2000 and 40 MW, respectively. At efficiencies of just a few percent, it pays to recover the unspent energy in the electron beam. So Los Alamos installed an energy recovery loop that circles the electron beam back to the linac, where deceleration of the electrons pumps up to 70% of their energy back into the rf cavities. Charles Brau of Los Alamos told us the design goal had been 50% recovery. This loop functioned stably even while the FEL was lasing.

Last fall Los Alamos operated a new type of injector based on photoemission technology, which uses a laser to generate very short pulses of electrons that give a high-quality beam. Their current injector produces a long pulse which must then be compressed, with subsequent degradation of the beam quality. The new injector has produced a peak current of 400 A for an 80-psec pulse with an energy of 1 MeV. (The average current over a 10-μsec burst of pulses was 3 A.) The brightness at a peak current of 120 A exceeded the specifications for the White Sands demonstration. Brau emphasized that the injector may be of potential interest for many accelerator applications.

Perhaps the major limitation on rf FELs is the capability and survivability of the optical resonator at high power levels. The high-reflectivity mirrors at either end of the cavity are readily damaged by intense radiation. Such damage has so far prevented the Los Alamos team from operating at the design point of the wiggler. The group plans to try copper mirrors with increased cavity length. In a separate experiment with an argon ion gain medium, the Los Alamos team has shown that they can fabricate and align a 64-m-long optical resonator with 4° grazing incidence mirrors.

Another obstacle to high-power rf FEL operation has been the low power available from existing accelerators. The Boeing Aerospace Company has just finished constructing a 120-MeV rf accelerator designed to operate with a short-wavelength (0.5 micron) FEL. They hope to produce average currents as high as 100 A and increase power output by generating more closely spaced packets of micropulses. Spectra Technology and Rockwell's Rocketdyne division have provided the 5-m wiggler and the optical resonator, respectively. Boeing project director Donald Shoffstall told us the company hoped to get the device to lase by late May and would gradually work toward high-power operation. Boeing is competing for selection as the contractor to work with Los Alamos to develop an rf FEL design for the White Sands facility.

More FEL work. While the efforts just described focus on defense applications, other FEL work is directed more toward such applications as medicine or materials science, where average power levels of a few watts suffice. A Stanford–TRW collaboration has recently reported operation of an FEL at a wavelength of 525 nm. The Stanford FEL uses the electron beam from Stanford's superconducting linear accelerator, whose energy is 60 MeV. To get wavelengths in the visible, the Stanford–TRW team needed an electron beam energy above 100 MeV. Thus they extracted the beam emerging from the linac at 60 MeV and piped it back for a second pass through the linac to boost its energy to 115 MeV. Only one other FEL—at Orsay, France—has operated in the visible before and it did not achieve the power obtained in the experiment at Stanford, where the peak power output was 170 kW. The collaborators on this experiment are Todd Smith and Alan Schwettman of Stanford and George Neil, John Edighoffer and Steven Fornaca of TRW.

Smith said they are now refurbishing the laser and hope to push for ultraviolet wavelengths when it is running again in October. The group has also developed an energy recovery scheme in which they take the electron beam from the wiggler exit and feed it back into the linac 180° out of phase with the field. As the electrons are decelerated they give their energy back to the radiofrequency field for acceleration of a fresh bunch of electrons.

The White Sands GBFEL program will explore whether ground-based FELs can direct high levels of radiant power to mirrors in space, which would in turn direct that energy toward enemy targets. The program must evaluate not only the potential for high-power FEL operation but also the performance of beam control systems and problems of atmospheric transmission.

The Army has asked a team of experts called the Technical Advisory Group to recommend which of the two FEL concepts—induction or rf—should be chosen. The group is headed by Lieutenant Colonel Tom Johnson of the US Military Academy (West Point). Because they must consider not only which laser is most feasible but which will give the beam with the most promise for atmospheric transmission, the 14 members and 5 consultants on the advisory group include not only experts on accelerators, FEL physics and optics but also experts on atmospheric propagation. Five of these experts, including Johnson, participated in or reviewed the APS DEW study. Johnson said his group would be looking at FEL technologies now in even greater detail.

The APS DEW study group stated in its report that "FELs suitable for strategic defense applications, operating near 1 micron, require validation of several physical concepts." Among those they cited were the demonstration of optical guiding and transverse sextupole focusing for the induction FEL, and control of sideband instabilities and harmonic oscillations for the rf-type FELs. Andrew Sessler (University of California at Berkeley), a member of the DEW panel, feels it is unlikely that enough technical information will be developed for a proper choice to be made between the two approaches by June 1988.

While recognizing that the Army might have to make a decision before all the questions are completely answered, McNulty nevertheless feels it is necessary to take some risks and set challenging goals to move the FEL time schedule ahead. Asked which type of FEL now held the edge, McNulty said that he felt they were tied at this point. He cited optical guiding as the critical issue for induction FELs and optical resonators as the challenge for rf FELs.

—Barbara Goss Levi

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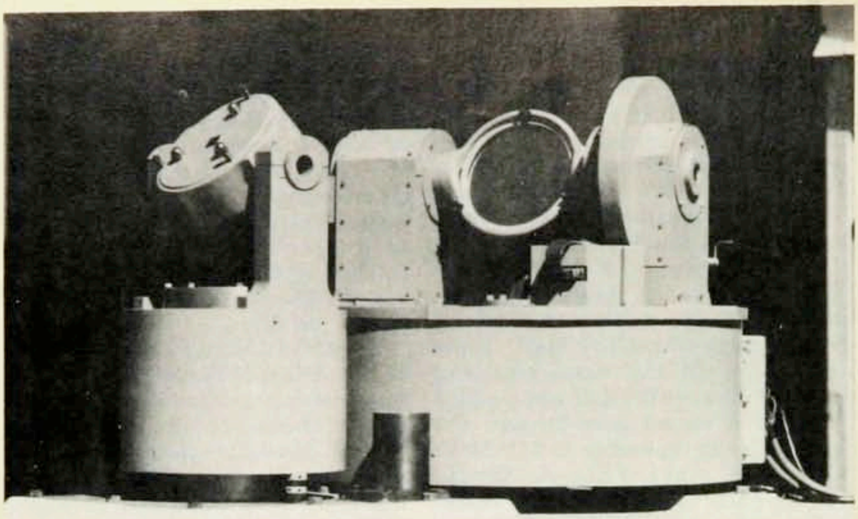
Astronomers seek high resolution

Astronomical advances often depend upon technological advances. In recent years charge-coupled-device detectors on existing telescopes have reached photon efficiencies approaching 100%, significantly better than those of photographic detectors. (See PHYSICS TODAY, March, page 19.) "The 5-meter Hale telescope with a charge-coupled-device detector is equivalent to a 50-meter diameter telescope equipped with 1948 photographic plates," says Peter Waddell (University of Strathclyde, Glasgow), who is trying to develop large



One of the light-collecting elements for the University of Sydney prototype stellar optical interferometer is shown above. The installation was used to make the first angular diameter measurement of a main-sequence star (Sirius) by amplitude interferometry. (Photograph reproduced by permission of John Davis.)

membrane mirrors that may eventually be used in space. "Detector sensitivity cannot go much further, which is why astronomers are looking once again for larger telescopes."

Telescopes both detect faint sources and resolve fine detail. The theoretical resolving power of a telescope, that is, the ability to resolve two stars as separate point sources, is diffraction limited. In practice astronomical seeing—governed by turbulent elements in the Earth's atmosphere—at the most favorable ground-based sites such as Hawaii is at best about 0.2 arcseconds. This is about ten times poorer than the theoretical resolution of the Hale telescope. Thus large ground-based telescopes have functioned chiefly as "light buckets," dependent on a mirror's collecting area, which is proportional to the square of the diameter. But in addition to planning several new-technology telescope projects that rely on new ways of making mirrors, astronomers want to exploit diffraction-limited optics to obtain high angular resolution—usually despite the presence of the Earth's atmosphere.

Optical interferometry. In 1890 Albert A. Michelson's article "On the application of interference methods to astronomical measurements" published in the *Philosophical Magazine*, described interference methods for measuring the angular size and brightness distribution of sources too small to be resolved by a single telescope (see PHYSICS TODAY, May, page 24). Thirty years later Michelson and Francis Pease used two mirrors in front of the 100-inch Hooker telescope at Mount Wilson to make the first successful measurement of the angular diameter of the star α Ori, Betelgeuse, as 0.047 arcseconds. Michelson's ideas have been particularly successful in achieving high angular resolution in radioastronomy, especially in very-long-baseline interferometry.

In the 1950s and 1960s Robert Hanbury Brown, Richard Twiss, John Davis and coworkers at the University of Sydney developed the Narrabri intensity interferometer, which they then used to measure, over about a six-year period, angular diameters of 32 smaller and hotter stars. Restricted to observing only the brightest stars, the observatory was closed in 1972. Encouraged by a pilot model of a modern version of Michelson's interferometer developed by Twiss and William Tango, the Australian group[1] decided to build an amplitude (Michelson) interferometer instead of trying to reach somewhat fainter stars with the intensity interferometer.

Davis, Tango and Hanbury Brown have received a grant to start construction in 1987 of a very-long-baseline stellar interferometer with 400 times the sensitivity of the Narrabri instrument. External phase errors resulting from turbulence in the Earth's atmosphere are reduced by using small apertures of about the phase fluctuation length—a few centimeters—and an active optical servo to maintain beam alignment within 0.1 arcsec. A working prototype used for more than a year has 15-cm-diameter mirrors at the ends of an 11.4-m north–south baseline; the high-resolution interferometer will have eleven 20-cm mirrors with baselines from 5 m to 640 m. Using the prototype, Davis and Tango found the angular diameter of Sirius to be within 0.5% of the Narrabri result, but the new method took only 2% of the Narrabri observing time. This was also the first independent check on any Narrabri measurement.

Antoine Labeyrie (now at Centre d'Etudes et de Recherches Géodynamiques et Astronomiques, near Nice, France) suggested about 1970 that a "boiling" stellar image observed through the turbulent atmosphere should consist of bright "speckles" similar to the bright features seen in coherent laser light. Labeyrie's stellar speckle interferometry technique uses very short exposures (typically 0.01 sec) to get diffraction-limited resolution from large telescopes. This technique can map surface features on large luminous stars such as Betelgeuse. And it provides yet another method to measure stellar angular diameters. According to Labeyrie, the method at present can be used as faint as magnitude 18—about 10^{-5} the brightness of the faintest naked-eye stars.

But Labeyrie is interested in milliarcsecond resolution. Since 1974 he has operated a small interferometer consisting of a pair of 25-cm telescopes with a 67-m (now 120-m) baseline and more recently he has used a pair of 1.5-m telescopes with spherical mounts—"boules"—made of concrete and mounted on railway tracks. Labeyrie says, "To allow mobility on tracks, with minimal Coudé complexity, high stiffness and no dome, it was decided to develop a novel mount principle, involving a sphere and a robotic 'sphere walking' mechanism." The main difficulties encountered are the vibration and drift of the fringe system, both of which increase with system size. In reporting the successful observation of fringes in the visible from the star α Lyr (Vega) with a 13.8-m baseline using the large "boules" interferometer, Labeyrie's group[2] concludes "the technology is now ripe for a far-reaching improvement of imaging capabilities in optical astronomy."

Labeyrie has proposed an Optical Very Large Array in the same spirit as the Very Large Array, a multi-antenna radio interferometer at Socorro, New Mexico. An Association of Laboratories for Optical High-Resolution Astronomy is being created to build it, probably on Mauna Kea in Hawaii, for use by astronomers worldwide. And Harold McAlister (Georgia State University) is planning a Y-shaped array of seven 1-m telescopes as an optical analog of the Very Large Array. McAlister has been using Labeyrie's speckle imaging technique for stellar astrometry (positional astronomy) to compile measurements of binary stars.

Stellar mass data derived from orbits of binary stars are essential in our modeling and understanding of the physical structure of a star and its life cycle. At Cambridge, UK, a group headed by John Baldwin, a radioastronomer, has received funding to start the Cambridge Optical Aperture Synthesis Telescope project. There are several other optical interferometry projects at various stages of planning and funding.

Why has optical interferometry so suddenly become prominent? About optical interferometry applied to astrometry and stellar angular diameter measurements, Peter Nisenson (Harvard–Smithsonian Center for Astrophysics) tells us: "It is not that hard; there are no really substantial difficulties in making interferometers work. Now it is an engineering project; there are no technological problems." The reason is the enormous advances in computing (fast digital processing) and electronics (image intensifiers, high-speed amplifiers) over the last five to ten years. "This is really an emerging area," says Robert Stachnik (NASA, Washington, DC, on leave from the Harvard–Smithsonian Center for Astrophysics). "The relevant technology had not changed after Michelson, but then good sensors and precision actuators needed for interferometry became available—also image recovery algorithms developed by radioastronomers and the optical community."

Although little money was invested in it, and despite its being very primitive, the French system has worked well. The system was not just restricted to white light fringes. The French workers first obtained a spectrum of the light, then put the data through a computer. Therefore the mechanical requirements that Michelson had could be relaxed. "You do not need to see fringes," Nisenson says, "just count the photons." After measuring angular diameters of a dozen stars, the French group working with Labeyrie used their interferometer to measure the size of the ionized hydrogen shell surrounding the star γ Cas.

Only half jokingly, Stachnik says, "I don't see any reason why within 20 years you shouldn't be able to turn to the weather map page of *The New York Times* and in addition to a satellite picture of the Earth be able to see what Betelgeuse looks like that day."

The Grand Interferomètre à deux Télescopes is located at Centre d'Etudes et de Recherches Géodynamiques et Astronomiques near Nice, France. A pair of 1.5-m "boules" telescopes are mobile on railway tracks. Spherical concrete shells containing the optical elements are mounted on motorized carriages. Coudé beams are received in the central laboratory, where they are recombined to produce interference fringes. (Photograph reproduced by permission of Antoine Labeyrie.)

On Mount Wilson a large group[3] involving four institutions is operating the third working interferometer placed there since 1979. Initial fringe observations were made in September 1986 with a 12-m north–south baseline. The group consists of Michael Shao (Harvard–Smithsonian Center for Astrophysics), David Staelin (MIT), Kenneth Johnston (Naval Research Lab) and James Hughes (US Naval Observatory) and seven others from those four institutions.

Since Michelson and Pease measured Betelgeuse, interferometric measurements of the angular diameters of fewer than 50 stars have been made. "Last year, in our tests, we routinely made over 150 astrometric interferometric observations per night," Shao tells us. "This summer we will operate in a fully automated mode for stellar diameter as well as astrometric measurements and we expect to be able to repeat the total number of previous diameter measurements in our first four hours of operation."

Charles Townes, Edmund Sutton, William Danchi, Manfred Bester and Bernard Sadoulet (Berkeley) have been testing[4] an infrared interferometer consisting of two 65-inch (1.6-m) primary mirrors, which will also be located on Mount Wilson within a few months. Already back in 1978–79, Townes measured phases in the infrared on a prototype. He has completed fringe visibility tests on prototypes with up to 5.5-m separation. But the telescopes are intended to be movable on trailers to get baselines as large as 1 km. Townes is extending radioastronomy techniques to shorter wavelengths by using the heterodyne principle. Incoming radiation is mixed with radiation from a laser so that spectroscopy can be done by scanning the intermediate frequencies. (This is similar to a radio with a local oscillator.) This means that Townes must work with a very narrow bandwidth and thus limited sensitivity. For future systems Townes is considering using the wideband—instead of the heterodyne—approach.

Wide-bandwidth optical interferometers have all operated with north–south baselines because in that orientation the fringe motion due to Earth rotation of the baseline is small when a star is near transit—the line through north and south points on the horizon and the overhead point (zenith). However, Townes's and Shao's groups are planning to operate in other orientations including east–west baselines.

With most interferometers, only fringe amplitude has been measured. But for true aperture synthesis, as in radioastronomy, fringe phase measurements are crucial. Only Shao's group and Townes's group have published fringe phase measurements with long-baseline optical interferometers. This phase determination is important for mapping the image position and shape.

"Most of the work is in getting sufficient stability and accuracy to get the amplitude measurements," says Shao. "Labeyrie showed that this could be done many years ago. The next part is making the phase measurements. We have to go from two-star trackers to three-star trackers and one delay line to two delay lines, but of course three separate fringe detectors to make the closure phase measurements to obtain the image shape." Three telescopes is the minimum number. This minimum configuration of triplets also turns out to be the optimum. Shao predicts that more studies on optical array configurations will be coming out soon because "people haven't really done all the signal-to-noise calculations."

Baldwin's group[5] has reported successful measurements of fringe visibility and closure phase by methods established in very-long-baseline interferometry at radio wavelengths. In its simplest form such an array consists of three elements. Measurements of the amplitude and phase of the spatial coherence function are made on each of the three baselines. The true phases are disturbed by unknown atmospheric and instrumental phases, but the sum of the measured phases—the closure phase—depends only on the coherence function and is independent of atmospheric and instrumental effects. The closure phase is zero for a point source.

According to Shao, the US Naval Observatory is planning to build in 1989–91 a long-baseline interferometer having two orthogonal baselines operating simultaneously for fundamental astrometry. Townes's and Shao's groups, both supported by the Navy to do astrometry, are planning to extend their current instruments to multi-element imaging arrays. If the multi-element arrays are funded, the tentative plans are to build in the capability to operate the two arrays as a single large optical array with around 12 elements, and 45 to 105 baselines, covering the spectral region from 0.4 to 10 microns—perhaps as early as 1993.

In Arizona another group is carrying out seeing and seismic tests to select an observing site, either Mount Hopkins or Mount Lemmon, for a project with an expected completion in spring 1989. This group consists of Nisenson, Nathaniel Carleton, Costas Papaliolios, Robert Reasenberg and Wesley Traub (Harvard–Smithsonian Center for Astrophysics); Edward Kibblewhite and Stephen Ridgway (National Optical Astronomy Observatories); Stephen Strom (University of Massachusetts at Amherst) and Melvin Dyck (University of Wyoming). Tim Cornwell (National Radio Astronomy Observatory) was also originally involved. Funding is from the New Initiative Fund in Astronomy through the National Optical Astronomy Observatories. The project is designed to operate with a bandwidth of 0.1 micron at wavelengths from 0.5 to 3.7 microns, with the dual purpose of observing in the visible and in the infrared.

Prior to his coming to Tucson, Kibblewhite worked with Baldwin's group. Kibblewhite and Dyck are particularly interested in infrared imaging of protoplanetary systems and material ejected from stars. Kibblewhite tells us: "There is a high entry fee in interferometry. Because of the difficulty of observing fringes with the equipment, much manpower is required. The hard part is getting everything working together. Also there is a credibility problem. The potential is enormous, but until someone actually gets some pictures it will be hard to fund these projects—nobody has made it work yet."

For infrared imaging both north–south and east–west baselines are necessary. The plan is to start with three 0.5-m telescopes on tracks on a 100-m north–south baseline to test the system. Three is the minimum number to get closure phase information for determining image shapes. Aperture synthesis as developed by Martin Ryle for radioastronomy did not involve moving the radiotelescope elements, but instead let the Earth's rotation move the elements. As a result observing near the horizon is often necessary. But for infrared observations the increased path length through the atmosphere is unsatisfactory.

There are some important differences between this project and Townes's, although both are designed to operate in the infrared. In gaining an increased bandwidth, the Arizona infrared project has obtained an optimum number of five to seven elements in the array for active fringe tracking, if all beams are combined simultaneously. The reason is that the signal is divided among all the baselines (whose number is proportional to the square of the number of elements) so that with more than about seven elements too much signal is lost. Because of detector noise the signal-to-noise ratio goes down as the number of elements goes up.

However, Nisenson, who is interested in observing sources in the visible, stresses that if the information is combined pairwise, then each pair is measured separately and independently. In this case there can be an unlimited number of elements and the signal-to-noise ratio is not reduced, but as many detectors as baselines are required.

In general the size of array elements is restricted by mechanical vibrations and the correlation distance of the atmosphere. So in effect mirror sizes are restricted to about 1-m diameter for a sufficiently stable interferometer of reasonable cost.

Mirrors in space. Optical interferometry really started getting off the ground just a few years ago. In radioastronomy, until the adoption of interferometric techniques, resolution was much inferior to that obtainable with optical telescopes. Stachnik says, "I don't think there is a one of us who does not believe that in a few decades astronomy will be revolutionized by the kind of instruments we have been talking about." An important step in attaining this goal is to put interferometers in space.

Stachnik tells us that important stimuli were the workshop on high-angular resolution optical interferometry from space held in Baltimore during the 164th AAS meeting in June 1984, and the conference Kilometric Optical Arrays in Space sponsored by the European Space Agency at Cargèse, Corsica, France, in the fall of 1984. In October 1985 a workshop on space imaging interferometry sponsored by NASA met in Cambridge, Massachusetts, to develop recommendations about future projects to be presented to both NASA and the National Academy of Sciences.

This year in January the European Southern Observatory and National Optical Astronomy Observatories sponsored a workshop at Tucson, Arizona, with about 50 participants, on high angular resolution from the ground using interferometric techniques. The meeting concentrated on speckle and ground-based interferometry. Similar meetings will be held regularly; the next is already planned for Munich in the spring of 1988. And in June this year the European Space Agency is sponsoring a conference on space interferometry at Granada, Spain. These meetings demonstrate the surge of interest in achieving high-angular-resolution astronomy through interferometric techniques.

Several paper studies of space interferometers are being discussed: Coherent Optical System of Modular Imaging Collectors—Traub; Spacecraft Array for Michelson Spatial Interferometry—Stachnik; Optical Aperture Synthesis in Space—Alan Greenaway (Royal Signals and Radar Establishment, Malvern, UK) and Jan Noordam (Royal Greenwich Observatory).

Reasenberg has proposed an astrometric interferometric project in space, dubbed POINTS (Precision Optical Interferometry in Space), with *micro*arcsecond resolution, following up on Irwin Shapiro's (Harvard–Smithsonian Center for Astrophysics) suggestion in 1974 that the light deflection in the solar potential in general relativity could be performed to second order by means of an optical interferometer in space.

"Eventually a space interferometer may be built at the Lagrangian points of the Earth–Moon system, possibly based on the concept of free-flying telescopes stabilized by solar sails," Labeyrie says. This project is named Trio after its original design of three components.

And ever ready with new ideas, Labeyrie suggests using molecules trapped by lasers—gaseous mirrors—instead of conventional mirror materials. "In space huge mirrors may become feasible in this way, but the principle does not seem applicable to ground-based telescopes," Labeyrie tells us. "The recent success of Arthur Ashkin at Bell Labs [see David Wineland and Wayne Itano's article on page 34] in cooling sodium atoms with laser interference patterns may be a step toward implementing such gaseous mirrors, although considerable work is still required to develop workable schemes. The principle involves a standing wave pattern of laser light with paraboloidal nodal surfaces. Molecules are trapped on these surfaces, producing the equivalent of a Lippmann–Bragg hologram that focuses starlight."

—Per H. Andersen

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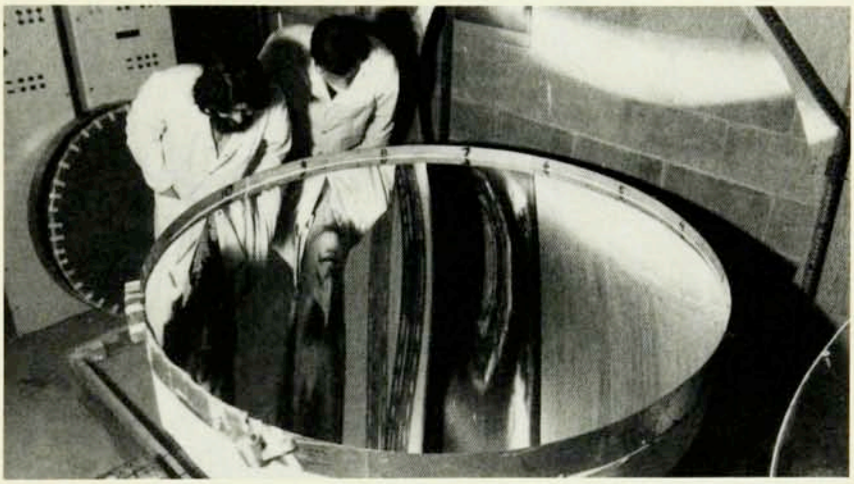
Will future astronomers observe with liquid mirrors?



A liquid mercury mirror having a diameter of 1.65 m and focal length of 1.5 m is shown in this photograph (reproduced by permission of E. F. Borra).

Experiments with liquid-mirror prototypes go back at least to the early 1800s. Isaac Newton, who invented the reflecting telescope and certainly thought about spinning liquids, may be the originator of the concept. In 1908 Robert Wood (Johns Hopkins University) made a 0.5-m liquid-mirror telescope. Vulnerable to jarring motions, Wood's mirror could detect "the footsteps of a person running 50 yards from the telescope house." The problems were serious: Variable motor speed caused distorting ripples on the fluid surface and such a transit telescope is unable to point in any direction other than the zenith, that is, straight up. Hence a liquid-mirror telescope would seem impractical.

Although a liquid-mirror telescope could observe only what is directly overhead, it could make deep-sky surveys of galaxies while sweeping a strip of sky as the Earth's rotation moved the instrument. Despite a similar restriction in pointing ability, the 305-m (1000-foot) diameter Arecibo radiotelescope in Puerto Rico has proved its worth with quasar observations, for example. Surveys with presently available telescopes are restricted by either the telescope's faintness limit or its angular field size, but nowadays charge-coupled devices and image-reduction software on large-scale computers permit massive data accumulation and analysis. Slitless spectroscopy in deep-sky surveys under conditions of excellent astronomical seeing would be a boon to observational cosmology in particular.

Recently Ermanno Borra (Université Laval, Québec) has revived[1] interest in making mirrors from surfaces of spinning liquids. Modern vibrationless air bearings and synchronous motors can overcome the problem of surface ripples. A layer of silicon lubricant can be used to damp out vibrations, which in any case turn out to be only a minor problem. Since June 1986, after extensive optical shop testing, Borra's team has operated a 1-m mercury liquid-mirror telescope, getting 180 hours of data on 38 nights and obtaining stellar images comparable to those from conventional imaging. A thin Mylar cover eliminates wind disturbances without affecting image quality. Examination of 2-minute star trails recorded with a 35-mm camera and the prototype mirror suggests that the basic concept is sound.

As the container holding the mercury rotates around an axis of symmetry perpendicular to the Earth's surface, the liquid forms a paraboloidal equipotential (surface). For a given value of the local acceleration due to gravity, the focal length of the liquid mirror is uniquely determined by the angular velocity. A person walking could keep up with the motion of a point on the rim of an $f/2$ 5-m mirror and a runner could follow a rotating $f/1$ 30-m mirror.

Detailed plans already exist for 3-m-diameter liquid-mirror telescopes. Eventually one may be able to scale up the mirror size to as much as 30 m. A liquid-mirror telescope is cost effective: The 1-m prototype costs about $7500. Although liquid-mirror telescopes could be built at a range of latitudes for maximum sky coverage, their restricted pointing ability remains a serious limitation.

—Per H. Andersen

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