LIQUID MIRROR TELESCOPES: HISTORY

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Abstract

A history of Liquid Mirror Telescope (LMT) experimentation is provided. The concept can be traced to Ernesto Capocci of the Naples Observatory (1850), but it was not until 1872 that Henry Skey of the Dunedin Observatory in New Zealand constructed the first working laboratory LMT. The 1909 experiments by Robert Wood at Johns Hopkins University exposed some of the strengths and weaknesses of the LMT as an astronomical tool. The recent work of Ermanno Borra and colleagues at Laval University has culminated with the realization of large diffraction-limited mirrors. An offshoot of the Laval laboratory research is the University of British Columbia/Laval fully-automated 2.7-meter $f/1.9$ LMT, a prototype deep-sky survey instrument.

1. Introduction. The arguments for the scientific gains to be made by the next generation of 10-meter class telescopes, especially as large-scale survey instruments in observational cosmology, are well-documented (e.g. Kirshner 1987; Hayakawa 1989). While the last decade has seen remarkable advances in detector technology, such as the advent of highly efficient, large-format Charge-Coupled Devices, or CCDs (e.g. Janesick *et al.* 1989), the practical physical limit to the diameter of conventional glass telescope mirrors, $\sim$6m, was reached over ten years ago (Schroeder 1987). The few 8- to 10-meter telescopes which will be commissioned during the next decade use new materials and technology and are expensive. The growing trend towards increasing the power of ground-based optical observations demands that newer, innovative mirror designs be entertained, in order to complement these new telescopes.

With this in mind, a collaboration between the University of British Columbia and Laval University was begun in late 1988 to explore one particularly promising possibility, a Liquid Mirror Telescope (LMT), which has a rotating, paraboloidal "pool" of liquid metallic mercury as its highly-reflective primary mirror. By necessity, the telescope is a stationary transit instrument, observing a narrow strip of sky passing through the zenith. The lack of mechanical tracking is overcome, in part, by employing a CCD at the mirror's prime focus in the Time Delay and Integrate (TDI) mode (e.g. McGraw, Cawson, and Keane 1986; Mackay 1986).

The restriction to the zenith is an obvious drawback to many aspects of astrophysical research. Nevertheless, it is still very appropriate for many survey applications, including large-scale structure, galaxy evolution, deep QSO and galaxy surveys, and the determination of cosmological parameters via the classical tests discussed by Sandage (1988). Therefore, the LMT design is directed toward those applications which need large samplings of data, not necessarily from any specific direction in space. These very same projects, requiring a great deal of dedicated large-telescope time, will be the ones most difficult to accommodate in the very competitive schedules of the planned 10m instruments. Indeed, this is the prime motivation behind this LMT project: providing relatively inexpensive 10m-class telescopes for broad surveys that are impractical with conventional instruments.

The LMT offers several practical advantages over the construction and operation of conventional telescopes. Pointing, tracking, and telescope flexure problems are eliminated. Zenith observations minimize atmospheric extinction and refraction, and take optimum advantage of local seeing conditions, but by far, the most important advantage held by the LMT is its cost: an order of magnitude *less* for telescopes of the same aperture (Borra 1982).

The concept of an LMT has been extensively investigated over the last decade by E.F. Borra and his colleagues at the Optics Laboratory of Laval University in Quebec City (e.g. Borra *et al.* 1990, and references therein). Their research to date has culminated in a diffraction-limited $f/2$ liquid mirror of diameter 1.5 meters (Borra *et al.* 1989) whose image quality in laboratory tests is comparable to the finest quality glass or ceramic mirrors. The next logical step was to proceed with the construction of a prototype LMT to be used in a more realistic observatory environment. This led to the collaboration between UBC and Laval, drawing upon the existing strengths of the two groups in instrumentation and observational cosmology, to construct a 2.5-m class LMT to conduct astronomical surveys.

Preliminary outlines of this project appear in Gibson *et al.* (1989), Henbest (1990), Gibson and Hickson (1990), and Gibson (1990).

Before giving the results of this collaboration, it would be useful to re-examine the key steps in the development of the LMT as an astronomical tool. Such a detailed history, from the initial LMT concept in the 1850s, to the latest state-of-the-art instruments is provided here. A complementary treatment of *early* LMT research can be found in Steel (1984, 1986).

2. History. The development of the LMT in astronomy can be traced through three distinct eras of progress discussed in the next three sections and summarized in Table I.

a). *1850 – 1872.* The first published reference to the use as an astronomical telescope of a parabolic mirror formed from a rotating vessel containing liquid mercury appears to be a letter from Ernesto Capocci of the Naples Observatory read before the Royal Academy of Belgium in 1850 (Mailly 1872). A subsequent search of Capocci's personal memoirs and papers (S. Maffeo 1989, private communication) showed that he did not follow up this concept. A similar (equally brief) allusion to this idea was given by a "Mr. Buchan of the USA", in the late 1850s, as recounted by Sir David Brewster in his personal diary (Gordon 1870; Steel 1984, 1986).

While it is difficult to definitely identify who constructed the first LMT, that distinction seems to belong to either Robert Carrington or Henry Skey, both English astronomers of note during the nineteenth century. Wood (1909b) reports that Carrington built an LMT driven by a steam engine, near Redhill, England as early as 1868, although a literature search of Carrington's numerous papers does not corroborate this claim. It is known that Carrington used liquid mercury at his observatory (Carrington 1874), but in conjunction with a conventional telescope to accurately measure the latitude of his site.

The first published account of a working LMT was provided by Skey (1872), who, upon emigrating to New Zealand, constructed a $\sim$0.35m diameter telescope near Dunedin. To give the mercury-bearing container a rotation rate as uniform as possible, Skey tried two different techniques, both of which yielded clear images of test objects in the laboratory: (i) an electromagnetic engine whose velocity was regulated by a conical pendulum, and (ii) a small hydroelectric turbine, driven by a regular flow of water. By varying the rate of flow, and hence the mercury's angular velocity, ω, Skey demonstrated the ability to alter the focal length, f, of an LMT, via the well-known relationship between ω and f: $f = g/\omega^2$, where g is the local gravitational acceleration (see Gibson (1990) for a derivation).

b). *1909 – 1922.* Skey's preliminary work in the lab was followed by about 35 years of inactivity in LMT research. A claim by Sharples (1989) that David Todd of Amherst College was an early proponent of the LMT at the turn of the century is not confirmed by any of his refereed publications. It was not until Prof. Robert Wood of Johns Hopkins University began his well-documented series of experiments with liquid mirrors that interest was revived (Wood 1909a, 1909b, 1909c).

Unlike Skey, whose goal was simply to prove that an LMT could work, Wood intended from the outset to build an instrument of optical quality suitable for astronomical research. To that end, his goal was first to quantify and then minimize the optically degrading effects caused by ripples in the reflecting surface of the mercury mirror.

Wood (1909a) started with a 0.18m mirror surrounded by an empty barrel to protect it from air currents. It was driven by a revolving ring of small magnets which "pulled" a concentric ring of magnets attached to the mercury-bearing basin. In this way, the mercury was insulated from any bumps that might be transmitted from the motor along the drive belt, a problem which had plagued Skey. In addition to vibrations and bumps from the driving mechanism, Wood pinpointed three other major sources of ripples on the mercury's surface: (i) shaking due to the continual "grinding" of the bearing surfaces of the mercury basin itself, (ii) leveling the mirror inaccurately, resulting in "tidal waves" in the mercury pool, and (iii) fluctuations in the angular velocity of the basin. This last problem proved to be the most troublesome to solve (Wood 1909a).

Having identified the main ripple sources, Wood then proceeded to construct a functional 0.51m LMT, situated away from the city's inherent vibrations to minimize these unwanted mechanical effects. The mirror was set up on a concrete pad located at the base of a 14-ft ($\sim$4.3m) deep pit adjacent to his barn. The original plan of applying power magnetically to the basin was abandoned, since the use of fine threads of India rubber for the drive belt, which transmitted little or no vibrations, worked just as well, and was much simpler (Wood 1909b). The basin was then accurately leveled with a spirit level. The end result of this first attempt was the elimination of all mechanical sources of serious ripple except one: the angular velocity variations imparted by the 110V AC electric motor.

By obtaining photographic trails of stars such as γ Cyg, Wood demonstrated another effect of these velocity variations: a periodic change in the mirror's focal length over a $\pm$2cm range (Wood 1909a). Despite these problems, Wood's telescope successfully resolved both the ϵ^1 and ϵ^2 Lyrae double star systems (with angular separations of $2''.6$ and $2''.3$, respectively). This work constitutes the first astronomical observations made with an LMT.

Wood's final contribution to LMT technology was to investigate means by which the residual surface ripples could be eliminated, once mechanical design was optimized (Wood 1909a). He concluded that the most practical method available was to cover the mercury surface with a thin layer of transparent glycerine or castor oil. This fluid resulted in complete damping of all surface waves within 1-3 wavelengths of their creation, without any noticeable degradation in the optical quality of the image (Wood 1909c). Despite his early successes, Wood soon abandoned the LMT because he felt that its restriction to zenith observations made the astronomical applications too limited.

Until 1982, the only other published reference to LMTs was a 1922 proposal by a "B.A. McA." to construct a 15.24m LMT in Chile (Rigge 1922)! The announced goal was to test the instrument in 1924 during the opposition of Mars. However, the incredible design flaws inherent in this proposal were exposed by Rigge (1922), and not surprisingly, this telescope was never more than a pipe dream.

c). *1982 – Present.* The current era of LMT research began with Ermanno Borra's landmark paper (Borra 1982). He reassessed the details of the theory and the practical limitations of LMTs as true astronomical tools in the light of the technological advances since Wood's time. He proposed the use of near-frictionless air bearings upon which a mercury basin could be rotated by a synchronous motor driven by an oscillator-stabilized AC power supply, thus eliminating the various sources of image-degrading ripples in the mercury's surface. Borra and his colleagues at Laval University have been refining the basic technology that is necessary to implement a fully functional LMT (Borra *et al.* 1984 - 1990). Some of their key results are summarized below.

It should also be noted that independent of the research at Laval University, Vasil'ev (1985) at Khar'kov State University was working on the construction of a 1m $f/0.72$ LMT. For his optical shop testing though, Vasil'ev constructed a portable 0.14m LMT which used castor oil instead of mercury for the parabolic reflecting surface of the mirror, due to the ease with which it could be handled. To avoid "edge-effects", the mirror was diaphragmed to yield an effective diameter of only $\sim$0.1m. His design incorporated a modification to Borra's basic mirror structure similar to Wood's (1909a) suggestion, in which the mirror is placed in a rotating system of intermediate damping liquids (IDL). The concept is quite simple; a liquid (in this case, water) is spun in some large container. Within this outer container, an inner floating vessel is placed which supports the rotating liquid mercury mirror. In equilibrium, both the IDL and the vessel of mercury spin at the same angular velocity. His results showed that these moving components are essentially self-centering and self-leveling. Vasil'ev reports that the optical surface of his mirror is very close to the diffraction limit (although no quantitative evidence is presented), as the surface instabilities are suppressed by the IDL system. The mirror's surface quality was limited only by external background noise (*i.e.,* quality was independent of rotational velocity). Another benefit of an IDL-type LMT is that the entire base of the mirror is uniformly supported by the IDL, not just the part in direct contact with the air bearing. This removes any practical weight limit on the size of the mirror. Despite the success of this laboratory prototype, no further reports of the 1m LMT discussed by Vasil'ev (1985) has been found in the literature.

Returning to the LMT research done over the past decade at Laval University, as this has been the most sophisticated to date, Borra (1982) systematically explores each of the major sources of ripple in an LMT: (i) bearing/drive/floor vibrations, (ii) leveling inaccuracies, and (iii) rotational velocity fluctuations.

The primary source of vibrations in Wood's LMT was his inferior bearing mechanism. Borra (1982) shows that the use of air bearings removes this problem and makes vibrations from the local environment the major source. Knife-edge tests by Borra *et al.* (1984) reveal the existence of low-amplitude, concentric ripples induced by vibrations from a nearby building transmitted through the floor of the mirror lab (this should not be a problem at an isolated mountain site). The surface waves that can arise from large leveling inaccuracies are easy to eliminate by using Wood's method of aligning the mirror's rotational axis with a spirit level.

The major problem for Wood was drift in the angular velocity, ω, of his mirror. This velocity must be stable to better than one part in a million to maintain the required optical quality and a stable focal point (Borra 1982). This severe requirement is now one of the easiest to solve, by driving the turntable with a synchronous motor (a luxury unavailable to Wood at the turn of the century). Synchronous motors are ideal because they rotate at a speed controlled by the frequency of the voltage signal that feeds it (e.g. oscillator stabilized AC power supply). Quartz oscillators can provide a stable clock of accuracy better than one part in 10^{10} (Borra 1982), much greater than the necessary stability. Long-term stability (*i.e.,* greater than one turn of the motor) of ω is assured by this motor, and the short-term stability (*i.e.,* less than one turn) is controlled by inertia of the mirror rotating on the air bearing (Borra *et al.* 1984).

Borra's group at Laval University have also investigated the feasibility of the LMT concept in a laboratory environment. Their results provide the first quantitative analysis of the surface structure of a liquid mercury mirror, including the stability of focus, high spatial-frequency defects, and the mirror's overall shape, each of which can vary with time (Borra *et al.* 1982 - 1990).

Detailed optical shop testing (e.g. Hartmann, Ronchi, knife-edge, direct imaging, and scatter-plate interferometric tests) has shown that large, astronomically useful diffraction-limited mirrors are now a reality (Beauchemin 1985; Borra *et al.* 1989).

Preliminary research with a 1.2m ($f/4.58$) mirror in the field, near Quebec City, showed that even with a rudimentary set-up (see Borra, Beauchemin, and Lalande 1985 for photo) star trails of width $\sim 2''$ FWHM were attainable. Their conclusion was that seeing at the sea level site was the limiting factor for image attainment in their system, not the liquid mirror's surface quality (Borra *et al.* 1988). These results formed the basis of the first scientific paper based solely on the data collected from a LMT: a search for optical flares and flashes (Content *et al.* 1989).

The initial experiments of the Laval group are documented by Borra *et al.* (1984,1985) and Beauchemin (1985). The three main concerns of this early work was to better quantify the stability of focus, high spatial-frequency defects, and the overall shape of the mirror, all of which can vary rapidly with time. Two mirrors were used predominantly, a 1-meter $f/1.6$ and a 1.65-meter $f/0.89$. Focus stability and high-frequency defects were addressed by the knife-edge test (Ojeda-Castañeda 1978), and supplemented by direct imaging of a standard resolution bar-chart. A Hartmann test (Ghozeil 1978) was employed to estimate the overall shape of the mirror. Each of these tests was performed at the mirror's center of curvature, hence spherical aberration was a problem, and in fact the mirror had to be stopped down to 0.4m for some of the tests, because the group did not have access to corrector lenses for this early work.

The mirrors themselves had a very simple composition, a stiff plywood base with a metal retaining strip around the outside. The final surface was a spuncast polyester resin. The mercury layer then acted as a liquid high-reflectivity coating of four to seven millimeters in thickness. Surface tension tended to break the mercury into puddles if thinner layers were used (Borra *et al.* 1985).

Borra *et al.* (1984, 1985) used a modified linear Hartmann test (Ghozeil 1978), which incorporated a screen which had 18 holes, 12.7mm in diameter, in a single row, with 50.8mm separation between each of the holes. They would sample one direction at a time, then position to a different angle, etc., so as to detect defects such as standing waves, with respect to the laboratory frame. Exposure times of $\sim$100 seconds were used (*i.e.,* seeing effects were not important). Deviations from a perfect paraboloid having an rms amplitude of about $\lambda/10$ at 5000Å were seen. A problem with this optical test is that one cannot study surface quality on scales smaller than the linear space between the screen's holes (*i.e.,* 50.8mm), a point which will be referred to shortly.

The second optical test employed was the knife-edge test (Ojeda-Castañeda 1978), a test renowned for its extreme sensitivity. In fact, it can detect defects as small as $\lambda/600$, as well as time-varying defects such as traveling waves or a time-varying focal length. Two defects were found at this stage: (i) the surface of the mirror "puckered" around dirt particles, due to surface tension, that had accumulated on the mirror, resulting in the introduction of scattered light, and (ii) concentric rings were seen on the surface, which were apparently caused by vibrations communicated through the floor, originating in a nearby building, not from the drive/bearing system. The first defect was found to be easy to control, as mercury can be skimmed/filtered on a daily basis, if so desired. The second problem can also be minimized by constructing a support mount which contains a large amount of damping and possesses a resonant frequency as far as possible from the peak of the vibration spectrum, as it is background noise that excites the resonant frequency of the three-point mount on which the mirror rests (Borra *et al.* 1985). Beauchemin (1985) showed that the amplitude of these concentric ripples was in the range $\lambda/10$ to $\lambda/15$, at 5000Å.

The knife-edge test was supplemented by directly imaging a resolution bar-chart. Like the knife-edge test, this revealed high spatial-frequency defects which were not detected by the Hartmann test. The Borra *et al.* (1984,1985) papers show that a resolution of $\sim 0''.75$ had been realized, very close to the theoretical resolution expected from this diaphragmed 1m mirror. A faint fuzz seen around the bars in the chart corresponded to a ripple amplitude of $\sim \lambda/10$, in agreement with the knife-edge tests (Beauchemin 1985).

The above tests were repeated after introducing a thin layer of glycerin onto the mercury's surface (Borra *et al.* 1985). Glycerin does not affect the system's reflectivity, and has the advantage of being very insensitive to vibrations and wind-induced surface disturbances. In fact, no ripples were detected with the knife-edge test. Unfortunately, the viscosity of glycerin did pose a problem as nonhomogeneities which are generated while pouring the liquid were still present several hours afterwards, whereas the mercury surface without the glycerin normally takes on the order of ten minutes to stabilize (Borra *et al.* 1985). These variations in the glycerin thickness led to a substantially poorer image quality.

Two final points are addressed by Borra *et al.* (1985): (i) mercury tarnishes slowly, taking approximately one week for there to be a noticeable decrease in reflectivity, but can be cleaned on a daily basis if so desired; and (ii) damping times are short, e.g. disturbances having amplitudes $\gtrsim$1mm dampen out in a few seconds.

The second stage of the Laval group's work was to apply the success of their laboratory mirrors to a working LMT. Two mirrors, one a 1m $f/4.7$, the other a 1.2m $f/0.89$, were operated over two consecutive summers (1986 and 1987) on the campus of Laval University. The primary references are Borra, Beauchemin, and Lalande (1985) and Borra *et al.* (1988).

In 1986 the 1m $f/4.7$ mirror was used exclusively. Longer focal lengths were used in the field than were used in the lab because they did not have access to any corrector lenses. Coma would have made the usable field of the 1m $f/1.6$ mirror too small. The support for the mirror was very simple, there being no bracing and no foundations (see Borra, Beauchemin, and Lalande (1985) for a photograph of the rudimentary setup).

The primary goal of this initial observing season was to acquire data for star trails as they pass through the zenith, using a 35mm photographic camera with its shutter left open. Focusing errors in this crude setup dominated. Still, the FWHM of the star trails was $\sim 2''$; an excellent result considering the site's sea level location on the Laval University campus, as well as the accompanying focus errors just mentioned. The star trails wiggled with an apparent amplitude of $\sim 1''$ at a time scale of $\sim$2 seconds. Seeing-induced image motion due to the location near a warm building was the most probable cause of this effect (Borra, Beauchemin, and Lalande 1985), although some inherent structural movement of the mirror's frame could not be excluded.

The one detectable problem with this original data was an accompanying faint "fuzz" surrounding the trails due to the same type of low-amplitude ripples that were seen during the optical shop tests (Borra *et al.* 1984). The estimated fraction of light contained in the central peak, found by scanning across the star trail itself, was $\sim$70%, with the remainder being found in the rings. Thus, if the ripples are assumed to be sinusoidal this would correspond to surface deviations having amplitudes of $\sim \lambda/16$ (Beauchemin 1985).

Borra, Beauchemin, and Lalande (1985) also found that the mercury surface could not tolerate turbulent winds much stronger than 10 km/hr, although no thorough study was done. A silo-structure was suggested to minimize this problem, and has been incorporated into the UBC/Laval 2.7m LMT.

The 1.2m $f/4.58$ mirror was the primary instrument for the second observing season (Borra *et al.* 1988). Similar conclusions were found ($\sim 2''$ FWHM) from the accumulation of more than 200 hours of data. The main difference in the second season's observing procedure was the introduction of a mylar cover to shelter the mirror from the wind. The result of this step was the unavoidable added presence of some scattered light. For a site with $2''$ to $3''$ seeing, the mylar does not affect the images noticeably, but at the $1''$-level, there may be some problems. The use of mylar as an optical window has been recently explored by Thompson (1990). Monomolecular layers of oil which are effective at dampening wind-induced waves were also utilized and will be involved with future experimentation.

The results of this second season formed the basis of a scientific paper whose goal was to put better constraints on the occurrence of optical flares and flashes (Content *et al.* 1989).

The last two years of research at Laval (1989 - 1990) have involved further detailed optical shop testing of a 1.5m $f/2$ mirror (Borra, Content, and Boily 1988; Borra *et al.* 1989). The Hartmann test used by Borra *et al.* (1985) has been dropped in favour of scatter-plate interferometric techniques (Mallick 1978) and the Ronchi test (Cornejo-Rodriguez 1978) has also been used (Borra, Content, and Boily 1988). Null Offner lenses have been added to correct for the large spherical aberration that occurs at the center of curvature of the $f/2$ paraboloid, thus eliminating the need for reducing the mirror diameter (as was done by Borra *et al.* 1985).

The Ronchi test shows that image quality seems to be limited by seeing in the testing tower, as well as by 'print-through' effects from the surface of the container (Borra, Content, and Boily 1988). Print-through arises because the liquid flows slowly across the surface of the container. These low-speed flows are caused by alignment uncertainties, as well as from the friction of the air on the surface of the liquid. By resurfacing the container with an epoxy resin, the print-through is expected to decrease below the detectable level (Borra, Content, and Boily 1988; Borra *et al.* 1989).

A recent technological development in the lab has been the ability to establish thinner mercury layers on the mirror cell (Borra, Content, and Boily 1988). In the past (Borra *et al.* 1984) layers could not be less than 4mm or else surface tension would break the mercury into puddles. Currently, channels 1cm wide and 0.5cm deep are formed around the periphery of the cell. The interaction by surface tension with the container now only takes place at the edges where the layer is deep, allowing a very thin layer everywhere else.

Thin layers are much less sensitive to vibrations and wind because waves interact with the container's bottom, thus increasing friction (Borra, Content, and Boily 1988). As such, it was no longer necessary to shelter the mercury from the air with mylar. A 2.5mm layer was used to establish the results reported here. As the dominant cost of their instrument was the air bearing itself, reducing the thickness of the dense mercury layer is obviously of prime importance as it reduces the weight that the bearing must support. The use of molten gallium, or one of its eutectic alloys, in place of mercury, is another potential option (Dickson 1988; Borra 1991, private communication).

Recently, Borra *et al.* (1989) have observed the actual Airy disc of their 1.5m $f/2$ mirror. Diffraction rings are seen at the predicted locations, although the intensity and symmetry of the rings varies, possibly due to seeing in the testing tower. This is the first time that the diffraction pattern of a large mirror has been directly observed, despite imaging through two null lenses, two folding-flat mirrors, and a beam splitter. Imperfections and alignment errors of these additional optical elements are expected to introduce some aberration. Interferometric measurements confirm that the mirror is indeed diffraction-limited.

The central part of the Airy pattern is produced mostly by low spatial frequency components of the mirror's surface, whereas high spatial frequency ripples are responsible for extended "wings" and scattered light far from the center of the PSF (Point Spread Function). As before (Borra *et al.* 1985) low amplitude high frequency ripples originating from the local environment are observed. The peak-to-valley amplitude of these ripples is less than $\lambda/30$, and contain only 3% of the total energy of the Airy pattern (Borra *et al.* 1989). The PSFs do not show any detectable energy beyond $20''$ from the PSF center, thus these vibration effects should be unimportant, especially when the observatory is moved to an isolated site.

The mirror surface is accurate to $\lambda/17$ rms deviation, with a corresponding Strehl ratio of $\sim$0.76 (Borra *et al.* 1989). Note that a surface accurate to better than $\lambda/14$, or a Strehl ratio $>$0.8 can be considered to be diffraction-limited (Schroeder 1987). In other words, diffraction itself, rather than the aberrations of the system, is the main contributor to image degradation. So, this 1.5m $f/2$ liquid mirror can be considered essentially diffraction-limited. A summary of recent activities of the Laval group can be found in Borra *et al.* (1990).

The 2.7m $f/1.9$ mirror recently constructed at UBC (Gibson 1990) is a departure from the design of the earlier Laval mirrors (Note: an identical mirror was simultaneously constructed for use as a LIDAR instrument to study the Earth's atmosphere (Lowe and Hickson 1991, private communication). Using construction techniques borrowed from the aerospace industry, a composite laminate structure has been utilized for the mirror cell. Layers of epoxy resin-impregnated bidirectional weave Kevlar fabric surround a dense foam core; the upper surface of the mirror consists of a spuncast layer of pure epoxy which supports the mercury. An aluminum ring attached to the mirror rim retains the mercury. A detailed structural analysis can be found in Hickson and Gibson (1990).

NASA is also involved in the construction of an LMT (at the Johnson Space Flight Center in Houston); its primary function will be to monitor the zenith at its planned equatorial site for orbiting space debris (Potter 1991, private communication).

3. Summary. Now that the success of the liquid mirror concept has been successfully exploited in the lab, the culmination of which is the realization of large diffraction-limited mirrors, the time has come to explore the potential of LMTs as astronomical tools. The UBC/Laval collaboration was formed with this particular goal in mind. Future papers in this series will detail the UBC/Laval instrument's design and imaging performance.

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