The New Planet Machine

Astronomers ante up their bankrolls and reputations in a high-stakes bid to build the world's largest telescope

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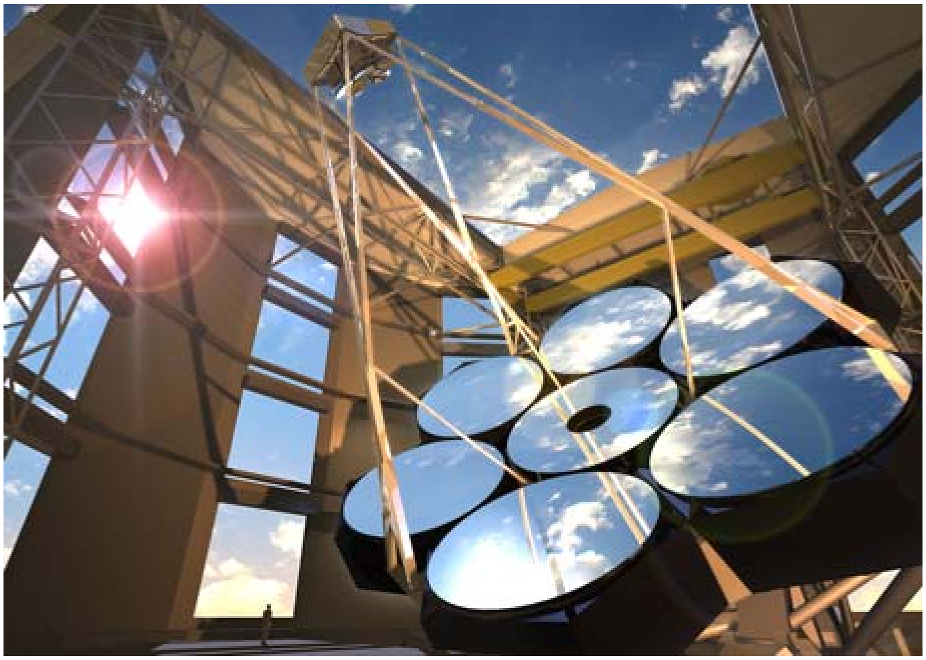


Courtesy Todd Mason & Carnegie Observatories

Plans call for the Giant Magellan Telescope, which is scheduled for completion in 2016, to be housed in a 213-foot-tall rotating enclosure. Seven 27.6-foot mirror segments would be combined to create a giant light-gathering instrument with up to 10 times the resolving power of the Hubble Space Telescope.

You would not want to play poker with Wendy Freedman. Even her children say so, she admits, and as she sits across the table on a summer morning in Tucson, Arizona, she gives no hint that she has just pushed almost all her chips into the middle of the table.

At this moment, about six miles away, a giant orange oven rotates, spinning up to its target speed of five revolutions per minute, on its way to its programmed temperature of about 2130 degrees Fahrenheit. By then, it will hold a lake of glass, 20 tons of borosilicate.

For another three days the oven will continue to spin, driving that lake of liquid glass into a parabola 330 inches across. Over the next several months, the glass will be slowly cooled and then polished exquisitely, to within .000001 of an inch of the theoretically perfect shape. Add an aluminum coating about 400 atoms thick, and there it will be: a telescope mirror, one of the largest in the world.

Yet having one of the largest telescope mirrors in the world offers little satisfaction to Freedman and her colleagues. The single mirror will not be much good without the next six just as big, scheduled to be produced by a group led by Roger Angel, director of the Steward Observatory Mirror Laboratory at the University of Arizona. Assembled in a honeycomb pattern of six giant disks surrounding a central segment, the seven mirrors will form a single optical surface, a telescope measuring 25.4 meters—an iconic 1,000 inches—across. Named the Giant Magellan Telescope, this seven-eyed giant would become by far the largest telescope in the world, more than four times the size of the current champions.

But that's if the Giant Magellan works—and if it ever gets built.

For even as the first mirror flows into shape, there is no guarantee that the rest of the telescope will ever come to anything. The instrument's unprecedented design demands a series of technological advances that have not yet been made, and the project will consume a mountain of money—about $500 million—that has yet to be found. So far the team has raised only $17 million. Freedman, who is director of the Carnegie Institution of Washington's observatories in Pasadena, California, is confident that more is on the way.

The stakes could not be higher. Whoever builds the next giant telescope will own the cutting edge of astronomy for years, perhaps decades. Those astronomers—and only those—will have first crack at the very biggest questions out there. The next great telescope will help discover what 96 percent of the universe is made of, unraveling the mysteries of so-called dark matter and dark energy. For now, we know of life on just one planet around just one of the 1022 stars in the known cosmos. The Giant Magellan Telescope may be able to detect Earth-size planets around a nearby star and may even be able to identify the traces of living chemistry in exoplanet atmospheres. How our universe evolved from its simple beginnings, what it contains, what its ultimate fate may be—these are the fundamental human questions the new telescope is designed to address.

Finding the answers to such grand questions—and being the first to do so—drives Freedman to risk beginning without knowing precisely how her team will finish the job. You have to start somewhere, she argues: "We have to learn if it is feasible." She stops speaking, looks to see if her questioner understands, smiles slightly. "If you got daunted by these things, you would never try." She is prudence itself, calm, cool, absolutely confident. Do not play poker with Wendy Freedman.

As Freedman speaks, the glass in Roger Angel's oven continues to spin. In three days the oven will be turned down, and the disk will begin to cool in an agonizingly slow process called annealing. When glass changes temperature quickly, it can crack. The Giant Magellan team will take no chances, allowing their mirror months of cooling before it is cleaned and moved to the polishing shop.

There, it will take its turn in line. A 256-inch mirror already sits on the polishing machine, an order from military contractor Lockheed Martin. No one talks much about how it will be used. Propped up against a wall near the oven stands another 330-inch mirror. It is up next for the polishing process. When it is ready, it will be hauled up to the Large Binocular Telescope, an unconventional observatory featuring two mirrors on a single mount that is being built on nearby Mount Graham. That instrument is one of the latest of the current generation of telescopes, instruments ranging in diameter from about 256 to 465 inches. The Giant Magellan Telescope will render all of them obsolete.

Such ruthless competition is a fact of life in the telescope world and has been for the last century. Modern astronomy—the exploration of deep space—effectively began in 1908, when the Carnegie Institution of Washington completed the first large-aperture high-mountain instrument, a 60-inch telescope on Mount Wilson, near Pasadena. With that telescope and its successor, the 100-inch scope that began operations on Mount Wilson in 1917, Edwin Hubble discovered the modern universe. In 1924 he showed that the Milky Way is not the only galaxy; five

Photo courtesy David Harvey & Carnegie Observatories

A rotating furnace at the Steward Observatory Mirror Laboratory at the University of Arizona spin-casts the first mirror for the Giant Magellan Telescope.

years later, he and his colleagues revealed that we live in an expanding universe—one with a history that human beings could trace to its origins.

The furnace heats 20 tons of glass to 2130 degrees Fahrenheit and turns at approximately five revolutions per minute. Spinning the glass while it is molten gives the mirror a slight parabolic shape.

The 60-inch and 100-inch Mount Wilson instruments yielded sharper pictures and more light than any previous telescopes—exactly what Hubble needed to see a larger, more dynamic, and vastly more complex universe than anyone had imagined. But building bigger and bigger telescopes became an obsession. If a 100-incher was that much better than a 60-incher, what would a 200-incher show us?

The inevitable race began. The 100-inch was superseded in 1948 by the famous 200-inch telescope on Palomar Mountain, which in 1993 took second place to the first of the two 400-inch Keck instruments on Mauna Kea. Every 30 years or so—just about the length of a professional astronomer's career—technological advances and astronomers' covetousness intersect, generating a breakthrough telescope that about doubles the diameter of the preceding champion. In the last century, telescope size increased eightfold, surface area by a factor of 64.

Now, as always, the best telescopes have made discoveries that plant the seeds of their own obsolescence. The two most important lie at opposite ends of the scales of size and time. Close to home, the Keck telescopes and others have observed more than 160 planets, most of them the size of Jupiter and orbiting stars other than our sun. But these enormous instruments can't actually image other planets; they can only detect wobbles in their stars caused by the planets' gravitational pull. And they can't hope to even indirectly find planets as small as Earth. The Giant Magellan would be the first telescope able to image—actually see—a planet beyond our solar system. At the other end of the cosmic ecosystem, the new telescope could help clear up a mystery created by the most surprising discovery made by the current generation of telescopes: the fact that the universe is not merely expanding but accelerating, propelled by a mysterious phenomenon that, in their ignorance, astronomers have dubbed dark energy.

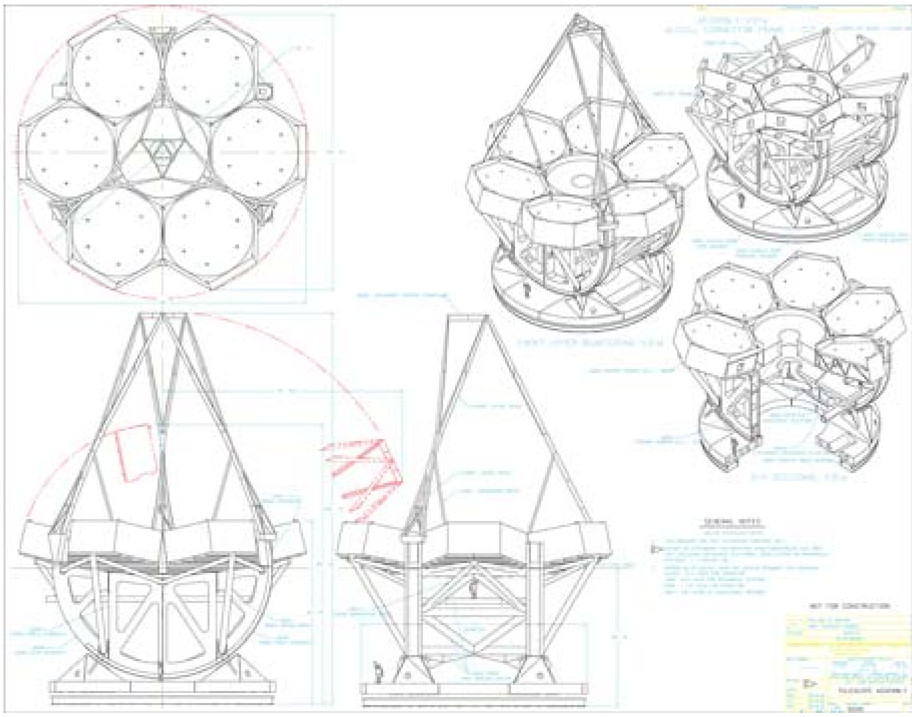
If the Giant Magellan—unlike any previous telescope—stays on schedule, operations will begin in about 10 years, almost a quarter of a century after Keck I opened for business. "I would have loved another decade to use my current telescope," Freedman says, "but the science that this telescope could do is so exciting. We can't even list the things we may do."

For the next several years, the fate of the Giant Magellan Telescope will rise or fall on the efforts of Roger Angel. If his team fails to deliver seven enormous mirrors to the accuracy needed, the entire project will collapse.

Angel gives no hint of the pressure. Rather, it seems as if merely creating the world's largest telescope is not challenging enough for him. He wants to build at least two. The Giant Magellan will sit at a conventional high-mountain site—most likely Las Campanas Observatory in northern Chile. But the other? "I'd like to see another one built at Dome C," Angel says.

Why not? Dome C would be perfect: It is a bone-dry high plateau site with low winds—ideal observing conditions. But Dome C is in Antarctica, about 900 miles from the South Pole, with winter temperatures that touch –120°F.

And if the prospect of building and maintaining a 1,000-inch telescope there seems insufficiently challenging, why not think really big? Angel points out that there is an even better site available, one with no wind whatsoever and an endless night. It can be found at the lunar pole. You have to think ahead, Angel says. "People need road maps."



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Engineering sketches offer a glimpse of the technical grandeur of the Grand Magellan. 1) Top left: The seven-segment design was chosen to take advantage of the current state of technology in casting large mirrors. Six segments are "off axis," or offset from the center segment. The center segment is "on axis." 2) Bottom left: The telescope is considered an "alt az" design: The entire structure rides on a circular track for azimuth positioning, and the upper structure is elevated with giant C-rings for altitude control. The moving mass of the telescope is 1,100 tons. 3) Top right: Light reflects from the seven primary mirrors up to seven secondary mirrors 115 feet above the floor. They are supported by carbon-reinforced steel legs. 4) Bottom right: Light reflected from the secondary mirror passes through a hole in the central primary mirror and is received by scientific instruments located on a platform underneath. Instruments are raised and lowered via an elevator in the core of the telescope pier structure.

Forced to contemplate the telescope at hand, Angel asserts that there are no truly daunting obstacles, despite the fact that elements of the telescope design have not been invented yet. "If there were any really tall technological tent poles," he says, "I'd be looking at them." Still, he admits, there is one problem that has him thinking. The new telescope's mirror will be assembled out of seven enormous pieces of glass that must work together perfectly to form a single parabolic optical surface.

No one has ever built such optics—and for good reason: Six of the seven mirrors will form the sides of the parabolic shape of the telescope as a whole. In the jargon of telescopemakers, these mirrors will be asymmetrical, shaped to a curve that changes from top to bottom. Asymmetrical curves are very hard to perfect on optical surfaces, especially considering the combination of size and surface curvature that the Giant Magellan instrument demands.

The hard part will not be the actual polishing of the mirrors—that uses old technology, unchanged in principle from the days of Newton. You rub the disk with carbon grains and jeweler's rouge—an iron oxide compound—and glass comes off. The tricky part is measuring the precise shape of the mirror at each stage of the process. This is what keeps telescopemakers up at night. Angel remembers, as all astronomers do, what happened to the Hubble Space Telescope. That mirror was beautifully polished, precisely curved. But the testing apparatus was just slightly, imperceptibly off kilter—enough that the Hubble ended up with the wrong curvature, one that left it unable to focus.

To prevent any similar disaster, Angel's group is building a brand-new optical testing system, specifically for the new telescope. At its heart will be a 157-inch mirror—itself larger than all but a handful of telescopes in operation a decade ago. Time and again as they polish their blanks the team will bounce one beam of light off the mirror destined for the telescope and another off the test mirror. When the two beams intersect, they will produce light and dark rings, called interference patterns. The patterns reveal a three-dimensional image of the surface of the mirror being tested—in essence, a contour map showing all the peaks and valleys that still need to be polished. In addition, a computer model of a perfect mirror will be used to create a hologram to stand in for the real mirror, providing an independent check on the precision of the interference-pattern tests.

None of this is remotely as easy to do as it is to describe. Peter Strittmatter, Angel's boss at the University of Arizona, says: "What we are doing now is dealing with the biggest technological issue. We have to demonstrate that we can accomplish the testing and figuring of the mirror if people are to invest in the project."

That doesn't faze Angel. "The whole business of working out how to do telescopes is a rewarding exercise. It's interesting enough that Newton and Galileo did it." Angel adds, "If it's worth a few minutes of Newton's time, who is to say it isn't worth mine?"

When and if Angel succeeds, the risk shifts. Optics that test perfectly in the lab can behave differently in the wild. Thousands of precisely engineered pieces of steel and glass will have to be assembled into a machine that weighs 2 million pounds and holds its shape perfectly on an exposed mountaintop.

The first and greatest challenge for the builders will be to defeat the wind. Astronomers crave size, but the larger the telescope, the more vulnerable it is to wind shake. "When you put a big telescope mirror the size of a spinnaker on top of a mountain with the wind blowing, and you want it to hold its shape to one millionth of an inch," Angel says, "wind buffeting becomes a serious issue." Project manager Matt Johns puts it baldly: "Wind shake has been a problem for the current generation of telescopes," he says. "It is likely to be more so on the Giant Magellan Telescope."

To compensate, the structure of the telescope must be almost impossibly stiff. In big telescopes, stiffness comes from steel—hundreds of tons of it. But no amount of steel can hold a 1,000-inch seven-piece mirror in perfect alignment.

And so, as it has become clear that brute force won't work, the Giant Magellan team will try cleverness. When the wind bends the big mirror segments out of alignment, small and fast actuators will eliminate the distortion by tipping and tilting each of the segments in a secondary mirror array located above the focal point of the primary array.

Another technological trick called active optics will nullify changes in the telescope's structure that result from the effects of gravity and temperature. Arrays of fist-size computer-controlled pistons will move the segments of the primary mirrors every minute to counteract any errors.

An even more sophisticated technological trick—adaptive optics—will be used to get rid of the astronomers' greatest annoyance: the turbulence in the atmosphere that makes stars twinkle. Romantic, of course, but for astronomers that flickering starlight means that motion in the atmosphere is smearing out fine detail in the night sky. In response, adaptive-optics pioneers reasoned they could correct any errors in the light signals reaching the telescope by changing the shape of one or more of the mirrors that light will encounter as it follows its path to the electronic detectors.

For the Giant Magellan Telescope, that process will begin with several laser beams shooting into the sky. Measuring how those laser beams flicker should yield a map of the turbulence above the telescope. Then the seven small, thin secondary mirrors, one for each large segment in the primary mirror, will change their shapes as many as 100 times a second to cancel out any atmospheric distortions.

At least that's the theory. In practice, no one has yet come close to achieving the adaptive-optics performance the Giant Magellan Telescope requires. Paul Schechter of MIT, one of the project scientists, notes that people are still trying to make the lasers work in the field. "What fraction of the time is the system working while you are trying to do science?" he asks. "What fraction of the light your primary mirror collects makes it to your detector? What fraction of the sky can you cover? Right now, these are all small numbers. This is not a mature technology."

Angel agrees, but remains optimistic. "We've been doing adaptive optics for 15 years now. It's bloody hard. It takes a lot of time to sort it out." But, he adds: "Most astronomers look back and say no one has ever done adaptive optics, so how do you know it will ever work? I look around and I see that the engineering has advanced enormously. Where we are now is pretty damn encouraging."

Such is the reality of working at the bleeding edge.

This is a key reason Wendy Freedman was chosen to head the project. She knows that building a telescope much bigger than any previous instrument involves irreducible risk. She knows that she must gamble sometimes, placing her bets on unproven technology. But what counts is that she is a good gambler, one with an acute ability to calculate the ratio of risk to reward. "I have great confidence in the capability of the people now working on the Giant Magellan," Freedman says. "It is an incredibly talented group with a phenomenal track record. The odds of winning at poker are better if you are holding a great hand."

Freedman's team shares her confidence. They are certain that the telescope can be built. But will it be? They are less sure. Cash is short—and the Giant Magellan project faces determined competition.

The chief rival in the race to build the next great telescope is a partnership—led by Caltech, the University of California, and the National Optical Astronomy Observatory—that aims to build a 30-meter (1,181-inch) telescope. The team has proposed a design that will assemble 760 hexagonal segments into a mosaic, forming a single optical surface. It is the Henry Ford approach—using hundreds of relatively small, cheap components to build a giant telescope.

Each group thinks that it has the better plan. But both sides concede that either telescope can be made to work. "The fact is that there are two plausible paths," says Harvard University astronomer Robert Kirshner, of the Giant Magellan team. From the Thirty Meter Telescope group, Richard Ellis of Caltech says, "There are many ways to build a good telescope."

But there may not be a way to build two $500 million telescopes. At worst, the outcome could be mutual annihilation. Funders may simply choose not to choose. Jerry Nelson, an astronomer at the University of California at Santa Cruz and the design leader for the Thirty Meter Telescope, says, "Our worst fear is that we shoot at each other, in some way poison the well, and that we get zero telescopes."

Despite that risk, leaders of both teams show no signs of backing away from the battle, even at the risk of losing both instruments. Freedman says that "in general, in the scientific community, competition is a healthy thing. We don't know what the best way to do this is. The competition forces us to concentrate on what we do best." Nelson agrees: "Science is not a democracy. Science is elitist. Science works because it brings out the best in the best people."

That is true enough, but for all the "let the best telescope win" sentiment, each group wants to capture the cutting edge of astronomy for the foreseeable future. For the better part of a century, that edge has gone to a handful of California-based institutions. The

Carnegie Observatories started that run with their telescopes on Mount Wilson—the ones Edwin Hubble used. Then Caltech, and later the University of California, displaced Carnegie. Those institutions will not give up their predominance without a fight. For Ellis, "it is inconceivable for Caltech that we wouldn't want to have a frontier telescope," and Nelson agrees: "There is a California axis that derives from the Keck tradition. We want to be top of the heap."

Thus, the Giant Magellan project represents a revolt of the have-nots—MIT, Texas A&M University, the universities of Arizona, Michigan, and Texas, along with Carnegie, Harvard, and the Smithsonian Astrophysical Observatory—all those left out of that California axis. For Kirshner, "this is mankind's best effort to find out where we are and how the universe works. We don't want to be left behind." Exactly so, says Freedman.

The new telescope represents the Carnegie Observatories' shot to reclaim its place at the top of the heap. "If we are going to stay at the forefront, which Carnegie has managed to do for a century, we have to do this." By casting a mirror now, well ahead of the competition's plans to pour glass, Freedman and the Giant Magellan group have challenged the Thirty Meter group to ante up or drop out of the game.

Finally, four months after it was cast, the Giant Magellan's first mirror has cooled to ambient air temperature. Wendy Freedman still has more than $400 million to raise. There are no guarantees of success, financial or technological. And yet, dozens of highly successful scientists and engineers have wagered huge chunks of their careers against the chance to build these instruments. Why? Roger Angel knows. "If you are building cathedrals, you don't think about what you can build in your lifetime," Angel says. "You think about building the best." The choice of metaphor is deliberate. Cathedrals and telescopes—both enormous, both expensive, and both bridges humans construct to connect themselves to the heavens.

FARTHER, BETTER, DEEPER: A SHORT HISTORY OF PENETRATING THE COSMOS

HOOKER Completed in 1917, the Carnegie Institution's 100-inch Hooker telescope at the Mount Wilson Observatory in California was the largest telescope in the world for more than 30 years. Using the Hooker, astronomer Edwin Hubble discovered galaxies beyond the Milky Way as well as the first evidence that the universe is expanding.

HALE At the heart of Caltech's Hale telescope is a 200-inch Pyrex primary mirror that was a technological marvel when it was cast in the mid-1930s. The mirror rests on 36 supports and is shielded by covers that open and close like flower petals. Secondary mirrors allow astronomers to vary the scope's effective focal length from 660 inches to 6,000 inches. The 135-foot-high dome of the observatory is divided into two sections, with a movable upper section that weighs 1,000 tons and can adjust to reveal any region of the sky. The telescope was completed in 1948 and remained the largest active reflecting telescope in the world until 1993. It has allowed astronomers to view celestial objects 1¼400,000,000 as bright as those visible to the naked eye, including faint galaxies and quasars billions of light-years from Earth.

KECK The twin Keck telescopes atop the dormant Mauna Kea volcano in Hawaii were the first major instruments to feature a segmented mirror design, making possible the creation of the largest reflective surface yet mounted on any telescope. Each scope's primary mirror—measuring 10 meters, or 394 inches, in diameter—is a mosaic of 36 ultrasmooth hexagonal segments, individually regulated by computer-controlled actuators. Completed in 1993 and 1996, the Kecks have provided astrophysicists and astronomers with measurements of the accelerating universe and evidence of extrasolar planets.

VLT The European Southern Observatory's Very Large Telescope on Cerro Paranal in Chile consists of a cluster of four scopes, each of which is 8 meters, or 315 inches, in diameter. Completed in 1999, the scopes can be used in concert to study a distant object, such as a supernova or a quasar, at different wavelengths of light. Plans are also in the works to turn the VLT into an interferometer array that would combine the four scopes into a single light-gathering instrument with an effective width of 630 inches, dwarfing the capacity of other observatories.

WIYN Completed in 1994, WIYN is a 3.5-meter (138-inch) telescope on Kitt Peak in Arizona that has served as a test bed for state-of-the-art adaptive optics to adjust for light distortions caused by changing atmospheric conditions. The primary mirror is controlled by 66 actuators that adjust the face for optimal focus; thermal controls keep the mirror's temperature close to that of the ambient air. The acronym WIYN is derived from the consortium that operates the telescope: the University of Wisconsin, Indiana University, Yale University, and the National Optical Astronomy Observatory.

SUBARU The Japanese-built Subaru, which is perched near the twin Kecks on the summit of Mauna Kea, was completed in 1999 and boasts the largest single-piece mirror in the world—an 8.3-meter (327-inch) piece of glass that took seven years to fabricate and polish. The telescope employs the latest in adaptive-optics technology, with 261 robotic fingers constantly adjusting the shape of the mirror for maximum image clarity. It is also outfitted with a high-tech, magnetically driven tracking system that allows the telescope to move with minimal friction. *—Alex Stone*