Liquid Astronomy

Eagle Gamma

The Large Zenith Telescope's mercury mirror provides critical insights for next-gen instruments.

Deep within the forests of British Columbia, on a granite outcrop atop a hill, sits a hidden gem — a shining pool of mercury. At 6 meters in diameter, the Large Zenith Telescope (LZT) ranks among the world's largest scopes. It's also the largest of a unique type of instrument: the liquid-mirror telescope.

After a long trek through tranquil forests — surrounded by scents of western red cedar and sights of sprawling woodland growth — it feels surreal to stand next to the cool, clear primary "mirror," like stumbling on a spaceship in a fairy tale. A thin layer of mercury mere millimeters deep rests on a dish designed to minimize the volume of liquid. This dish spins the mercury at a constant speed of 8.5 revolutions per minute, creating a smooth, highly reflective parabolic surface. (Stir a cup of coffee with circular motions, and you'll see a similar valley form in the center.) When united with corrector lenses and other telescope hardware, the immense mirror works like a conventional scope.

PAUL HICKSON / UNIVERSITY OF BRITISH COLUMBIA

The Large Zenith Telescope sits in the University of British Columbia's Malcolm Knapp Research Forest, about 50 kilometers (30 miles) east of Vancouver.

This unique instrument is clearing the way for other incredible technology. Researchers are using studies of Earth's atmosphere undertaken with the LZT to design the next generation of superscopes, particularly the proposed Thirty Meter Telescope and the 39-meter European Extremely Large Telescope. Liquid-mirror telescopes might also be the inexpensive solution astronomers need in order to pursue survey work that eats up valuable time at conventional observatories.

Simple Has its Perks

Paul Hickson (University of British Columbia, Canada) built and directs the Liquid-Mirror Observatory, the home of the LZT. He leads the world in designing these exotic telescopes. A clever, acute man with a sense of adventure, Hickson also flies and builds experimental aircraft, and his telescope's design has influences from aerospace.

When it came time to build the Liquid-Mirror Observatory, his team surveyed several candidate sites within reach of the university — looking at weather statistics and maps, flying overhead, and driving around by Jeep. They selected this forest sanctuary, far away from city lights, over several other locations.

The LZT has a relatively tiny price tag. Large conventional telescopes cost many millions of dollars to build, and tens of thousands of dollars per night to operate. That's orders of magnitude more than the Liquid-Mirror Observatory, which was built for half a million dollars. Canadian physicist Ermanno Borra (Laval University), pioneer of liquid-mirror telescopy, thinks that cost is the essential advantage of these instruments.

"It's something like a factor of 100, the difference in the cost of the mirrors," he says. "It's really very, very inexpensive."

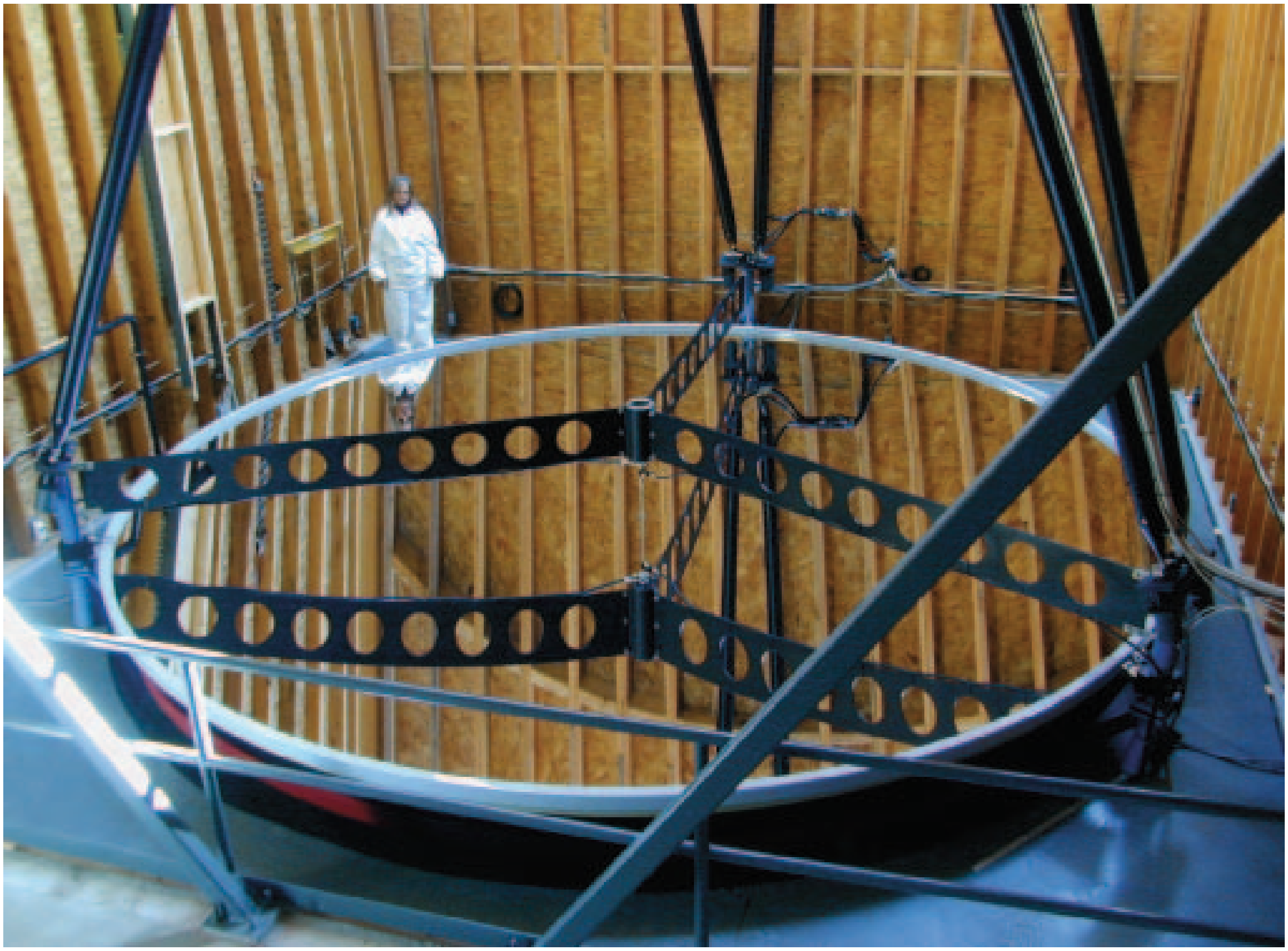
The same simplicity that makes liquid-mirror telescopes so affordable also results in excellent optical quality. The LZT produces astronomical observations with resolutions comparable to a conventional telescope of similar size, and it observes stars and distant spiral galaxies at around the atmospheric resolution limit. Because a fluid naturally flows to a smooth shape, liquid mirrors achieve impeccable optical quality far more easily than polished glass, with the potential to produce a perfect mirror.

That perfection depends on finely tuned hardware. A display in the control room shows variations in the rotational speed of the spinning mirror: nine parts of error per million. When Hickson first built the mirror, he measured the rotational error at 1,000 parts per million. The ensuing jitters set mercury sloshing, destroying the reflected images.

How Liquid-Mirror Telescopes Work

Isaac Newton first described the rotating-fluid concept that makes the liquid-mirror telescope possible. When a liquid spins at a constant speed, the combination of gravity and rotational acceleration finds a dynamic equilibrium that makes the top surface of the fluid form a smooth parabolic shape. The paraboloid arises because a liquid surface always forms its local surface perpendicular to the net acceleration it experiences. In the case of a spinning mirror, the net acceleration becomes stronger and more inclined with distance from the spin axis at the mirror's center.

Put a camera at the focal point of the paraboloid, where the reflecting surface focuses light into a single point, and you have yourself a liquid-mirror telescope.



Mercury vapors from the Large Zenith Telescope can be dangerous during the first hours after its setup. But oxidation soon prevents vapor emission, and after a day or so gas masks are unnecessary.

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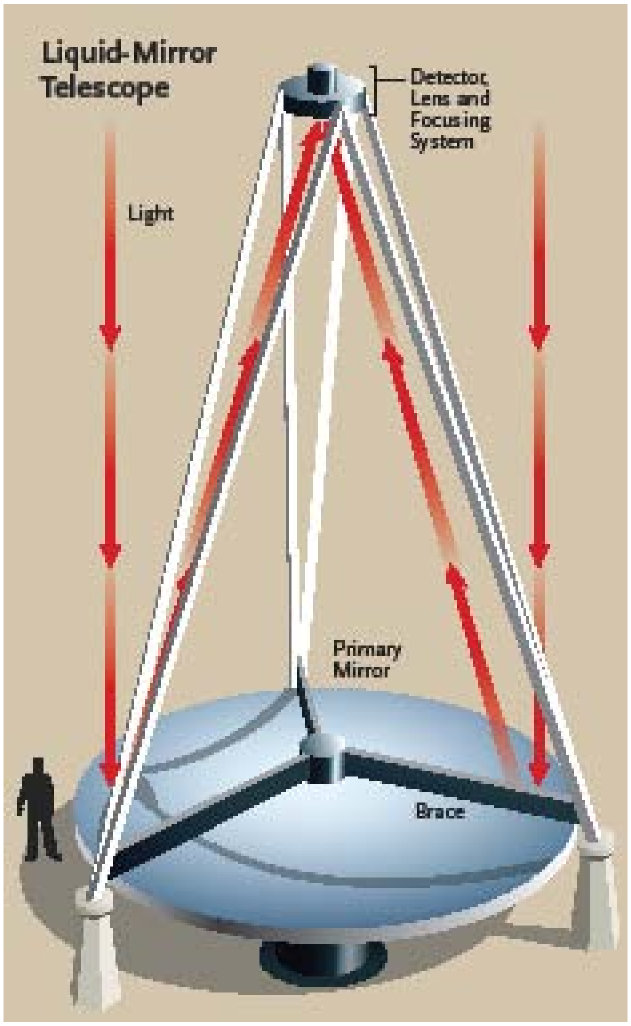

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A liquid-mirror telescope's defining trait is its rotating primary mirror. Paired with correcting lenses and a detector, the parabolic liquid surface becomes an inexpensive large-aperture scope.

Hickson added an optical encoder that measures angular movement, allowing better control. He also installed an optically clear cover of Mylar film, only a few microns thick, that sits a few centimeters above the mercury and rotates with the mirror. This cover protects the liquid from wind blowing in through the open roof and also prevents the formation of small vortices in the air above the moving liquid, which create tiny waves that degrade images.

As the name implies, the Large Zenith Telescope only sees the portion of the sky directly above the observatory: tipping the mirror would spill the mercury, so the liquid mirror must face straight up. Researchers get around the limitation somewhat by "drift scanning," delaying the CCD's readout to match the sky's drift speed and allow for artificial tracking. But liquid-mirror telescopes still only serve for astronomical studies that do not require steering. The observatory sits at a latitude of 49°, which means that as Earth rotates, the telescope observes a strip of sky at 49° declination. Such zenith strip surveys are useful for a variety of scientific pursuits, ranging from cosmology to the detection of supernovae.

The LZT currently pursues none of these science projects, though. It has a far greater demand on its time: guiding astronomers in designing the upcoming gargantuan telescopes by studying sodium in the atmosphere.

Solving the Sodium Problem

A new generation of so-called "extremely large telescopes," such as the Thirty Meter Telescope and the European Extremely Large Telescope, have major design challenges to tackle. The telescopes will house primary mirrors three to four times the diameter of today's largest optical telescopes. Huge mirrors make it possible to get large, sharp, intense images — yet that very same sensitivity subjects the telescopes to atmospheric distortions

PAUL HICKSON / UNIVERSITY OF BRITISH COLUMBIA (2)

The liquid mirror's construction began with its large supporting steel trusses (*left*). Over these went segments made of a composite of fiberglass, foam, and epoxy (*above*).

that smaller instruments don't notice. Optical sensitivity grows proportionally with the diameter to the fourth power, which means that increases in size have dramatic impacts on scopes' abilities.

One particular challenge facing the upcoming giants is their adaptive optics. Adaptive optics systems compensate for the atmosphere's blurring effects by distorting the shape of a telescope's secondary mirror. At some observatories, astronomers map these atmospheric changes by beaming a laser into the mesophere's sodium layer, effectively creating a bright fluorescent lamp in the sky that acts as a "guide star." The secondary mirror then adjusts its shape rapidly and repeatedly — sometimes more than 1,000 times per second — in order to match the distortions in the atmosphere detected from the laser guide star. Large ground-based telescopes require adaptive optics to perform better than the seeing limitation imposed by Earth's atmosphere.

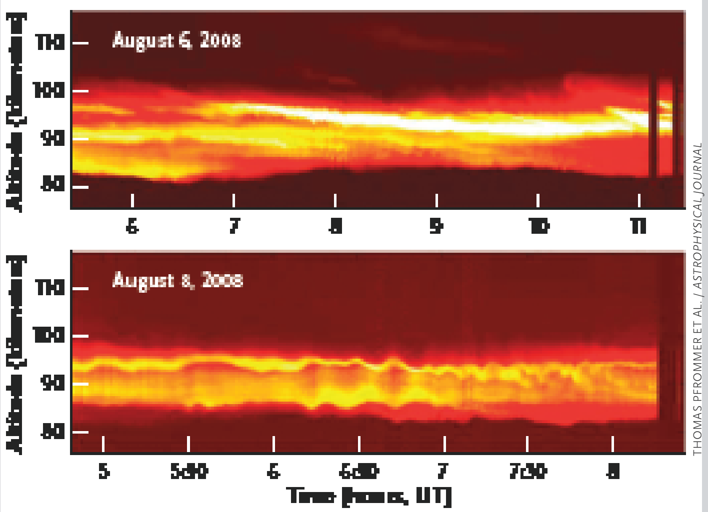
The sodium layer consists of several distinct levels, varying in density and altitude. Ocean-like waves roll along the entire layer, and turbulence induces variability. These irregularities, coupled with changes in the entire layer's average altitude, change the structure and distance of guide stars, confusing the adaptive optics system. Even five meters of variation in the sodium layer's altitude can affect the system.

"If a meteor trail occurs in the middle of an observation, it can change the average range to the sodium layer by a hundred times that much, or more," says Brent Ellerbroek, department head of instrumentation for the TMT. The consequent error would be bigger for larger telescopes, increasing with the square of the diameter. Such errors would wreak havoc on the behemoths' observations. "So it's very important to understand how the sodium layer is evolving in time."

Scientists had come to this conclusion by extrapolating from data taken on timescales six orders of magnitude longer than those on which adaptive optics operate. To verify that the sodium layer would behave on small scales as they thought it would — before building the billion-dollar observatories — the scientists needed a way to measure the actual variations of atmospheric sodium density at a fine enough resolution to correct for any errors. The best existing data in the world would not do.

It turns out that the LZT can collect precise enough data to resolve the problem. During a lull created by a broken camera sensor, Hickson and one of his graduate students installed a laser at the facility. The laser effectively turned the observatory into the world's largest test bed for "lidar," or light radar, the laser technique used to create guide stars.

Using lidar, the LZT picked up never-before-seen eddies and vortices in the sodium layer, as well as details of both its structure and dynamics. Observations have also revealed the first detection of turbulence waves in the mesosphere — curling licks of sodium that interact chaotically with neighboring layers of the atmosphere.



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The atmosphere's sodium layer varies over time. Two nights of observation by the Large Zenith Telescope show multiple, transitory layers, with densities, altitudes, and structures that evolve over time. The brightest layers are about two to three times denser in sodium than the background. The dark vertical bars are from aircraft interruptions.

Ellerbroek lauds the unique situation that such a large telescope can be devoted to lidar studies. The LZT has 100 to 500 times the collecting area of other lidar systems, he says, and its incredible sensitivity enables measurements with resolutions in meters and on timescales of much less than one second.

"For an 8-meter telescope that's not important," he says. "But for future 30- to 40-meter telescopes, under-

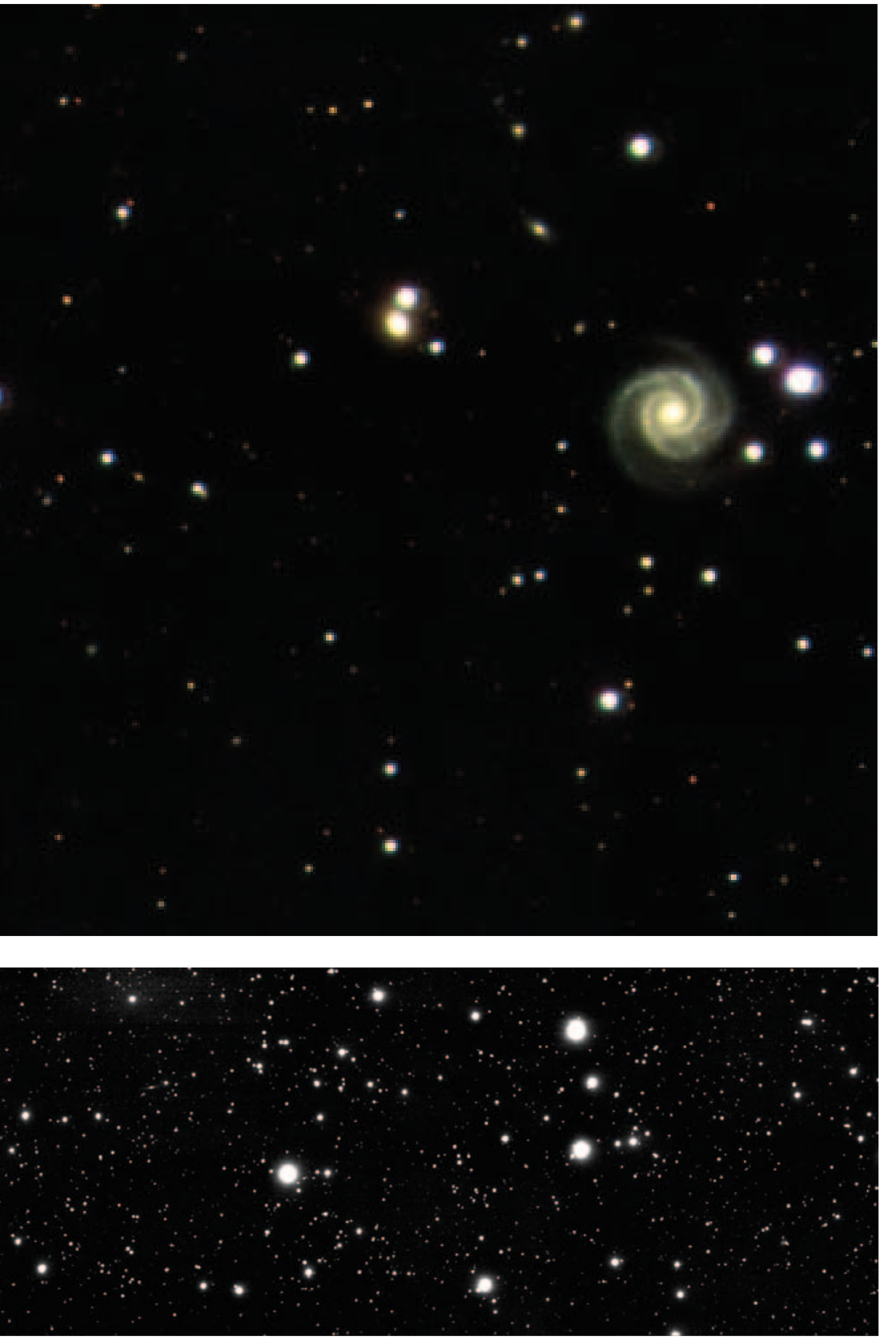
Brief History of Liquid-Mirror Telescopes

Despite coming up with the rotating-fluid idea, Newton apparently did not consider a telescope based on a liquid paraboloid. The concept went through several periods of development and dormancy. In 1982 Ermanno Borra revived the idea and soon realized, in his words, "Whoa, wait a second, you can do science with that!"

In 1994 he and Hickson built a successful 2.64-meter telescope. After that, Hickson created a series of mirrors, enhancing the size and performance with each iteration. At first he essentially worked out of his garage, building liquid mirrors for North American universities. Then NASA found out about his work and contacted him. The agency wanted a large, affordable telescope — both of which describe liquid-mirror scopes. Hickson built a 3-meter mirror for a device housed at NASA's Johnson Space Center in Houston. NASA later moved the scope to the Orbital Debris Observatory, in the Lincoln National Forest of New Mexico. The telescope collected data on space debris for many years, earning a NASA Group Achievement Award. Some surplus NASA components made their way into the Large Zenith Telescope.

standing how the range to the sodium layer changes on that timescale becomes important."

Ellerbroek says that he and his colleagues use the LZT's lidar data to design the wavefront-sensing equipment they'll use on the TMT, even to determine what kind of lasers they need to buy. "We're actually able to input this data into simulations of the adaptive optics systems, then predict how well the components we're designing and buying will work with the sodium layer as we understand it," he explains. A carefully planned adaptive optics system will give the TMT three or four times better resolution than one of the Keck telescopes on Mauna Kea, which are among the world's premier ground-based visible and near-infrared telescopes and the standard by which others are measured. "It's going to have a dramatic impact on the types of observations that can be done."



PAUL HICKSON / UNIVERSITY OF BRITISH COLUMBIA (2)

The 6-meter f/1.50 Large Zenith Telescope can observe objects fainter than magnitude 25. These images are from its perpetual view of declination 49° 16′.

Futuristic Scopes

The LZT may herald a new wave of liquid-mirror telescopes, even though this particular scope will not immediately contribute to astronomical research. Hickson says that they chose the observatory's site because it's a good location for testing and developing liquid-mirror technology, but the site sees few clear nights. Good weather comes mostly in the short summer nights.

"Our aim all along was to put one of these telescopes at a competitive astronomical site once the technology had been perfected," he says.

One of these future instruments, the 4-meter International Liquid Mirror Telescope, was developed independently from the LZT but has benefited from knowledge gleaned from its forest counterpart. The ILMT is being installed at Devasthal in the Himalayas, a high-altitude site already home to two observatories.

Bigger dreams include a network of mirrors reminiscent of the Atacama Large Millimeter/submillimeter Array in Chile. Moreover, a few years ago Hickson and Borra contributed to a proposal to place a telescope of ionic liquid (basically, molten salt) as large as 100 meters in diameter on the Moon. The innovative technology, including superconducting bearings and a cryogenic vacuum, would allow astronomers to observe the early universe at higher resolutions and fainter magnitudes than the upcoming James Webb Space Telescope (*S&T*: January 2010, page 24). Even a much smaller Moon-based liquid mirror would be a useful survey instrument to follow up on JWST's observations.

Borra also proposed that technological developments in future decades might allow scientists to launch an orbiting liquid-mirror telescope as large as one kilometer across. "It was propelled by a solar sail," he says. "It was really a monster."

The space proposals received serious consideration: at the time (before the cancellation of the Constellation program) NASA thought that the 100-meter mirror would be a major reason for going back to the Moon, Borra says. Despite changes in NASA's focus, Borra thinks that the gigantic lunar liquid-mirror telescope will one day see first light.

In the meantime, astronomers' next-gen scopes will stand on the shoulders of a shining pool of mercury in the forests of British Columbia. ✦

Freelance writer ***Eagle Gamma*** *covers adventurous science, particularly discoveries in astronomy and optics.*