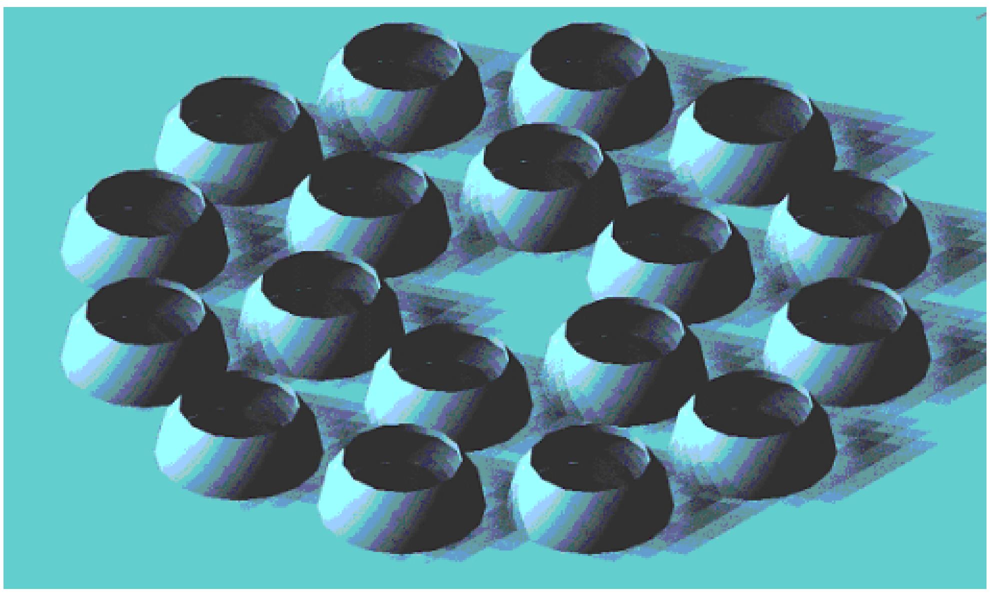
Large-Aperture Mirror Array



A 60-meter Optical-Infrared Deep Survey Telescope

LAMA

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By P. Hickson and K. Lanzetta	

1 Executive Summary

The Large-Aperture Mirror Array (LAMA) will be a 60-meter optical telescope designed to survey selected areas of the night sky with unprecedented sensitivity and clarity. With 7.5 times the angular resolution of the Next Generation Space Telescope and as much as 1000 times the sensitivity, it will be able study the formation and evolution of galaxies over 98% of the age of the universe, determine how and when most of the elements were produced, resolve the innermost regions of active galaxies and quasars, and detect and study the oldest stars in the Universe.

In order to achieve these goals at a modest cost, LAMA will employ three emerging technologies: liquid mercury mirrors, adaptive optics and optical interferometry. It will not be a universal facility, designed to serve the needs of all astronomy, but instead is designed to address a selection of highly interesting scientific questions with great power. It is this combination of new technology and a specific scientific focus that will allow LAMA to be built for less than a tenth the cost of competing projects.

The baseline design for LAMA uses 18 ten-meter diameter liquid mirrors to collect light and relay it to a central room where it is combined coherently on a detector. The array will be capable of tracking and imaging fields surrounding natural guide stars as they pass overhead. These fields will be observed night after night in order to increase the signal-to-noise ratio and to detect variable objects such as supernovae. Over the course of a year an area of sky comparable in size to that of the Hubble Deep Field but with 25 times the resolution and more than 100 times the depth.

2 Context

The current generation of 8 and 10 meter telescopes are extending the frontier of astronomical research. These telescopes form an essential compliment to the much smaller Hubble Space Telescope. Because of their large apertures, they are able to measure spectra for objects too faint to be measured by HST. With adaptive optics, ground-based telescopes can reach the diffraction limit at near-infrared wavelengths, providing higher resolution even than present and planned space telescopes. Impressive as this is, it is widely recognized that significant progress in many key scientific areas will require ground-based telescopes of much larger aperture. For this reason, the US Decadal Survey has called for a 30-meter class segmented mirror telescope to be built by the end of the decade.

Presently, several groups are actively planning telescopes with apertures in the 20-30 meter range. These projects include CELT (California Extremely Large Telescope) and MAXAT (Maximum Aperture Telescope), and NCFHT, a 20-30 meter replacement for the CFHT. They are expected to have costs on the order of $500M and take at least 10 years to complete. Conceptual studies are also underway for larger telescopes, such as the European 50 meter telescope and the 100 meter OWL (OverWhelmingly Large) telescope. It is generally believed that such telescopes would cost about $1B and be at least 15 years away.

No technology has been demonstrated that would enable conventional telescopes with apertures larger than approximately 30 meters to be built. However, we believe that it is possible to build a specialized telescope with an aperture exceeding this limit using the combined technologies of adaptive optics and interferometry and liquid-mirrors. Moreover, we believe that such a telescope could be built for a fraction of the cost of current 8 to 10 meter telescopes. This instrument, the Large Astronomical Mercury-mirror Array (LAMA) would be capable of resolution and sensitivity exceeding all present and planned optical telescopes for at least the next decade.

What tradeoffs are required to achieve this? LAMA would not point to any desired region of the sky, but rather would observe selected fields as they pass near the zenith. These same fields would be observed night after night, building up, over the course of a year, a very deep and sharp picture of the distant universe.

3 Science goals

Over the next two decades, many ambitious scientific programs will be undertaken, first with HST and 8-10 meter telescopes, then with the Next Generation Space Telescope (NGST) and possibly larger ground-based telescopes. Almost all of these high-priority programs can be addressed by the kind of observations that LAMA can conduct. Here, we briefly summarize some of the most exciting projects.

3.1 The first luminous systems

Observations of distant galaxies reveal that many of them contain old stellar populations. These stars must have been formed very early in expansion of the universe, perhaps in galaxies with redshifts as high as $z \sim 20$. The Hubble Space Telescope (HST) has detected a few very luminous galaxies with redshifts as high as $z \sim 6$ but this is clearly the limit for this small telescope. Most of the faint sub-millimeter sources detected by the James Clerk Maxwell Telescope do not have visible counterparts and are believed to be either at very high redshift, or obscured by dust.

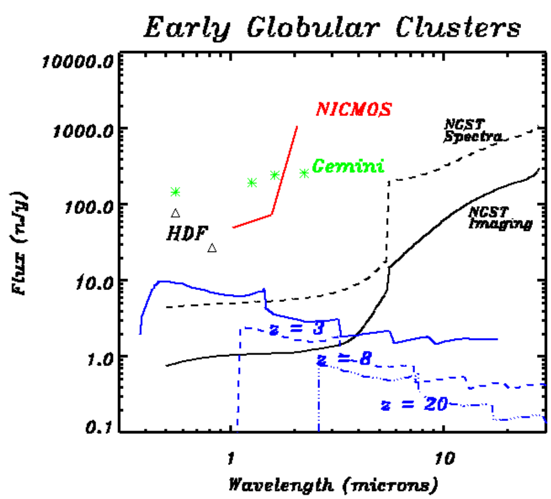

Figure 3.1. Predicted flux of early globular clusters (blue curves) for redshifts 3, 8 and 20. Detection limits for HST, NGST and Gemini telescopes are also shown. The detection limit for LAMA lies below the bottom of the graph (courtesy NGST Project).

The very first systems of stars that form in the universe should not be obscured by dust, as that is produced later by the evolution of these stars. We might therefore expect to detect them at near-infrared wavelengths. These first star-forming regions are expected to be very compact. To detect and study them requires both high resolution and great light gathering power. Theoretical estimates of the brightness of these first star-forming regions place them within the grasp of LAMA (Figure 3.1).

3.2 Galaxy formation and evolution from z ~ 20 to the present

HST and ground-based observations have shown that galaxies at moderate redshift ($z \sim 2$) are generally smaller and more fragmented that present-day galaxies. This is expected in the hierarchical clustering model, which predicts that galaxies are built up over time by merging of smaller galaxies. As Figure 5. illustrates, LAMA will not only detect these galaxies, but will be able to resolve them. It will allow us to study the process of assembly and evolution of galaxies over 98% of the age of the Universe.

3.3 The star formation history of the Universe

HST observations indicate that stars were forming at a more rapid rate in the past. As redshift increases, the star-formation rate, estimated from the ultraviolet flux) rises until $z \sim 2$ after which it has been reported to decrease. This result, if true, would be important in that it suggests that the bulk of the stars (and heavy elements) in the Universe formed fairly recently. These observations, however are in doubt because absorption of light by dust will reduce the observed ultraviolet flux. The amount of dust is highly uncertain.

There is a better way to approach this problem. The frequency of type II supernovae (those produced by explosions of massive stars) is directly related to the star-formation rate. The star formation rate can therefore be determined from the number of such supernovae that are detected as a function of redshift. LAMA will be able to detect type II supernovae to a redshift of at least $z \sim 6$ and thereby provide a definitive answer to this question.

3.4 The cosmological parameters

Type Ia supernovae have been shown to make very good "standard candles" which can be used to probe the expansion history of the universe. Two recent very extensive surveys have yielded about a half dozen such supernova at $z \sim 1$. These studies show evidence that the expansion of the Universe is accelerating, rather than slowing as would be expected due to the mutual gravitational attraction of normal matter. This acceleration, if confirmed, implies that about 70% of the mass of the universe is in some unknown and unseen form of "dark energy" which has repulsive gravity.

Observations of larger samples of supernovae at higher redshifts will provide a definitive measurement of the variation of the expansion rate. This in turn will constrain the properties of the putative dark energy.

3.5 The innermost regions of AGN and QSOs

Quasars or quasi-stellar objects (QSOs) are the most luminous objects in the universe (with the possible exception of fleeting gamma-ray burst explosions). Over time scales as long as hundreds of millions of years, they outshine entire galaxies. Yet, the source of this energy is a region no larger than the solar system, embedded in the center of a galaxy. Other galaxies show a milder form of emission of optical or radio radiation and often have collimated jets of matter emanating from their nuclei.

The only plausible explanation for these phenomena involves radiation and particle acceleration by a disk of matter orbiting a massive black hole. Such an accretion disk is expected to form whenever stars approach the black hole too closely and are torn apart by strong tidal forces.

Recent observations have convincingly shown that most large galaxies contain a black hole at their center, with masses ranging from millions to as much as a billion solar masses. Yet, most galaxies do not show signs of quasar activity. Evidently some other process is required to feed the black hole. Galaxy interactions are implicated as essentially all high-redshift quasars are observed to be located in small groups of interacting or merging galaxies.

What remains to be learned is the process by which black holes form, grow and feed. The best way to study this is by direct observation. However, since these objects only found at great distances, very high resolution is needed to observe the inner regions. LAMA will be able to resolve a region of size smaller than typical interstellar distances a distance of 50 Mpc – far enough to encompass many AGN.

3.6 The oldest and faintest stars

An important independent way to estimate the age of the Universe is to measure the age of the oldest stars. Old stars with mass comparable to that of the sun will by now have evolved to produce white dwarfs. By detecting old white dwarf stars located in globular clusters and measuring their temperatures, one can determine their ages. These stars are too faint to be detected by HST, and even NGST will have difficulty seeing them.

4 Conceptual Design

LAMA achieves the performance of a very large telescope by bringing together light from an array of many smaller telescopes. The simplest way to do this is to combine the light incoherently. The light gathering power is then equivalent to that of a telescope having the same total area as the array. The resolution achieved is equivalent to that of a single element of the array. Adaptive optics, on each telescope, would correct atmospheric seeing, giving angular resolution equal to the diffraction limit l / d, where l is the wavelength and d the diameter of an individual element.

A more ambitious goal is to combine the light coherently. This requires equalization of the optical path lengths from every telescope, and a phase tracking mechanism to maintain equality of the path lengths to within a fraction of a wavelength of light. Coherent beam combination allows the array to achieve a resolution l / D, where D is the diameter of the array, thereby providing better resolution. This translates into a gain in sensitivity for point-like or unresolved sources. Because the light is concentrated into a smaller image, the intensity of the image is boosted by a factor $(D / d)^2$ compared to the incoherent case. For the baseline LAMA design, this gives a sensitivity gain of a factor of 36.

A further simplification and cost saving arises if the telescopes are not required to point to arbitrary directions in the sky. For many reasons, the best direction for a telescope to point is directly overhead. In the zenith direction, atmospheric turbulence and absorption is minimum and dispersion is essentially zero. This last consideration is an important one. For a 30-meter telescope imaging a field 45 degrees above the horizon through a standard blue broad-band filter, atmospheric dispersion will spread the light from a point source into a spectrum 120 times larger than the diffraction limit!

Pointing near the zenith allows great simplifications of the primary mirror mounting system, the telescope structure, and the enclosure. The path-length equalization system is also simplified as the maximum path length differences are an order of magnitude lower than in other optical interferometers, such as those employed by the Keck and VLT telescopes.

A third simplification and cost saving comes from the use of liquid-mirrors. The cost per unit area of a liquid mirror is approximately one twentieth of that of the best alternative technology (thin actively-supported segmented glass mirrors), yet the performance (for near-zenith-pointing observations) is comparable. Liquid mirrors of 3-meter aperture have been in regular use for astronomy, space and atmospheric science for more than 5 years. Testing of a 6-meter liquid-mirror telescope will soon begin at UBC. It now appears feasible to extend the 6-meter technology to a 10-meter.

We are thus lead to the *baseline LAMA design*: Eighteen 10-meter liquid-mirrors forming a coherent 60-meter telescope. The mirrors are arranged in two concentric rings as shown in Figure 4.1. Light collected by the individual liquid-mirrors is directed, by means of secondary and tertiary mirrors, to a central room. This room contains the adaptive optics, path length compensation and phase tracking systems, a beam combiner, and imaging and spectroscopic instruments.

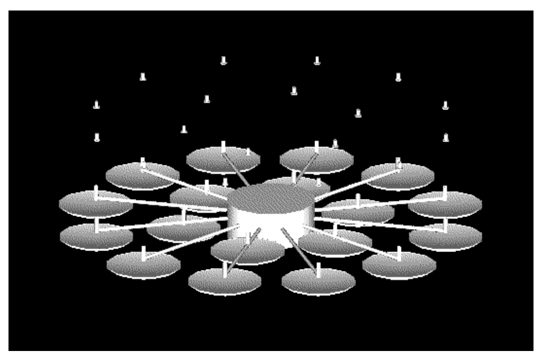

Figure 4.1 The baseline LAMA design. Eighteen 10-meter liquid-mirror telescopes collect light and direct it to a central beam-combining room.

Although liquid-mirrors must rotate about an axis that it precisely vertical, the telescope itself can steered, in the vicinity of the zenith, by means of a system of moving auxiliary mirrors. Optical design studies indicate that, with a system of relatively-small relay mirrors including two aspheric reflectors, it is possible to point and track objects within four degrees of the zenith while maintaining diffraction-limited image quality. This will allow exposure times as long as 30 minutes.

5 Performance

Located at a premier astronomical site, LAMA will have truly unique and outstanding capabilities. Two main optical configurations are envisaged, and are summarized in Table 1. In *high-resolution mode*, coherent beam combination gives maximum sensitivity and the resolution of a 60-meter telescope.

The performance of LAMA in high-resolution mode is illustrated in Fig 5.1, which shows a simulation of how a distant galaxy might appear, as viewed by HST, NGST and LAMA, for the same integration time.

In *wide field mode*, adaptive optics is used to remove atmospheric seeing, but the beams are combined incoherently. This allows a wider field of view than is possible in high-resolution mode. In this mode, the resolution is comparable to that of the Keck 10-meter telescopes, currently the largest in the world, but the image intensity is 18 times greater.

In both high-resolution and wide-field modes, a reference star is required for adaptive optics correction. Natural stars give better performance than laser beacons and are essential for tracking and atmospheric tip-tilt correction. Experience with adaptive optics on 4-meter telescopes indicates that a star of 14-15 magnitude will suffice. We propose therefore to observe fields surrounding such stars as they pass near the zenith. Each field can be observed for up to five minutes using the tracking optics. At the end of the exposure, a new field is aquired. In this way we can achieve complete coverage of approximately 360 fields located around the sky at a declination equal to the latitude of the telescope. Typically 150 fields could be observed each night, and over the course of a year, each of the 360 fields could be observed about 150 times. This gives a total integration time of as much as 45,000 seconds per year. This is comparable to the longest exposures envisaged for the NGST.

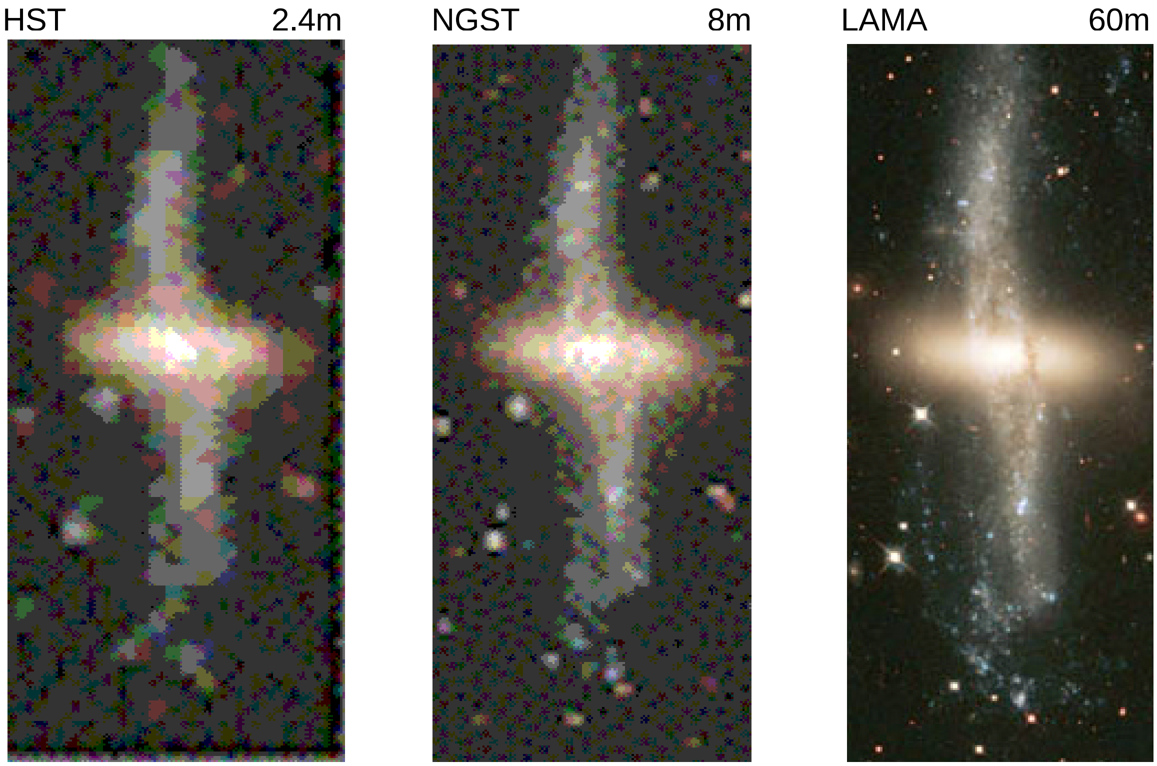

Figure 5.1. Simulation illustrating LAMA's imaging performance in high-resolution mode. The images are representative of what would be obtained, with an equal amount of observing time, by the Hubble Space Telescope, the Next Generation Space Telescope, and LAMA.

Table 5.1. LAMA observing modes

Mode:	High-resolution	Wide-field
Resolution (at $l = 1$ um)	0.004 arcsec	0.02 arcsec
Pixel size	0.0020 arcsec (IR) 0.0010 arcsec (visible)	0.0125 arcsec (IR) 0.0065 arcsec (visible)
Instantaneous field of view	30 arcsec	30 arcsec
Maximum detector size	12k x 12k (IR) 24k x 24k (visible)	2k x 2k (IR) 4k x 4k (visible)
Maximum exposure time	1800 sec	1800 sec
Flux limit (single pass, K band)	575 pJy	2.5 nJy
Flux limit (1 year, K band)	70 pJy	275 pJy
Magnitude limit (single pass)	32.0	30.4
Magnitude limit (1 year, K band)	34.3	32.8

6 Feasibility

The LAMA project, as proposed, will employ three new primary technologies in order to achieve its goals. These are liquid mirrors, adaptive optics, and optical interferometry. What is the status of these technologies and what are the associated risks?

6.1 Liquid mirrors

Liquid mercury mirrors have been used successfully for astronomy and atmospheric physics for more than 6 years (Figure 6.1). Continuing refinement of the existing 3-meter class telescopes has resulted in performance that now rivals that of conventional glass mirrors, but at a fraction of the cost (Figure 6.2). The 6-meter Large Zenith Telescope (LZT) is extending liquid-mirror technology to the 6 to 10 meter range (Figure 6.3).

Effects that can reduce the performance of liquid mirrors are 1) rotational speed variations (caused primarily by wind gusts), surface waves (caused primarily by wind or local turbulence), 3) and imbalance or misalignment. We now have techniques for aligning and balancing these mirrors to high precision, so this last factor is not longer an issue. What remains is disturbances to the mirror caused by wind and turbulence. Variations in rotational speed can be reduced by shielding against the wind, and by increasing the mirror's ratio of inertia to surface area. The 3-meter NASA telescope has operated in winds as high as 25 knots with no special consideration being paid to shielding. Larger mirrors have a higher inertia per unit surface area, and are therefore less prone to mirror speed fluctuations.

Figure 6.1 The 3-meter liquid-mirror telescope of the NASA Orbital Debris Observatory (C. Simons).

A possible issue for large liquid mirrors is waves induced by turbulence in the air above the mirror. As the mirror rotates, it induces rotation in the air that is in contact with it. This sets up a velocity gradient in a boundary layer close to the surface. At a sufficiently high linear rotation speed (which increases with radius), the boundary layer becomes turbulent and spiral waves on the mercury surface result. Optical tests of the 3-meter mirror show spiral waves beginning at a radius of about 1 meter, which roughly corresponds to the critical velocity for turbulence. These surface waves have a wavelength of a few cm and an amplitude that is a small fraction of the wavelength of visible light, so their main effect is to scatter light out of the central, diffraction limited, image core into a diffuse halo. To a good approximation, the Strehl ratio (the fraction of light remaining in the image core) is given by

$$S = \exp(-8p^2 s^2 / l^2) \qquad (6.1)$$

where s is the RMS surface height variation (about 1/5 of the peak-to-peak wave amplitude). Measurements of stellar images obtained with the 3-meter telescope give typical Strehl ratios in the range 0.5-0.7 at a wavelength of 0.75 um. Strehl ratios exceeding 0.8 have been measured for laboratory liquid-mirrors. As Equation (6.1) indicates, the Strehl ratio increases with wavelength. At 2 um, the predicted liquid-mirror Strehl ratio is in the range 0.91-0.99.

It is important to note that the amplitude of surface waves is a very strong function of the thickness of the mercury layer. Tests at Laval University indicate that waves that are very pronounced are almost completely eliminated when the thickness of the mercury layer is reduced from 2 mm to 1 mm. For this reason, the LZT primary mirror has been designed with sufficient surface accuracy to allow a mercury layer as thin as 1.

6.2 Adaptive optics

Adaptive optics (AO) using natural guide stars has become a well-proven technology that is routinely used on large telescopes. No adaptive optics system can remove all of the atmospheric phase distortion, and the residual errors diffract light out of the central core into an extended halo, just as for the case of liquid-mirror surface waves. The efficiency of AO systems is described in terms of the Strehl ratio that is achieved. Present day systems achieve Strehl ratios of 0.5 or more at 2 um. Future AO systems will employ a greater number of active elements to provide a more complete correction.

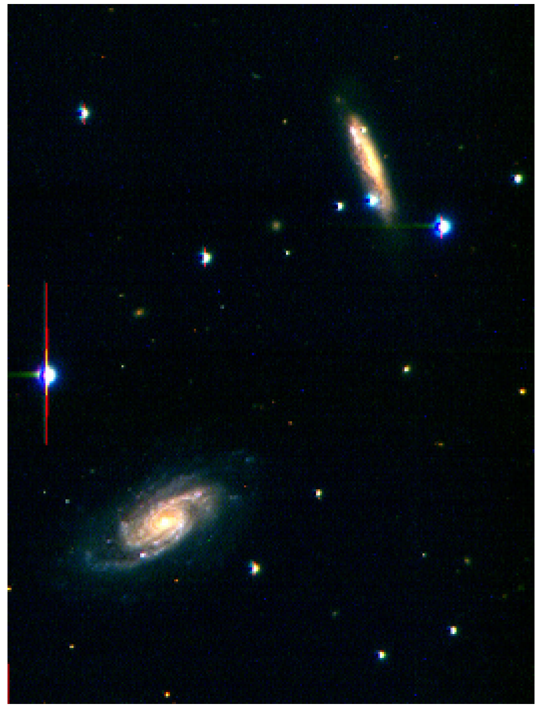

Figure 6.2. Image from the 3-m LMT (M. Mulrooney & P. Hickson)

Current AO systems perform well at long wavelengths (1.5 – 2 um) but the performance degrades rapidly at shorter wavelengths. This is due in part to the wavelength dependence of Equation (6.1) and also to the increased temporal bandwidth of atmospheric fluctuations at short wavelengths. For this reason, we do not foresee using wavelengths shorter than 0.5 um in high or medium resolution modes.

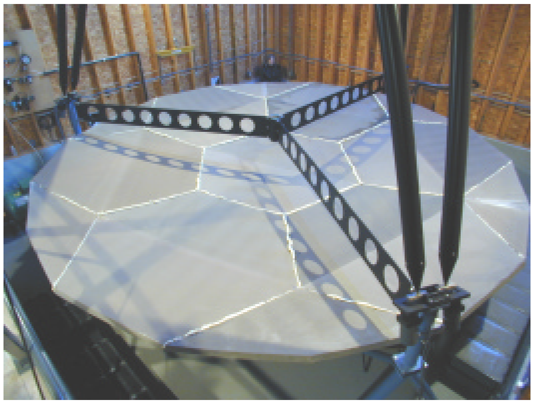

Figure 6.3. The 6-meter LZT primary mirror under construction (P. Hickson).

6.3 Interferometry

Optical interferometry is a rapidly-developing technology of great current interest. Used successfully for decades by radio astronomers, it has only recently become feasible to extend the technology to optical and near-infrared wavelengths. A dozen or more interferometer projects are presently underway worldwide. Both the Keck and the European VLT as well as many smalle interferometer project have demonstrated the ability to combine light from individual telescopes coherently.

LAMA is distinct from most of these projects in that it is a Fizeau (or imaging) interferometer. Unlike most stellar interferometers, in which fringe visibilities are measured between pairs of telescopes, LAMA will produce an image, just as a conventional telescope does. The key to this lies in the optical design. To achieve coherent images over an extended field of view, the beam combining optics must exactly preserve the geometry of the array. More specifically, it must obey the Abbé sine condition: the sine of the angle of incidence of any ray arriving at the detector must be proportional to the lateral position of that ray in the telescope entrance pupil.

This problem has been solved by at least one other project, the Large Binocular Telescope (LBT). This facility will combine light from a pair of 8.4-meter telescopes, on a common mount, by means of a Fizeau beam combiner. An optical design for the beam combiner has been found which gives coherent images (with a Strehl ratio in the range 0.80-0.96) over a 40-arcsec-diameter field of view.

The optical design for LAMA will be more difficult. We must not only ensure that the beams combine with the correct geometry, but we also need to track objects as they pass overhead. Preliminary studies have shown that we can control the geometric aberrations that occur when a parabolic mirror is used off-axis. However, we are not yet at the point of having a complete design for the entire optical system. This is perhaps the most challenging technical aspect of the LAMA project, and one that should be addressed in the earliest stages of the project.

6.4 Skylight reduction

A problem that affects all ground-based telescopes is diffuse light emitted by OH molecules high in the Earth’s atmosphere. At near infrared wavelengths, this light is much brighter than the faint objects that we wish to detect, and is the dominant source of noise. If a way could be found to block this skylight, the sensitivity of the telescope at these wavelengths would be increased by an order of magnitude.

Fortunately, the light emitted by the OH molecules is concentrated in a finite number of narrow emission lines. In principle, the light could be blocked by means of a filter that absorbs light only at the wavelengths of these emission lines. There is at present no way of making such a filter. However, we are pursuing a new technique which appears promising.

OH molecules are capable of absorbing radiation at the same wavelengths as the radiation that they emit. Thus, if the light collected by the telescope is passed through a tube containing OH molecules in the appropriate energy states, these molecules can absorb a large fraction of the undesired sky light. Such a tube (technically a gas-phase absorption cell) would then act as a perfect filter, absorbing almost all of the sky light while leaving most of the light from the astronomical objects unaffected.

Because OH is an unstable molecule with a very short lifetime, the construction of an OH absorption cell poses several technical challenges. Further studies and laboratory testing is needed to confidently determine the feasibility and performance of such a cell. This work is a high priority for the LAMA team because of its potential for a huge gain in sensitivity.

7 Conclusion

The Large-Apeture Mirror Array will be the world's most powerful optical telescope. Located at a premier astronomical site, it will observed selected fields across the sky night after night, producing the deepest and sharpest images and providing a comprehensive view of the formation and evolution of galaxies over 98% of the age of the universe. By focusing on key scientific programs and employing novel and innovative technologies, it will have an impact far beyond what might be expected from its modest cost.

We now have a unique opportunity. Liquid-mirror technology has just reached the maturity needed to enable this project. At the same time, adaptive optics and optical interferometry are undergoing rapid development and testing. We believe that LAMA could be built on a relatively short time scale, and thus be operating well before the end of this decade, and before any of the next generation large ground-based telescopes. Not only would LAMA be the most powerful telescope, but it would have a lead of at least several years over its closest competitors – if we act now.