The Very Long Mystery of Epsilon Aurigae

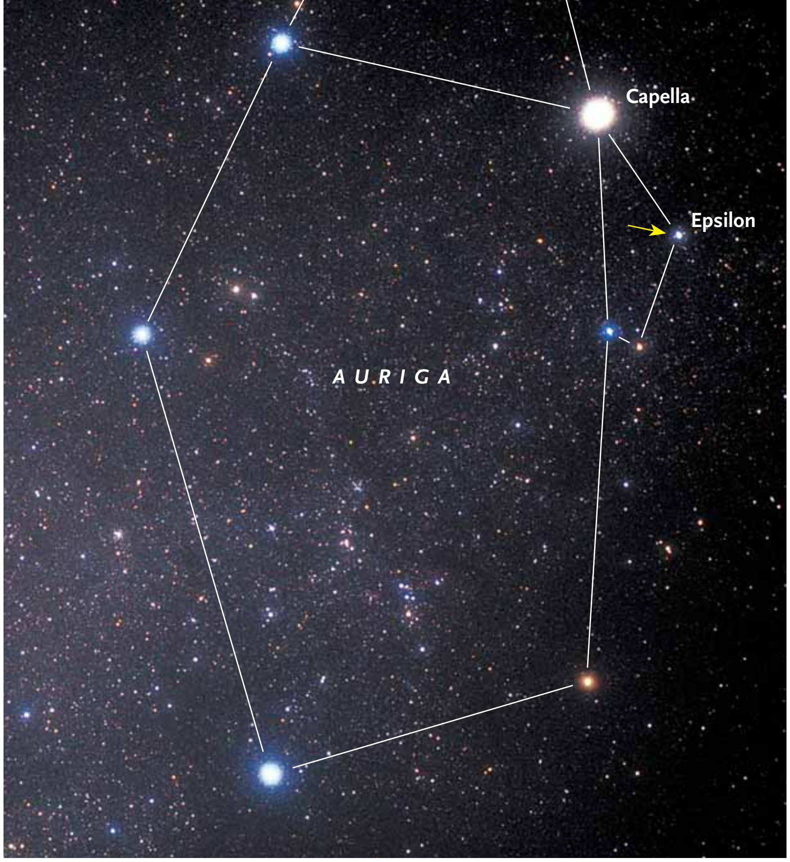
ROBERT E. STENCEL

A remarkable naked-eye star will soon start dimming for the eighth time since 1821. What's going on is still not exactly clear.

ONE OF THE GREAT scientific advances of the 20th century was the theory of stellar evolution, as physicists worked out not just how stars shine, but how they originate, live, change, and die. To test theory against reality, however, astronomers had to determine accurate masses for many different kinds of stars — and this meant analyzing the motions of binary pairs. Theorists also needed the stars' exact diameters, and this meant analyzing the light curves of *eclipsing* binaries in particular. A century ago, giants of early astrophysics worked intensely on the problem of eclipsing-binary analysis. Henry Norris Russell's paper "On the Determination of the Orbital Elements of Eclipsing Variable Stars," published in 1912, set the stage for what followed.

S&T ILLUSTRATION BY CASEY REED

BIG WHITE STAR, BIGGER BLACK PARTNER Epsilon Aurigae, hotter than the Sun and larger than Earth's entire orbit, pours forth some 130,000 times the Sun's light — which is why it shines as brightly as 3rd magnitude even from 2,000 light-years away. According to the currently favored model, a long, dark object will start sliding across its middle this summer. The object seems to be an opaque warped disk 10 a.u. wide and appearing roughly 1 a.u. tall. Whatever lies at its center seems to be hidden — though there's also evidence that we see right *through* the center.



AKIRA FUJII

AURIGA IN THE SKY Bright Capella leads the way to Epsilon and its nearby companions. During May in the Northern Hemisphere, Auriga is sinking low in the northwest right after dark. See the comparison-star magnitudes on page 63.

That same year, a German astronomer named Hans Ludendorff published a paper on the curious eclipsing binary Epsilon Aurigae. As astronomers would eventually realize, its brightness variations in 1874 and 1903 contradicted eclipsing-binary theory and threatened to gum up the works. Shining at 3rd magnitude near Capella, Epsilon Aurigae today remains one of the most perplexing of all bright stars, continuing to defy full explanation.

But perhaps not for long. In August it should begin the next of its two-year-long eclipses, which come every 27.1 years. This time astronomers hope finally to figure out exactly what is happening. And amateurs are already playing an important role in this effort.

A Long History

The star is a seemingly normal type-*F*0 supergiant 2,000 light-years distant. But periodically, something covers it partially. During each very long eclipse the star loses half its light, dimming from magnitude 3.0 to 3.8. Tantalizingly, the change is plain to see with the naked eye if you pay close attention.

The German astronomer Johann Fritsch first reported Epsilon Aurigae dimming in 1821. In 1847 Friedrich W. Argelander and Eduard Heis tracked the next dimming well enough to establish the eclipsing nature of the system and suggest its extremely long period. These heroic visual observers also noted a shorter-term, low-amplitude variation (roughly 0.1 magnitude), which is now often ascribed to Cepheid-like pulsations of the *F* supergiant. But this variation, I suspect, may actually have a very different cause and may turn out to be key to understanding the whole system.

The next eclipses happened on schedule in 1874 and 1903. In 1928, with the next eclipse impending, Harlow Shapley of Harvard Observatory applied Russell's methods of eclipsing-binary analysis. Shapley concluded that the *F* star has 100 times the diameter of the Sun (today the accepted figure is about 300 solar diameters), and, crucially, he found that the companion doing the eclipsing is nearly equal to the supergiant in mass (still true).

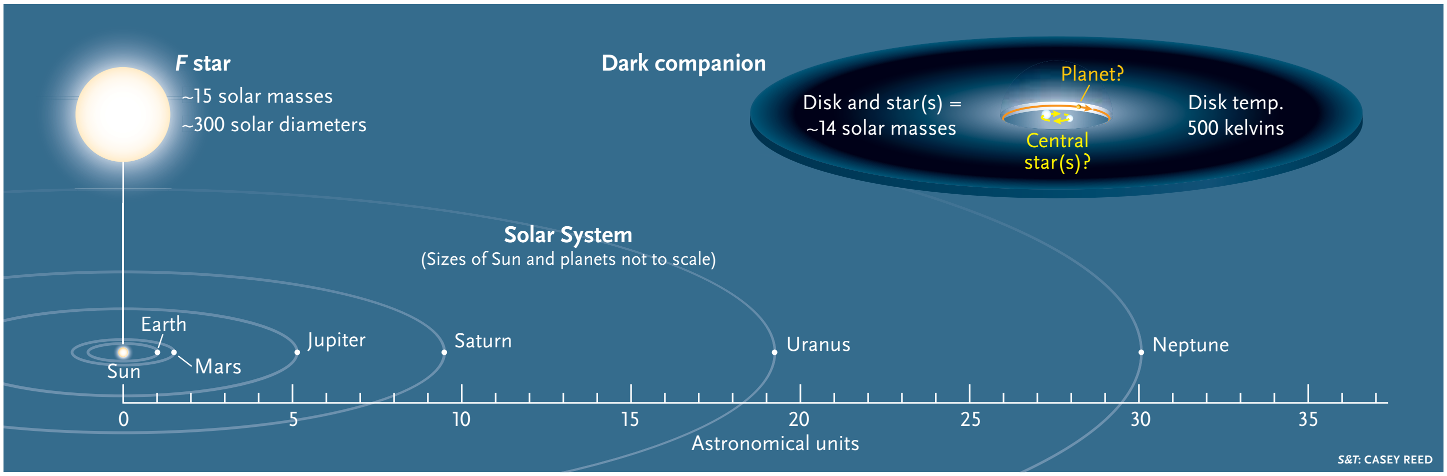
A companion with so much mass ought to shine nearly as brightly as the *F* supergiant. But the spectrum of the system showed no light from the companion at all! This problem, compounded by the remarkably long yet only partial eclipse, is what makes Epsilon Aurigae so mysterious.

During the 1928–30 eclipse, Dean B. McLaughlin and others detected spectroscopic Doppler shifts that indicated a vast rotating object crossing in front of the *F* supergiant. This suggested some kind of disk structure — similar to the way gas flows had been deduced in other close binary stars. Nonetheless the star in the massive companion object did not reveal itself, if there was a star there at all.

Today's Best Estimate

Decade after decade, great names of 20th-century astrophysics tried to account for this behavior. Gerard Kuiper, Otto Struve, and Bengt Stromgren proposed in 1937 that an enormous, semi-transparent "shell star" partially eclipses the *F* supergiant, with electrons in its illuminated side scattering light to account for the eclipse properties. This model failed to satisfy the observations fully.

In 1965 Struve's student, Su-Shu Huang, proposed the basic model accepted today. Huang suggested that an opaque disk, seen nearly edge on, slides across the middle of the *F* star, leaving the top and bottom parts unobscured and shining in view. We know that the two objects orbit each other 27 astronomical units apart, nearly Neptune's distance from the Sun (as measured by the orbital period combined with the *F* star's radial velocity on the two



STAR AND DISK TO SCALE The leading explanation for why we don't see a brilliant, massive star in the center of the dark disk is that it's actually two smaller stars orbiting each other; they would produce less total light. Their orbital action might also be keeping the disk from accreting inward. And could a massive planet be defining the disk's inner edge?

sides of the orbit). This means that the disk has a radius approaching 10 a.u. — larger than the orbit of Jupiter.

Huang's disk model accounted nicely for many aspects of the eclipse behavior, but details had already emerged from the 1954–56 eclipse that raised yet more questions. In 1970 Kjeld Gyldenkerne summarized much of the data then available, and he noted several perplexing aspects.

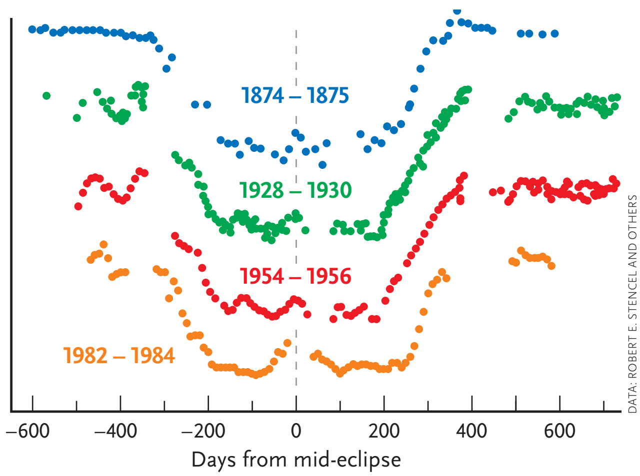
First, there was a slight brightening during mid-eclipse. This seemed to suggest a hole in the disk's center through which some of the *F* star shone for a time. But if the disk's center is clear and we see through it, why don't we see the massive secondary star that ought to be shining there? Moreover, the central brightening was stronger in the 1954–56 eclipse than in the earlier ones (as seen in the red light curve below), as if the opening were growing larger before our eyes.

The eclipse duration was changing, too. The time of minimum light had lengthened by about 64 days, while the overall length of the eclipse, including the entry and exit phases, had decreased by about 44 days! Gyldenkerne noted that the slight, 0.1-magnitude variations of the *F* star might account for some of this, since they confuse the dates when each phase of the eclipse begins and ends. Even so, something more seemed to be going on.

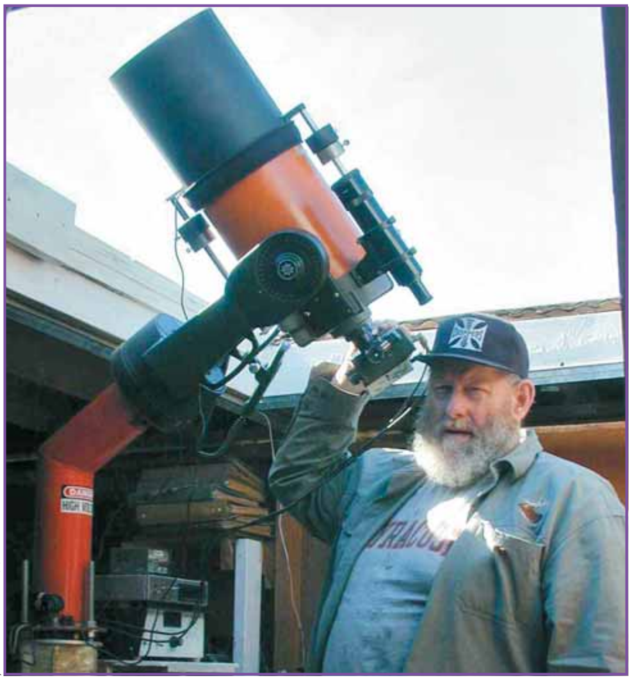
The 1982–84 eclipse was the best-studied ever, by a new generation of observers using modern equipment. Although it was no easier to separate the low-amplitude variations from the actual eclipse events, the strange trends noted by Gyldenkerne increased. The central brightening was the strongest yet, the duration of minimum lasted longest, and the fading and brightening before and after happened fastest. Clearly the gigantic eclipsing body is changing its aspect on a timescale of mere decades.

A leading idea right now for why we don't see the secondary star is that its mass is divided between *two* stars in a relatively tight orbit, each of them a main-sequence star of spectral type *B*. Such a pair would account for the high mass while being much less luminous than the *F* supergiant. And indeed, weak traces of *B*-star light have been identified in spectra of the system, perhaps reflected or scattered by gas or dust clouds while the stars themselves remain hidden.

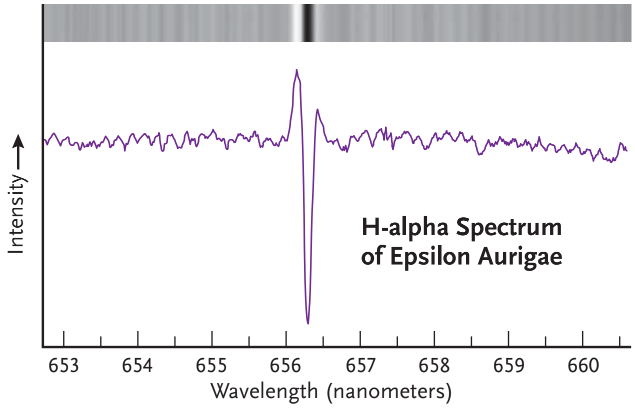
A pair of stars at the disk's center would act as a gravitational eggbeater to keep the center clear, and they would also hold back the disk's material from spiraling in and disappearing as high-mass protoplanetary disks normally do. We can imagine that the disk is kept so massive and dense in this manner that planetesimals keep forming, colliding, and pulverizing one another inside it, with the disk stuck in this stage of life and unable to settle into a normal planetary system.



THE EVOLVING LIGHT CURVE In 109 years the eclipses shortened measurably, the duration of minimum lengthened, and the central brightening became more prominent. Physical changes are clearly happening in the occulting body.



JEFFREY HOPKINS (2)



AMATEUR STAR Jeff Hopkins has tracked Epsilon Aurigae's behavior since its last eclipse in 1982–84. In addition to doing precise photometry, he has taken high-resolution spectra of the star's red hydrogen-alpha line, including the spectrum above. It shows the H-alpha line in absorption (dark core at top) flanked by emission (white). This profile shows that while hydrogen is absorbing light just above the star's photosphere, a thinner hydrogen wind glows brightly as it flies far out from the star in all directions, both toward and away from us.

If (as polarimetry data suggests) the disk's central binary is somewhat tilted with respect to its orbit around the *F* star, the disk's inner, middle, and outer parts could be warped into different tilts accordingly, the way we often see galaxies showing warped disks. This could account for the disk's oddly thick, apparently cigar-shaped profile during the eclipses.

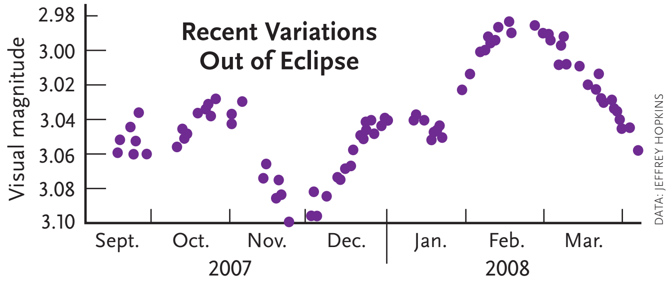
Out of Eclipse

As a young NASA postdoc during the last eclipse, I was fortunate to use the International Ultraviolet Explorer (IUE) satellite to help study this star, and I organized the 1985 workshop where astronomers shared their observational results. Ever since, Epsilon Aurigae has continued to fascinate and frustrate me. However, today's astronomical tools should help us better resolve this challenging system during the eclipse about to begin.

Key insights have emerged from data collected in recent years. Il-Seong Nha at Yonsei Observatory, South Korea, published a very precise light curve spanning the out-of-eclipse years 1984–87. Nha found a quasi-periodicity of 96 days in the low-amplitude light variations. Amateur Lou Boyd, at his private observatory in Arizona, has diligently monitored Epsilon since 1987, and his data through the 1990s indicated a slightly faster, 89-day quasi-periodic variation. Amateur Jeff Hopkins, who provided one of the very best photometric records for the 1982–84 eclipse from his private observatory in Phoenix, resumed his photometric work on this star in 2003. He found that the quasi-periodic variations had speeded up to a 71-day period during the 2003–04 observing season. They continued speeding up to a period of 65 days as of 2007–08.

U.S. NAVAL OBSERVATORY / NPOI / NAT WHITE

WIDE APERTURE, SHARP VIEW Near Flagstaff, Arizona, the Navy Prototype Optical interferometer (NPOI) consists of telescopes in a Y-shaped array that feed light through vacuum pipes to a beam combiner. If the pieces of the same, individual light waves arriving at different telescopes can be correlated and put back together, the array gives the resolution of a single telescope mirror 430 meters wide. NPOI should thus be able to resolve the dark object crossing Epsilon Aurigae's face.



SOMETHING UNSTABLE Even when no eclipse is in progress, slight, semi-periodic variations of about 0.1 magnitude indicate an instability in the *F* star — or perhaps in something else that's modulating some of the system's light.

It is always risky to extrapolate, but at this rate, within a few decades the low-amplitude light variations may become very fast, perhaps signaling some important approaching destiny. Given the 2,000-light-year distance to Epsilon, this event may have already happened, and we're just waiting for the signal to arrive.

Meanwhile, the published data for the four eclipses of the 20th century show that the duration of totality has increased steadily: from 313 days in 1901 to 445 days in 1983. Yet the overall eclipse duration, including the fall and rise, declined from 727 days in 1901 to 640 days in 1983. Acknowledging again the risk of extrapolation, will the partial phases of the eclipse nearly vanish in coming decades?

Perturbations by a Giant Planet?

All of these changes can be understood, I suspect, by drawing on recent developments in the study of protostars and extrasolar planets: namely, hot Jupiters. These are commonplace among exoplanetary systems. They are interpreted as protoplanets that migrated inward through a massive disk, spiraling toward a fiery accretion end in the central star — but somehow got parked in tight orbits just before then. If one or more proto-hot-Jupiters are on their way through the disk toward being accreted by Epsilon Aurigae's central object (or perhaps being flung off by an eggbeating pair), the changes should affect the distribution of matter in the disk.

An infant hot Jupiter in a final, rapid inward death-spiral, with accompanying rings of disturbed disk material, might account for the low-amplitude brightness variations as well as their decreasing period. If so, the *F* supergiant could be constant after all. The changes would redefine the disk's inner and outer edges and thus alter the eclipse's light curve. The 2009–11 eclipse offers several ways to test this idea, and astronomers need your help.

Epsilon Aurigae Timetable

Eclipse begins: Aug. 11, 2009
Minimum light begins: Dec. 19, 2009
Mid-eclipse: Aug. 4, 2010
Minimum light ends: Mar. 19, 2011
Eclipse ends: May 13, 2011

Dates are approximate. Every year Epsilon Aurigae is lost in the Sun's glare from mid-May through early July depending on your latitude; the farther north you are the better, up to about 50°. (North of that there's little or no darkness in June).

The Coming Campaign

Given the rare opportunity, professionals will aim large telescopes at Epsilon Aurigae during this eclipse to obtain detailed spectra with the best possible information about the system's parts, their motions, temperatures, and compositions. But in other ways, we have *less* capability to work on such a bright star than in 1983 — because it would blind modern setups designed for faint, cosmological objects. The answer to this problem, especially in tracking Epsilon's light curve, lies with skilled amateurs doing high-quality photometry with modest scopes (see the facing page) or even camera lenses.

In other ways, we have ideal new tools for the job, from digital cameras to giant interferometers with apertures spaced hundreds of meters apart (see photo on previous page). Several colleagues and I have resolved the disk of the *F* supergiant using the Palomar Testbed Interferometer; the star measured 2.3 ± 0.1 milliarcseconds across. We found no sign of size pulsations. An earlier interferometry group measured essentially the same diameter in 2001.

Interferometry should provide a direct test of the dark-disk model during the upcoming eclipse — by actually seeing the disk's narrow silhouette sliding across the *F* star and dividing it in half! That's if, of course, the model is correct. Nature often surprises us when new technology is brought to bear, so this eclipse will prove interesting.

In addition to the impressive array of modern large telescopes, there's impressive technology that may already be in your possession, including digital imagers. An army of observers with small telescopes, photometers or CCD or DSLR cameras, and in some cases even spectrographs, will contribute to the scientific database needed to carefully define the eclipse in detail. You can join too. The U.S. node of the International Year of Astronomy has defined Epsilon Aurigae's eclipse as a key project for "Citizen Science" participation. The American Association of Variable Star Observers is providing instructions and coordination, as told on the facing page.

The eclipse is predicted to begin during August and reach totality around year's end. Totality ought to last all of 2010 and end in March 2011, followed by rapid egress and return to full brightness that spring.

We don't want to let any opportunity slip. If we don't get the eclipse right this time, we'll have to wait until 2036 for the next!

***Robert Stencel** is a professor of astronomy at the University of Denver, director of Chamberlin and Mt. Evans Observatories, and coauthor with Jeffrey Hopkins of* Epsilon Aurigae: A Mysterious Star System *(Hopkins Observatory, 2008).*

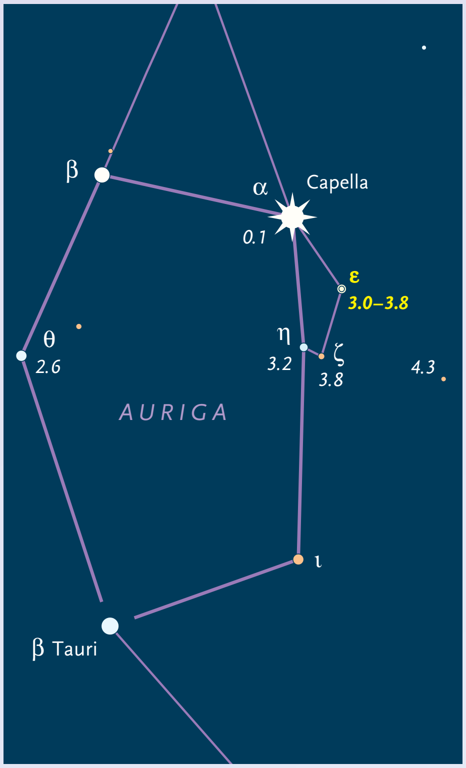
A Variable Star for Everyone

THE UNIVERSE
YOURS TO DISCOVER
INTERNATIONAL YEAR OF
ASTRONOMY

THE EPSILON Aurigae eclipse has been chosen as the flagship U.S. "citizen science" project for the 2009 International Year of Astronomy (IYA). There are many ways anyone can participate.

Visual Observations. At 3rd magnitude, Epsilon Aurigae is bright enough to spot even from most urban areas. This makes it a fine target for people interested in learning how to observe variable stars: the art of pushing the eye to its limit for making the most accurate possible judgments of fine brightness differences. The American Association of Variable Star Observers (AAVSO) has created a "Ten Star Tutorial" to help a new observer learn how to do this and report observations.

Granted, visual estimates can't compete with modern photometric measurements for precision. But they may offer better time coverage, filling gaps in the photometry.



If you're new to variable stars, here's the basic method. On the map below, comparison stars are plotted with their magnitudes. Find the star that appears just a little brighter than Epsilon, and the one that appears just a little fainter. (Defocusing the stars slightly often helps you judge their relative brightnesses.) Estimate, as best you possibly can, what fraction of the way the variable is in brightness from the brighter to the fainter comparison.

For instance: Suppose you decide that Epsilon looks two-thirds of the way in brightness from the magnitude 2.7 star to the magnitude 3.2 star. That is, you've convinced yourself that it's more than halfway there, but less than three-quarters of the way there. Do the math later indoors: two-thirds of the way from 2.7 to 3.2 is 3.03, which you can round to 3.0. Submit reports at the AAVSO website.

Photometric Observations. Electronics can do this job much more accurately than your eye — and this is where amateurs really stand to make a difference. Epsilon Aurigae is too bright for most observatory CCD systems. What it needs is an amateur-sized scope (or even a camera lens), a good DSLR or CCD camera or a photoelectric photometer, the right photometry software, and a diligent, thoughtful, persistent user. The AAVSO Photometry Discussion Group is a good place to start for advice on how to deal with saturation, scintillation, differential atmospheric extinction, and other road-bumps caused by particularly bright stars.

Data Analysis. One goal of the IYA project is to involve participants in more than just collecting data. The data will be made publicly available, and the AAVSO is developing data-analysis software and tutorials for its use. A special edition of the *Journal of the AAVSO* will be dedicated to papers on Epsilon Aurigae by amateur astronomers.

Education and Public Outreach. The star's brightness provides an opportunity to engage the public in citizen science. People are needed to help write and newspaper articles, prepare talks and slide shows, develop artwork, and give talks. This will also make a fine laboratory project for astronomy classes.

BRIAN MCCANDLESS

For precision variable-star work, Brian McCandless of Newark, Delaware, uses an Optec SSP-4 photoelectric photometer on a 14-inch scope.

This summer a workshop on observing strategies will be held at the Adler Planetarium & Astronomy Museum in Chicago. In the summer of 2010 a workshop on data analysis and scientific paper writing will happen at the California Academy of Sciences in San Francisco. Both will be open to the public, with video available online.

Where to go: The AAVSO is coordinating these projects through a website called Home Base, at **www.aavso.org/iya.** Take a look.

For a printed copy of the Ten Star Tutorial, you can call 617-354-0484. Funding for some projects is still subject to negotiations with the National Science Foundation. ✦

— *Aaron Price, AAVSO*

TOM RUTHERFORD

Tom Rutherford of Blountville, Tennessee, has been using an SSP-4 photometer on an 8-inch telescope to measure Epsilon Aurigae's infrared brightness. He plans to switch to a larger scope during the eclipse.