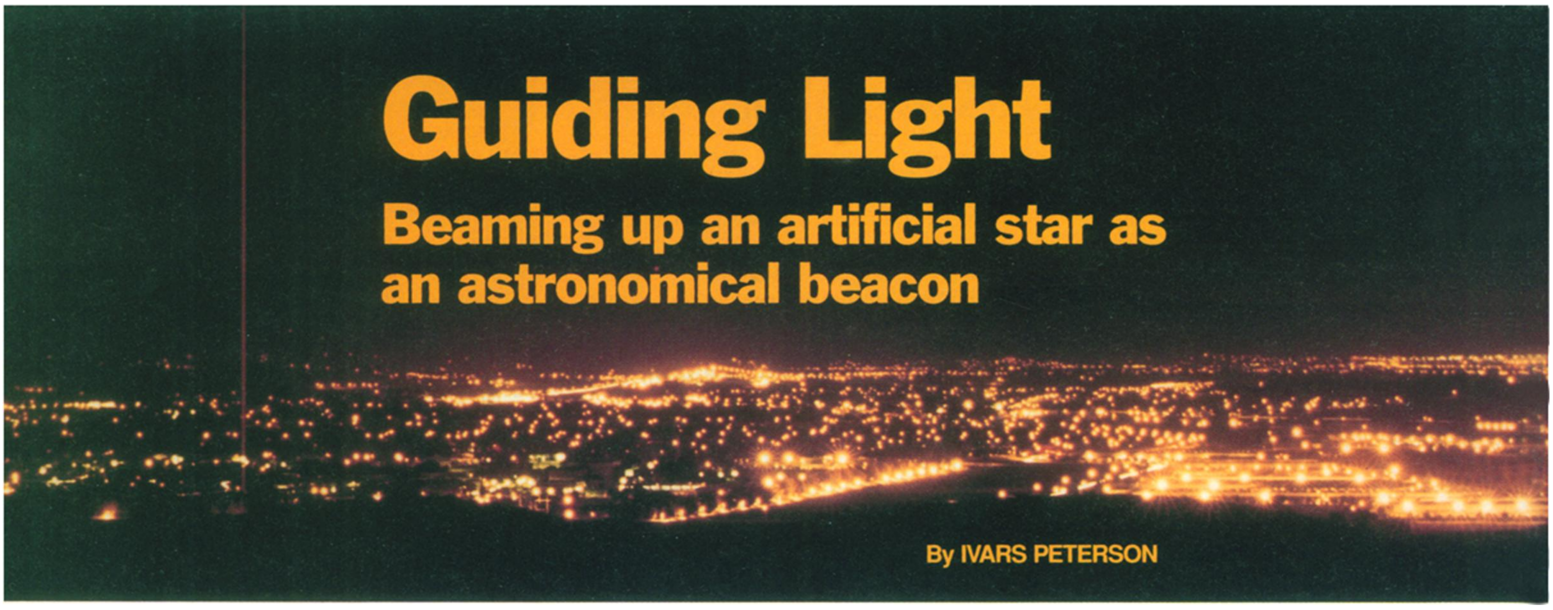

Guiding Light

Beaming up an artificial star as an astronomical beacon

By IVARS PETERSON

A shaft of brilliant yellow light streaks into the night sky. Fired from a powerful laser and focused by a mirror, it pierces the atmosphere.

At low altitudes, the beam appears as a faint, shimmering thread. Air molecules scatter a fraction of the beam's photons, sending the deflected light in all directions and making the beam's path visible to the eye.

At 15 kilometers and higher, the air is thinner. Less scattering occurs, and the beam fades from view.

It reappears about 95 km above Earth's surface. At this height, the atmosphere has an unusually high concentration of sodium atoms. The yellow laser light excites these atoms, which in turn emit yellow light.

Seen from directly below, this tiny, glowing patch of sky looks like a bright star. It even twinkles.

Such artificial guide stars—astronomical beacons—play a key role in various schemes aimed at improving the performance of ground-based telescopes. By locking onto these laser guide stars, astronomers can adjust their instruments to take much of the twinkle out of starlight. Caused by atmospheric turbulence, this troublesome effect blurs images and limits the resolving power of optical telescopes on Earth.

Earlier this year, astronomers at the Multiple Mirror Telescope atop Mount Hopkins in Arizona for the first time used a laser beacon to guide adjustments of a large telescope's mirrors to compensate for air disturbances. "We demonstrated all of the elements working together," says J. Roger P. Angel of the Steward Observatory at the University of Arizona in Tucson. "Even in the simple configuration we used, we made the images better."

Coming after years of discussion and various tests of individual components, this achievement represents an encouraging step toward the general use of laser-guided adaptive optics in astronomy. "Angel and his team are the first ones to actually do it," notes Claire E. Max of the Lawrence Livermore National Laboratory in Livermore, Calif.

The next few years will see this capability added to several more telescopes, with the promise of dramatic improvements in resolution at infrared wavelengths. Eventually, nearly every major observatory may have such a system in operation.

Stars twinkle because random temperature variations continually ruffle the atmosphere, creating shifting air pockets that act as little, mobile lenses. Even on the clearest night, a pinpoint of starlight looks like a small, quivering blob. Captured in a long exposure through a telescope, a star's picture is inevitably smeared.

If there were no atmosphere, a large ground-based telescope could concentrate light from a star into a spot having a width limited only by diffraction—the bending of light waves passing through a small opening. The presence and persistence of atmospheric turbulence means that the same telescope at the best site in the world actually produces images of stars blurred to a diameter at least 10 times greater than the telescope's diffraction limit.

Adaptive optics represents one way to obtain sharper pictures. The idea is to measure how far the atmosphere deflects rays of light coming from a star. A computer then calculates how much to alter the shape of a small, deformable reflector—inserted in the telescope's light path—to straighten out the rays.

In effect, this "rubber mirror" directs starlight back to its original straight and narrow path, compensating for optical distortions caused by the air. It's almost as if Earth's atmosphere has been peeled away.

Typically, a deformable mirror mounted on an array of pistons must readjust its shape 50 to 150 times a second to keep up with atmospheric fluctuations. "You would tailor how often you [make adjustments] to how fast the atmosphere is changing on a particular night," Max says.

In some instances, the star being observed is bright enough to serve as its own reference beacon for making these optical corrections. More often, however, the object of interest is either faint or extended (for example, a galaxy).

Because there's no practical way to compute the necessary adjustments when only a little light is available or when the source is not a point, astronomers must use a brighter, nearby star as a reference. But such beacons are not always well placed for astronomical observation.

That's where the laser guide star shines. Because scientists can place an artificial star in practically any location, "It lets you look at essentially any object in the sky," Angel says.

The notion of using a laser beacon together with an adaptive optics system originated in the early 1980s. At that time, the Defense Advanced Research Projects Agency and the Strategic Defense Initiative Office were interested in using adaptive optics for viewing faint military targets, including orbiting satellites. Laser beams offered a means of probing the atmosphere to measure atmospheric distortions.

In 1982, Will Happer of Princeton University and Gordon J. MacDonald of the University of California, San Diego, suggested that free sodium atoms located in a layer from 90 to 100 km above Earth's surface and excited by a laser could serve as just such a beacon. Working together over the next 2 years, Livermore's Max and Freeman J. Dyson of the Institute for Advanced Study in Princeton, N.J., worked out how to apply this scheme to astronomy.

Originally classified, a report describing these contributions appeared in the January JOURNAL OF THE OPTICAL SOCIETY OF AMERICA A. "We were finally able to pry it loose," Max remarks.

Independently, two French astronomers, Renaud Foy and Antoine Labeyrie, described a similar laser beacon concept in a 1985 paper published in Astronomy and Astrophysics. But efforts outside of the military yielded little progress for a number of years, partly because of difficulties in building a sufficiently powerful laser of just the right wavelength to excite sodium atoms.

In 1987, however, Laird A. Thompson of the University of Hawaii in Honolulu and Chester S. Gardner of the University of Illinois at Urbana-Champaign conducted experiments at Mauna Kea Observatory to test the feasibility of generating an artificial guide star in the sodium layer. Although their beacon proved too weak and unfocused for use in adaptive optics, they demonstrated the concept's viability.

Meanwhile, Robert Q. Fugate and his coworkers at the Starfire Optical Range at Kirtland Air Force Base near Albuquerque, N.M., completed a series of secret experiments on laser beacons and adaptive optics, particularly for use at visible wavelengths. This project was declassified in May 1991 (SN: 6/8/91, p.358), and the fruits of that research are now beginning to have an impact on astronomy.

"We want to offer our facilities to astronomers for instrumentation development," Fugate says. "We're trying to get a program established through the National Science Foundation that would support astronomers to use the equipment here and gain experience with adaptive optics."

One of the more dramatic tests of the concept of a sodium laser beacon occurred at Livermore, starting in the summer of 1992. Bothered by the slow rate of progress in developing this technology for astronomy, Max and her coworkers decided to experiment with creating a sodium guide star, measuring the distortions suffered by rays of light emanating from this artificial star and computing the necessary corrections to compensate for these distortions.

They coupled a powerful copper-vapor laser, originally developed for use in atomic-vapor-laser isotope separation, to a dye laser emitting light at the sodium wavelength of 589 nanometers. Optical fibers delivered the light to a vertical pipe, from which it emerged into the open air as a yellow beam. Two nearby telescopes monitored the resulting laser spot in the sodium layer.

Running for about 9 months, these tests attracted considerable attention. Local residents could readily see the scattered light from the laser beam in the lower reaches of the atmosphere. Many amateur astronomers also observed the sodium guide star with modest backyard telescopes. Several managed to obtain high-quality photographic images of the artificial star.

Photos: LLNL

Laser guide-star site at the Lawrence Livermore National Laboratory. The laser beam shoots out of a vertical pipe (center).

Preliminary results from the Livermore experiments appeared in the February Journal of the Optical Society of America A.

"What we've done so far is use the laser guide star to get accurate measurements at high speed of the turbulence of the atmosphere," Max says. "The next step is to use that information to run an adaptive optics system."

Max and her collaborators are now building a scaled-down version of their dye laser for use with an adaptive optics system for infrared light at the Lick Observatory on Mount Hamilton in California. They plan to install the system on the observatory's 3-meter telescope this fall. They're also starting to design a laser-beacon adaptive optics system for the Keck telescope on Mauna Kea in Hawaii.

While the Livermore group was working with its dye laser, Angel and Edward J. Kibblewhite of the University of Chicago explored the possibility of using less powerful lasers. "We realized that some of the lasers you can buy in the store are now adequate to do some useful corrections for astronomy," Angel says.

Astronomers could get away with such a strategy at the Multiple Mirror Telescope (MMT), because its remote site is excellent for viewing. Moreover, by making observations at infrared wavelengths rather than in visible light, the adaptive optics systems didn't require as many adjustments to keep up with atmospheric fluctuations.

"How much laser power you need depends very strongly on what you want to do," says Thomas H. Jeys of Lincoln Laboratory in Lexington, Mass. "If you're doing it at a good observing site, at longer wavelengths, and if you're not insisting on perfect compensation, then you can get by with a lot less laser power. But if you want to do very good compensation for imaging at visible wavelengths and you're not at the best possible site, then you need more laser power."

Angel and University of Arizona colleague Michael Lloyd-Hart tested a variety of lasers as sodium beacons and used these signals, along with light from a natural star, to correct the positions of two of the MMT's six mirrors and improve imaging.

"What we've pushed is understanding—by experiment with a big telescope—what the whole system can do," Angel says.

The results have been encouraging enough that Angel plans to install an adaptive optics system at the MMT in 1996, when a single, 6.5-meter mirror replaces the facility's present array of six smaller mirrors. In the March 17 Nature, Angel describes how adaptive optics, along with laser beacons, may eventually allow Earth-based observation of planets around stars other than the sun.

Nearly any observatory can benefit from the use of adaptive optics. "We are starting to realize that there are several different uses for adaptive optics," Max says. "One of them is getting down to the true [diffraction] limit of the telescope. Another is taking all the mediocre [observatory] sites in the world—of which there are many—and turning them into sites that are competitive with Mauna Kea."

Kibblewhite and his collaborators are pursuing ways of making adaptive optics systems affordable for observatories with large telescopes. "We have developed a way of making low-cost deformable mirrors along with high-speed [computers to process the data]," Kibblewhite says. "We're hoping to set up a company to market these systems."

A major part of the research effort involves the development of a robust, easy-to-use, yet inexpensive laser specifically for this application. One promising candidate is a novel laser developed by Jeys and his colleagues at Lincoln Laboratory. This laser generates a powerful beam of yellow light by mixing together two wavelengths of infrared light in a special crystal.

The pieces for astronomical adaptive optics are beginning to fall into place, at least for observations at infrared wavelengths. It's a matter of getting them to work together.

"Dramatic improvements in resolution are really possible," Max says. "But we all have a long way to go yet."

Laser-guided adaptive optics for visible light, which would need deformable mirrors with many more pistons and stronger laser beacons than required for infrared astronomy, remain a more distant goal. "Things get exponentially more difficult at shorter wavelengths," Fugate says.

Still, over the next few years, some new stars will shine in the astronomer's sky. □