

Gallium Liquid Mirrors: Basic Technology, Optical-Shop Tests and Observations

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ABSTRACT. We have investigated the use of gallium and low-melting-temperature gallium alloys for liquid mirrors. They have advantageous characteristics with respect to mercury. Simple knife-edge and Ronchi optical tests indicate that gallium mirrors have optical qualities similar to those of mercury mirrors. We have observed stars with a 1-m diameter liquid-mirror telescope that used a gallium-indium alloy. The instrument operated satisfactorily, within the limitations of a very simple telescope and instrumentation. Arguably, our most interesting finding is that the high melting temperature of gallium is not an obstacle since our experiments show that it is easy to supercool in large volumes and quite stable in the supercooled state. Furthermore, eutectic alloys of gallium have significantly lower melting temperatures than pure gallium and are also easy to supercool and stable in the supercooled state. The results of our experiments are encouraging and warrant further, more rigorous, continuation of this work.

1. INTRODUCTION

Modern technology has rendered practical an old theoretical curiosity: that a spinning liquid surface takes the shape of a paraboloid which can, in principle, be used as the primary mirror of a telescope. In the past, the lack of mechanical tracking capability of a liquid-mirror telescope (LMT) was a major handicap that would have severely restricted its usefulness to astronomy. Liquid mirror has undergone a revival following the suggestion (Borra 1982) that modern technology gives us alternate tracking techniques. Taking imagery as an example: one can obtain images with a CCD detector in the driftscan mode, store the information on disk and coadd the nightly observations with a computer. Imagery with a fixed LMT has been demonstrated by Hickson et al. (1994). Borra (1987) has argued that essentially any type of astronomical instrument could be adapted for observations with a fixed telescope.

Over several years, we have carried out a research and development program to determine whether, in practice, it is possible to generate an optical quality surface on a spinning liquid. Extensive optical shop tests of mercury mirrors have been reported by Borra et al. (1992) and Borra et al. (1993), showing that diffraction-limited mirrors can be made with mercury. Borra (1995) gives a review of the liquid-mirror project. At the time of this writing, several liquid mercury mirrors are used for a variety of scientific and technical purposes (Sica et al. 1995; Ninane 1996).

In this paper we explore the use of liquid gallium and its low-melting temperature eutectic alloys, and report the results of simple optical-shop tests of a 1-m diameter gallium-indium mirror as well as observations with a 1-m diameter gallium-indium mirror.

2. LIQUID GALLIUM

2.1 Why Gallium?

Gallium has three main advantages over mercury: It has a reflectivity about 15% higher, a density lower by a factor of

2.2 and has no known toxicity. The higher reflectivity is a relatively minor advantage. Likewise, lack of toxicity is a minor advantage since mercury vapors can easily be controlled. The lower density of gallium gives its main advantage for one can then use a smaller bearing and a lighter, less stiff container. Finite element computations (Arrien 1992) and analytic (Hickson et al. 1993) studies of the containers of liquid mirrors show that the flexure of a centrally supported container is a major consideration with liquid mirrors. Realistic containers do not have analytic solutions and must be analyzed with finite elements computations but there are analytic solutions for circular disks that can be used as approximate models. Let us consider one such analytical solution for a circular disk supported at the edges subjected to a central load (Timoshenko and Woinowsky-Krieger 1959). The central load would represent the bearing while the support at the edges would be equivalent to having all the weight of the liquid on an annular ring at the perimeter of the mirror. While an obvious idealization, this simple model illustrates the advantage of using a lighter reflecting liquid. The deflection of a centrally loaded clamped plate is given by

$$w = Pr^2/(8\pi D) \ln(r/a) + P/(16\pi D)(a^2 - r^2), \quad (1)$$

with

$$D = Et^3/[12(1 - \nu^2)],$$

where P is the total load applied, E is Young's modulus, ν Poisson's ratio, a the radius of the plate, and t its thickness.

The maximum deflection w_{\max} occurs at the center of the plate and

$$w_{\max} \sim Pa^2/t^3. \quad (2)$$

For a given deflection and thickness t , we see that $a^2 \sim 1/P$ and, since $P \sim \rho$ ($\rho =$ density), $a^2 \sim 1/\rho$. Since $\rho_{\text{Hg}} = 2.2 \rho_{\text{Ga}}$, a container of a given thickness can support a gallium mirror that has 2.2 times the area of a Hg mirror. Since most of the weight of a liquid mirror is in the liquid, a given bearing can

support a gallium mirror that has approximately twice the area of a mercury mirror. In practice, the prices of commercially available airbearings increase rapidly with the maximum load that they can bear.

Borra (1991, 1992) has considered the feasibility of using liquid mirrors in space and lunar-based telescopes. While the solar sail LMT described by Borra (1992) is unlikely to be funded in the foreseeable future, the case for a lunar LMT is of more immediate practical interest. Given the very high transportation costs to our moon, the low mass of gallium gives it an important advantage. Evaporation is an important consideration for a LMT operating in vacuum (Borra 1991), giving gallium an advantage over mercury, which has a much larger evaporation rate.

2.2 Eutectic Alloys of Gallium

The main disadvantage of gallium comes from its high melting temperature (29.6 °C) that, *prima facie*, renders it unsuitable for astronomical or room-temperature applications. Fortunately, gallium is very easy to supercool and quite stable in that state. There also exist several eutectic alloys of gallium that have significantly lower melting temperatures than pure gallium. A eutectic alloy has a lower melting temperature than those of any of its constituents. We have made a eutectic alloy made of 76% Ga and 24% In (by weight) that has a melting temperature of 15.7 °C as well as a eutectic composed of 62.5% Ga, 21.5% In, and 16% Sn having a melting temperature of 10.7 °C. The mirrors discussed in this article were made with the Ga–In eutectic because it is liquid at room temperature (18–22 °C) and therefore easy to handle. Eutectics alloys of gallium are easy to make. The components are first weighed, then the solid gallium sample is placed in an oven at a temperature of about 50 °C. After a few hours, the In sample, hammered to a thin strip to speed up the process, is placed in the molten Ga. Although In has a melting temperature of 156 °C, it dissolves in the molten Ga. Our preparation of Ga–In lasted 10 h. The melt was stirred every half hour. During our experiments, we found an unexpected phenomenon. After a few hours, that the eutectic had reached room temperature, we noticed the formation of solid In crystals in the liquid. We put the mix back in the oven where the crystals disappeared to reappear again upon cooling. We filtered out the crystals finding that the remaining alloy did not solidify above the melting temperature of the original eutectic but this may possibly be due to supercooling of the liquid. A much smaller quantity of crystals was found two weeks after first filtering the indium crystals. We have ruled out trivial errors (such as weighing) in the preparation of the eutectic. The literature does not mention this effect. On the other hand, experiments quoted in the literature used small quantities of the metals (a few grams) while we used almost 10 Kg.

The literature indicates that adding additional metals to an alloy reduces further its melting temperature. For example, we found a patent claiming that an alloy containing 68% Ga, 23% In, 8% Sn, and 1% Ag solidifies at –5 °C.

2.3 Supercooling

Supercooling is a well-known property of many liquids, including water: the substance remains liquid at temperatures below its melting point. The supercooled state of water is however unstable as outside perturbations to the supercooled liquid cause it to crystallize rapidly. Supercooling is not fully understood theoretically but one can consider at least two mechanisms that can solidify a supercooled liquid: homogeneous and heterogeneous nucleation. Homogeneous nucleation (Chalmers 1964) assumes that seed crystals (embryos) appear at random in the liquid and that solidification takes place when the radius of the embryo exceeds a critical radius given by

$$r^* = 2\sigma T_m / L\Delta T, \quad (3)$$

where σ is the free interface energy, L the mean escape energy of an atom from the crystal, T_m the melting temperature and $\Delta T = T_m - T$, where T is the temperature of the liquid.

Heterogeneous nucleation (Turnbull 1952) occurs when a seed crystal forms at an interface between the liquid and a surface such as the surface of a container. It is difficult to estimate a rate of heterogeneous nucleation for it depends on factors such as the nature of the solid and its surface texture.

Homogeneous nucleation rates can be computed far more easily: They are functions of the volume of liquid and of the temperature. Miyazawa and Pound (1974) determined experimentally the nucleation rate for gallium drops suspended in a viscous fluid. They show that the nucleation rate is given by

$$\ln J = \ln M - N/[T(\Delta T)^2], \quad (4)$$

where M and N are experimentally determined constants. They find, for gallium, $M = 10^{39.8}$ and $N = 10^{8.19}$ for J expressed in $\text{cm}^{-3} \text{s}^{-1}$. The time of solidification can readily be estimated from Eq. (4) by assuming that solidification occurs when one solid nucleus is formed. If we assume a 10-m diameter liquid mirror having a 1.0-mm deep layer of liquid gallium supercooled to –30 °C, Eq. (4) predicts a nucleation rate of $8.35 \times 10^{-39} \text{cm}^{-3} \text{s}^{-1}$ giving 6.56×10^{-34} events s^{-1} for 78.5 liters of gallium, assuring stability for 5×10^{25} years. Homogeneous nucleation can therefore be safely neglected since this time is greater than the age of the Universe. The nucleation rate increases linearly with volume so that volume effects are not as important as temperature effects. Homogeneous nucleation is therefore not a problem unless one works at substantially lower temperatures. Consider however that this rate neglects not only heterogeneous nucleation, but also perturbations such as vibrations.

Gallium can be supercooled to very low temperatures. For example, Miyazawa and Pound (1974) have supercooled Ga droplets to –70 °C. We have not found any article studying the supercooling properties of gallium eutectics so that we made our own experiments.

2.4 Supercooling Experiments

We have made a number of experiments to study the supercooling properties of gallium and its alloys in macro-

scopic quantities and in realistic conditions. An early experiment (Gauvin 1992) was made with a 10 cm^3 sample of liquid gallium contained in a glass dish. The dish was placed in an unheated shed on the roof of the building that houses the Physics Department so that its temperature varied with the ambient winter temperature. The sample remained liquid for two weeks while ambient temperatures fluctuated between 0 and $-20 \text{ }^\circ\text{C}$. The sample eventually solidified on the third night of three consecutive nights during which the temperature dipped to $-30 \text{ }^\circ\text{C}$. Vibrations on the roof of the building were so severe that vibration-induced concentric ripples could easily be seen on the surface of the liquid. Furthermore, ice crystals had formed on the surface of the sample. Both factors should be expected to favor solidification.

A 1-m diameter Ga–In liquid mirror (see Sec. 5) was operated in the Fall of 1995 for a continuous two-week period during which the nighttime temperature routinely dropped below $10 \text{ }^\circ\text{C}$. On several nights it decreased below $6 \text{ }^\circ\text{C}$. Although we did not record the temperature inside the building, temperatures obtained from the weather service for the city showed that it dropped below freezing on two separate nights. We could only estimate the temperature in the observatory by visually reading a thermometer and this was done either in the first half of the night or in the early morning before sunrise. The coldest temperature visually recorded inside the observatory was 4 degrees. Clearly the mirror operated and remained liquid well below its nominal solidification temperature of $15.7 \text{ }^\circ\text{C}$. We did not operate much below freezing temperatures because water vapor in the compressed air line to the airbearing would have frozen and interrupted the air supply.

We made laboratory experiments by placing several 30 cm^3 , and a single 120 cm^3 , liquid samples of gallium, gallium–indium, and gallium–indium–tin eutectics in two separate programmable freezers. The cooling rates were set at either $2^\circ/\text{hr}$ or $1^\circ/\text{hr}$, with a couple of day-long pauses at constant temperature, to the coolest temperatures of the freezers ($-27 \text{ }^\circ\text{C}$). Each freezer had two separate samples of each of the alloys. A thermometer probe was placed in one sample while its twin did not have any. The temperature of a supercooled liquid increases sharply during solidification, so that the probe, monitored with a computer, gives the time of solidification. The second sample, monitored by eye periodically, allowed us to verify whether the solidification of the first sample was provoked by the probe: We did not see any evidence of this. The samples were periodically visually inspected to ascertain whether the samples had solidified.

We carried out a single experiment with gallium and Ga–In–Sn, all of our other experiments were carried out with Ga–In samples only. Because this is the only experiment that dealt with all three metals, we shall describe it in some detail. Figure 1 shows the temperature variations registered by probes inside the samples. The sharp spikes indicate the times the phase transitions occurred. All gallium samples solidified the first day at a temperature of $16 \text{ }^\circ\text{C}$ during the early cooling stage. This is to be contrasted to our previous experience that demonstrated liquid gallium to $-30 \text{ }^\circ\text{C}$. The discrepancy between the two experiments was not unex-

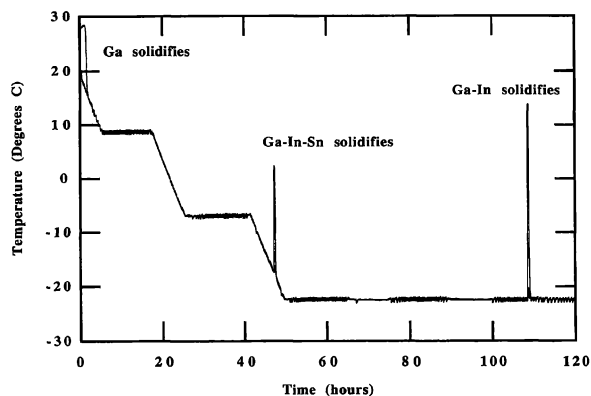


FIG. 1—Data from a supercooling experiment. The temperature inside the Ga, Ga–In, Ga–In–Sn samples are plotted as function of time. Solidification times are indicated by the sharp temperature spikes.

pected since numerous early experiments ended in failures to attain supercooling. Success obviously depends on the way the samples are prepared. We only have a qualitative understanding of what is happening. Basically, what happens is that any solid nucleus in the liquid will induce solidification; hence if the oven was not warm enough or not kept long enough in the oven, there may have been some nuclei left. We also have evidence that pieces of the surface oxide skin may also induce solidification, presumably because they contain solid metal nuclei.

As indicated in Fig. 1, at the end of the first day, the freezer reached a temperature of $+8 \text{ }^\circ\text{C}$. All Ga–In and Ga–In–Sn samples remained liquid. The second day, the freezer reached $-7 \text{ }^\circ\text{C}$. The samples were liquid at the end of the day. They spent the night at those temperatures and remained liquid. The final cooling brought the temperature to $-22 \text{ }^\circ\text{C}$. The Ga–In–Sn samples solidified during cooldown at $-17 \text{ }^\circ\text{C}$. The Ga–In sample remained liquid for an additional 61 hr after which it solidified.

We made two additional cooling runs with Ga–In samples. They gave similar results. We found that the solidification times between samples poured directly from the bottle differed from those drawn from under the oxide skin. The samples drawn from under the skin solidified at $-24 \text{ }^\circ\text{C}$ in 65 hr, while those directly poured from the bottle solidified significantly sooner.

Solidification times at two different temperatures, along with Eq. (4), should allow us to estimate the two constants in the equation, allowing one to predict solidification times as function of temperature and mass of liquid. Unfortunately, solidification times vary steeply with temperature and, at a given temperature, there is significant scatter among solidification times. It is therefore necessary to carry out experiments at sufficiently spaced temperatures but this involves long times at the warmer temperature. We could not use the freezer, which belongs to a separate laboratory, for sufficiently long times to observe solidification times at temperature significantly warmer than those in Table 1.

Consequently, although we can get estimates of solidification times at cold temperatures from Table 1 and Fig. 1, we only have a lower limit at warmer temperatures from a

TABLE 1
Results from a Supercooling Run with Ga-In

| Sample | Solidification time (hours) | Solidification temp. (°C) | Volume (cm ³) | Comment |
|--------|-----------------------------|---------------------------|---------------------------|----------|
| 1 | 65 | -24 | 30 | Drawn* |
| 2 | 65 | -24 | 30 | Drawn* |
| 3 | 65 | -26 | 120 | Drawn* |
| 4 | 2 | -20 | 30 | Poured** |
| 5 | 38 | -23 | 30 | Poured** |

*Drawn from under the oxide skin.

**Poured directly from a bottle.

sample that remained liquid at $-13\text{ }^{\circ}\text{C}$ for 27 days; the experiment was then terminated. This only allows to obtain lower limits for $N(1.276 \times 10^6)$ and $\ln M(-12.0957)$. At $T = -10\text{ }^{\circ}\text{C}$, one liter of Ga-In would stay liquid for more than 75 hr, more than 138 days at $T = -5\text{ }^{\circ}\text{C}$ and more than 1000 yr at $0\text{ }^{\circ}\text{C}$. A 10-m diameter liquid mirror having a 1-mm thick liquid layer carries 78.5 l of liquid. Taking the numbers derived for N and $\ln M$ at face value, a 10-m mirror would only remain liquid for 1 hr at $-10\text{ }^{\circ}\text{C}$, less than 2 days at $-5\text{ }^{\circ}\text{C}$ and 13 years at $0\text{ }^{\circ}\text{C}$. Keeping in mind the steep dependence on temperature, and the fact that the coefficients were derived from a lower time limit at $-13\text{ }^{\circ}\text{C}$, these are certainly gross underestimates. Considering that in typical good sites on Earth the temperature usually stays above $-5\text{ }^{\circ}\text{C}$, it would appear that the solidification times are long enough to make Ga-In mirrors viable alternatives to Hg mirrors. However, ours is only an exploratory investigation of this problem and there clearly is a need for more extensive and careful experiments.

In conclusion, supercooling gallium and gallium eutectics appears to be a viable technology. On the other hand, we had some puzzling failures in our supercooling experiments. For example, our earliest experiments with supercooled gallium were systematically unsuccessful. At the time, we simply poured the liquid gallium in a container and it always solidified at room temperature. Guessing that solid nuclei on the oxide surface skin induced solidification, we drew our liquid sample from underneath the oxide skin with a siphon, meeting success. We had other failures with Ga-In eutectics. On the other hand, we were quite successful with our 1-m Ga-In notwithstanding the inevitable rough conditions and handling we subjected the alloy. We conclude that, although we did not totally control the supercooling experiments, they were successful since we have clearly demonstrated that stable supercooling of gallium and its eutectic alloys can occur considerably below the nominal melting temperatures. Most importantly, we have demonstrated supercooling of a 1-m Ga-In mirror in a working astronomical observatory and observed for several nights when the temperature was below nominal solidification values.

2.5 The Reflectivity of Gallium and Gallium-Indium

The reflectivity of mercury and liquid gallium have been measured by Schulz (1955) who found that the reflectivity of liquid gallium is comparable to the reflectivity of aluminum and about 15% higher than the reflectivity of mercury. We

have carried out experiments (Gauvin 1992) that monitored long term variations of the reflection coefficients of mercury and liquid gallium. The samples were exposed to the air inside our laboratory. We found that at 6000 \AA , the reflectivity of liquid gallium is 25% higher than the reflectivity of mercury. We monitored the reflectivity of liquid gallium at 5000, 6000, and 7000 \AA for a period of 30 days, finding no evidence of variations within our experimental precision ($\pm 3\%$). Borra (1992) has computed reflectivity curves for liquid gallium and indium, using the Drude theory that gives excellent results for liquid metals (Schulz 1955). The computations shows that liquid indium has a slightly better reflectivity than liquid gallium so that, as argued by Borra (1992), a Ga-In eutectic should have slightly higher reflectivity than liquid gallium.

3. GALLIUM OXIDE

The main difficulty encountered with our Ga-In mirrors comes from the rapid oxidization of the metal.

3.1 Gallium Oxide

Gallium belongs to the chemical family of aluminum and, like aluminum, oxidization generates a transparent thin oxide skin that protects the metal underneath from further oxidization. Experiments with mercury LMs show the formation of a transparent oxide crust that plays an essential role (Borra et al. 1992) in stabilizing the surface quality of the mirror. While it takes a few hours to form a mercury oxide skin, the surface of Ga oxidizes almost instantly, forming a transparent skin. This rapid oxidization presents us with the most frustrating difficulty encountered making Ga mirrors. The problem arises from the fact that, to close the surface of the mirror, the liquid must be stirred; so that the protective oxide skin is continuously broken and rapid oxidization forms an opaque messy skin on the surface of the mirror. We have dedicated a large effort trying to either prevent or eliminate this messy skin.

Oxidized liquid gallium sticks to most surfaces, making it very hard to clean any container or tool that has been in contact with it. This problem is, however, easily solved by cleaning with a mixture of water containing 5% HCl or NaOH. In practice, we prefer NaOH. The reaction between the Ga oxide and NaOH (or HCl) very effectively eliminates the oxide responsible for the stickiness and allows for easy cleaning. Depositing a tiny drop of diluted HCl on an oxidized Ga surface cleans it to a shine and what seems, to the naked eye, an optical quality surface. However, our optical tests show that the surface is far from having a good optical quality. Seen under a knife-edge test, the Ga surface has the appearance of a polar icepack seen from an aircraft flying at high altitude. In practice, diluted NaOH (or HCl) are only useful as cleaning agents. They must be used sparingly since, besides corroding what they contact, they also prevent Ga from wetting causing problems when one tries to close the surface of a Ga mirror.

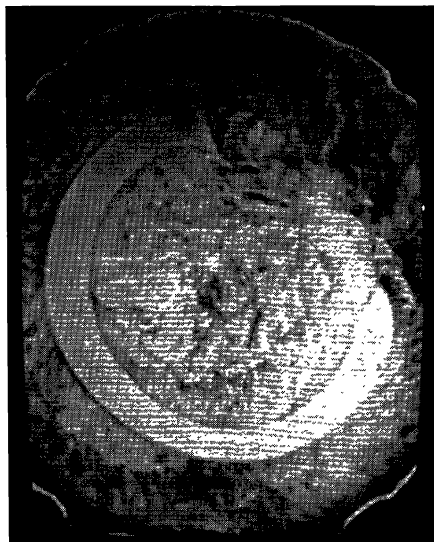


FIG. 2—Photograph of a knife-edge test of a 50-cm Ga-In mirror partially cleaned with a mylar strip.

3.2 Preventing Oxidization

We have tried closing a 50-cm Ga-In mirror in an inert atmosphere. We first tried to flush the oxygen with nitrogen and argon gases. The container was sealed with a plastic cover and we flushed it for about an hour. The Ga-In layer was closed by dragging, inside the sealed container, a strip of mylar plastic film on the surface of the liquid metal. We never managed to obtain a satisfactory surface. The problem is that there always remain some traces of oxygen in the inert atmosphere that oxidize the surface. In principle, a more sophisticated system and long flushing times may solve the problem. We, however, gave up on this technique.

We also tried closing the layer of Ga-In covered with liquids such as water, alcohol, acetone, etc. Our attempts were unsuccessful since the messy oxide layer formed every time. Evidently, oxygen in the liquid oxidizes the surface.

3.3 Removing the Oxide

We always worked with layers of liquid metal about 2-mm thick. Thin layers of liquid are important to decrease the weight of liquid and to dampen disturbances (Borra et al. 1992). We found that the best technique to close a Ga-In layer in air is by pushing on it with a jet of air from a hairdryer. It takes about four minutes to close a 1-m diameter mirror. The resulting surface has a very poor optical quality as can be seen in the image of a knife-edge test of a 50-cm Ga-In mirror (Fig. 2). The semicircular band on the surface was generated by dragging a mylar sheet on the surface. The appearance of the band in Fig. 2 illustrates the effectiveness of mechanical cleaning.

We tried cleaning the surface by dragging a mylar sheet, a blade, etc. Our best results were obtained by dragging a plastic blade shaped to follow the proper parabola. The bottom of the blade must travel roughly at mid-distance between the bottom of the container and the surface of the liquid. The rotation of the blade must be smooth, otherwise it generates

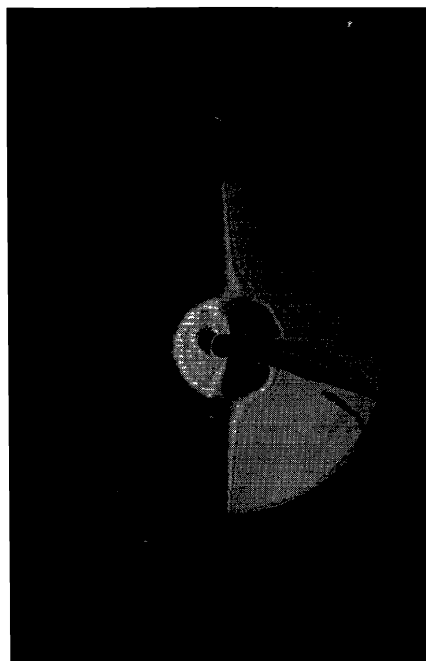


FIG. 3—Shows an image obtained from a typical knife-edge test of a 1-m Ga-In mirror.

thin radial spikes. A jerk in the rotational velocity can also let an oxide lump slip under the blade, marring the surface.

4. OPTICAL TESTS OF A 1-M DIAMETER GA-IN MIRROR

Optical testing was done in a small testing tower adjacent to the testing tower used to test large mirrors (Borra et al. 1993). Like the large tower, it has excellent local seeing. However, the small tower does not have an interferometer and we only can carry out simple tests such as knife-edge tests and Ronchi tests. Unlike the tests reported by Borra et al. (1993) we did not use null lenses so that the mirror, tested at the center of curvature suffers from a large amount of spherical aberration. All tests reported in this section were done with 1-m Ga-In mirrors having 2-mm thick layers.

Figure 3 shows an image obtained from a typical knife edge. One can see the characteristic signature of a parabola. One can also see some typical defects resulting from mechanical cleaning. The large radial bar is the most conspicuous defect. It is caused by the accumulation of gallium oxide on one side of the skimming blade: Removing the blade leaves the accumulation on the mirror. In this particular case, drips of liquid caused an additional small bar adjacent to the large one. The oxide bar is not a problem since it could be removed by skimming the oxide with a second blade that skims radially. It could also be left on the mirror and simply masked, losing a small fraction of the area. Figure 4 shows the image of a Ronchi test. The bars of the Ronchi grating subtend 12 arcsec. We can see the characteristic signature of the Ronchi test of a parabola. We see the oxide bar as well as the concentric rings and spirals seen in mercury mirrors. Ga-In mirrors show the same defects typically seen in mer-

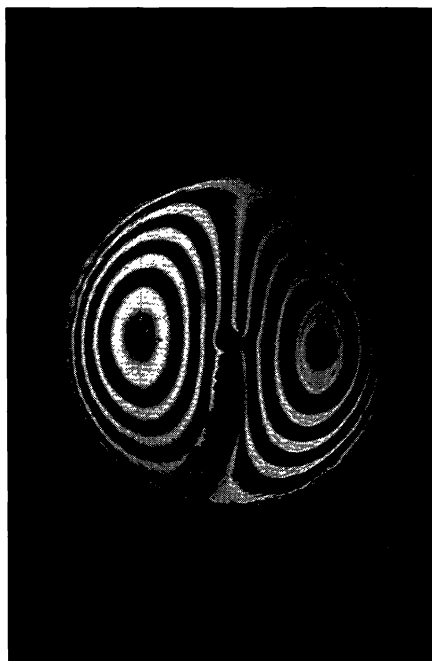


FIG. 4—It shows the image of a Ronchi test of a 1-m Ga-In mirror.

cury mirrors (Borra et al. 1993). These defects have the same amplitudes as for mercury mirrors and are thus not of major concern.

5. OBSERVATIONS WITH A 1-M DIAMETER GA-IN MIRROR

At some stage, it is necessary to test these mirrors on the sky. For this purpose, we made a 1-m diameter gallium-

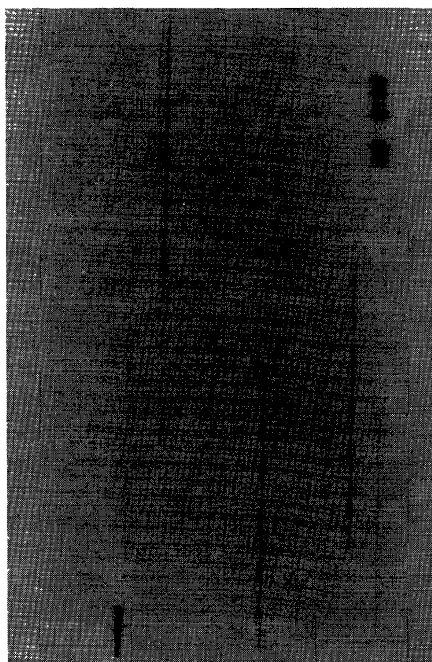


FIG. 5—Stellar trails obtained with a 1-m diameter Ga-In liquid mirror. The frame is 15 arcmin wide and 22 arcmin long.

indium liquid mirror using the same equipment and observatory previously used with mercury mirrors (Borra et al. 1988). The detector was a programmable 35 mm camera that registered star trails of 1 min duration. Figure 5 shows a frame containing several trails. The star trails give information on the behavior of the liquid mirror during actual working conditions. Star trails are convenient for our purpose, since the time dimension runs along one spatial dimension, allowing us to see the behavior of the point-spread function (PSF) as a function of time. Our crude setup and poor seeing conditions at the sea-level campus location (a few arcsec FWHM) do not allow us to make a thorough quantitative analysis. However, we see that the trails are very similar to those reported, at the same location, and with the same equipment, with mercury mirrors by Borra et al. (1988). We therefore conclude, within the limitations of this simple setup, that we should expect Ga-In mirrors to perform like mercury mirrors.

6. CONCLUSION

We have explored the use of gallium, and low-melting-temperature gallium alloys in liquid mirrors. These alloys have advantageous characteristics with respect to mercury. The main advantage comes from the fact that these alloys have densities lower than the density of mercury, resulting in lower costs for the bearings and the containers. Estimating the exact cost saving is not straightforward since it depends on the fluctuating cost of gallium, the thickness of gallium used and the cost of commercially available bearings. However, an estimate for a 5-m mirror indicates that the cost of a gallium mirror would be about half the cost of a mercury mirror.

Gallium oxidizes very rapidly and forms a transparent thin oxide skin that protects the liquid from additional oxidation. However, this skin is repeatedly broken upon startup, ruining the optical quality of the mirror. This has been our major problem. We however have overcome it with a simple blade skimmer.

Simple knife-edge tests indicate that gallium-indium mirrors have optical qualities similar to those of mercury mirrors.

We have operated for a few nights a 1-m diameter liquid mirror that used a gallium-indium alloy. The instrument operated satisfactorily, within the limitations of a very simple telescope and instrumentation.

Perhaps our most interesting finding is that the high melting temperature of gallium is not a major problem since our experiments show that it is easy to supercool and quite stable in the supercooled state. Eutectic alloys of gallium have significantly lower melting temperatures than the pure metal and are also easy to supercool and are stable in the supercooled state. Our experiments indicate that a supercooled 10-m class gallium-indium mirror should remain liquid to temperatures of the order of -10°C .

The experiments, optical tests, and observations that were carried out were very simple, since they were meant to simply explore the feasibility of gallium liquid mirrors. We did not have much time nor energy to dedicate to this project

since the main impetus of the laboratory work went to perfecting the mercury technology, which works. The results of our experiments with the gallium–indium alloy are quite encouraging and warrant further, more rigorous, continuation of this work. The present article can be seen as analogous of two early articles that explored the mercury technology (Borra et al. 1985; Borra et al. 1985). As a matter of fact the same basic instrumentation was used at that time. We are planning to continue work on the development of gallium–alloy liquid mirrors.

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REFERENCES

- Arrien, F. 1992, unpublished M.Sc. thesis, Université Laval
 Borra, E. F. 1982, JRASC, 76, 245
 Borra, E. F. 1987, PASP, 99, 1229
 Borra, E. F. 1991, ApJ, 373, 317
 Borra, E. F. 1992, ApJ, 392, 375
 Borra, E. F. 1995, Can. J. Phys., 73, 109
 Borra, E. F., Beauchemin, M., Arsenault, R., and Lalande, R. 1985, PASP, 97, 454
 Borra, E. F., Beauchemin, M., and Lalande, R. 1985, ApJ, 297, 846
 Borra, E. F., Content, R., Poirier, S., and Tremblay, L. M. 1988, PASP, 100, 1015
 Borra, E. F., Content, R., Girard, L., Szapiel, S., Tremblay, L. M., and Boily, E. 1992, ApJ, 393, 829
 Borra, E. F., Content, R., and Girard, L. 1993, ApJ, 418, 943
 Chalmers, B. 1964, Principles of Solidification (New York, Wiley)
 Gauvin, J. 1992, unpublished M.Sc. thesis, Université Laval
 Hickson, P., Borra, E. F., Cabanac, R., Content, R., Gibson, B. K., and Walker, G. A. H. 1994, ApJ, 436, L201
 Hickson, P., Gibson, B. K., and Hogg, D. W. 1993, PASP, 105, 501
 Miyazawa, Y., and Pound, G. M. 1974, J. Cryst. Growth, 23, 45
 Ninane, N. 1996, Opt. Eng. (Bellingham), in press
 Schulz, L. G. 1955, JOSA, 47, 64
 Sica, R. J., Sargoytchev, S., Borra, E. F., Girard, L., Argall, S., Sarrow, C. T., and Flatt, S. 1995, Appl. Opt., 34, 6925
 Timoshenko, S. P. and Woinowsky-Krieger, S. 1959, in Theory of Plates and Shells (New York, McGraw-Hill)
 Turnbull, R. 1952, J. Chem. Phys., 20, 1327