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Cosmic Vision

A new generation of giant telescopes will carry the eye to the edge of the universe.

By Timothy Ferris

When you start stargazing with a telescope, two experiences typically ensue. First, you are astonished by the view—Saturn's golden rings, star clusters glittering like jewelry on black velvet, galaxies aglow with gentle starlight older than the human species—and by the realization that we and our world are part of this gigantic system. Second, you soon want a bigger telescope.

Galileo, who first trained a telescope on the night sky 400 years ago this fall, pioneered this two-step program. First, he marveled at what he could see. Galileo's telescope revealed so many previously invisible stars that when he tried to map all of them in just one constellation, Orion, he gave up, confessing that he was "overwhelmed by the vast quantity of stars." He saw mountains on the moon—in contradiction to the prevailing orthodoxy, which declared that all celestial objects were made of an unearthly "ether." He charted four bright satellites as they bustled around Jupiter like planets in a miniature solar system, something that critics of the Copernican sun-centered cosmology had dismissed as physically impossible. Evidently the Earth was a small part of a big universe, not a big part of a small one.

And soon, sure enough, Galileo went to work making bigger and better telescopes. Large light-gathering lenses were not yet available, so he concentrated on making longer telescopes, which produced higher magnifying powers and reduced the halos of spurious colors that afflicted glass lenses in those days. Subsequent observers took the design of glass-lensed, refracting telescopes to great lengths, sometimes literally so. In Danzig, Johannes Hevelius deployed a telescope 150 feet long; hung by ropes from a pole, it undulated in the slightest breeze. In the Netherlands, the Huygens brothers unveiled lanky telescopes that had no tubes at all: The objective lens was perched on a high platform in a field, while an observer up to 200 feet away aligned a magnifying eyepiece and peered through it. Such instruments proffered fleeting glimpses of planets and stars that, like the dance of the seven veils, only aroused a burning desire to see more.

The reflecting telescope, pioneered by Isaac Newton, made it practical to gratify such desires: Mirrors required that only one surface be ground to gather and reflect starlight to a focal point, and since the mirror was supported from behind, it could be quite large without sagging under its own weight, as large lenses tended to do. William Herschel discovered the planet Uranus with a handmade reflecting telescope—he cast his metal mirrors in his garden and basement, and once had to flee from a coursing river of molten metal after the horse-dung mold fractured. Spiral-armed galaxies were first glimpsed through a massive reflecting telescope, with a six-foot diameter primary mirror, that Lord Rosse constructed on his estate in Ireland.

Today's largest telescopes have mirrors up to some ten meters (33 feet) in diameter, with quadruple the light-gathering power of the legendary five-meter Hale Telescope at Palomar Observatory in southern California. Looming large as office buildings, some of these giants are so highly automated that they can dust off their optics at sundown, open the dome, sequence and carry out observations throughout the night, and shut down come threatening weather, all with little or no human intervention. Yet humans, being human, still intervene a lot, if only to make sure nothing goes awry: To lose just one night's work at a big telescope these days is to squander as much as $100,000 in operating costs.

Three of today's largest telescopes—Gemini North, Subaru, and Keck—stand within hailing distance of one another atop the nearly 14,000-foot peak of Hawaii's Mauna Kea, an inactive volcano. The altitude puts them above 40 percent of Earth's atmosphere—and most of its water vapor, which is opaque to the infrared wavelengths the astronomers like to study—but also makes it difficult for the astronomers and engineers who work there to breathe and think. Many wear clear-plastic oxygen tubes in their nostrils as routinely as we might wear eyeglasses. Others rely on the body's ability to adapt but worry about making what they call a CLM, or "career-limiting mistake." "At altitude, we don't improvise; that would be a disaster," says Gemini astronomer Scott Fisher. "We're kind of trained monkeys up here. The real thinking goes on at sea level."

These big Mauna Kea observatories are comparably smart and costly, yet each exudes a distinct personality. The 8.1-meter Gemini telescope is housed in an onion-shaped silver dome ringed by a set of shutters that, when closed during the day, make the observatory look as ungainly as a fat man in an inner tube. But the shutters open at dusk to create an enormous set of windows, three stories tall and stretching nearly three-quarters of the way around the observatory, that let in the night air and happen to afford a panorama of the blue Pacific all the way to Maui and beyond. Gemini's four main digital detectors—cameras and spectrometers, heavy as cars and costing around five million dollars each—are attached to a carousel surrounding the telescope's focal point, where they can be rotated into place in minutes. Computers run the telescope by night, shuffling requested observations to make the most of every minute. "We're all about nighttime efficiency," says

Fisher.

The Subaru telescope's instruments are housed in alcoves like jeroboams of champagne in a heavenly wine cellar. (The comparison is not entirely fanciful; one leading Japanese astronomer propitiates the gods at the start of each Subaru observing run by pouring vintage sake on the ground outside the dome at the four points of the compass.) When a particular instrument is required, a robotic yellow trolley makes its way to the alcove, picks up the detector, ferries it to the bottom of the massive telescope, and locks it in place, attaching the data cables and the plumbing for the detector's refrigeration system. Subaru happens to be one of the few giant telescopes that anybody has ever actually looked through. For its inauguration in 1999, an eyepiece was attached so that Princess Sayako of Japan could have a look through the scope, and for several nights thereafter eager Subaru staffers did the same. "Everything you can see in the Hubble Space Telescope photos—the colors, the knots in the clouds—I could see with my own eyes, in stunning Technicolor," one recalled.

Keck consists of two identical telescopes. Both have ten-meter mirrors made of 36 segments; with its support structure, each segment weighs close to a thousand pounds, costs close to a million dollars, and would suffice to create a fine, university-grade telescope on its own. The telescopes' "tubes" are spindly steel skeletons that look as delicate as spiders' webs but are more precisely configured than a racing sloop's rigging. "We use the telescope's mission to motivate ourselves," one Keck astronomer told me. "If a little wire or something is found intruding into the optical path, we think, If the light has been traveling through space for 90 percent of the history of the universe, and it got this close to the telescope, we'd better make sure it gets the rest of the way."

Few of the astronomers awarded time on the big telescopes actually go there to observe anymore. Most submit their requests electronically—on a recent night at Gemini, the scheduled projects ranged from "Primordial Solar System Masses" to "Magnetic Activity in Ultracool Dwarfs"—and the results are sent back to them. Geoff Marcy, a modern-day Prince Henry the Navigator whose team has discovered more than 150 planets orbiting stars other than our sun, gets more observing time than most at Keck but has not been there for years. Instead, his extrasolar planet team observes from a remote operating facility at UC Berkeley. During observing runs, Marcy reports, "we settle into a routine of working all night. We have all our books and other resources here at hand, plus enough normal life so our spouses don't forget us."

In addition to their unprecedented light-gathering power, today's big telescopes benefit from their adaptive optics (AO) systems, which compensate for atmospheric turbulence. The turbulence is what makes stars glitter; telescopes magnify every twinkle. A typical AO system fires a laser beam into a thin layer of sodium atoms 56 miles high in the atmosphere, causing them to glow. By monitoring this artificial star, the system determines how the air is churning and adjusts the telescope's optics more than a thousand times each second to compensate. Gemini pays a pair of students ten dollars an hour to sit outside the dome all night, walkie-talkies in hand, ready to warn the astronomers to turn off the laser should an airplane approach. "It's incredible to see in practice," says Scott Fisher. "When the AO system is off, you see a nice, pretty star that looks a little fuzzy. Turn the AO on, and the star just goes *phonk!* and collapses to a tiny point."

Objects in the night sky are measured in degrees, the full moon spanning about one half of a degree. Without AO, a powerful telescope on a fine night can perceive objects separated from each other by as little as one 3,600th of a degree, or one arc second. Thanks to Keck's AO system, UCLA astronomer Andrea Ghez was able to make a motion picture of seven bright stars whirling around the invisible black hole at the center of our galaxy over a period of 14 years: The entire movie takes place *inside* a box measuring only one arc second on a side. Based on the frenzy of the stars in the grip of the black hole, Ghez calculated that it has a mass of four million suns, generating enough gravitational force to slingshot some stars that pass too close right out of our galaxy. Several such hypervelocity stars have been located, speeding off toward the depths of intergalactic space like party crashers ejected from an exclusive nightclub.

What's next? Even bigger telescopes, of course, with the capability to shoot cosmic pictures faster, wider, and in even greater detail. Among the behemoths due to come on line within a decade are the Giant Magellan Telescope, the Thirty Meter Telescope, and the 42-meter European Extremely Large Telescope—a scaled-down version of the 100-meter Overwhelmingly Large Telescope, which was tabled at the planning stage when its projected budget turned out to be overwhelming too.

Particularly innovative is the Large Synoptic Survey Telescope, or LSST, whose 8.4-meter primary mirror was cast last August in a spinning furnace under the stands of the University of Arizona Wildcats' football stadium in Tucson. (The rotation technique produces a mirror blank that is already concave, reducing the amount of glass that must be ground away to bring the mirror to a proper figure.) Conventional telescopes have narrow fields of view, typically spanning no more than half a degree on a side—much too narrow to take in the enormous patterns that grew out of the big bang. The LSST will have a field of view covering ten square degrees, the area of 50 full moons. From its site in the Chilean Andes, it will be able to image galaxies far across the universe in exposures of just 15 seconds each, capturing fleeting events to distances of over ten billion light-years, 70 percent of the way across the observable universe. "Since we'll have a big field of view, we can take a whole lot of short exposures and—*bang, bang, bang, bang*—cover the entire visible sky every several nights, and then repeat," says LSST Director Tony Tyson. "If you keep doing that for ten years, you have a movie—the first movie of the universe."

The LSST's fast, wide-angle imaging could help answer two of the biggest questions confronting astronomers today: the nature of dark matter and of dark energy. Dark matter makes its presence known by its gravitational attraction—it explains the rotation speed of galaxies—but it emits no light, and its constitution is unknown. Dark energy is the name given to the mysterious phenomenon that, for the past five billion years, has been accelerating the rate at which the universe expands. "It's a little bit scary," says Tyson, "as if you were flying an airplane and suddenly something unknown took over the controls."

The LSST could help solve these immense riddles thanks in part, oddly enough, to the science of acoustics. The big bang was *noisy*. Although sound cannot propagate through the vacuum of today's space—as pedants are fond of reminding the directors of science-fiction films—the early universe was a thick plasma and as alive with sound as a drummers convention. Certain tones resonated in the primordial plasma, like the tones of struck wine glasses, and these harmonies, etched into sheets of galaxies that today shamble across billions of light-years, contain precise information about the nature of dark matter and dark energy. If astronomers can map these large-scale structures accurately, they should be able to identify the signatures of dark matter and dark energy in the big bang's harmonics. The Sloan Digital Sky Survey, a pioneering wide-angle study, captured some of this information when it mapped the sky from 1999 through 2008. The LSST is designed to go much deeper into cosmic space. It may not resolve the mysteries, but, predicts Tyson, "it will go a long way toward showing what dark energy and dark matter aren't."

The LSST's photographic "speed" will also give astronomers a better look at events too short-lived to be readily studied today. Most astronomers, even amateurs using backyard telescopes and off-the-shelf digital cameras, regularly record fleeting events of unknown origin. You take a series of digital exposures, and in one of them a spot of light appears where none was before or after. It may have been a cosmic ray hitting the light-detection chip, a high-velocity asteroid hurtling through the field of view, or a blue flare on the surface of a dim red star. You just don't know, so you shrug and move on. Because the LSST will take so many repeat exposures of the entire sky, it could resolve many such riddles.

Tomorrow's enormous telescopes will do as much in one night as today's do in a year, but that will not necessarily render the older telescopes obsolete. When the giants come on line, says Scott Fisher, "the Geminis of today will become the telescopes that get to go out and do the surveys," finding interesting phenomena for the largest scopes to investigate in detail. "It's like a pyramid, and it feeds both ways: When a really big telescope finds something exciting that we can't spend every night observing, the astronomers can apply for time on a smaller telescope to, say, check it out every clear night for a year and see how it changes over time."

Orbiting space telescopes are opening up another dimension. NASA's Kepler satellite, which launched in March 2009, is methodically imaging the constellation Cygnus, looking for the slight dimming of light caused when planets—some perhaps Earthlike—transit in front of their stars; Geoff Marcy's team will then use Keck to scrutinize stars flagged by Kepler to confirm that they have planets. In the future, pairs of mirrors deployed in orbit and linked by laser-ranging systems could attain the resolving power of telescopes measuring thousands of meters across. One day, observatories sitting in craters on the far side of the moon may probe the universe from surroundings ideally quiet, dark, and cold. The coming combination of smart satellites talking to big, increasingly automated ground telescopes, themselves linked together by fiber-optic networks and employing artificial intelligence systems to search out patterns in the torrents of data, suggests a process as much biological as mechanical, akin to the evolution of global eyes, optic nerves, and brains.

Film directors like to say that each movie is really two movies—the one you make, and the one you say you're going to make while raising the money. The point is that nobody can accurately predict the outcome of any genuinely creative venture. The same is true of scientific discovery: Scientists can explain what they expect to accomplish with bigger and better telescopes, but such predictions are mostly just extrapolations from the past. "If you're going to Washington to seek funding for a new telescope and you make a list of what you'll see through this new window on the universe, you know that the most interesting thing it will discover is probably not on your list," says Tyson. "It's likely to be something totally new, some out-of-the-box physics that's going to blow our minds."

The marvelous model of the big-bang universe pieced together in the 20th century arose largely from just such unanticipated discoveries. Edwin Hubble discovered the expansion of the universe accidentally, at the telescope: Cosmic expansion had been implied by Einstein's general theory of relativity, but Hubble knew nothing of the prediction, and not even Einstein had taken it seriously. Dark matter was discovered accidentally; so was dark energy. A telescope doesn't just show you what's out there; it impresses upon you how little you know, opening your imagination to wonders as big as all outdoors. "The spyglass is very truthful," said Galileo.