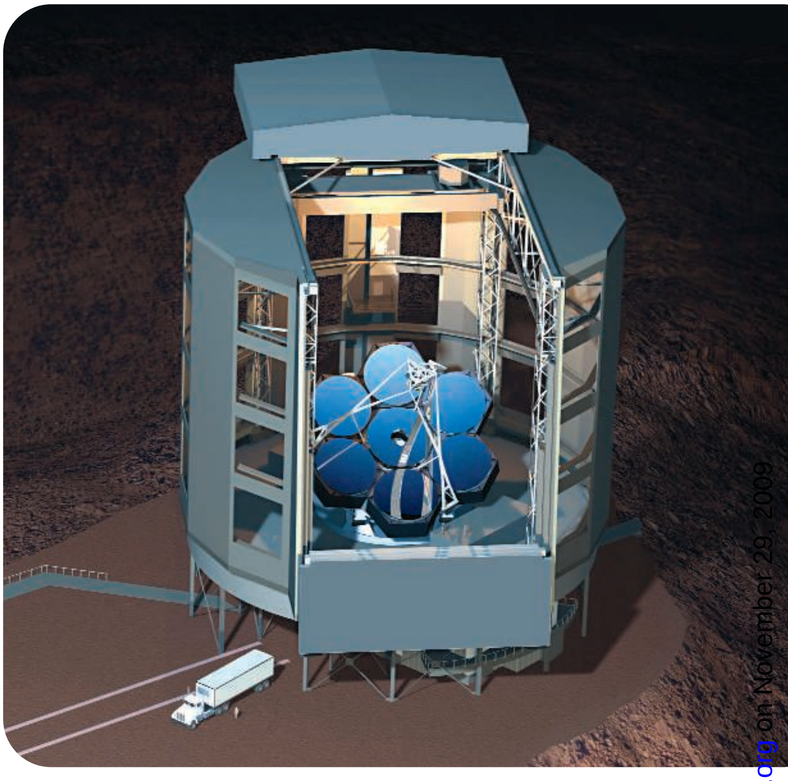

CREDITS (TOP TO BOTTOM): COURTESY OF TMT OBSERVATORY CORP.; GIANT MEGELLAN TELESCOPE/CARNEGIE OBSERVATORY

# Race for The Heavens

**Two very different telescope projects are jostling to give the United States its biggest-ever eye on the sky. Can the country afford both?**

IN 1977, JERRY NELSON, AN APPLIED physicist at the Lawrence Berkeley National Laboratory in California, made a bold proposal to the University of California (UC). The university was looking to build a 10-meter telescope—twice the size of the Hale Telescope at Mount Palomar, which for 3 decades had been the largest telescope in the country. Nelson was convinced that standard telescope mirrors—"monoliths" made from a single piece of glass—had reached their limits. Instead, he proposed to make the primary mirror for the new telescope from a few dozen thin, hexagonal segments joined together into a smooth parabolic surface.

"I knew I could build a 10-meter monolith. But I didn't want to, because it would be the last of the dinosaurs," says Nelson, whose concept was greeted with skepticism by UC astronomers. "I didn't just want to build a telescope. I wanted to build a system that could be extrapolated into a bigger telescope in the future."

Meanwhile, a physicist named Roger Angel was melting Pyrex dishes in a makeshift backyard kiln in Tucson, Arizona, to figure out how to make monolithic mirrors bigger and better. Although less radical than Nelson's approach, Angel's posed equally daunting engineering challenges. The two men would exchange competitive jibes at conferences. Making no secret of his view of monoliths as obsolete, Nelson—a native Californian with an irreverent style—would jokingly ask Angel why he kept wasting time on a dead-end technology. Angel, a transplanted Brit of gentlemanly bearing, would smile back and note the risks of an untested one.

> **Online**
> **sciencemag.org**
> Podcast interview with author Yudhijit Bhattacharjee.

By the early 2000s, each side had points on the scoreboard. Nelson's team had built segmented mirrors for the twin 10-meter Keck telescopes on the summit of Mauna Kea in Hawaii; Angel's had fabricated 6.5-meter monoliths for the two Magellan telescopes at Las Campanas in Chile. Those successes set the stage for a new contest, now in full throttle: building the world's largest telescope. For the past 5 years, Nelson and his colleagues at UC have been working on plans for the Thirty Meter Telescope (TMT)—whose primary mirror will be a glinting mosaic of 492 hexagonal segments controlled with such precision that even light won't discern the edges between them. Meanwhile, Angel and his collaborators have set their sights on building the Giant Magellan Telescope (GMT)—whose seven monolithic 8.4-meter mirrors, arranged like flower petals, will function as a primary mirror 24.5 meters in diameter.

If the telescopes are built—TMT on Mauna Kea in Hawaii, GMT at Las Campanas—each will capture images up to 10 times sharper than today's best ground-based telescopes. Both will shoot for the same scientific goals, which include bringing into focus the first stars and galaxies, studying the formation of planets and stars, understanding the growth of black holes, and probing the nature of dark matter and dark energy. And both will cost a fortune: The segmented TMT's price tag is $1 billion; GMT's is $700 million.

So far, neither side—UC and the California Institute of Technology for TMT, and a consortium led by Carnegie Observatories and the University of Arizona for GMT—has come close to securing the total funding it needs. "These facilities are so big that they could die of their own weight," warns Richard McCray, a professor emeritus at the University of Colorado, Boulder. Even if both GMT and TMT get built with little federal support, he says, the U.S. National Science Foundation (NSF) would be hard pressed to help out with the substantial operating costs of each. Given the funding challenges, some astronomers say




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**Rivals.** Artists' conceptions of the Thirty Meter Telescope (*left*) and the Giant Magellan Telescope.

the two sides should have joined hands to build one telescope to rival the European Southern Observatory's proposed 42-meter segmented-mirror telescope, the European Extremely Large Telescope (E-ELT), which is also in the works (see sidebar, p. 514).

Such a merger has certainly crossed the minds of key figures on each side, but everyone agrees that it's too late now. Differences in technology, personal egos, and institutional rivalries have driven an insuperable wedge between the two efforts. "This is a human endeavor," says Nelson, adding that to him, the two projects "look like oil and water." But even though that divide implies an arduous task ahead for both GMT and TMT, along with the risk of delays or failure should funds run short, leaders of both TMT and GMT project absolute confidence that their artists' conceptions, videos, and miniature models are destined to become the real thing. And officially, at least, the two sides conjure up a future in which both telescopes coexist. "Let two flowers bloom, I say," says Angel.

### Worlds in collision

Nelson and Angel are both stars, now in their 60s, with gray hair and membership in the National Academy of Sciences. Their different backgrounds and contrasting personalities in some ways mirror their approaches to telescope building: radical versus traditional, new-worldly and risky versus more tried and true.

The son of a Lockheed tool planner and raised in a rural California town, Nelson grew up a tinkerer with an affinity for electronics. He learned lathing, welding, and polishing at the machine shops of Caltech while receiving an undergraduate degree in physics. Nelson has a cheerful, round face and a prosperous middle, likes to wear Hawaiian shirts, ends his e-mails with "Aloha," and grins widely when he's mocking the competition. Student-like, he often carries a backpack slung across his shoulder.

Working on the Keck design 30 years ago, Nelson had to solve two main challenges in constructing the segmented mirror. One was polishing each mirror segment into an aspherical surface, so that the segments would together make a dish. The other was controlling the segments precisely to make them act as one seamless reflector.

Standard polishing renders surfaces spherical. To get around the problem, Nelson—along with Coby Lubliner, a civil engineer at UC Berkeley—prestressed each piece with weights before polishing it into a spherical surface. When the weights were removed, the segment elastically relaxed into the desired shape.

Nelson and his colleagues solved the control problem with electronics and computing, using edge sensors and pistonlike actuators to keep the segments perfectly positioned against the destabilizing effects of wind, gravity, and temperature change. It was a scheme that many considered too complex to work. "In 1980, control systems were like, 'How do you spell that?' to the astronomical community," chuckles Nelson. Clearing such practical hurdles, he says, was key to moving the once-outlandish idea of segmented mirrors into the astronomical mainstream. "The world is full of dreamers who say, 'Gee, I'll get in my car, I'll fly to work, then I'll go under water.' The question is, do you know how to do it?"

Angel grew up in foggier climes than Nelson did—in a suburb of Manchester, U.K.—but like his competitor, he studied physics in college and spent time at Caltech on a master's degree. After earning a doctorate from the University of Oxford, U.K., he flitted between different fields of high-energy physics and astrophysics before settling on optics and mirror design as a young faculty member at the University of Arizona. Angel is slim, bespectacled, and more reserved than Nelson. He seems to fit the mold of the absent-minded professor, asking students for help in turning on the lab coffeemaker and driving an old truck through Tucson wearing a straw hat and gloves to shield himself against the merciless Arizona sun.

*"It's a matter of the devil you know versus the devil you don't."*

**—ROGER ANGEL, UNIVERSITY OF ARIZONA, TUCSON**

*"The world is full of dreamers. ... The question is, do you know how to do it?"*

**—JERRY NELSON, UNIVERSITY OF CALIFORNIA OBSERVATORIES**

Angel's innovation in the early 1980s was to design monolithic mirrors that weighed one-fifth as much as conventional mirrors, allowing them to be cast in larger diameters, and that cooled more quickly at night, which would reduce the image distortion caused by air turbulence at the mirror surface. The trick was to melt cheap borosilicate glass into a mold with hexagonal columns made of heat-resistant foam. Spinning the cast spread the glass into a saucerlike shape, with some of the glass trickling down to fill up the empty space between the foam columns. Once the glass solidified, the foam was washed away, producing a thin, smooth top supported by a hollow, honeycombed base a few inches tall. To polish the surface, Angel and his colleagues built a computer-controlled precision lathe that ground down the glass to nanometer-level accuracy.

In the 1980s, Angel set up a warehouse-sized laboratory under a wing of the university's football stadium to make and test these mirrors. The lab in recent years has delivered two 8.4-meter mirrors for the Large Binocular Telescope on Mount Graham in Arizona, which began doing science in 2007. The seven-part GMT mirrors will have a more complex topology than the binocular mirrors, Angel says, but each will be the same size they were and can be made with the same proven technology. His team recently cast the first 8.4-meter mirror for GMT and is now polishing it.

CREDITS (TOP TO BOTTOM): MICHAEL BOLTE/LICK OBSERVATORY; RAY BERTRAM/UA STEWARD OBSERVATORY

"With the making of the first segment, we have pretty much retired the risk of how you put the telescope together," he says. He has come home in the middle of the day to tend to his ailing cat. Sunlight bouncing off a pool in the back dances on his face as he peels a pomegranate at the lunch table. Making the 492 segments of the competitor TMT work together, Angel says, is inherently riskier than GMT's seven-piece design: "It's a matter of the devil you know versus the devil you don't."

Caution and thrift come up a lot when members of the two teams pitch their projects. "If you look at the two telescopes, you say *that* [TMT] is really sexy; *this* [GMT] is old-fashioned stuff," says Jonathan Kern, an engineer with GMT. "But *this* is old-fashioned for a reason. We are not trying to do anything that hasn't been done, that we can't put a cost on."

Nelson, who otherwise enjoys the label of risk-taker, stresses that segmented mirrors are now a rock-solid technology, too. Controlling 492 segments (inconceivable when the 36-segment Keck mirror saw first light 16 years ago) is "completely trivial" for modern computers, he says. "The bottom line is that today segmented mirrors are cheaper per square meter than monoliths," and the savings on mirror construction far outweigh the cost of more-powerful computing and denser actuators. The American telescope projects' transatlantic rival, the E-ELT, will use 1000 segments, Nelson notes. "Nothing can stop a good idea," he says with a grin.

**Big plans.** E-ELT would dwarf every other telescope on Earth.

## THE COLOSSUS OF EUROPE

With a 100-meter primary mirror, it would have been the big daddy of all telescopes, worthy of the label "Overwhelmingly Large" (OWL) bestowed by its architects at the European Southern Observatory (ESO). Now, astronomers joke that the acronym means "Originally Was Larger." Even so, the scaled-down successor that ESO has committed to building—the European Extremely Large Telescope (E-ELT)—would still outsize the U.S. entries in its class, the Thirty Meter Telescope and the Giant Magellan Telescope (see main text), by a fair margin, with a primary mirror 42 meters in diameter.

E-ELT's estimated cost of $1.5 billion also makes it the most expensive of the three. Its funding prospects, however, seem rosier than those of GMT and TMT because governments are backing it: The 14 member states of ESO have agreed to provide a third of the money over the next 10 years. To make up the difference, ESO members are discussing whether to increase their contributions to the ESO budget, attract outside partners, or do both, says Jason Spyromilio, director of the E-ELT project office.

The project's planners, who are currently finishing up a detailed design, want to build the primary mirror with 1000 segments about the same size as the hexagonal panels in TMT. Spyromilio says using a handful of larger monoliths between 7 and 8 meters in diameter could also have worked. "There is no a priori clear solution that would say one is better than the other," he says of the two designs. "The selection reflects the different risks that each project associates with its supply chain."

The resolution provided by E-ELT's collecting area of 1200 square meters—nearly twice that of TMT and three times that of GMT—will enable a lot of exciting science, says Spyromilio. "A nice example might be the power of imaging exoplanets. Here the E-ELT will achieve a contrast about an order of magnitude better than the next best telescope," he says, adding that E-ELT in principle will be able to detect exoplanets as small as Earth. Officials hope to pick a site for the telescope from among candidate sites in the Canary Islands, Chile, Morocco, and Argentina by the end of this year. **–Y.B.**

### Winner take all?

The race for telescopic supremacy began in 1999, when astronomers' decadal survey—an official rank-ordered "wish list" of proposed projects that researchers submit to the government—cited a giant telescope as a top priority. Nelson's group was first off the block, with a proposal for what was then called the California Extremely Large Telescope (CELT).

At first, the leadership at Carnegie Observatories mulled the idea of joining CELT. It was a controversial proposal. Carnegie Observatories and Caltech, both nurtured by George Hale and located 8 kilometers apart, had been managed jointly until 1971, when differences culminated in a divorce. Rivalry ran deep.

When Carnegie researchers approached astronomers at Caltech with an offer to collaborate on CELT, they were turned away, according to scientists on both sides who did not wish to spell out the details. Stung by the rebuff, researchers at Carnegie joined with other institutions to create what is now Angel's GMT consortium. "No question that we got going because the other group was making headway," says Stephen Shectman, project scientist for GMT and a researcher at Carnegie. Nelson and others on TMT acknowledge that they were less than thrilled to see GMT entering the arena. "They wanted to be the only U.S. project in this area," Shectman says.

Behind-the-scenes maneuvering followed. In 2003, TMT sent UC Berkeley astronomer Richard Ellis to the Harvard-Smithsonian Center for Astrophysics, a Magellan partner, to woo Harvard away from GMT and into TMT. Josh Grindlay, a Harvard University researcher who was involved in the talks, calls Ellis's visit "a political move … to squash the competition." Nelson is unapologetic. "Harvard's rich. We needed rich partners," he says.

Grindlay says some at Harvard were tempted but that loyalty to the Magellan consortium and confidence in the GMT proposal—"which really is simpler"—carried the day. Friends at Caltech still jokingly ask him if Harvard would like to join TMT, he says: "They say you might as well join us because there may not ever be a GMT."

Nelson's TMT scored a coup in June 2003 when it signed a technical agreement with a major users' group. The Association of Universities for Research in Astronomy (AURA),

CREDIT: EUROPEAN SOUTHERN OBSERVATORY

## THE TWO TITANS

### THE THIRTY METER TELESCOPE (TMT)

**PARTNERS:** University of California, Caltech, Association of Canadian Universities for Research in Astronomy

**PRICE TAG:** $1 billion

**PRIMARY MIRROR:** 30 m (492 hexagonal segments, 1.44 m each)

**ADAPTIVE OPTICS (AO):** Special instrument outside telescope

**LOCATION:** Mauna Kea, Hawaii

**FIRST LIGHT:** 2018

**FUNDING STATUS:** $200 million from the Moore Foundation; $100 million pledged by UC, Caltech; commitment by Canada to be a 25% partner; contribution expected from Japan

### THE GIANT MAGELLAN TELESCOPE (GMT)

**PARTNERS:** Carnegie Observatories, University of Arizona, Harvard, Smithsonian Astrophysical Observatory, Texas A&M, U Texas at Austin, Australian National University, Astronomy Australia Ltd., Korea Astronomy and Space Science Institute

**PRICE TAG:** $700 million

**PRIMARY MIRROR:** 24.5 m (7 monoliths, 8.4 meters each)

**ADAPTIVE OPTICS (AO):** Integrated into secondary mirror

**LOCATION:** Las Campanas, Chile

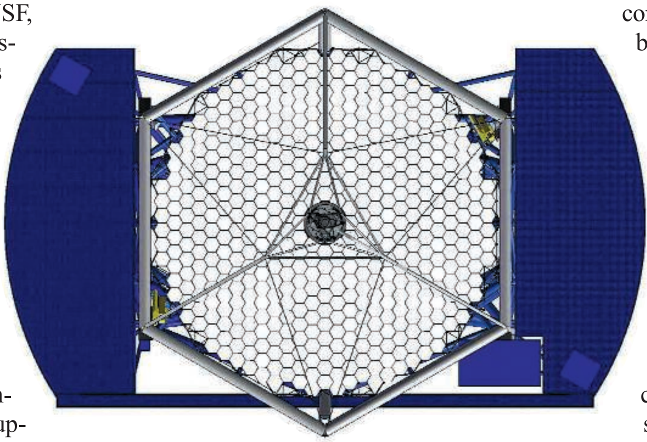
**FIRST LIGHT:** 2018

**FUNDING STATUS:** $72 million from Australia; > $120 million pledged by other partners

a consortium of some three dozen U.S. and international institutions that channels NSF funding to astronomers and facilitates access to observatories, nailed down terms of collaboration. The partnership seemed to bring TMT one step closer to NSF funding. Angel and his colleagues fired off a letter to AURA complaining that it was essentially picking a winner without an open competition.

In late 2006, on the advice of NSF, the TMT-AURA partnership was suspended. AURA has since served as the program manager for all technology development related to giant telescopes and has so far provided GMT and TMT with about $17.5 million each for design work. However, TMT is still lobbying AURA to resume the partnership, arguing that it is the more developed of the two projects and deserves exclusive NSF support. "[TMT's] board is concerned that NSF funding may not support timely substantial public participation in two US-led large telescopes and urges AURA … to examine carefully the merits and feasibility of advocating support for two large US telescopes in the context of the upcoming Decadal Survey," TMT board chair Henry Yang wrote in a letter to AURA in April 2008. The 2010 survey is expected to be completed by the middle of next year.

NSF officials won't comment on which project is ahead or what its plans are for supporting either telescope in the future. But it is keeping tabs on the progress of both. This summer, a panel appointed by AURA submitted community assessments of TMT and GMT to NSF. The reports do not go into a comparative analysis, but they suggest that TMT is further along. "We believe [TMT] will be ready within a few months for an NSF-led Preliminary Design Review, and could seek funding assistance from the NSF MREFC [Major Research Equipment and Facilities Construction account] in the near future," the panel writes. GMT, by contrast, needs to make "significant progress" in a number of technical and managerial areas to reach the same stage.



**Compound eye.** TMT's 30-meter mirror would consist of 492 tiles guided by computer to maintain a smooth parabolic surface.

SOURCE:TMT; GMT; CREDITS (TOP TO BOTTOM): JUPITERIMAGES; COURTESY OF TMT OBSERVATORY CORP./RENDERING BY TODD MASON

Wendy Freedman, director of the Carnegie Observatories and chair of the GMT board, acknowledges that the projects are at different stages but says the gap between them is more apparent than real. "We've concentrated on different things," she says. "They have completed their detailed design study, while we've cast the first mirror."

TMT also took an early lead in fundraising thanks to a $200 million gift from the Gordon and Betty Moore Foundation and a pledge by UC and Caltech to come up with another $100 million. "When you have a big pile of cash on the table, it shows that somebody has confidence that the thing is going to get built," says Michael Bolte, a UC Santa Cruz astronomer and a TMT board member. Canada has pledged 25% toward construction and operation, and Japan is interested, he says.

GMT has been working the international circuit as well. In July, the Australian government promised $72 million for the project. Korea is a partner, too, although the details of how much it would contribute are not available. "We're about a third of the way there," says Patrick McCarthy, director of the GMT consortium. But he is reluctant to provide a breakdown. Both sides have been aggressively courting China and India, McCarthy says, noting that E-ELT officials have been making similar trips.

Amid the scramble for funding and favor, one question looms: Is the game really winner take all? Does NSF have to choose one telescope at the end of the day?

Freedman believes it does not. One possibility, she says, would be for the agency to provide 25% of operating costs to both and guarantee a quarter share of observing time on both for the U.S. community. Furthermore, Angel says, differences between the two projects could lead to different kinds of science. TMT will scan the northern sky, GMT the southern; TMT's adaptive optics system may be better at resolving point sources, whereas GMT's system might produce better images of wider fields, making it more appealing for cosmology.

Nelson takes a hard line. "TMT is inevitable," he says. "I am just doing my job, making it happen." But even he won't entirely rule out a two-scope solution. "If you go back to 1980, you could easily have said, 'Oh, these telescopes are so expensive, they'll never get built'—and lo and behold, there are several 6- to 10-meter telescopes today that back then were the tiniest glint in a few people's eyes." He pauses, then adds: "So, maybe we'll build both." **–YUDHIJIT BHATTACHARJEE**