

The Large Zenith Telescope is a liquid mirror telescope that uses a 6-m-diameter rotating container filled with a thin layer of mercury.



The International Liquid



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This year, the International Liquid Mirror Telescope—a collaboration between astronomical institutions in Belgium, Canada and India—will see first light. The instrument will provide substantial, in-depth sky coverage and make an unprecedented number of nightly observations.



NASA/Photo by Paul Hickson (University of British Columbia)

Mirror Telescope



Scientists have known since Newton's time that the surface of a spinning liquid takes the shape of a paraboloid. However, it wasn't until two centuries ago that an astronomer—the Italian Ernesto Capocci—suggested using a rotating container filled with mercury as the primary mirror of an astronomical telescope. At that time, the concept was not taken seriously, primarily because a mercury mirror cannot be tilted to track moving objects.

Because of the Earth's rotation, astronomical objects would produce streaks instead of images on the photographic plates used in astronomy until the late 20th century. The advent of charge coupled devices (CCDs) in the 1970s changed the situation. CCDs enable a technique, called time-delayed integration (TDI), to compensate for the rotation of the Earth. This is done by electronically moving the electronic charges on the surface of the CCD at the same speed as the image drifts in the focal plane of the telescope, thereby yielding sharp images. TDI has revived scientific interest in liquid mirrors (LMs), which are considerably less expensive to build and operate than glass mirrors.

Starting in the early 1980s, scientists have been engaged in significant development work in the laboratory and observatories. Researchers at Laval University demonstrated the feasibility of large liquid optics and developed the basic technology behind it. Optical shop tests of liquid mirrors with diameters as large as 2.5 m have shown diffraction-limited optical quality.

Several telescopes have also been built and operated, starting with a 2.7-m diameter LMT at the University of British Columbia that was used for two observing seasons. The practical experience that scientists gathered from this first-generation observatory was incorporated in the NASA Orbital Debris Observatory (NODO), which used a 3-m-diameter LM to observe space debris. NODO, which was successfully operated for six years, yielded a wealth of data. Although it was not optimized for astronomical observations, NODO was nonetheless used to obtain more than 100 nights of astronomical data, resulting in published astronomical research.

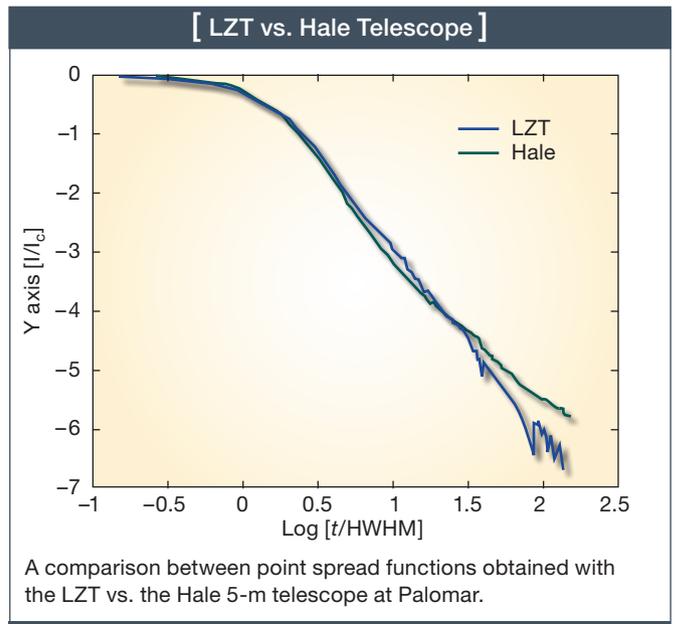
One of the more recent LMTs is the Large Zenith Telescope (LZT) built at the University of British Columbia. It employs a 6-m-diameter liquid mirror and is now in routine operation. The point spread function of the LZT closely follows a Kolmogorov atmospheric seeing profile, and detailed analysis confirms that the mirror is diffraction-limited.

Liquid mirrors play an important role in other areas of science besides astronomy. For example, atmospheric scientists are using mirrors for lidar applications. The University of Western Ontario (UWO) and UCLA have built world-class Rayleigh scattering lidar systems that use 2.6-m LMTs. These instruments have been in continuous routine operation for several years or longer (since 1993 for UWO). Recently, the LZT has been equipped with a high-performance sodium lidar system; this allowed the structure and dynamics of mesosphere and lower thermosphere to be studied with a resolution that is two orders of magnitude greater than previous studies.

For zenith-pointing telescopes, LMTs can deliver the same performance as solid mirrors, with much lower cost and greater simplicity of operation. Even though the 6-m-diameter mirror of LZT is the 14th largest optical astronomical mirror in the world (it would have been the largest one a quarter of a century ago), LZT is a relatively simple and inexpensive project. LMTs are low-maintenance instruments that can be operated in a semi-automated mode with minimal staff. Because they do not



An image obtained with the Large Zenith Telescope (University of British Columbia) shows faint stars and galaxies.



currently point and track, the telescope structure is simplified and no rotating dome is needed. The complex mirror support systems and tracking systems of conventional telescopes are eliminated. This reduces maintenance and greatly lowers operating costs.

The International Liquid Mirror Telescope

The International Liquid Mirror Telescope (ILMT) project is a scientific collaboration in observational astrophysics between the Liège Institute of Astrophysics and Geophysics (Liège University), the Royal Observatory of Belgium, the Aryabhatta Research Institute of Observational Science (ARIES, Nainital, India) and several Canadian universities (British Columbia, Laval, Montréal, Toronto, Victoria and York). It will allow the

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participants to develop, construct, install and operate a 4-m liquid mirror telescope at Devasthal, India.

The company AMOS (Advanced Mechanical and Optical Systems) at the University of Liège is fabricating the telescope. The mercury mirror has a 4-m diameter and a focal ratio of $f/2$. A CCD that is $4,000 \times 4,000$ pixels and operates over a 400- to 1,100-nm spectral range (also known as a 16-Mega-pixel CCD) will be positioned at the prime focus 8 m above the mirror. Since the primary mirror is parabolic, it requires a glass corrector to obtain a good image quality over a field of view that is approximately 30-arcminutes in diameter. No mercury vapors are generated by the telescope because the surface

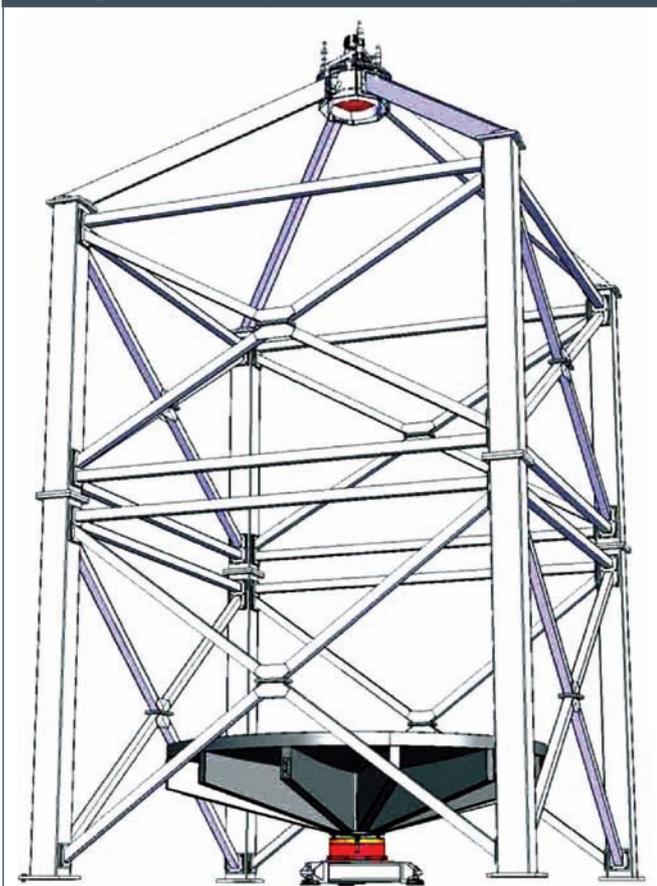
of mercury is covered with a thin layer of mercury oxide that prevents evaporation.

The CCD detector will operate in TDI mode, allowing a nightly integration time of 90 s, corresponding to the time an object's image remains within the active area of the detector. To reduce noise, the detector will be cooled to -50°C . The complete telescope will be protected by a building with a shuttered roof.

The Devasthal observatory is ideally located in latitude ($+29^\circ 23'$) to observe the North Pole of our Galaxy. From this site, a deep survey will cover approximately 90 square degrees at high galactic latitude—which facilitates studies of gravitational lensing and the identification of various classes of interesting extragalactic objects (cf. supernovae, clusters, etc.) as well as galactic ones (RR Lyrae stars, etc.).

The uniqueness of the ILMT survey resides in its depth (the faint magnitudes it will reach), substantial sky coverage and unprecedented number of nightly observations and total time of observation per object. While liquid mirror telescopes have been previously used for astronomical observations (e.g., the 2.7-m and the 6-m University of British Columbia and NODO LMTs), they were first-generation instruments that either were not optimized for astronomy or not located at high-quality astronomical sites. The ILMT has been developed specifically for astronomical research from a good astronomical site.

[Principal components of the telescope]



This sketch shows the components of the telescope pictured on p. 32 assembled together. The container is gray; the airbearing is red; the three-point mount (white) sits below the airbearing; and the vertical steel frames (white) hold the corrector and CCD detector at the top.

Astronomical research with the ILMT

Mercury LMTs cannot be tilted and therefore can only observe the strip of sky centered on the zenith. However, this limitation is not a handicap for the science drivers of the ILMT. The ILMT will use a high-quantum-efficiency CCD covering a 30×30 -arcminute field. As the Earth rotates, the detector thus scans a 30-arcminutes-wide strip of sky passing through the zenith of the observatory. In a year of observations, the half-degree-wide (equal to the apparent angular width of the Moon) strip of sky covers a total of 155 square degrees.

The CCD detector will give nightly integration times of about 90 s. The expected stellar blue magnitude limit per night is $B = 23.5$, and about $B = 25.8$ can be achieved over an observing season by co-adding nightly observations of the same regions. The telescope will scan a strip of constant declination equal to the latitude of the observatory. As the earth rotates and the seasons change, the telescope will scan a strip of constant declination moving in and out of the galactic plane and passing close to the north galactic pole. The strip of sky will thus sample a fair slice of the Universe.

We can estimate the number of extragalactic objects that one can observe in a strip of sky from number counts/square degree of astronomical objects gathered in the literature. We expect to detect roughly 1.5 million galaxies and 25,000 quasars with $B < 24$. This will allow the telescope to observe over 100 million galaxies to $B < 27$.

Gravitational lens studies with the ILMT

Given the small number of known multiply imaged quasars (fewer than 100), which are almost randomly distributed over the sky, the probability of observing even only one of these within the 30' zenith field of view of the ILMT is virtually zero. Therefore, the observational strategy for studies of gravitational lensing effects with the ILMT will be to first survey a narrow strip of sky as deep as possible (typically $B \sim 23.5$ per night). Gravitational lens candidates will be identified based upon their complex morphologies (several variable point-like components superimposed over an extended object, i.e. the lensing galaxy), easily recognizable by subtracting pairs of images taken at two different epochs with the ILMT. (This function is performed by the software during analysis.)

When a foreground galaxy (the macro-lens) produces multiple images of a background quasar, one would expect that time delays will become measurable between the light travel times of photometric variations of the quasar along the different trajectories. Such measurements offer a totally independent way of determining the value of the Hubble parameter or constraining the distribution of mass, including dark matter, of the lens.

In addition, those macro-images are usually seen through rather dense parts of the galaxy, and there is a good chance that one or several macro-images are affected by micro-lensing. The micro-lens is a star (or several stars) in the galaxy that acts as a magnifying lens with a very small "field of view" (typically on the order of one micro-arcsec) that produces an intricate network of micro-caustics. When the light beams coming from different regions of the source cross this network, they undergo different amplifications, according to their sizes and locations. The result is a differential amplification of the various components of the quasar that is detectable down to an angular resolution on the order of 10^{-6} arcsec.

From previously published studies of gravitational lenses, we have estimated that, for a flux-limited sample of quasars, down to the limiting magnitude $B \sim 23.5$ achievable with the ILMT, the expected number of multiply imaged quasars should exceed 50. More detailed studies of these will be achieved thanks to the steerable 3.6-m Devasthal Optical Telescope equipped with a spectrograph that will be erected very near to the ILMT.

Searching for supernovae

Because one will observe the same objects passing through the zenith night after night, time-resolved data are a natural byproduct of the survey. Indeed, that information will



The container of the ILMT with the frame of the telescope in the background.



The container of the ILMT holds the reflecting liquid. It rests on an airbearing mount.



The ILMT's airbearing, which rests on a three-point mount.

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arguably be the ILMT's most unique scientific contribution. To show this power of the ILMT survey, consider a classical project concerned with measurements of the cosmological parameters.

Right now, the astronomical community is intensely interested in determining the cosmological parameters with Type Ia supernovae because they give standard candles that can be used to solve cosmological problems. A single nightly pass with the ILMT can detect a Type Ia supernova (SNIa) near maximum light to a redshift $z = 0.8$. Binning six nights would allow us to improve the signal-to-noise ratio and observe useful light curves to $z = 1.0$. Using known SNIa rates, we expect ILMT to find and measure light curves for about 1000 SNIa per year having $0.3 < z < 0.5$ and 8000 to $z = 1$.

By comparison, with classical telescopes, it has taken more than a decade for several teams of astronomers to gather data on less than 1,000 Type Ia supernovae, mostly using rudimentary light curves. The ILMT survey will obtain several tens of thousand light curves in a few years, allowing us to study and understand the characteristics of the sample, including extinction and light-curve-dependent luminosity effects. (Extinction refers to absorption and the reddening effect caused by the interstellar and intergalactic medium.) Such an understanding is crucial in order to avoid errors. The data will allow us to study the velocity field and peculiar motions, and to create a map of the mass distribution of the Universe. ILMT will also detect tens of thousands of type II supernovae per year. Type II supernovae are core-collapse objects that occur as the final death throes of very massive stars.

In addition to supernovae, the survey is expected to produce an unprecedented sample of variable stars and extragalactic objects. Two main scientific goals of the project are to understand the formation of galaxies and the evolution of clustering of galaxies.

The history of astronomy shows that, whenever a new type of telescope was introduced, unexpected discoveries follow. For example, radio telescopes heralded the discovery of quasars and pulsars. We expect that the ILMT will be subject to the same serendipity. ILMT will explore the synoptic frontier. This will be the first time that such a large telescope will observe the same region of sky, night after night, to faint limiting magnitude. ILMT will detect objects that flash or streak in the night. Expect the unexpected.

The ILMT will complement the forthcoming Large Synoptic Sky Survey Telescope (LSST). While the LSST will observe the entire sky, the ILMT will conduct an unbiased, ultra-deep, high-spatial-resolution, time-resolved survey of a single strip of sky, night after night. Observing always at the zenith, ILMT

will benefit from the best seeing and transparency conditions, and it will provide highly accurate photometric results. The ILMT will probe time scales of days to months with a precision that is not available to conventional telescopes.

We expect that ILMT will not be the end of LMT development, but rather the beginning. It will establish LMTs as competitive astronomical instruments. We plan to upgrade the facility by building additional telescopes, each of which will observe with a different filter. In the long term, LMTs promise to be more versatile than zenith telescopes. With further technological improvements, LMTs will be able to observe off-axis and track. This could be accomplished by tilting the mirror or with innovative off-axis corrector designs. Recently, the Laval laboratory has demonstrated a tiltable liquid mirror that uses a viscous liquid covered with a high-reflectivity coating made of silver nanoparticles. ▲

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