THE BETTER TO SEE YOU WITH

Astronomers have always wanted to see more and better than they do. Recent developments in telescope design and data processing promise a veritable new generation in astronomy—a generation with ways around long-frustrating problems.

BY DIETRICK E. THOMSEN

Given the news that American astronomers are seriously considering plans for a telescope with a mirror effectively 25 or 30 meters across, the average person might comment, "Far out!" The response is likely to be, "Not necessarily."

Ever since observations of distant galaxies revealed the expansion of the universe and caused a revolution in cosmology, publicity about the building of larger and larger telescopes has been based heavily on cosmological considerations. As mirror diameters have gone to 5 meters (at Mt. Palomar) and 6 meters (the world's largest at the Crimean Astrophysical Observatory), much has been said about seeing farther and farther into the universe and examining new objects of cosmological interest. In comparison, much less has been said about the amount of work yet to be done on nearer objects.

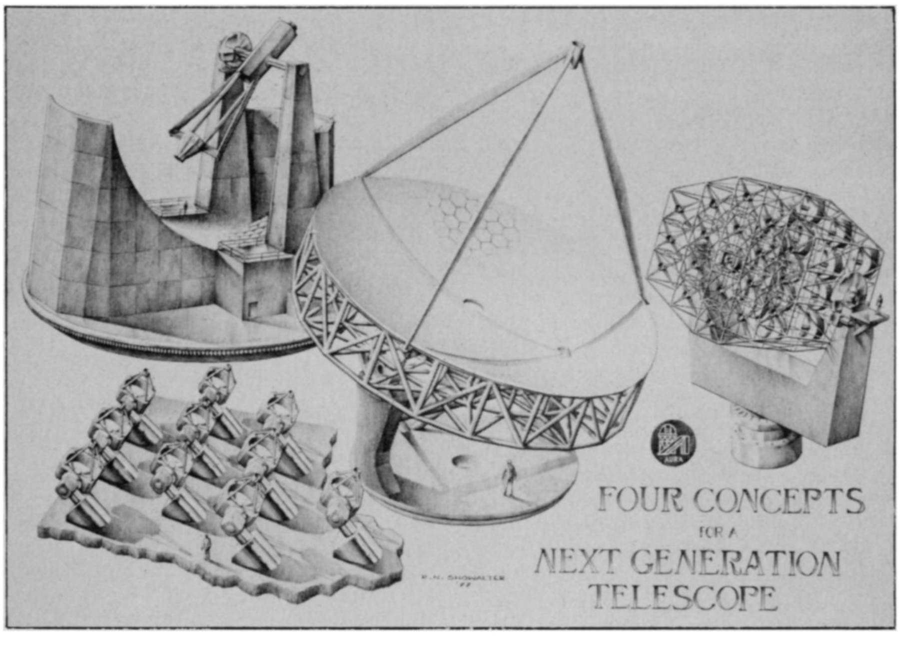
An astronomer involved in the planning of the New Generation Telescope, as the 25 to 30 meter prospect is called, Donald B. Hall of Kitt Peak National Observatory, points out that we can already see objects with redshifts beyond 2. Depending on the scale used to relate redshift to distance, that can work out to something more than 10 billion light-years away. There are some astronomers who suspect that we are now seeing nearly as far as the geometry of the universe will ever permit us to see.

If the NGT is built, it will probably not see much farther into the universe than the 200-inch, says Hall, but the proposal is being urged for the astronomical community on the basis of what it will do for their observations of nearer objects (including the distant galaxies and quasars that cosmologists now have to play with). A larger mirror means more light gathered, and that means more information and more details about any visible object. More efficient use of the light in new recording and resolving equipment, more sensitive and faster spectroscopic analysis and computerized data processing and telescope control multiply the advantage. The result will be more information about a larger number of objects than ever before, and in a science as dependent on statistics as astronomy that can be crucial.

The limit of what can be done in astronomy has always been the number of astronomers and pieces of equipment available and the money to keep the enterprise going. The work is always there. The thing to stress about recent developments is that they make more work possible in less time. With modern recording equipment and computerized pointing, even a 36-inch telescope (quite small by present standards) can do yeoman work. What, after all, could be more yeoman than a spectroscopic survey of 125,000 stars? (That is expected to take the 36-inch telescope part time for five years [see p. 323].) Astronomers will be gratified even if the average citizen loses count.

It would be unlikely that the NGT or any instrument as big that might be built would be used for such a survey of stars in our galaxy—there are a number of smaller installations that can do it—but one use for the NGT would be a spectroscopic survey of individual stars in *other* galaxies, to the limits of our own cluster of galaxies. That, says Hall, might "finally nail down the chemical abundances." One of the important questions in astronomy (and cosmology) is whether the abundances of chemical elements seen in our galaxy apply to the universe as a whole. Without spectra of stars in other galaxies we can't be sure.

A telescope as big as a football field?



Galileo, they say, made the first telescope by putting lenses at the two ends of a tube, and promptly started astronomical observations with it. Since then, telescopes have continually gotten bigger. The fashion has shifted from refractors to reflectors because mirrors can be made bigger than lenses, but now, at 5 or 6 meters, the mechanical and financial limits on the casting of single mirror blanks has been reached. All plans for greater light-gathering capacity involve segmented or multiple mirrors.

The segmented mirror concept uses a

number of pieces like those in a puzzle to build up a single large mirror shape, perhaps a paraboloid or a section of a sphere. The multiple-mirror technique is similar to aperture synthesis arrays in radio astronomy. It uses an array of several mirrors, each in itself a complete paraboloid, that are arranged so that (with the aid of subsidiary mirrors), they all throw their images in the same place and thereby equal the light-gathering capacity of a single mirror much larger than any of them.

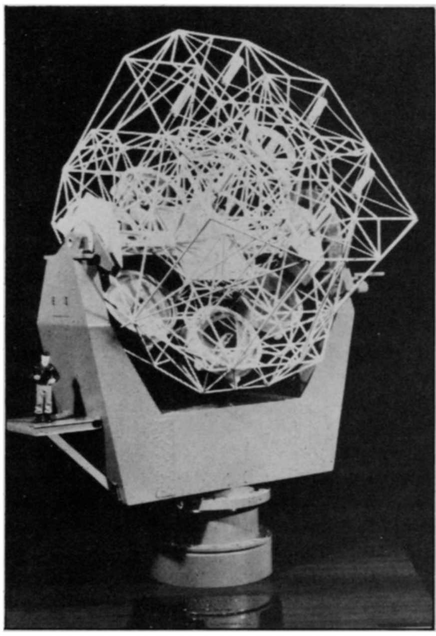
The first example of the multiple-mirror technique will use six 72-inch mirrors to equal the light-gathering capacity of a single 175-inch mirror. A joint project of the Smithsonian Astrophysical Observatory and the University of Arizona, it is called the Multiple Mirror Telescope (SN: 8/18-25/73, p. 118) and is nearing completion on the summit of Mt. Hopkins, about 40 miles south of Tucson. Hall and Larry Barr, an engineer involved in the NGT design, say it should be called the Multiple Telescope Telescope, because it is really six telescopes designed to combine their efforts. Indeed, one of the advantages of the MMT design is that it can be instrumented to work as six telescopes or as one, as desired.

The MMT's progress so far has influenced the people working on the NGT proposal. One of the astronomers leading the MMT work, William F. Hoffmann of the University of Arizona, remarks that when the NGT people started their work, they did not at first consider a multiple mirror plan but now they have included such options in the configurations they are studying. The NGT people call the MMT "a prototype or test bench for concepts we might use," and they remark about "how linked our fortunes are to the MMT."

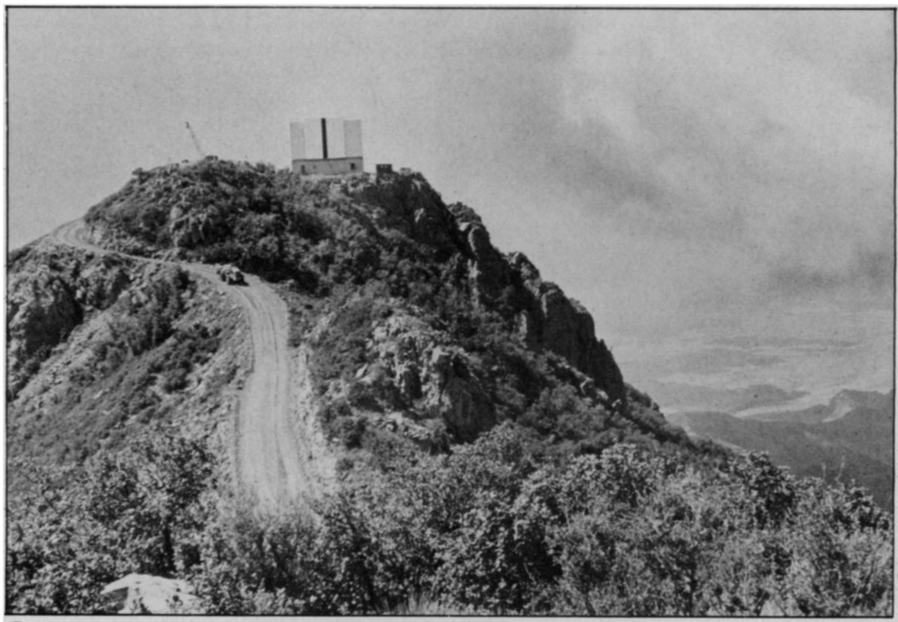
The MMT expects to see its first light in the early spring of 1978, and, says Hoffmann, they will install some astronomical instruments "as soon as we can," but a full observing program will wait at least until fall. The MMT's building stands complete "as an enclosure" on top of the mountain, and the servo-controlled drive that slews its 500-ton weight around has been tested.

In mid-September the support structure for the mirrors was erected. Getting it up the rather primitive road to the top of the mountain and erected in the building was more crucial as a construction problem than will be the hauling and installation of the mirror cells themselves. Installation of the mirrors is expected in January. Before that, weights equivalent to those of the mirrors will be hung on the support structure, and its motions will be tested.

But the moment of truth will come when light begins to follow the rather complicated optical path from the six mirrors to the common image. Usually when a new telescope is constructed, equipment to be used with it is designed and built so as to be ready when the telescope is. In the MMT's case there is less of this than ordinarily. Funding agencies and interested astronomers seem to be waiting to be sure the concept works. Everyone confidently expects that it will but, because the MMT is the first of its kind in the world, final certainty will wait until after the light goes through.


George Kew/Univ. of Ariz.

Six mirrors work together in the MMT.


Lori Stiles/Univ. of Ariz.

Cranes crawled up Mt. Hopkins to install MMT's mirror support frame in its building.

Meanwhile two multiple-mirror options are among four possible designs being considered by the NGT people. The idea is to make feasibility studies and cost analyses for each of the four and then decide. When they started a couple of years ago, the first design that came under scrutiny was a segmented mirror they call the "rotating shoe" because of its shape. The rotating shoe, says Barr, would probably be the most expensive and perform least well but, because it is a section of a sphere, it has one capital advantage for a segmented mirror: The figure or shape of the mirror is easy to control, and the individual segments are easier to make.

Telescope mirrors are usually paraboloids. This shape has the advantage that it will focus a plane wavefront on a point. The wavefronts that come to us from distant objects are to all intents and purposes plane, so the paraboloidal shape has an obvious advantage for astronomical mirrors. There is, in fact, a segmented paraboloid among the plans under consideration for the NGT, but it belongs to a later stage of evolution. It was taken up after the planners convinced themselves that a segmented mirror of spherical shape could be made to work.

The sphere has the advantage that it has the same curvature everywhere. This makes the segments easier to grind and to fit together properly. It also makes alignment easy to check. If the tester sends a beam of light from the center of curvature of the sphere to the mirror, a part that is properly aligned will send the test beam right back to the center. But a sphere will not focus a plane wave to a point. The secondary optics have to correct for the "spherical aberration" in focussing, and that, says Hall, amounts to hanging a 2 meter telescope 50 feet in the air.

The segmented paraboloid, called the "rotating dish" to distinguish it from the rotating shoe, would avoid the necessity for complicated secondary optics—it takes only a rather simple secondary mirror to send the light to a focus at the side of or behind the main mirror, but one pays for this by having a more complicated curvature to fit segments to and serious problems monitoring the alignment of the segments. With the rotating dish, Barr points out, "You don't have a structure out here at the center of curvature to send a test beam from." To check the tilt of segments of the paraboloid one has to start from one of the foci (in this case the Cassegrain focus, which is behind the primary mirror), send a beam to the secondary mirror, from there to the primary, back to the secondary and then back to the focus. For the rotating dish this adds up to a light path 80 to 100 meters long. "There's a lot of funny things that the air path can do to the beam that we want to know more about," says Barr. The planners are developing laboratory schemes to test the control principles. "If we can see the mirror through 80 to 100 meters of air," Barr continues, "then we can control the mirror. If we can control the mirror, we can build the telescope."

The rotating dish has the advantage of taking up a smaller area than the rotating shoe although the saving in cost would probably be cancelled by the more complex control requirements of the paraboloid. Multiple-mirror, or rather multiple-telescope, designs—"They're all multiple-mirror telescopes," says Barr, and from the point of view of the glass that's true—will need a larger flat area. Currently, two variations are being considered, a ring of 16 6-meter telescopes and an array of six 10-meter telescopes in a configuration similar to the MMT now going in on Mt. Hopkins. According to Hall, it begins to look as if the array of six 10-meter mirrors would be preferable.

Siting will be considered when a final concept is chosen and the astronomical community decides what things it most wants the NGT to do for it. A multiple-telescope array would require a large fairly flat mountain top, or it might not be built on a mountain at all. If you don't care too much about the infrared, says Hall, you could build it on the plain at the foot of Kitt Peak or on the (New Mexican) plains next to the Very Large Array radiotelescope.

However, modern astronomers tend to be more interested in the infrared than not, and that would make the highest practicable site desirable in order to get above the largest part of the atmospheric water vapor that absorbs infrared. It is quite possible that the NGT would be built more than 12,000 feet in elevation. White Mountain in California is one of the places mentioned. Experience on Mauna Kea in Hawaii has shown that telescope construction is possible at such elevations. Workers function adequately if they are given an opportunity to acclimate and can go below 9,000 feet to sleep.

Cost estimation will be done at the end of the planning review, but Barr and Hall suggest the NGT will cost about as much as the VLA. In current dollars this is in the $100 million range.

The data gathering and processing practices of modern astronomy change the constraints under which telescopes are designed. Astronomy is ending its long dependence on the photographic plate. The telescope is nowadays much less an extension on the front of a camera and much more an extension on the front of a vidicon tube or, in extreme cases, a photon counter. Astronomers are more and more interested in wavelengths that the photographic plate will not record (infrared or ultraviolet) and in intensity distinctions too subtle for it. Indeed, the builders of the MMT stress its usefulness in the infrared and ultraviolet; one of the instruments being built for use with it is an infrared spectrometer. Telescope designers can now pay less attention to what the eye will see and more to what the photomultiplier tube will record.

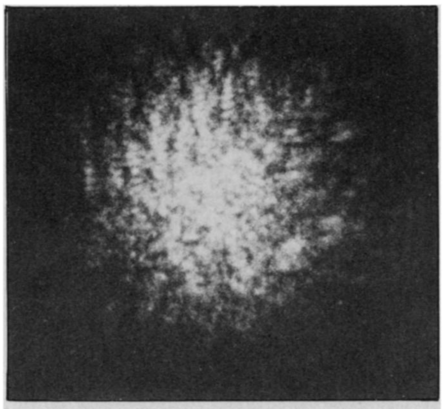
Exorcising the demon of the atmosphere

Oddly enough, but not paradoxically, it is the modern techniques of data processing and servo control that may finally enable astronomers to see better. One of the possible advantages of the NGT, Hall says, is to use its large collecting area to gain more angular resolution, more information about the structural details of astronomical sources. It's a long time since astronomers gave up the search for better resolution—at least on this earth. The laws of optics say that a bigger mirror will give better resolution, but the atmosphere inserts itself. The continually changing turbulence of the atmosphere means that the refraction of light by it varies continually. In consequence, astronomical images jump around. The eye is sometimes quicker than the atmosphere, and it may now and then get a fleeting sharp view, but the photographic time exposures on which astronomers have depended are necessarily blurred.

A technique to reconstruct an unblurred image, at least for certain classes of fairly bright sources, has been developing in recent years. It is called speckle interferometry, and it can be used to process the data after they are recorded or to make real-time corrections in the telescope while it is operating. Speckle interferometry was just beginning when the NGT planners started their work. Now it has progressed to the stage where it can produce diffraction-limited images of Jupiter's satellites, and planning for new telescopes has to allow for its possibilities. (A diffraction-limited image has a resolution governed only by the size of the telescope.)

Throw a dart into the middle of a board listing atmospheric change rates, and you might hit 50 times a second, but the actual rate varies quite widely from place to place and time to time. Astronomers traditionally seek the best seeing locations, the places with the most stable air—the coastal mountains of California and the northwest slopes of the Hawaiian Islands are especially good—and that will remain a criterion, because it will always be easier to correct an image that changes every 20 or 30 milliseconds than one that changes every 2 or 3 milliseconds. (One of the things that speckle interferometry is learning is a good deal of detail about the behavior of the atmosphere.)

If a series of images is taken of a star at a rate comparable to that of the changes in the atmosphere (50 a second is a good figure), it will yield a pattern of speckles that scatter themselves over a given area.



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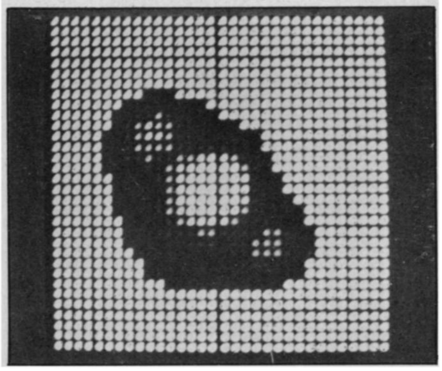
Speckle pattern of binary star 12 Persei (above) yields autocorrelogram (below) that gives distance between components.



It is this speckle pattern that causes the blur in time exposures. The speckle pattern contains enough information for the reconstruction of a much better resolved image than the time exposure, provided the information can be extracted. The technique is useful, of course, only for objects that are bright enough to make an impression in the short time of the individual takes.

Speckle interferometry works by adding up information from light that comes through a given turbulent cell, a section of the atmosphere through which the momentary turbulence is constant. In an example cited by P. R. Vokac of Kitt Peak, the turbulent cells are about 2 seconds of arc across. The optical theoretical resolution limit of Kitt Peak's 4-meter telescope is 0.3 seconds of arc, so each one-fiftieth-of-a-second snapshot should carry fairly accurate information about objects within a given turbulent cell. The trick is adding together the information from hundreds or thousands of such images, and separating it from the accompanying noise, to build up the best possible resolved image.

"Binary stars are simple," says Vokac, "because they're centrosymmetric. To get a high resolution image of a distant star like Betelgeuse, you have a whole different thing. There you have to get an image from each turbulent cell and orient it with its neighbors and stack them up properly in order, and so you get enough signal over the noise to distinguish the details."

Autocorrelation is a processing technique for speckle interferometry that works for centrosymmetric objects. A simple method of autocorrelation called vector autocorrelation begins by finding the center of each speckle. The image is divided by a grid into squares called pixels. The pixel in the center of each speckle is called "on"; all the others are "off." The distance between every two on pixels is measured, and the distances are arranged in a distribution. Since each speckle is one of a pair representing the two stars at a given moment, the distance between such pairs will repeatedly show up in the measurement, while the distances between speckles that are not pairs will be a scatter of numbers. The distribution of distances will peak at the separation between the two stars.

This system is simple and quick to apply, says Vokac, but it has two serious drawbacks: The center of the speckle has to be determined with accuracy, and the operator has to be sure that it is a speckle. For an autocorrelator that Vokac developed for Kitt Peak as a breadboard prototype for a possible permanent piece of equipment, he chose a more complicated data processing system.

"Our technique is far more powerful and slower," he says. "We chose a smaller section of the picture. Instead of 256 pixels squared, we chose 64 pixels squared." Instead of one bit of information per pixel, on or off, black or white, each pixel is digitized to four bits, representing different shades of gray. The center of the picture, 32 pixels by 32 is chosen as a fixed array. Each element of the fixed array is multiplied by the corresponding element of a scanning array, also 32 by 32, which is scanned over the input of the whole 64 by 64 image. This yields 1,024 products. The 1,024 products are summed and the sum becomes an element of the autocorrelogram. The autocorrelogram is 32 by 32, so the operation needs to be done 1,024 times to get one autocorrelogram. "We did five autocorrelograms a second," Vokac says. The autocorrelogram combines so many levels that it turns out to be 32 bits deep. "We had four billion levels," says Vokac.

What comes out is a diagram that shows a central bright spot and two wings. The distance from the center of the center spot to the center of either wing is the separation of the binary star. An example of such observation is the star 12 Persei with a separation of .048 seconds of arc. This corresponds to a five-pixel separation on the autocorrelogram, which Vokac calls "quite clean."

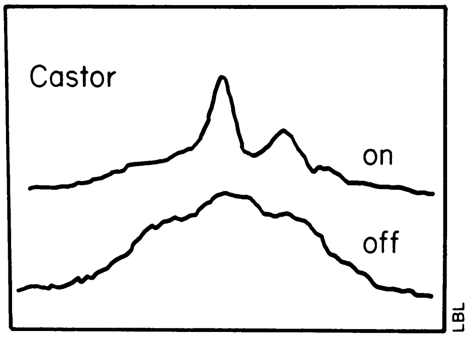
At five autocorrelograms a second, they were able to see this right at the telescope. Previous techniques had stored the data on tape and processed it later through a computer which made an autocorrelogram from perhaps 50 frames. With the on-line technique, the observers can watch the autocorrelogram building up and stop with as many frames as they need for the information they want. Vokac says that it can be argued that the older technique could collect a larger total of information, especially since in practice, because of noise problems, they had to slow the on-line method's rate to two autocorrelograms a second. But now it seems possible to raise the rate to 10 a second "which is every bit as time efficient as the older methods."

Another method of correcting for atmospheric turbulence is to adjust the light before it gets to the recording apparatus. This is called the rubber mirror or, as the people working on it (Frank Crawford, Richard Muller and Andrew Buffington of the Lawrence Berkeley Laboratory and graduate student Steve Pollaine) might now want to call it, the rubber correction plate.

In this technique, a mirror is divided into segments that should correspond to the size of the turbulent cells or, as they are also called, the isoplanatic patches in the atmosphere. A mathematical function is determined so that its value will be a maximum when the seeing is best and programmed into a servo mechanism. The servo mechanism senses the output of each mirror segment and tries to keep correcting it so that it stays on the good seeing maximum.

A natural limitation on such a technique is the speed of the servo mechanism which must go through all the mirror segments, trying several possible correcting moves for each segment in the time it takes for atmospheric turbulence to change. In no place can there be a very large number of segments, and the best place to use such a technique is where the atmosphere changes most slowly.

A 12-inch prototype rubber mirror exists, has been under test and has been gradually improved during the last year or so. It was set up first at Berkeley and then at the Lick Observatory on Mt. Hamilton near San Jose. A major problem was that the atmosphere changes too fast at Berkeley—on a scale of 3 to 6 milliseconds. The group built an apparatus for checking speckle time changes and found that the situation was no better at Lick. "Andy and Steve went to a meeting in New Mexico," says Crawford, "and they carried this portable speckle time measurer with them. They got times of 20, 30, 40 milliseconds. At that point we decided, 'Aha! We can't sit here in Berkeley.'" Crawford and Pollaine went off and did a survey of speckle change times around the southwest and got similar long times at Mt. Wilson, Mt. Palomar and mountains around Tucson. As a result, the rubber



On a not-so-clear day you can resolve two components in the binary star Castor if you have the rubber mirror on, not off.

mirror was installed at Mt. Wilson.

Before going to Mt. Wilson, the rubber telescope had made diffraction limited images of single stars. The latest project was to see how the rubber mirror could resolve an extended object, a double star. This involves the question "over how much of an area can an image be stabilized?" If the bad air that is causing the trouble is near the telescope, one correction may do the job, but if it is 50,000 feet up, it may be possible to get a good image of one star but not of its companion a few seconds of arc away. Now Pollaine has come back from Mt. Wilson with a resolved image of the double star Castor that shows the trick is possible.

"Of course everybody knows Castor is a double star with a separation of about 2 seconds of arc," Muller writes. "I suspect that it has been resolved many times, by both amateurs and professionals. The key point of the image we obtained is that on a day when the seeing did not allow an ordinary telescope to resolve the double star, the rubber telescope was able to sharpen the image and resolve the two components. The separation and relative brightness of the two component stars are just what was expected."

Further studies of bright extended objects, such as the sun and planets, are contemplated. Many features of the sun and planets—solar prominences, Jupiter's red spot, surface details of Mars—are just at the resolution limit. Studies of such things may benefit materially from the rubber mirror technique.

Ultimately, with developments in the direction of simultaneous adjustment of the mirror segments, the rubber mirror may be scaled up from the present 12-inch size to a larger rubber telescope or to a correction device to be inserted somewhere in the optical path of an even larger telescope. The present 12-inch gets a clear view of about half a second of arc of sky, but astronomers at Mt. Wilson say they see that now and again with their present equipment. The thing to do to convince colleagues of the usefulness of the rubber mirror, says Crawford, is to go to a 36-inch rubber mirror, which ought to get clear seeing over three times that area, and show them a diffraction-limited image of something they've never seen before. □