Money for the Big Eyes

by

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ABSTRACT

Since ancient civilization, humanity has kept its eyes on the heavens, and the invention of telescopes has only increased its scrutiny. As astronomers strive to see the universe with increasing clarity, telescopes have been getting bigger, better, and more expensive. The astronomy community is currently preparing for the next generation of ground-based optical telescopes: giant behemoths that will have mirrors of over twenty meters in diameter, set atop of high, dark mountains. Technological advancements have finally made it possible to create telescopes this large, and they will be able to view the skies ten times more sharply than the Hubble Space Telescope. Once completed in a decade or so, these telescopes will shine light on our most pressing questions in astronomy.

However, with price tags of around a billion dollars each, raising the money to build them is a challenge. This thesis explores the technology behind the extremely large telescopes and the politics behind their funding. Telescope research began as private ventures, the Medici family's patronage of Galileo being a famous historical example. Today, the story is not so simple, involving public governments, international collaborations, and endless fundraising. While over a dozen different extremely large telescopes have been proposed in the last two decades, only three remain as viable ventures: the Giant Magellan Telescope, the Thirty Meter Telescope, and the European Extremely Large Telescope. This thesis recounts their unfinished story.

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The Tell-Tale Cookies

The cookies at the reception were a tell-tale sign that the afternoon's MIT physics colloquium was something special. It was a well-accepted fact that those cookies were always and disappointingly crisp and hard. This week, however, they were chewy and soft.

"Are the cookies different because of the speaker?" a grad student asked after biting into a chocolate chip one.

There was indeed a rock star visitor that day: Adam Riess, an alumnus from 1992 and an astrophysicist from Johns Hopkins University. MIT's physics community was abuzz about his public colloquium that afternoon. People began filing into the 425-seat colloquium lecture hall more than half an hour early. A few minutes before the lecture, the only seats that remained were a smattering in the first two rows, and they were clearly labeled as "RESERVED." The unluckier audience members were left to stand in the back or sit in the aisles.

Adam Riess had long been scheduled to speak at MIT, but less than three weeks before his colloquium, he was announced as a recipient of 2011 Nobel Prize in Physics. If his colloquium were three weeks prior, he may still have had a respectably-sized audience, but the room would not have been nearly as packed, nor would the reception's cookies have been nearly as good.

Riess spoke mostly about his Nobel-winning discovery during his lecture. "I'm going to give a talk today on how observations of exploding stars thirteen years ago revealed that we live in a universe that is accelerating now in its expansion," he said, "propelled by this mysterious stuff called dark energy that we really do not understand."

Riess, Brian Schmidt, and Saul Perlmutter were awarded the Nobel for discovering that the universe seemed to be defying gravity: the universe's expansion was not slowing down from gravitational attraction, but accelerating! The hints leading to the discovery were found in remote supernova bursts—the exploding stars Riess mentioned. The bursts were clearly more distant than expected, meaning that the universe has expanded more rapidly than we predicted, sweeping faraway stars (and their bursts) even further away.

Scientists could only explain this accelerating expansion with dark energy, a mysterious, permeating energy that causes gravity to become repulsive at the grand scale of the universe. The snag with dark energy, however, is that scientists remain flummoxed of what it actually is. Still, Riess, Schmidt, and Perlmutter were awarded the Nobel Prize for "merely" discovering it!

Riess ended his presentation to long applause. After the last few claps faded away, the floor opened for questions.

A woman with straight, dark hair raised her hand from the left-front section. "I was wondering when you're finished," she said. "You gave us several things that will be next, but when does this question of understanding the acceleration of the universe via astronomy—when's it over?"

"Right, uh..." began Riess. This woman wasn't just any audience member. She was Sara Seager, a leading exoplanet astronomer at MIT. "Sara asked when will we be done," Riess continued, repeating her question to the audience. "I should say that Sara works on exoplanets, so I think she's eager for us to get done, because they want to use the other time on the telescope, right?"

Immediately, the audience broke out in chuckles.

To astronomers like Riess and Seager, every available minute of a year's 365 nights is coveted, and those minutes are not cheap. Telescopes are expensive to construct and operate. Those costs are shouldered by the institutes that pay, in cash or services, for observation time for their astronomers. These costs have grown as astronomers build successively more ambitious observatories for scrutinizing the skies. For instance, Yale ponied up $12 million in 2008 for 150 nights of observation spread over a decade at the

Keck Observatory in Hawaii. At $80,000 a night, it is an expensive gig.

Ground-based optical telescopes, which are designed to view visible and infrared wavelengths from the Earth's surface, have come a long way since Galileo discovered Jupiter's moons in 1610. The progression of telescope technology is apparent not just looking at its overall size, but also at apertures, the part of the telescope that collects starlight, usually a mirror or lens. The apertures have been getting bigger, as bigger apertures collect more starlight and thus produce the better pictures and data that astronomers crave.

The scope Galileo used to spot Io, Europa, Ganymede, and Callisto had a 0.6-inch aperture. Three centuries later, telescopes grew to giant sizes. By that time, telescopes had grown so large that lenses were shunned for mirrors as apertures. Forty-inch lenses were the practical limit, held back by optical difficulties that prevented successful lenses from being cast. In 1908, the "60-inch-mirror telescope" saw its first stars at the Mount Wilson Observatory in California. Ten years later at the same observatory, the "100-inch telescope" also went into operation. Both telescopes dwarfed their human operators.

In the latest wave of optical telescope construction, mirrors of six to ten meters were placed on mountains, for use in telescopes like the Large Binocular Telescope, the Large Zenith Telescope, the Southern African Large Telescope, and the Very Large Telescope.

Today, astronomers are betting on another round of skyward tools, bigger, better, and more expensive than ever before. These telescopes are known, ever-so-creatively, as the extremely large telescopes.

But bigger comes with a price.

Let the Race Begin

There is a mischievous twinkle in Paul Schechter's eyes as he reaches from the floor and pulls up a box, big enough to fit a large loaf of bread. According to the label, it contains a small amateur telescope. Schechter places it on the table in front of him and says, "That's a smaller telescope!" before laughing at his own joke and apologizing.

Schechter, an astrophysicist at MIT, had just been asked about astronomy projects that are smaller and more affordable than the trend of "large" telescopes and the even larger "extremely large" telescopes. The small boxed telescope, fit for the backyard, is his response-in-jest.

He is more serious in his actual answer: "There's a telescope called the OGLE telescope. It's a 1.3-meter telescope, and those guys have done fantastically good stuff by choosing their problems very, very carefully, even though they don't have the light-gathering power of bigger telescopes." Then he adds with another laugh, "It's possible to do great science with smaller telescopes, but it's much easier with big telescopes!"

OGLE, which stands for Optical Gravitational Lensing Experiment, is not short of stellar achievements, including contributing data that revealed that our galaxy contains billions of exoplanets. However, its ability is definitely limited: OGLE astronomers mostly ogle at the Milky Way and the Magellanic clusters (two satellite galaxies of the Milky Way), a move calculated to take advantage of those regions' abundances of close-by and closely-spaced stars.

Logically, astronomers would not mind having telescopes with more power and flexibility. After all, they have a lot of questions.

Once the trend of six to ten meter telescopes became well-established in the 1990s, proposals for the extremely large telescopes, or ELTs, began popping up, each boasting designs with aperture widths on the order of twenty, thirty, fifty, and even a hundred meters. Emails were exchanged, phone calls were made, conferences were held, and ideas flew. "I think I once counted eighteen different sorts of future giant telescope proposals that were out there," says Larry Stepp, an engineer who has worked on ELT designs for over a decade. "And over time, these began to coalesce into more real projects."

The ELTs hold a lot of promise: they will be able to collect images more quickly than their existing counterparts, and look into more distant reaches of the universe. Their images will be ten times sharper than that of the Hubble Space Telescope, despite being on the ground rather than in space. Their sheer sizes make them too big to launch into orbit, but there are clever technological workarounds that negate the atmospheric turbulence that would otherwise muddle the view of the sky. Armed with an ELT, one could easily spot a truck on the moon, though of course, scientists would use the instruments for research far more ambitious. These telescopes, once built, promise astronomical delights, such as snapping pictures of exoplanets, studying the universe's very first stars, exploring the physics of black holes, and investigating the natures of dark energy and dark matter—the most pressing questions in astronomy today.

In 2000, the first stars were seen through the first of the two 6.5-meter Magellan Telescopes on the dark Chilean mountain of Las Campanas, Two years later, the second one followed suit, but even before then the collaborators of the Magellan Consortium, a group of five universities and institutions, were thinking ahead. A small but core group of people involved in the Magellan telescopes had some questions in mind: What's next? Would they be satisfied with these twin 6.5-meter telescopes in ten, fifteen, twenty years?

The answer was no.

Following the trend toward bigger and better, the consortium began planning an extremely large telescope dubbed the Giant Magellan Telescope. Meanwhile, Caltech and the University of California, emboldened by their success with the 10-meter Keck Telescopes, had already begun developing what became the Thirty Meter Telescope. The United States' national observatory also had plans for a next-generation telescope, the

Giant Segmented Mirror Telescope. The rest of the world was planning too: there were Canada's Very Large Optical Telescope, Japan's Japanese Extremely Large Telescope, the Canada-France-Hawaii coalition's Large Petal Telescope, and Europe's Euro50 and Overwhelmingly Large Telescope, just to name a few. All of them were aiming for at least 20-meter mirrors for their apertures, and the Overwhelmingly Large Telescope was aiming for an overwhelming 100 meters.

One by one, they all ran into the same problem: raising enough money. Proposing a next-generation telescope is one matter. Securing its funding is another matter.

Most of the proposed telescopes are no longer on the table due to that financial hurdle, but from them emerged three projects that can still succeed. They are the 24.5-meter Giant Magellan Telescope, GMT; the 30-meter Thirty Meter Telescope, TMT; and the 39.3-meter European Extremely Large Telescope, E-ELT. These three projects are all chasing the astronomical dream of completing their complex designs, a dream that needs collaborators, supporters, and—most of all—money.

Two years ago, three big figures in telescope development racked up one of the most lucrative awards in science: the Kavli Prize. One million dollars were split between Jerry Nelson for his work on segmented mirrors, Roger Angel for his work on large lightweight honeycomb mirrors, and Raymond Wilson for his work on mirror correction techniques. Without the work of Nelson, Angel, and Wilson, today's extremely large telescope designs would be very different, even nonexistent.

The three men are each affiliated with a specific telescope: Nelson holds the title of Project Scientist for TMT; Angel is the Scientific Director of the Steward Observatory Mirror Lab, which casts mirrors for GMT; and Wilson worked for the European Southern Observatory, which is planning the E-ELT. This particular three-way split is undoubtedly intentional. The TMT, GMT, and E-ELT are being developed on parallel paths and are often labeled as "competing" telescopes.

In some sense, they are competitors. They are competing over the same talent, trying to hire the best scientists and engineers from completed telescope projects, like Keck and Magellan. They are competing over project collaborators, be it universities, institutions, or countries. They are competing over the same money too; the Kavli Prize's one million dollars is just spare change to the experiments. And once built, they will compete over being first in breakthrough discoveries.

But they are also working towards the same goal: finishing the next generation of telescopes. They want to see each other succeed. After all, every minute on one of those telescopes will be precious for astronomers. Valuable observation time would be lost if one or more of those telescopes were never finished.

Feeling the Heat

Pat McCarthy is a man who walks fast, talks fast. He is an astronomer by training, but now he is the director of the GMTO Corporation, which is dedicated to building the GMT. He estimates his telescope will cost $700 million to construct, around four times more than the cost of today's best telescopes. His fast-paced demeanor matches his position; he is a man who has a lot to get done and gets a lot done.

His office at the GMTO Corporation is sparse, unsurprising given that he and the entire office recently moved to a new building in Pasadena, California. The only prominent decoration is an old brass telescope displayed on a small table. He found it in an antique shop for $300, he says. A bargain, really.

McCarthy's shelves are far from full, but tucked away on one is another decoration: a small paper-and-foam model of the Giant Magellan Telescope, the size of a soccer ball. Most prominent are its seven shiny circles, six arranged around a central one, all angled up from lying flat. The circles represent the telescope's primary mirror, and together, they will serve as the telescope's eye, its collector of starlight.

The actual mirrors will be far larger: each will sport 8.4-meter diameters, about the length of a bus. They will be made of glass and coated with a thin layer of reflective metal, thinner than the width of a human hair. The six outer mirrors (plus a seventh spare) will be radially asymmetric but identical to each other, and together with the eighth central mirror, they will collectively form a symmetrical concave surface that will gather starlight.

The GMT will be the first telescope to combine multiple giant mirrors together, and each will need to be ground to precisely perfect yet asymmetrical shapes. It's not easy to make mirrors like these, but Roger Angel, one of the Kavli Prize winners, figured out how.

On January 14, 2012, the second mirror of the Giant Magellan Telescope was cast in a giant oven at the Steward Observatory Mirror Lab, a high-ceilinged space located underneath the east wing of the University of Arizona's football stadium.

Chunks of glossy borosilicate glass, shipped in from Japan, are inspected by hand for imperfections. This mirror has to be perfect, and the twenty tons of glass that would be melted into the mirror have to be perfect too. The chunks that made the cut are neatly laid on top of a mold in a specific, predetermined pattern. The mold has its own special pattern too: blue-tinged indents outline a honeycomb lattice. Earlier, workers had painstakingly arranged over 1,600 hexagonal columns into the large oven to create the mold.

The oven, painted bright red and in the shape of a very squat cable-clad cylinder, resembles a rotor from an amusement park. It is big enough to accommodate the 8.4-meter mirror, yet it is still able to spin four revolutions per minute. When casting begins, the oven is lidded and sealed off, and it bakes the glass to 1,165 degrees Celsius, or about 2,100 degrees Fahrenheit, spinning all the while. The glass melts; it is hotter than lava and has the consistency of honey. As the oven spins, molten glass slowly oozes into the crevices of the mold and the upper surface smooths out. The glass is thicker towards the edge due the oven's rotation; the mirror makers planned this deliberately: concave, not flat, mirrors are used to gather starlight.

Those gathered in the lab to see the mirror casting begin can feel heat radiating from the oven as it twirls and whirls.

This high heating continues for a week, and then the three-month cooling phase begins. The Mirror Lab carefully controls the cool-down: once the glass stiffens into a solid, the spinning speed is lowered as well. The casting process is long and slow. The mirror's concave shape trumps all other needs, and only a slow cooling can be performed without compromising the mirror. Cool the mirror too quickly, and it could crack or deform.

The lab, while large, is not enormous. There is room to tinker with perhaps three mirrors in an assembly line. While the second mirror for the GMT begins its casting, the first already-cast mirror is also out in the lab, but for polishing. The distinct honeycomb pattern runs underneath the ice rink-like surface of the cast glass; its mold had already been removed with a high pressure water spray. While the second mirror's oven spins, a precision polishing machine grinds the first mirror into a precise, nearly-flat but still concave shape. The accuracy is within a millionth of an inch, so that when the glass is coated with reflective metal, the mirror will bounce starlight perfectly.

Precision is the name of the game at the Steward Observatory Mirror Lab, but its origins are littered with kitchenware.

British-born Roger Angel, founder of the Steward Observatory Mirror Lab, was already settled in Arizona when he began experimenting with a home-made kiln in his backyard in the name of telescope engineering. After hacking together the kiln with bricks and an electric heater coil, he began melting glass—first from fluorescent light tubes and then from Pyrex cups.

It was 1980 when Angel began investigating the idea of making lightweight mirrors with a hollow honeycomb base, albeit from his backyard. As his family began noticing the disappearance of the kitchen's glassware, Angel soon moved his experimentation to the University of Arizona, where he and a graduate student began toying with borosilicate glass instead.

Five years later, with an expanded team and a prototype oven in an abandoned Jewish temple, Angel's group completed a 1.8-meter mirror for their first big customer: the Vatican Observatory. The telescope, called the Vatican Advanced Technology Telescope, to be jointly operated with the University of Arizona, gained the nickname "Pope scope."

In 1992, another milestone was achieved: Angel's lab, which had now been completely moved underneath the university's football stadium, succeeded in casting a 6.5-meter mirror for the Multiple Mirror Telescope. Until Angel perfected the honeycomb pattern, it was impossible to make mirrors larger than six meters; any larger and they would droop under their weight. So back in 1980, when Angel told the Steward Observatory director that he wanted to make 8-meter mirrors, the director nearly laughed. Seventeen years later, Angel's mirror lab succeeded in casting an 8.4-meter mirror for the Large Binocular Telescope Observatory in Arizona.

The trademark of Angel's mirrors is the molded honeycomb design, which imparts several important properties. Each GMT mirror, for instance, will be able to float on water despite weighing about twenty tons. The mirrors are hollow and airy, reducing weight by a factor of five to seven and slashing density without compromising strength; lab technicians can walk on the Angel's rigid mirrors without fear of ruining them. Moreover, the hollow design also reduces the glass's susceptibility to warping from temperature change between daytime and nighttime. Just as misshapen eyeballs cause our vision to blur, a misshapen mirror causes the view of the heavens to blur. And above all, the mirror won't sag under its own weight.

Mirrors of 8.4-meter diameters are currently the limit of the Steward Observatory Mirror Lab. In order to create the desired 24.5-meter aperture of the Giant Magellan Telescope, astronomers and engineers plan to put together seven smaller (but still large) 8.4-meter pieces—an ambitious, never-before-attempted idea.

It was a gamble when the Giant Magellan Telescope team began casting the project's first mirror in July 2005. There was barely enough money for just that single mirror, but they knew—they hoped—that more money would come in after the first mirror's success.

Six and a half years passed before the second mirror was cast, during which money was raised and casting contracts were negotiated with the Steward Observatory Mirror Laboratory. The remaining six mirrors, McCarthy promises, will shortly follow at a rate of about one a year. The third mirror is already scheduled for a 2013 casting. After all, the GMTO Corporation is working on a deadline. They are aiming for a 2021 completion date, and nine more years is not a lot of time to finish fundraising and constructing this complex and ambitious telescope.

Mirrors on the Mountains

Painted on a patch of asphalt in Pasadena, California, are seven large white outlines of circles, arranged like a flower. Here, in the parking lot of the Carnegie Observatories, one of the GMT collaborators, people can walk, bike, drive over, and be dwarfed by a to-scale representation of the telescope's mirrors.

Adjacent is the Observatories' lab space, where Carnegie scientists and engineers are perfecting designs for the Giant Magellan Telescope. One of the more peculiar-looking sections of the lab contains what looks like a tall and unnaturally sturdy cardboard box, propping up a couple pieces of plywood with a grid of white PVC pipes poking through. Blue painter's tape covers some of the pipe openings. This odd arrangement is part of a mirror ventilation test for the GMT.

The GMT mirrors will always be at the mercy of warping under temperature fluctuations. While the airy honeycomb design will help decrease warping, GMT engineers will add an extra degree of temperature control with a system that will blow cooled air to the mirrors. The laboratory's mockup of piping, tape, plywood, and also a fan tests air flow rates. When the telescope is finally built, 1,800 nozzles and 45 fans will be fitted to each giant mirror to keep it cool and consistent.

While most of the Observatory's laboratory is sparsely decorated, a wooden relief sculpture hangs near the drop ceiling above the ventilation test box. It is a map of the Las Campanas Observatory, says Jeff Crane, a Carnegie staff associate. Several peaks are apparent in this model of a mountain ridge in Chile's southern Atacama Desert. Pins and small strips of paper mark important locations, including the twin Magellan telescopes and the OGLE telescope. The left side of the map contains more paper strips and pins, but Crane points out the lone peak to the right, marked with a small pinned strip of paper.

That spot is for the Giant Magellan Telescope. It stands over a mile and a half above sea level.

On the map, a road winds from one existing observatory to another, stretching across the empty mountain ridge, until it finally reaches the final peak of Cerro Las Campanas. There is not much else along that path, but somebody had the foresight, Crane says, to build a road to that peak, years before there were even plans for a Giant Magellan Telescope. Now, the peak needs to be primed for its future occupant.

Groundbreaking for the GMT begins with a bang: a large cloud of brown-yellow debris launches into the air, accompanied by several jetting plumes of red, white, and blue. Earlier this March, the first of over seventy controlled blasts at Las Campanas was kicked off with flying colors. The director of the Las Campanas Observatory had arranged for the colorful surprise, representing the flag colors of the four countries involved in the Giant Magellan Telescope: United States, Australia, South Korea, and Chile.

The blasts, performed over the span of several months, will level the mountaintop in preparation for observatory construction, lowering the elevation by as much as thirty feet in some spots.

"Just to level the site, to have a place to actually work and build the telescope, requires moving quite a lot of rock," says McCarthy. "It's a big deal, because you need a pretty big area for a telescope this size, and mountaintops are peaked, so you have to remove some material and redistribute." By the end of site construction, some four million cubic feet of mountain rock will have been moved.

While the GMT partners based their site selection on a four-year survey of locations, the decision to choose Chile's Cerro Las Campanas was a natural one. The Carnegie Observatories have operated there since the 1971 completion of the Swope Telescope and understood the site well. The GMT's "predecessors," the Magellan Telescopes, were also on Las Campanas. Moreover, the mountain's observation conditions are pristine: there is little light pollution, and year-round clear skies allow for a reliably clean view of the stars.

High, remote mountains are ideal for ground-based telescopes. As little atmosphere as possible is in the way between telescopes and the stars. The only clearer way to view the heavens would be from space, and it will be a long time, if ever, before a telescope of the "extremely large" caliber is sent into orbit. The engineering involved would be overwhelming. Even the $8 billion plus James Webb Space Telescope, the Hubble Space

Telescope's successor that is planned for a 2018 launch, requires complex engineering to send its 6.5-meter primary mirror into space: the primary mirror's segments will be folded at launch, and once the telescope is in its orbit position, the mirror segments will unfold like a flower. Such a feat is currently unimaginable for mirrors of an extremely large telescope on a technical level and a pocketbook level.

The Thirty Meter Telescope and the European Extremely Large Telescope will also take advantage of crisp mountaintop conditions. The E-ELT will be over 300 miles away on another Chilean mountain, Cerro Armazones. The TMT, on the other hand, will be built in the northern hemisphere on the volcanic mountain of Mauna Kea in Hawaii, not too far away from its predecessors, the Keck Telescopes. Viewing forecast: virtually always clear.

Pieces of a Puzzle

A few years before Roger Angel started experimenting with glass in his backyard kiln, Californian astronomer Jerry Nelson was invited to a committee tasked with designing a 10-meter telescope. Nelson accepted the invitation and its challenge. He knew that scaling up was not the answer. At the time, the telescope with the largest aperture was a 6-meter one in the U.S.S.R., and cost plus technical issues prevented apertures from going any larger. A 10-meter telescope would have been a $1 billion project, and then there was still the weighty problem of sagging glass.

By 1977 Nelson began toying with the idea of breaking up a 10-meter mirror into smaller, lightweight parts. Like Angel, he settled on a design with a honeycomb geometry, but with a very different approach: Nelson proposed arranging hexagonally-cut mirrors to form a telescope's primary mirror. Actuators and sensors would control the movements of the mirror segments so that they would act in concert, and the mirror segments would be ground asymmetrically so that they would form a symmetrical concave surface, like pieces of a puzzle.

Two years passed before his idea was taken seriously by the telescope community, and more than a decade later, the first segmented mirror telescope was completed in 1992 with 36 segments. This telescope was Keck I, the first telescope built at Caltech and the University of California's Keck Observatory. Keck I broke the record for aperture size at ten meters. Until then, the telescope with the largest aperture was still the 6-meter Soviet telescope completed over fifteen years prior. Other telescopes built in the interim hovered around apertures of around three to five meters. It was only until after the 1996 completion of Keck II that astronomers began to complete telescopes with comparable apertures, some of which were also built with the segmented mirror design.

Yet, over two decades after the completion of Keck I, only one telescope, the 10.4-meter Gran Telescopio Canarias in Spain, has exceeded the Kecks in aperture.

The External Factor

Murmurs of the extremely large telescopes began soon after the Kecks were completed, and the University of California and Caltech were in the thick of it. Their idea was to build the California Extremely Large Telescope, or CELT. But unlike its GMT competitor, this proposed 30-meter telescope was envisioned as a mega-version of the 10-meter Keck, containing a thousand or so segments rather than Keck's "mere" 36. Three computer-controlled actuators manage the movements of each mirror in the Keck telescopes, and advances in computer technology made it at last feasible to increase the number of actuators and therefore the number of segments.

When the CELT underwent review in the early 2000s, physicist Gary Sanders was asked to join the review panel. He was impressed. "I thought it was a discovery machine, something that would open a new window" says Sanders. He compares that fascination to his fascination with particle accelerators: as the high energy physics field's discovery machines, they have been smashing particles at higher and higher energies, sometimes increasing by a factor of five or ten. From reviewing the CELT, he saw that this telescope promised similar leaps and bounds in astronomy. Sanders, who had spent the last few decades managing different science projects and programs, was at the time the project manager of another ambitious project at Caltech known as the Laser Interferometer Gravitational Wave Observatory (LIGO).

A few years later, Sanders found himself involved with this telescope once more, except by then it had morphed into the Thirty Meter Telescope project. "I was on the search committee for the project manager," says Sanders, "and the tables got turned on me in the search. I ended up being asked by the committee to take the job!" Sanders considered his situation: his current project, LIGO, was running well, and here was the tempting opportunity to nurture an impressive "discovery machine" to completion. Plus, he adds, "I thought I was at the age where I had one more good big project in me."

Sanders took the job.

By then, Europe was in the game as well. It must have been with some mirth that European researchers initially named their project the Overwhelming Large Telescope—a clear spoof on other telescopes names, in particular the "Large," "Very Large," and "Extremely Large" ones. The OWL, as it was called, had ambitious designs including a 100-meter mirror and a view of the sky forty times sharper than that of the Hubble Space Telescope.

A consortium of fourteen European countries called the European Southern Observatory (ESO) took the OWL under its wing in the 1990s, and by 2004, the telescope had an estimated budget of 1.2 billion euros. The plan was to start observing with

OWL by 2016 or 2017, though the ESO's official OWL website reminded visitors that "A faster schedule would be possible with early funding." The ESO also acknowledged the opposite scenario, albeit humorously: if budgetary constraints forced the OWL to shrink, at least they could change OWL to stand for "Originally Was Larger."

By 2006, the OWL was no more. A panel reviewing a concept study of the telescope deemed its design sound—it was cost-effective and time-efficient for a telescope of its size—but rather expensive and technologically challenging. The telescope was too risky an investment. For perspective, more than four decades had passed between the building of the 5-meter Hale Telescope and the 10-meter Keck I telescope. How many years would be needed to make a tenfold jump from the 10-meter Kecks to the 100-meter OWL? Instead, the panel recommended that the ESO pursue a smaller telescope, and the European Extremely Large Telescope was ushered onto center stage.

The 42-meter E-ELT, though a downgrade from the OWL, would be larger than both the TMT and GMT. The E-ELT project proceeded at brisk pace, spurred along by the work already sank into the OWL as well as the Euro50, a 50-meter concept telescope spearheaded by five European countries, four of which were ESO members.

In the years since the E-ELT's inception, many changes occurred. The ESO decided to build the telescope observatory on the dark Chilean mountain of Cerro Armazones, about three hundred miles away from the GMT's Cerro Las Campanas and thirty miles away from the Paranal Observatory, where ESO's Very Large Telescopes are located. Brazil was welcomed to the project as the pending fifteenth member state of the ESO. The telescope's projected budget crept from 800 million euros to a billion euros. And the 42-meter mirror was shrunk to 39.3 meters to save money. Building a telescope is a financial game too.

On a clear day last October, stacks of large white cardboard hexagons found their way to a sidewalk arching by a grassy field in Garching, Germany. All that cardboard was for the flagship event of Open House Day at the European Southern Observatory's headquarters. Under the late morning sun, the first few dozen cardboard sheets were pegged into the grass around a large blue ESO banner. As the sun crept across the sky, the hexagonal stacks dwindled. Visitors flowed in and out of the grass, clutching cardboard pieces that were as tall if not taller than them. Each piece was laid down to fit the surreptitious outlines in the grass, filling the area like a honeycomb puzzle.

By late afternoon, all 798 pieces were in place, forming a spectacular white circular shape that shone bright under the sun. The three thousand open house visitors all could have stood within the to-scale replica of the E-ELT primary mirror, though of course, everybody would have had to stand rather cozily.

Like the TMT, the E-ELT also adopted a segmented mirror design, a first for the ESO, though the OWL and the Euro50 had segmented plans too. Each E-ELT mirror segment will be 1.45 meters across, about four feet and nine inches. It is a good size for the segments, an optimized compromise between cost and quality. Smaller mirrors in greater numbers might produce a better reflecting surface, but would also put a bigger dent on the budget. The TMT engineers had similar thoughts: they decided their segments are best fixed at 1.44 meters across.

A few months after the open house, ESO engineers began testing the E-ELT's mirror segments in earnest. In a mini mockup, four uncoated segments, bare of their reflective layers, were propped onto and wired into a structure laced with sensors and actuators. The big test: does the mirror design properly counteract external effects from gravity, temperature changes, and wind?

Exacting precision is needed for such behemoth mirrors, and that precision is easily broken. When a telescope mirror changes its tilt angle to aim at a particular patch of sky, gravity's tug is enough to nudge the mirror surface out of shape. Changes of temperature and windy conditions also distort the mirror away from perfection by warping the mirror surface and misaligning the segments. The mirrors of the three extremely large telescopes—GMT, TMT, and E-ELT—all face these issues. Without some sort of intervention, gravity, temperature changes, and wind can defocus the sharp images of stars into blurs.

The deformation issue was perhaps the biggest telescope engineering hurdle in the 1960s and 1970s. Telescope engineers had to rely on sturdy, cleverly shaped mirrors to counter the pulls of external forces, but even the cleverest of designs broke down with large mirror diameters. The era's largest telescope, the Soviet six-meter telescope built in 1976, was firmly the largest, but Western scientists dismissed it as a hulking instrument rather than a top-notch scientific tool—though Cold War rivalries undoubtedly played a large role in such sentiments.

This six-meter mirror was a hefty 42 tons, and astronomers faced a catch-22. If a telescope were to have a larger aperture, the mirror needed to be thicker in addition to have a larger diameter in order to be sturdy enough against external forces. However, this also meant that mirrors larger than six meters would be unacceptably heavy and expensive, and even six meters was bordering on impractical. And so, physicist Raymond Wilson proposed going in the opposite direction: making mirrors thinner.

In 1968, Wilson began developing a technology that would allow mirrors to breach the 6-meter barrier. This technology, called active optics, mechanically corrects deformations. Wilson's insight was to use thin, flexible mirrors that could be pulled and prodded back into their intended shape using an actuator. Every minute or so, before the mirror deforms too much, the actuators correct the mirror shape. The advent of modern electronics allowed the leap to active optics, as control systems were needed to sense and correct the changes.

A little over two decades later, the first telescope with active optics was completed: the ESO's New Technology Telescope (NTT). While the NTT's mirror diameter was less than four meters, it demonstrated the success of active optics, whose effects can be clearly seen in special photos that highlight the mirror's warpage. Without active optics, thick dark bands representing large deformations bend in and out of the mirror. With active optics, the mirror is nudged into the correct shape and the thick dark bands disappear.

While NTT's design relied on actuators controlling a thin, flexible mirror, active optics were soon applied to other mirror designs, like Nelson's segmented mirrors and Angel's honeycomb mirrors. In all cases, actuators placed on the back of the mirrors make corrections based on a computerized feedback system. How the system knows how much to correct depends on the telescope and the type of telescope mirror, but each will depend on sensors that track changes in the mirror surface.

Back at the ESO headquarters, the E-ELT's active optics controls are being tested with the four mirror segments. The actuators have nanometer precision, allowing for an exquisite control over the curvature and the alignment of the segments. In face of the effects of gravity, temperature change, and wind, that is what is needed to keep mirrors in shape.

Twinkles and Tinkers

Above our planet's surface, the atmosphere swirls with turbulent abandon. Cooler regions mix with warmer regions, creating a kaleidoscope of jumbled air densities that garbles any light that passes through—similar to a heat haze from an airplane jet engine. While the atmosphere's turbulence is much less marked than a jet engine's, we can easily spot this atmospheric effect at night in the twinkling of stars.

When a star emits light, it radiates it in all directions in a spherically symmetric manner. Like the circular ripples that emerge when a stone is dropped in a lake, expanding spherical "wavefronts" of starlight travel away from its star through space. At hundreds, thousands, millions, billions of light years away, a spherical wavefront of starlight that reaches our solar system has expanded to become practically flat (at least to us on Earth).

But after the flat wavefront of starlight makes its way through the ever-fluctuating atmosphere to the ground, it is no longer flat. It is a bit jumbled, or a "potato chip," as Gary Sanders likes to call it. A wrinkled potato chip, anyhow. In a place like Brooklyn, this effect is terrible, which is one reason that telescopes are not built near major cities, in addition to light pollution. However, even on crisp mountaintops like Hawaii's Mauna Kea, where the TMT will be built, Sanders says this effect is "still bad."

The incessant twinkling of stars caused by the atmosphere, though inspiring to lullaby rhymes, is a headache to astronomers. A cluster of stars can be smeared into a single blur after our atmosphere's filter, rendering it virtually useless for analysis by a telescope's scientific instruments. With the atmosphere in the way, our view of the sky is hazy. No wonder so many astronomers were eager for space telescopes like the Hubble.

Active optics, for all the good it already can do, cannot fully redeem a telescope's vision. Instead, astronomers rely on a similarly-named though different technology called *adaptive* optics. "Light comes into the telescope and it get splits in the beam splitter," explains Sanders. "Some of it goes off to a science instrument, but some of it goes off to a box called a wavefront sensor, which is a wonderful little gadget that's basically measuring this potato chip quality."

A computer then uses the wavefront sensor's readings to calculate what the real wavefront must look like, and sends signals to a deformable mirror, which is separate from the large primary mirror and bounces light that has already been bounced by the primary mirror. Whatever the wavefront's distortion is, the deformable mirror's distortion will be the opposite, straightening out the starlight. These corrections happen a thousand times a second, so adaptive optics operates at a much higher frequency than active optics.

A tricky requirement about adaptive optics, however, is that references are needed. If we want to know what Star A looks like, but it's obscured by the atmosphere, and if we know what the nearby Star B looks like, we can use Star B as a "guide" star because we know how to ungarble its garbled wavefront, and from there, we know how to ungarble Star A's wavefront. And voila—we now know what Star A looks like without all that atmosphere.

An adaptive optics' guide star system is actually more complicated than that. In practice, a constellation of guide stars is needed around an unfamiliar science object in the sky (be it a star, nebula, galaxy, or something else), but the stars aren't always in the right place to do that. "God didn't create enough natural stars exactly where you want them to be," says Sanders. "So what do I do? I make some: I launch a laser beam up the Earth's atmosphere and make artificial stars in a little constellation around my science object."

With lasers, deformable mirrors, and computer controls aplenty, adaptive optics will be found in the TMT, GMT, and E-ELT, allowing them to take pictures ten times as sharp as the space-based Hubble despite being on the ground.

Surprisingly, perhaps, the three extremely large telescopes will not be primarily focused on taking pictures with cameras. "The real strength of a large telescope is spectroscopy," says George Jacoby, GMT's instrumentation scientist. Spectroscopy works by analyzing the light by breaking it up into its individual colors and wavelengths. It is a key tool in astronomy, as it can determine properties like distance and the chemical composition of objects in the sky.

Light from atoms, ions, and molecules produce unique spectrums of colors: helium has its own spectrum, water has its own spectrum, iron has its own spectrum. By looking at which wavelengths of light are present in a light source from, say, a star, astronomers can determine the star's chemical composition. In addition, they can also tell how fast that star is moving away from us through a phenomenon called redshift. The faster a star is moving away from our point of view, the more redshifted it is, meaning its spectrum's wavelengths are lengthened. (Red has the longest wavelength out of the visible colors.) A similar effect is observed in sound, such as when an ambulance passes you and moves away from you, its siren's pitch gets lower.

Redshifting galaxies are a consequence of the expanding universe: as the universe expands, its galaxies seem to move away from us. Thanks to the research of Adam Riess and others, we also know that the expansion is accelerating, so the further away a galaxy is, the faster it is moving away from us and the more redshifted it is. As a result, knowing a galaxy's redshift also conveys how far away the galaxy is.

Good spectroscopy studies require a boost in telescope sensitivity, as the light is being broken down. This makes larger, more sensitive telescopes like the GMT more suitable. "Smaller telescopes can find the objects with an imaging camera," says Jacoby, "which the GMT would study in more detail with a spectrograph."

This does not mean the extremely large telescopes will all go without imaging cameras. "There is one instrument that will be more of a camera," says Jacoby about the GMT, "but it's for a very special purpose. It's to do very high-resolution, that is fine-detail, around bright stars, which will allow you to look for planets and maybe even possibly image planets." Taking pictures of faraway planets will undoubtedly be one of the most memorable achievements of the extremely large telescopes, given our fascination with exoplanets and the possibility of life outside the Earth.

There are currently six different instrumentation plans for the GMT. One contains the camera, and the remaining five will perform various types of spectroscopy. George Jacoby's office whiteboard contains a list of the six instruments' names, a jumble of acronyms: G-CLEF, GMACS, GMTIFS, GMTNIRS, NIRMOS, and TIGER. Also on his whiteboard, boxed off in its own corner, is a reminder: "Budget = $64.7M." That is all Jacoby has to spend on the GMT's instrumentation. Building all six instruments would cost about twice as much. A review panel has been formed to decide which three instruments will make the cut. Whatever the decision is, it will have to be within $64.7 million.

The New Normal

When we are looking at faraway redshifted stars and galaxies that are billions of light years away, we are looking way back in time. When we look at star that is a billion light years away, we're actually looking at what that star looked like a billion years ago. "I study very distant, early objects," says English astronomer Richard Ellis, "and one of the quests in this work is to find the very first generation of galaxies which switched on when the universe was about four percent of its present age." Our universe is just under 14 billion years old, and we currently can only look back to about eight percent of its age, according to Ellis. "At the moment those galaxies we can see with our current telescopes, we can barely detect them," he says. "They're so faint. We really are struggling."

The universe was a vastly different place in its youth. Today, stars (including our Sun) contain heavier elements like oxygen, magnesium, and silicon—forged from the burning cores of stars and supernova explosions. By contrast, the earliest stars and galaxies contained only hydrogen and helium, which were initially created from the Big Bang. The TMT and the other extremely large telescopes will probe deep into the universe to learn more about the very first generation of stars and galaxies. "How big were they? How many are there? This is in some sense one of the last remaining puzzles in cosmic history," says Ellis.

The chance to work with the cutting-edge Keck Observatory, with its deep views of the universe, along with the tantalizing prospect of being able to use an extremely large telescope drew Ellis to move from the University of Cambridge to Caltech. When Ellis arrived in 1999, there was no Thirty Meter Telescope yet; he had been invited to work on the California Extremely Large Telescope (CELT), in particular with its fundraising. Caltech and the University of California (UC) had just finished up their $180 million Keck Telescopes, and they assumed the same partnership would continue for the CELT, which was to have to a $700 million budget, split fifty-fifty.

Ellis, acting as the telescope's marketer, went to the Caltech president to share the fundraising plans. That's when CELT hit a roadblock. The president deemed the price tag too ambitious for only two institutions and asked Ellis to find two additional partners to join the project. If Ellis failed, the CELT would not have the money to be built.

With the future of the CELT at stake, Ellis made his way to two countries that already had plans for extremely large telescopes, Canada and Japan. He convinced both to climb on board to what was now the Thirty Meter Telescope project, the TMT. The two-partner benchmark was achieved, but that was no longer enough. The price of the telescope by then had ballooned from $700 million to $1.1 billion. "And that's when we realized that we needed yet more partners," says Ellis. Today, the Thirty Meter Telescope is expected to cost about $1.4 billion dollars.

Getting an additional partner is the most straightforward way to fund a telescope, even though the partner acquisition process is not short. Each of the three telescope projects woos potential collaborators with the promise of that ever-valuable commodity, telescope time, in exchange for, say, fifty to a few hundred million dollars. The more a partner pays, the more telescope time a partner gets. Currently, becoming a partner is the only guaranteed way for a country or institution to get telescope time for its astronomers. The exceptions would be in the cases of the University of Hawaii and

Chilean institutions, as part of Hawaii's and Chile's benefits from hosting the telescopes.

As of now, the GMT collaboration involves two American science institutions, five American universities, and Australia and Korea on board. The TMT has Caltech and UC, along with Canada, Japan, India, and China. The E-ELT has a consortium of fifteen countries. All three are considering more partnerships in order to acquire more funds and resources, but the partner acquisition business is not straightforward due to the financial cost of partnership.

For instance, in addition to the \$1.4 billion price tag of construction, the TMT will require \$40 million a year to operate. A country or institution who wants a five percent commitment to the TMT will have to spend not only seventy million dollars to pay for five percent of the telescope's construction costs, but also a yearly \$2 million subsidy to pay for the operating costs. There are not many institutions and countries left in the world that are willing to pay that price. Most of the ones that can afford to join a collaboration have already signed up. And some of the ones that can afford it do not want to join.

In the beginning, the Giant Magellan Telescope was slated to have five partners: Carnegie Institution, University of Arizona, Harvard University, University of Michigan, and MIT—the original consortium for the Magellan Telescopes. Today, the partner roster of the GMT has neither University of Michigan nor MIT.

"MIT is not a partner. I participated in early design work on it, but I have not participated in it for the last three or four years," says Paul Schechter, who currently continues to work with the Magellan Telescopes. "MIT's Dean of Science said, That's just too much money, I haven't got that, and to be honest, if I did have that kind of money, this would not be the highest priority.' So the stakes have gotten too high, and MIT can't play." With finances in mind, MIT opted out of the collaboration.

"It would be disappointing if MIT wasn't part of one of the big telescope projects," says McCarthy, "and it's particularly disappointing to us, because there are people there, like Paul Schechter and Rob Simcoe, who have an enormous amount to contribute, technically and intellectually. We would certainly welcome MIT back with open arms, but we'll see. It's an expensive proposition to be part of one of these, but it would be a painful situation to be just on the sidelines and not be able to use them when they're done. It's too bad."

University Michigan arrived at a similar conclusion as MIT. In the wake of their departures, the GMTO picked up more partners: a few more U.S. universities and institutions, along with Korea and Australia. Most recently, University of Chicago jumped on board in 2010, bringing a $50 million pledge with them. "It may not be the final group," McCarthy notes. "We might add one more partner. It remains to be seen."

The TMT consortium is considering adding new partners too, in particular a university that recently bought time on the Keck Telescopes: Yale. "Yale University is considering both," says Richard Ellis, referring to both the TMT and the GMT. "And we'll have to make a decision pretty soon."

The other American university that may be interested in joining the TMT, according to Ellis, would be the University of Hawaii, in addition to its role in hosting TMT on Mauna Kea. Other than that, options are running dry. Other universities are either disinterested or not wealthy enough to take part in this expensive telescope project. Then there is the competition to deal with, and not just over Yale.

"We were competing with the other projects to get many of these partners," says Ellis. "We would fly to China and find that the Giant Magellan Telescope had been there the previous week! It's like the presidential election. We're all flying around the world to get membership." The situation was similar across the board: many current partners had carefully considered all three telescopes. Australia chose the GMT. Brazil chose the E-ELT. And in the end, the TMT won over China.

International collaborations have become inevitable for astronomy. Particle physics took up this path years ago with its multinational collider projects, most recently the Large Hadron Collider. However, physicists and astronomers do not forget one spectacular failure of a project in particle physics: the Superconducting Super Collider. With an 86-kilometer circumference, the Texas-based Superconducting Super Collider could have smashed protons together at about three times the maximum energy of the 27-kilometer Large Hadron Collider. But four years into construction, 14 miles of tunnel drilled, and $2 billion already spent, the U.S. government withdrew funding from the Superconducting Super Collider in 1993. Its costs were too high for the government to want to shoulder, especially after the end of the Cold War, and there was not enough participation from other countries to share the burden.

The story of the Superconducting Super Collider brings up a troubling question: What happens if an extremely large telescope project cannot come up with enough money? "Well, there may be a mountaintop sitting flat waiting for a telescope," says Schechter. "There may be an off-axis mirror that's not doing much else." The prospect of empty mountaintops and lonely mirrors echoes the current state of the Texas collider of abandoned tunnels and facilities. Nobody wants a repeat of the Superconducting Super Collider fiasco.

So, the TMT, GMT, and E-ELT are not repeating one of the Superconducting Super Collider's major downfalls: they each have the backing of a multinational consortium of partners. International collaboration is now the new normal for cutting-edge telescopes.

Starry Night

The ESO was established four decades ago as a treaty-bound organization ratified by its fourteen member states. (Brazil is currently undergoing the ratification process as the fifteenth member state.) The treaty terms bind each country to pay a certain annual amount for the ESO's activities. As a result, the funding situation for the E-ELT, as ESO's flagship project, appears sounder than that of the TMT and the GMT. For the latter two telescopes, money has to be raised and gained, much of it in the form of donations through institutions.

Gone are the days when one person's money could fund an entire observatory. Until recently, ground-based optical telescopes were private ventures, funded by a single benefactor or philanthropic foundation. The Yerkes Observatory was built using transportation magnate Charles Yerkes's fortune. (Yerkes had decided he needed to fund a large science project to immortalize his name.) Other examples include James Lick and the Lick Observatory, and Howard Keck and the Keck Observatory. The chances of any of the extremely large telescopes switching their name to immortalize a single benefactor are unlikely, however.

"I get to talk to some of MIT's donors," says Schechter. "We had donors who gave us money for Magellan, and they say the Giant Magellan Telescope is out of their league. 'I have plenty of money, but not that much money,' they tell me."

The extremely large telescopes are not without backers. GMT received a donation pledge of $25 million from Texas oil businessman George Mitchell and his wife. Intel founder Gordon Moore and his wife have donated or committed a total of $250 million to the Thirty Meter Telescope through their Gordon and Betty Moore Foundation, which has the motto (and very long term goal) of "Creating positive outcomes for future generations." While the TMT telescope will take years to build, its top-notch science facilities will have a deep impact on research and education once completed. The largest chunk of money committed occurred in 2007, when the Foundation pledged $200 million. (It is rumored that Moore, whose alma maters are UC Berkeley and Caltech, wished to push GMT out of contention. In the past, it was uncertain if there was enough funding for both the TMT and the GMT to succeed.)

However, no one donor has stepped forward to completely shoulder a billion-dollar telescope. Have we reached the limit? "That's a good question," says Schechter. "Zuckerberg. There's somebody who we should hit up for money," he adds with a smile. While Mark Zuckerberg's Facebook fortune is certainly formidable (and could cover the construction cost of all three telescopes), don't count on there being a Zuckerberg Observatory. It is unlikely that any of the future extremely large telescopes will bear a benefactor's name. Instead, what is now required to fund these billion-dollar ventures is almost nonstop fund-raising from many donors.

On the evening of January 14, 2012 at a posh resort in Tucson, Arizona, a well-dressed crowd mingles while sipping on wine and nibbling on spring rolls, quesadillas, and empanadas. Cocktail hour fades into dinner time, and the crowd trickles into the banquet room, at which point audible gasps of delight are heard.

Black curtains unveil the dining area, dimly lit by three chandeliers. A number of colored LEDs light the wall, bathing the room in a blue-purple glow. Two stringy, glowing bundles of optical fibers set on plastic pillars decorate the center of every table. At the front of the dining room, behind a small stage, hangs a stretch of black cloth speckled with shining lights.

And most dazzling of all, black balloons bob at the ceiling, and dangling from them at the end of long strings are illuminated LEDs that shine like stars several feet above the diners.

It is no coincidence that this occurred the same day as the second GMT mirror casting. This was a flagship fundraising event for the telescope. As the guests dined on the baby spinach salads, ancho-chili glazed chicken breasts, and chocolate coffee toffee tortes, they were treated to talks about the telescope and astronomy. Many of the guests were prospective benefactors for the GMT or well-connected individuals who would know prospective donors, who would need to be convinced that yes, the GMT is a good investment of their money.

"There were times in around 2006 and 2007," says Patrick McCarthy, "when the project manager at the time would sit down with us and have a little budget sheet. It showed the amount of money we had and were spending, and the budget would be black, and then it would turn red—which meant we were out of money. And the time in which it was turning red wasn't very far away."

Whenever that happened, the GMT spokespeople would get out and secure donations and funding to scrounge up money, but the situation was far from ideal. "There was a period when we were really just barely getting by, and trying to figure out how we were going to get another six months," says McCarthy. "Fortunately, in around 2008 or 2009 or so, we transitioned away from that constant crisis mode. The GMT partners committed enough funds that we had a good cushion. And now we have essentially half of the total funds committed." Of course, that means they're still looking for the other half of their $700 million budget.

Along with the large fundraising event at the mirror casting, smaller fundraisers are held throughout the year. There are a few more gifts in the works, according to GMT's fundraising manager Charmeen Wing, but it will be about another year before the gifts are officially made. That may seem like a long time, but it will be about another decade before GMT catches its first starlight.

Building these telescopes is taking longer than originally planned. For example, the Thirty Meter Telescope originally had a planned completion date of 2011—so much for that. Richard Ellis is frank about the length of TMT's construction. Given his age, he probably will not use the telescope much by the time it's finished around 2021, but that does not stop him from promoting the telescope with enthusiasm. For example, in 2004, he gave a half hour talk that led to a $17.5 million donation. "Most productive half hour of my life!" says Ellis.

Since his arrival in the U.S., Ellis has had to go from a science cheerleader to a political lobbyist of sorts. "The politics of these large projects have taken me a little bit by surprise. I seem to be spending all my time worrying about the politics," says Ellis. But, he adds, "This is a billion dollar project, so it's quite reasonable it should be a political issue."

Home Soil Politics

Fifteen thousand feet above sea level, Warren Skidmore and Tony Travouillon were setting up towers adorned with instruments, robots, and tiny telescopes. The two TMT scientists would trek around high mountaintops and set up equipment to measure a potential location's atmospheric conditions—dustiness, humidity, wind, turbulence—to find their telescope's ideal site.

"Two of us would climb these towers, and the wind was so strong that there was no way you could talk to each other. It was absolutely roaring, the wind," says Skidmore. "It was incredibly dry and our lips were black and cracked. You see pictures of Arctic explorers sometimes. That's what's it was like. You're working at high altitudes, so you can't think very well. We'd sleep in some dodgy hotel if we were lucky or some metal container. It was a real adventure."

Skidmore and Travouillon's work provided the TMT partners with data for choosing the telescope's location. Each site had its ups and downs, but ultimately, the familiar Mauna Kea officially won out in 2008. "It was a combination of two things," says Skidmore. "They selected scientifically a site that would support the top science the TMT wanted to do, and they took into account how the telescope would operate at the site. And then they factored in things like logistics, you know, how easy it is to get stuff to the site. That stuff all boils down to money: how easy it is to construct and run the telescope."

The mountain on the Big Island is more accessible than the remote peaks of the Chilean mountains. It also has the best of the best conditions of all the sites, according to Skidmore and Travouillon. "If you look at some of the average conditions in Hawaii, you wouldn't be as impressed as some of the Chilean sites," Skidmore says. "But the best conditions in Hawaii are by far the best conditions of any of the sites. If you want to essentially set records, Hawaii is a good site to go, because when it's good, it's absolutely fantastic. On average, it's a little bit more cloudy, it snows a bit more, and that kind of thing. But the best ten percent of conditions are in Hawaii."

However, there was a third reason, in addition to better top conditions and logistics, according to Travouillon. "Obviously, there is also a political aspect of it. It's impossible to ignore. It's more attractive for U.S. astronomers to be within in the U.S. for funding reasons."

Ever since the establishment of Kitt Peak National Observatory in 1958, the U.S. government has played a prominent role in the country's astronomy through NASA and the National Science Foundation (NSF). The proportion of completely privately funded telescopes dropped as these federal agencies began to have a hand in telescope projects, such as the Hubble Space Telescope and even the initially privately funded Keck Observatory (NASA became a full partner in 1996, the year Keck II was completed). Government funding, however, has its limits, especially in the current economy, causing the government to set priorities for what projects to fund via an extensive decadal survey.

Officially, it is called the Astronomy and Astrophysics Decadal Survey, conducted once a decade by the National Research Committee, and it ranks the top projects in astronomy. Larry Stepp, who now heads TMT's telescope department, says, "In 1990, the highest priority was two 8-meter infrared-optimized telescopes. Those became the twin Gemini telescopes, one built in Hawaii, the other in Chile. In the year 2000, the highest priority for ground-based telescopes was what they called the Giant Segmented Mirror Telescope. It was envisioned to be a 30-meter telescope made with a segmented primary mirror and to be used for optical-infrared observing." This telescope, marked as high priority by the survey, was eventually folded into the Thirty Meter Telescope group.

When the next decadal survey for astrophysics came out in 2010, the results showed that support for giant telescopes had greatly waned. The report, entitled New Worlds, New Horizons in Astronomy and Astrophysics, did not list an extremely large telescope as first or even second priority in the category of large-scale ground-based projects. Instead, "Giant Segmented Mirror Telescopes" (as a whole) were relegated to third priority. Largely, this decision is suspected to be a matter of expense; a single very large and costly project could suck the feasibility of many smaller ones.

"You could interpret the decadal survey to be saying we've reached the limit of how much we want to invest in our flagship—what fraction of our resources we want to invest in our single biggest enterprise," says Schechter.

But in September 2011, slyly slid into a report accompanying Senate bill S.1572 was the following: "The Committee [on Appropriations] encourages NSF to pursue the astronomy and astrophysics decadal survey's recommendation to develop a giant segmented mirror telescope and to develop that telescope on domestic soil as a public-private partnership inclusive of international partners, through the agency's major research equipment and facilities construction process. This will help to continue America's leadership in optical astronomy, while supporting scientific and technical jobs to maintain our level of excellence in this field."

"I was surprised to see that language in there," says Schechter, though he also notes that the bill has not been passed by the House yet. "There's a question of whether the

U.S. National Science Foundation participates in one or the other, and that's a very sensitive issue."

When the Superconducting Super Collider's funding was cut off by Congress, it affected the U.S.'s prominence in particle physics. While the U.S. may still currently lead the world in astronomy, that situation may change depending on the country's relationships with the two extremely large telescopes that have U.S. connections.

"The NSF doesn't have a large budget for this telescope at this moment," says Richard Ellis. "There are two competing telescopes. Both are quite credible projects, and it's unfortunate that we're in competition with this other project, but the reality is that the National Science Foundation probably can only contribute to one of these two telescopes."

The Thirty Meter Telescope wants the support of the NSF badly, even though the NSF is strapped for cash. It's partly a matter of validation. "Canada, and to some extent China and maybe even Japan to some level are nervous until the National Science Foundation chooses which of the two U.S. projects it wants to support," says Ellis regarding TMT's foreign collaborators.

At the end of 2011, NSF put out a call for proposals from the GMT, TMT, and any other group that had to offer up an extremely large telescope. The agency did not promise much money, only $1.25 million, but it was more of an invitation for a telescope to begin working with the NSF, according to Sanders.

"We don't have much of a relationship with NSF right now," Sanders said in January, before the proposal deadline. "We are going to submit a proposal on April 16, which is what the NSF has called for, and we hope that NSF will ultimately be a partner in TMT." Beyond the need to confirm confidence in the TMT partners, Sanders wants to see the TMT work with the NSF for an altruistic reason: those 365 nights on the telescope will be precious, and if the NSF does join the TMT, it would open telescope time up to the scientists not affiliated with any of the telescope partners. “I think TMT is a global asset in astronomy,” says Sanders. “I think it will be shame if the U.S. astronomy community is not part of it. I think it will be a historic missed opportunity.”

As the NSF will likely only fund up to one telescope, TMT partners worried about competition with GMT. However, before the NSF proposal deadline, GMT people were categorically expressing a lack of interest in NSF participation in their telescope.

“The Carnegie people say they don’t want NSF support,” according to Schechter. “Do we really believe that? We don’t know, but that’s what they say.”

Likewise, Ellis reacted with surprise when he heard similar news a month before the proposal deadline. “A year ago, GMT wasn’t saying that they weren’t interested in NSF funding!” he said.

Meanwhile, McCarthy had this to say about the matter: “I don’t really see us in a big competition position as they do, I think. We see them as a project we’d like to see succeed and wish them the best of luck. They have a different point of view regarding the U.S. federal funding, so they are in a very competitive posture right now. So, we don’t want to get involved in the complications there.”

The GMT group did not submit a proposal.

Funding seems to loom as the heaviest challenge on these telescopes, but the collaborations remain optimistic, and perhaps rightly so. “I believe that in the end,” says Sanders, “the E-ELT will be built, TMT will be built, and GMT will be built, and maybe others. There’s a tremendous amount of scientific potential in these observatories. There’s tremendous competitive pressure and intellectual interest in these communities of astronomers. I think ultimately, they will all get built.”

Barely pausing, he continues: “When Keck was proposed in the mid-1980s as a 10-meter telescope, no one thought there was going to be more than one or two 8- or 10-meter class telescopes in the world. Now there is something like a dozen. What does that tell you? It tells you there are a lot of astronomers who want to look at the sky with a really powerful discovery instrument, and I think the same will happen in the next generation."

By Sanders' prediction, one day, we will not only have the GMT, TMT, and E-ELT pointing at the sky, but many more extremely large telescopes. The GMT is definitely keeping that option open on Cerro Las Campanas. Their site plans have an empty space next to the GMT, sized just right for another giant telescope.

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