socio-cultural context in which a certain kind of research is practiced is the continuous shift between the historical specificity of SETI's approach to technology (and its challenges) and the universal history that SETI researchers imagined. The factor L, the lifetime of a technologically advanced civilization, was meant to situate Earth's vicissitudes in a *universal* pattern. The search for artificial signals was not only meant to find cosmic companionships, but also to strengthen the hopes for humanity to successfully confront the risk of self-destruction.

Life, in SETI's approach, has not much to do with its physical structure. Heir of the Cartesian tradition that gives conceptual prominence to the mind over the body, the fundamental disembodiment of life as understood by SETI researchers can be seen in their use of the word *civilization:* intelligence is not an ability attributed to the individual, but possessed by the collective.[149] This position is brought to its extreme consequences in that SETI scientists envision the possibility of intercepting signals sent by post-biological civilizations (Dick 2006), or synthetic and engineered entities mastering technology after the fading out of their "biological" inventors. On the other hand, SETI's

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[149] At the same time, like many other scientists in other disciplines, SETI is said to be an enterprise of all humankind, democratized in distributed computing projects such as SETI@home (Anderson *et al.* 2002) and often detached from logics of ownership and authorship, as all the data and technologies are made available to everyone willing to contribute. The spectrometers built for SETI are designed to be as cheap as possible in order to increase the number of people using them. The data, once collected and archived, are often made available to everybody. The ecumenical claim on which SETI is based is indeed reflected in its research practices. The community they refer to, nevertheless, only includes scientists and members of the public that consider themselves mathematically minded.

approach to life foregrounds the idea that organisms might (and they are likely to) take endless forms, forms we might not even be able to imagine. Everything between “stardust” (according to SETI scientists the common starting stage) and “mathematics” (the higher achievement) is unknown, probably unknowable and certainly not very interesting.

The astrobiologists’ conception of life differs radically. The new institutional and disciplinary framework created by the emergence of astrobiology and its many funding schemes aimed towards the creation of collaborations across disciplines provided fertile soil for a new conception of what to look for, how to look for it and what kind of attitude to adopt in order to confer astrobiology a certain legitimacy and scientific authority. Scott Hubbard recognized this change in describing the “origin and development” of astrobiology in the early 2000s:

> As a consequence of this perceived scientific failure NASA sidelined exobiological experiments for space missions, especially to Mars, for many years. The scientific community proceeded to rethink its approach to the detection of biosignatures, or signs of life. Out of this redirection eventually came the concept of searching for habitable environments rather than the direct detection of organisms (Hubbard, 2008).

The repertoire of habitability encapsulates a different construction of life which, nevertheless, can still be considered “planetary”: habitability, being the characteristic of a certain site to sustain life, establishes a relation between its two referents: life and its environment. What the former is depends on how the latter is studied, catalogued and imagined. The vice versa is also true: what counts as an environment potentially hosting life depends on the kinds of life whose existence one is inclined to consider. The assortment of planets and satellites of the solar systems offer a first model for the potential variety of planets of other systems: from the acidic hotness of Venus’ surface, to Titan’s methane cycle, from Mars’ high mountains and deep canyon, to the vital Vulcans of Io’s surface. The situation seemed to offer even more variety when it was discovered that the solar system was not the archetype of a planetary system but, on the contrary, it is characterized by a number of not very common features. The recently discovered variety of planetary forms contributes to the openness about the mechanisms that life, if originated under different conditions, might have evolved to sustain its growth. This kaleidoscope of exoplanets corresponds to an even more striking exoticness of life forms potentially inhabiting them.

Measuring and detecting the traces of life that might be left behind – either on a planetary or on a very local scale – has become a major concern for astrobiology. The search for biosignatures partially collapses the difference between living and non-living, while emphasizing the ontological difference between biological and abiotic. Biosignatures are not living entities, but the by-product of a biological process. The production of oxygen during photosynthesis (one of the most common biological processes on this planet) is an example. Oxygen, nevertheless, can be produced in many ways, including some abiotic chemical processes, and thus would *not* count as a biosignature, even if it might point in that direction. The co-presence of methane and oxygen in a planetary atmosphere, however, seems more promising, as the two gases produce an energy imbalance that would rapidly collapse if not constantly maintained. The question astrobiologists ask is "can the same phenomenon be produced abiotically?" "Every time we think we come up with 'maybe not *just* this, but this *and* that'", said Jill Tarter, without hiding her frustration, "somebody says, 'but you can do it abiotically this way'" (JT, personal communication). This is the endless work of negotiation with which astrobiologists still engage. Learning from Schiaparelli's and Lowell's lesson, they keep questioning whether possible evidence for life might in fact be explained by non-biological processes; following the lesson of the Viking debate, they try not to assume how life on other planets might behave (if it exists at all). The assumptions embedded in the experimental design and the fallacies in the interpretation that might miss abiotic pathways producing the same outcome are still considered major issues. This discernment requires a continuous rebalancing of assumptions about the conditions in which a certain feature formed. The ongoing debate about what to look for when studying Mars and other planets continues to emphasize questions of what traces life might leave behind and how to tell them apart from abiotic chemical processes.

The 6th chapter further unpacks the question of 'what counts as a valid biosignature?' By a biosignature, astrobiologists mean a more or less unequivocal sign indicating the presence of life. A valid biosignature both has to make life visible – or *reveal* it – and has to allow scientists to identify what kind of life they are dealing with, or in other words, *recognize* it. In the case study presented, laboratory practices and devices are shown to be at least potentially *unreliable*, the dubious presence of a biosphere that is either invisible or unrecognizable is always a potential scenario to be taken into consideration.

Being able to deal with unknown conditions and types of life is a useful resource for astrobiologists to open a new sphere of inquiry (Rheinberger 1997; Hackett 2005). Out of the potential existence of a shadow biosphere that blurs the contours between Earthly and alien life, new research practices and a new understanding of life – changing, evolving, adapting – emerge.

To prepare for the unpredictability of other kinds of life, astrobiologists have to displace their research outside the traditional biological bench or make their laboratory walls permeable to other ways of asking questions about life. By moving their instruments to the field – where they might not work as efficiently as in the controlled environment of the laboratory – they lay the foundations for interdisciplinary collaborations with other disciplines. What the field of astrobiology wants to foreground is the idea that life has been understood only partially, and a better and broader understanding requires a "cosmic perspective" as opposed to the local and incomplete insight that is a result of only looking at Earth's example of life. To deliver on this insight, astrobiologists first of all have to give shape to the unknowns they aim to tackle. The first move is to expand the limits of life, deconstruct previously endorsed models and pull definitions apart. As such, non-knowledge claims do not appear to be different from scientific knowledge itself; they are also social institutions.

In the concept of life *as-we-don't-know-it* the ontological and the epistemological status of alien life (other and unknown) overlap: it is used for alien, extra-terrestrial forms of life, inherently other from the life we know on Earth; at the same time, it points to the lack of any knowledge about these forms of life, their being unknown and, perhaps, unknowable. It is a buzz-phrase that stands for a multiplicity of meaningful theoretical and practical positions toward the definition of life: it challenges more or less established definitions of life with examples that escape them, with the suspicion that some of the most common tools usually deployed to reveal and recognize life might in fact miss it, with the acknowledgement of the infinity of adaptations that living entities might have evolved, actually or potentially, to adapt to the kaleidoscope of environmental combinations that scientists expect to find in the Solar System and beyond.

One might wonder, at the end of this excursus, "what's left of life?" (Helmreich 2011b:675). Despite their attempts to unpack definitions of life, most astrobiologists never stop being positivists: they think science will manage, one day, to find a definition of life that will eventually encapsulate its very essence. If contemporary biology is only partial, astrobiology, they claim, will indeed be "universal". The situatedness of definitions of life is only a temporary condition and will one day be overcome, swallowed up by the logic of progress that science too often promises. Perhaps, we might tweak the question a little bit and wonder "what *can be* left *to* life?" and suggest that life might return to its *cultural nature* with the adoption of expressions such as "life as-we-don't-know-it", which makes explicit what the pretence of producing "universal" knowledge usually black-boxes and hides: the complex chain of social relationships and alliances that made it possible. Only by embracing the awareness that life – like any other concept – cannot but be inscribed in culturally situated practices, will astrobiologists successfully prepare for the underdetermination implied in future exploration.

Life as-we-don't-know-it: the role of non-knowledge in the establishment of repertoires

Life *as we don't know it* is a thread that runs through all the repertoires described in this thesis. In the interdisciplinary field of astrobiology, life is purposefully looked at in many different ways. SETI researchers scout the sky in search of artificial signals from the depths of the galaxy, sent by disembodied and collective forms of intelligence. Exoplanet astronomers and planetary scientists investigating the outer Solar System try to characterize what it takes for a planet to be habitable and hope, one day, to be able to look at spectral signals and chemical compositions that indicate some form of microbial *oikopoiesis* – the shaping of an ecology, a planetary "home". Geologists and geomicrobiologists turn to Mars to ascertain the history of the evolution of life, trace a boundary between living and non-living on an evolutionary level (i.e. wondering when and how chemicals became living matter) and discern these processes in order to figure out what might count as evidence of life – a biosignature – and what could be produced abiotically instead. In the laboratory, microbiologists' abilities to make microbes visible and recognizable are always called into question by the notion that their instruments, designed according to the "traditional paradigm" of biology, might fail when facing a parallel tree of life. This uncertainty – seldom explicitly explored but always kept in the back of their minds – induces astrobiologists to vacate their lab benches periodically and travel to the field. In their exploration of so-called "extreme environments" on Earth, and in the appreciation of their unforeseen liveliness, astrobiologists prepare to deal with life as-we-don't-know-it. By becoming used to recognizing different instances of life and revealing their presence in sites commonly considered hostile to life, they learn how to look purposefully for the unexpected. Their physical presence in the field – not different from the ethnographer's own presence among those whose practice she wants to appreciate – is crucial for turning analogue field sites into astrobiologists' truth-spots. From the very Earthly specificity of an analogue site, astrobiologists attempt to make their knowledge and non-knowledge claims *universally* valid.

Emphasizing the importance of life *as-we-don't-know-it* in astrobiology's repertoires might seem to be a contradiction: if the concept of repertoire was meant to challenge the primacy of theory in scientific change, what ought to be the role of this piece of non-knowledge within astrobiologists' repertoires? In fact, the agreement on "not-knowing what life is" is not mere adherence to an abstract claim but, as this thesis has shown, it is inscribed and at the same time inscribes the research practices and institutional arrangements that constitute the condition of possibility for the astrobiology scientific community to successfully coalesce and function. What might seem a mere theoretical shift concerning what is known, unknown and knowable about life is not, in this case, the primary motor of change. It is accompanied, underpinned and undercut by administrative, material, technological and institutional shifts and subsequently, when widely agreed upon by the astrobiology scientific community, it has become in its turn a resource to be strategically used. In other words. life as-we-don't-know-it is the outcome of the astrobiologists' repertoires, coming into existence every time a repertoire is performed. At the same time, once agreed upon by the scientific community, it becomes a cultural resource to be incorporated in the construction of other repertoires.

In this thesis, I took the emergence of expressions such as life as-we-don't-know-it in astrobiologists' repertoires as an entry point to look into the strategic role of non-knowledge claims. The possibility of questioning the successful use of instruments by means of which living organisms are known and made recognizable offered astrobiologists the opportunity to propose new sites and methodologies for life detection. To think differently, astrobiologists have to displace their research outside the traditional biological bench or make the laboratory walls permeable to other ways of asking questions about life, for example by moving their instruments to the field – where they might not work as efficiently as in the controlled environment of the laboratory – and look for anomalies. Importantly, I have shown how, despite their reference to traditional biology as a paradigm to be overcome by astrobiology, explicitly highlighting the necessary attention to anomalies, astrobiologists' unpacking of the microbial black-boxes is indeed partial, as they continue to capitalize on the assumptions embedded in most of the black-boxes they require for other practical needs, for example publishing papers with data obtained in the laboratory (with all its "traditional" techniques), elaborating experiments and measurements, and seeking collaborations with microbiologists, synthetic biologists and so on. The adoption of one or more repertoires should not be considered as a finished action, but understood as a fluid and revisable process. Researchers can and do shift between different approaches and models of work (Ankeny and Leonelli 2016), depending on circumstances; they can make use of traditional biology's black-boxes, perhaps without even realizing it, but at the same time unpack them and look into their functioning, giving shape to new unknowns and deploying them strategically. It is this contextual and always situated assessment of what can and should be taken for granted that the agreement on what is known, unknown and knowable is instrumental to the endorsement of new spheres of inquiry. If successfully negotiated, these newly created knowledge gaps contribute to the positioning of emerging fields of research within the larger scientific community. I thus advocate paying closer attention to the contingent, active, performative and always social nature of the making of what is unknown. Unknowns are not a negative and unavoidable aspect of scientific research. On the contrary, they are fundamental resources actively shaped and mobilized in discourse and practice and thus provide insight into the continuities and discontinuities inherent in scientific change.

Future research direction

Like every more or less accomplished piece of research, this thesis has tried to answer a few questions but, as a consequence, has opened many more whose answers are yet to come. Below I present a brief outline of potential research projects:

1. Talking to astrobiologists, I often tended to view space exploration as a science-driven enterprise. I realized, nevertheless, that science is only the tip of the iceberg, perhaps the most well-known and talked about because of its appeal to the lay public. Nevertheless, up to the present, the prevalent human presence in space has a commercial nature, and it will further move in that direction in the future. I would like to explore a sector in which a multiplicity of actors are involved, such as space traffic management and orbital junk tracking. Researchers, producers, politicians, launchers, policy makers, industries, ground radar facilities, the military and so on are all shaping the technological and political order of the outside-Earth, where outer space and biosphere do not simply interface, but overlap.

2. Another theme that I would be interested in exploring further is how fieldwork practices inform the design and operation of remote sensing instruments. Janet Vertesi's

work has shown the role of the camera instruments for both doing science and making assessments about how to safely drive a rover on Mars. Visual data, however, are only a small part of all the data that a rover collects, and a small portion of its "remote sensing" capabilities. Each rover carries a number of instruments that complement each other in the scouting of the surrounding landscape. The rover, the engineers that operate it from the control room and the extended network of scientists who designed the instruments and who will read and interpret the data once available, are part of a distributed cognitive system that is not only technologically, but also socially, informed. The study of analogue fieldsites on Earth inform this network and the decision making processes it continually sustains. I would be interested in exploring how analogies are shaped and move along this long process and what role they play in the design and operation of remote sensing instruments and practices.

3. The last theme that I would like to mention among the possible directions for further research is the set of relations of power that drive the landing site selection process. Before a mission is launched, scientists are allowed to propose the landing sites they consider valuable. Each landing site has to conform to both engineering and science needs (which are usually very different, if not opposed: engineers require a landing site to be "safe"; for a geologist, on the contrary, a flat and safe surface might be not very interesting). Each group proposing a site must demonstrate that their suggestion is the most suitable, and thus fight what might be deemed a battle for epistemic power.

Epilogue – writing the body of the *other*

I am almost at the end of my thesis-writing, and my desk looks like a small bookshop after an earthquake. Books, papers and scribbled notes are scattered all over the place. A few days ago, an old essay by Michel de Certau, a French Jesuit who wrote about ethnography and historiography in particular, crossed my path. The text begins with a description of a Jan Van der Straet illustration of Amerigo Vespucci's arrival in the New World and his first encounter with the Indian "America":

Figure 14. Jan Van der Straet. Allegory of America. Image from wikicommons.

> Amerigo Vespucci the voyager arrives from the sea. A crusader standing erect, his body in armour, he bears the European weapons of meaning. Behind him are the vessels that will bring back to the European West the spoils of a paradise. Before him is the Indian "America," a nude woman reclining in her hammock, an unnamed presence of difference, a body which awakens within a space of exotic fauna and flora. An inaugural scene: after a moment of stupor, on this threshold dotted with colonnades of trees, the conqueror will write the body of the other and trace there his own history. (Michel de Certeau, *The Writing of History*: xxv-xxvi).

De Certeau interrogates the representation of the power relations inscribed in the two bodies, and in the modalities in which the encounter with "the other", the "alien", presupposes an encounter between the bodies on which these relations are inscribed. Because notions of frontier, exploration and colonization are all metaphors that have been largely used to describe scientific and industrial enterprises in space, one might extend the analogy to its extreme and ask: what is the "body of the other" in astrobiology? What kind of power relations are inscribed (or perhaps inscribable not fully inscribed yet) on these different kinds of encounters?

Each chapter of this thesis has drawn the contours of various kinds of life, which overlap and contrast with other narratives. For example, the exploration of space, the exploitation of its resources and settlement establishment – possibilities that are not necessarily compatible – are aligned and joined together when seen through the lens of caves and mines as analogue field sites. Finding life on Mars and establishing a human presence on it (either as scientific outposts or long-term settlement) are often thought of as incompatible tasks, since the economic profitability and colonization of space as an exercise of political power is at odds with the ethical concerns about these environments. Other examples show different embodiments of power, from Elon Musk's dummy astronaut launched into space by his company's rocket prototype and riding his red Cabriolet to *infinity and beyond*, to the feminine (almost Gaian) vocabulary with which exoplanets are described and the gendered gestures with which they are addressed (Messeri 2017). Alien life is never abstract, but material, embodied. The alien "body" comes in different flavours (planetary bodies, microbial bodies with different properties etc.), but in its materiality, together with the materiality of the researcher and all her technological apparatus, new power relations are shaped and inscribed. It is in the making of astrobiology that new connections are built or discarded. Michel de Certeau wonders what the writing of history – and the positioning of the other in a historical sequence – does. He claims that historical writing is a form of *poiesis*; it transforms "otherness" into "differences" and produces an order. The same happens in astrobiology: the study and description of the way aliens might look does not simply tell us something about our identity, but also changes both self and other, identity and difference, and inscribes human relations and possibilities on not-yet-discovered lifeforms. It produces a possible order of the world – a scientific cosmology in which humans, non-humans and non-Earthlings need a reciprocal repositioning – and unfolds new possibilities within that world. Exploring astrobiology and astrobiologists' practices, which make and remake the relationship between Earth and outer space, Earthly and alien, urges a deeper attentiveness to the other knowledge and non-knowledge-making practices that are today shaping our cosmos. It is at their intersections that possible alternative futures will unfold.

Appendix I – project leaflet

Institute for the Study of Science,
Technology and Innovaton
The University of Edinburgh

Valentna Marcheselli
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Supervisors: Dr. Jane Calvert
Jane.Calvert@ed.ac.uk
Dr. Alice Street
Alice.Street@ed.ac.uk

PhD project - Are we alone in the Universe?
An ethnographic study of the emergence of life *as-we-don't-know-it*

Dear All,

You have been invited to participate in a research project, and this letter will help you to understand the purpose of the research, who is undertaking the research, and what being a part of the research would involve. You should read the information carefully before deciding whether to participate. If something is not clear or you have other questions, please feel free to ask.

<u>Who will be doing the research?</u>
My name is Valentina Marcheselli and I am a PhD student in Science and Technology Studies (STS) at the University of Edinburgh. My supervisors are Dr. Jane Calvert and Dr. Alice Street.
The aim of STS research is to find out how science and society mutually shape each other.

<u>What is the research about?</u>
I'm currently looking at how astrobiology and SETI (Search for Extraterrestrial Intelligence) produce new scientific knowledge about life forms and life processes. I'm interested in how these interdisciplinary fields are organized, institutionalized and how they develop through time. I am also looking at how these fields articulate the concept of life and how they define life while looking for it.

<u>What would it involve?</u>
Taking part would involve an interview with you on your work. With your permission, an audio recording of the discussion would be made, so that I could have an accurate record.

<u>How will the research be used?</u>
The research will be used to produce a PhD thesis that will be publically available from the University of Edinburgh library. The research findings may also be disseminated to academic and other audiences, for example in journal articles or conference presentations.

<u>What happens next?</u>
If you would be interested in taking part, please carefully read the consent form below. Having read this information, if you now have any further questions please feel free to contact me, by email at V.Marcheselli@sms.ed.ac.uk or by post at the address listed above.

Thank you very much for taking the time to read this information and consider taking part.

Appendix II – consent for interview

Institute for the Study of
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Technology and Innovaton
The University of Edinburgh

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Supervisors: Dr. Jane Calvert
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Dr. Alice Street
Alice.Street@ed.ac.uk

Plaese tick the appropriate boxes	Yes	No
<u>Taking part</u>		
I have been given the opportunity to ask questions about the research	☐	☐
I agree to take part in the research. Taking part in the research will include being interviewed and audio recorded	☐	☐
I understand that my taking part is voluntary; I can withdraw from the study at any time and I do not have to give any reasons for why I no longer want to take part	☐	☐
<u>Use of the information I provide for this project only</u>		
I understand my personal details will not be revealed to people outside the research	☐	☐
I understand that my words may be quoted in publications, reports, web pages, and other research outputs	☐	☐
Please choose one of the following two options:		
I would like my real name used in the above	☐	
I would not like my real name to be used in the above	☐	

____________________	____________________	____________________
Name of participant	Signature	Date
____________________	____________________	____________________
Researcher	Signature	Date

Appendix III - Interview questions template

Personal experience

How did you get interested in astrobiology/SETI? (any anecdote? Any particular memory? What do you say to young people that want to start a career in astrobiology/SETI?)

What's your academic background?

What is "astrobiology"/"SETI"?

What kind of work do you do in the field of astrobiology/SETI?

Research activities

What kind of facilities do you use for your research?

Where are they located (in which department, for example)?

How many people work there? Do they all work in astrobiology/SETI related projects? (and if not, how do other scientists think about astrobiology/SETI? How do you relate with them?)

To what extent does your research involve people coming from different disciplines?

What kind of living organisms do you handle in your lab?

What makes them a good fit for astrobiology?

What are you trying to explain/challenge/account for?

If you had to design a space mission/experiment to find living beings, what would it look like?

Pros and cons

What would a "relevant achievement" in your field look like?

Have you ever taken part in a field trip?

Where did you go?

Who else was part of the group?

What was your goal?

What are you trying to explain/challenge/account for?

Did this change your attitude toward the possible existence of life elsewhere in the universe? How?

What is life? Does this question make sense for you? How else would you phrase it?

Is there anything else you'd like to add?

Appendix IV – List of interviewees

	Date	home institution	career stage	specific field
1	13/11/2013	UKCA University of Edinburgh	professor	astrobiology
2	03/02/2015	UKCA - University of Edinburgh	PhD student	astrobiology and geomicrobiology
3	04/02/2015	ROE - University of Edinburgh	postdoctoral fellow	astronomy - exoplanetary detection
4	12/02/2015	UKCA - University of Edinburgh	PhD student	astrobiology
5	12/02/2015	UKCA - University of Edinburgh	PhD student	astrobiology and microbiology
6	20/03/2015	University of Edinburgh and NASA Jet propulsion Lab	undergraduate student	evolutionary biology
7	02/04/2015	University of Bologna	research scientist	geomicrobiology
8	08/05/2015	UKCA - University of Edinburgh	PhD student	astrobiology
9	21/06/2015	University of Arizona - Vatican Observatory	professor	planetary science
10	07/07/2015	UKCA - University of Edinburgh	postdoctoral fellow	biologist
11	09/07/2015	UKCA - University of Edinburgh	postdoctoral fellow	microbial molecular biology - astrobiology
12	21/07/2015	University of Stirling	senior lecturer	physics and environmental sciences
13	22/07/2015	UKCA - University of Edinburgh	postdoc scientist	astrobiology - mars analogues
14	22/07/2015	ROE - University of Edinburgh	reader	astronomy - exoplanetary detection

15	23/07/2015	University of St. Andrews	lecturer	geomicrobiology
16	23/07/2015	ROE - University of Edinburgh	postdoctoral fellow	astronomy
17	23/07/2015	University of St. Andrews	research fellow	astronomy
18	23/07/2015	University of St. Andrews	reader	paleogeology
19	23/07/2015	University of St. Andrews	senior lecturer	geology and planetary science
20	26/07/2015	INAF - IRA	senior scientist	engineer
21	30/09/2015	SETI Institute	senior research scientist	biology - planetary protection
22	09/10/2015	NASA Ames Research Center	senior researcher	planetary science, Mars analogues
23	19/10/2015	NASA Ames Research Center	senior scientists, journal editor in chief	astrobiology
24	20/10/2015	SETI Institute	research scientist	environmental sciences
25	20/10/2015	NASA Ames Research Center - Standford	senior scientists, professor	astrobiology and synthetic biology
26	21/10/2015	NASA Ames Research Center	research scientist	microbiologist
27	26/10/2015	SETI Institute	research scientist	marine biology and geophysics
28	25/11/2015	SETI Research Center - UC Berkeley	research scientist	computer science
29	04/12/2015	SETI Institute	senior scientist	astronomy
30	12/01/2016	SETI Institute	senior scientist	astrobiology
31	08/02/2016	Arizona State University	professor (team member for the Mars Exploration Rover mission)	geobiology
32	08/02/2016	Arizona State University	Co-investigator NExSS team	evolutionary microbiology

33	08/02/2016	Arizona State University	professor, writer	astrobiology and cosmology
34	09/02/2016	Arizona State University	professor	physics
35	11/02/2016	Arizona State University	professor	astrobiology and theoretical physics
36	12/02/2016	Arizona State University	PhD student	engineering and biology
37	16/02/2016	SETI Institute	enterpreneur	
38	18/02/2016	SETI Research Center - UC Berkeley	research scientist	radio astronomy
39	22/02/2016	SETI Institute	senior scientist	planetary scientist - exploration and simulation
40	24/02/2016	SETI Research Center - UC Berkeley	project scientist	radio astronomy
41	24/02/2016	SETI Research Center - UC Berkeley	PhD student	astronomy
42	25/02/2016	NASA Ames Research Center	research scientist	biochemistry
43	29/02/2016	University of California	professor emeritus	astronomy
44	07/07/2016	Yale University	postdoctoral research fellow	geobiology
45	08/07/2016	Cranfield University	professor	space biotechnology
46	08/07/2016	NASA Ames Research Center	principal investigator	planetary science
47	08/07/2016	NASA Goddard Space Flight Center	research scientist	planetary simulations

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Figures

Figure 10. Representation of TRAPPIST-1 planetary system. Credits: NASA/JPL-Caltech. February 2018.

Figure 11. Cover of Nature 542, 23 February 2017. Image credits NASA/JPL-Caltech

Figure 12 Trappist 1e travel poster. Image credits: NASA/JPL, available at https://www.jpl.nasa.gov/visions-of-the-future/

Figure 13 Pascal Lee, Mars Mobility Systems, (Acrylic on board, 9 x 11.5 inches, 2004), available at www.pascallee.net/artwork/