Astrophysics Faces the Millennium V

New Technologies: Master or Servant?

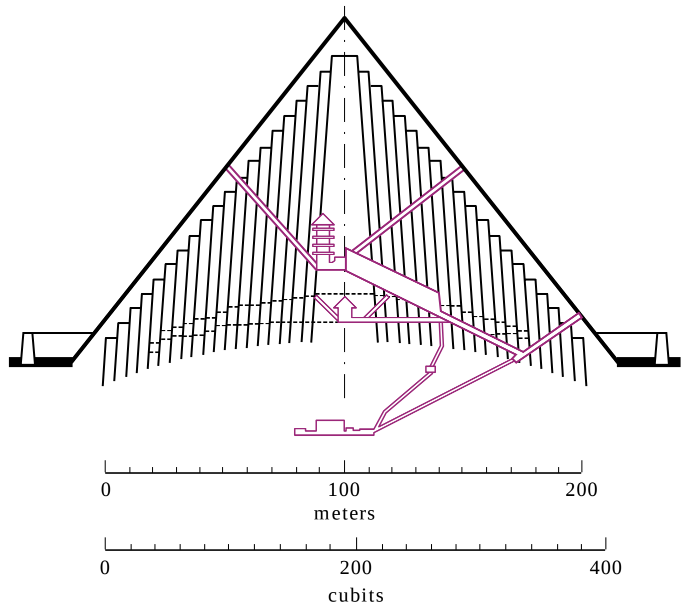
by VIRGINIA TRIMBLE

"Both, please," (as Winnie-the-Pooh said to the choice between honey and condensed milk on his bread for tea) is the correct answer to many astronomical dichotomies. Are really bright, distant galaxies experiencing bursts of star formation or vigorous accretion onto central black holes? Are stellar coronae heated by acoustic or magneto-hydrodynamic waves? Is interstellar gas ionized by ultraviolet photons or by shocks? Inevitably "both" is also the answer if you ask whether major astronomical discoveries result because a new technology becomes available or, conversely, because people develop new technologies so as to be able to make specific observations or discoveries.

IT OCCURRED TO ME only as I started to write this (though it is surely known to many others) that there is usually a fairly sharp distinction, based on use, of astronomical devices past and present into: (1) research (Tycho's quadrant, the Keck 10-meter telescope, and Ray Davis's tank of perchlorethylene for instance); (2) applications of existing knowledge (a mariner's sextant, tables of the times of occultaion of the moons of Jupiter, to be used in finding longitude at sea, and the GPS); (3) information storage, calculation, and prediction (armillary spheres, volvelles, astrolabes, and N-body computer simulations, for instance); and (4) education (planetaria, orreries, globes, and college physics lab experiments). This time around, we'll look only at research devices, except for noting that they are not always actually bigger or more expensive than the others and that a few things do both. The classic astrolabes, for instance, had a set of metal arcs, ovals, and pointers on the front for calculating astronomical positions and on the back an alidade for measuring them.

Notice that, to separate research devices and to decide whether they were built to make specific observations or primarily because they could be built (and the observations followed) you have to have some sense of the motivations of the builders. Thus I have nothing relevant to say about large, old sites that line up rather well with the cardinal directions or the rising, transiting, and setting of sun, moon, planets, or stars, like Stonehenge, Egyptian pyramids, and the Mayan pyramids of Chichen Itza (etc), and mention them only to provide an excuse for the illustration on the right.

Another territory that will go untrod here includes the observatories of Chinese, Hindu, and Islamic civilizations, some of which were earlier, larger, and more accurate than their European contemporaries before about 1600 and which were equally intended for making deliberate, accurate observations of planetary positions, eclipses, and the seasons, with a view to forecasting future events and their implications.



The Great Pyramid of Cheops or Khufu at Giza, which is accurately aligned to the cardinal directions, in N-S cross section. The two shafts extending from the upper (king's) chamber to the surface pointed, at the time of construction, to the upper culminations of Thuban (then a pole star) to the north and the middle star of Orion's belt to the south. The shorter shafts leading out of the lower (queen's) chamber are not parallel to the others, and the southern one is pointed in what was then the direction of the transit of Sirius, presumably by intent. Original figure drawn by the late Alexandre Mikhail Badawy to illustrate a 1964 paper by the present author. The lower length scale is in ancient Egyptian cubits.

THE BEGINNINGS

As the torch of astronomical knowledge passed from the Babylonians (lots of accurate eclipse records by about 900 BCE) to the Greeks (Eratosthenes who measured the size of the earth, Aristarchus who found the distance to the moon and had a go at the sun, Ptolemy and Hipparchus with their star catalogs) to the Islamic Arabs (who perfected the astrolabe) and back to medieval Europe, motivations included both the astrological (knowing positions in advance well enough to use them as omens and forecasts) and the ceremonial (celebrating seasonal festivals at the right time). Western measuring devices remained small and portable, and artistic merit appears to have ranked as high as accuracy in their construction. Thomas Aquinas (see the Winter 1999 issue of the *Beam Line*, Vol. 29, No. 3) was the theoretical starburst of the European recovery. During the hundred years following his synthesis of church doctrine and Aristotelian philosophy (1250 to 1350), Jacob ben Mahir (of Montpellier) invented a quadrant-astrolabe combination, and Levi ben Gerson (of Provence) invented the cross-staff. Things to note are that not all Jewish astronomers were theorists in those days, that the devices were heavy (because vertical was established by hanging them out in the open) but still small and portable, and that both were used for measuring the height of celestial objects above the horizon and angles between two objects. They are also arguably the last major instrumental advances of "business as usual" earth-centered astronomy. Then came Copernicus, whose *De Revolutionibus* appeared as he was dying in 1543 and laid out the details of a sun-centered cosmos, within which you ought to see parallax—small shifts in the apparent positions of stars, planets, and whatever else you see that arise because the observer moves with the rotation and orbit of the earth.

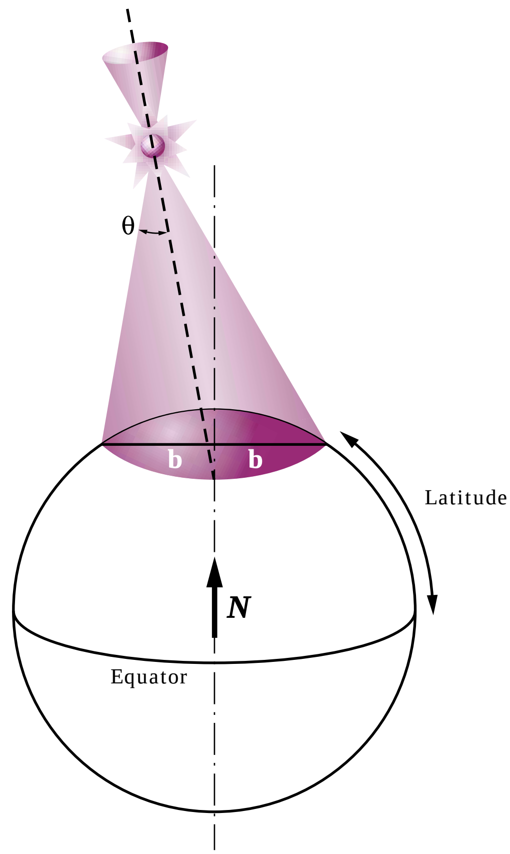
FROM TYCHO TO BRADLEY

Up front, what these two had in common was the desire to discover (see for the first time) heliocentric parallax, in pursuit of which they had built observing equipment of new and better sorts. Both failed in their primary goal but found other entities of comparable importance. The only lesson I see here is that if you want to discovery America by setting out to sail to India, you had better have a state-of-the-art ship.

It would be nice if we could tell the story of Tycho Brahe (born three years after the publication of *De Revolutionibus*) by saying that he set out to find parallax, persuaded his sponsoring agent (Frederick II of Denmark) to make him P. I. of a major program (Uraniborg and Stjerneborg on the Island of Hven), and used the funded facility to establish that the nova (actually supernova) of 1572 and the comet of 1577 were more distant than the moon (whose parallax he could measure) and, therefore, that the heavens are not immutable.

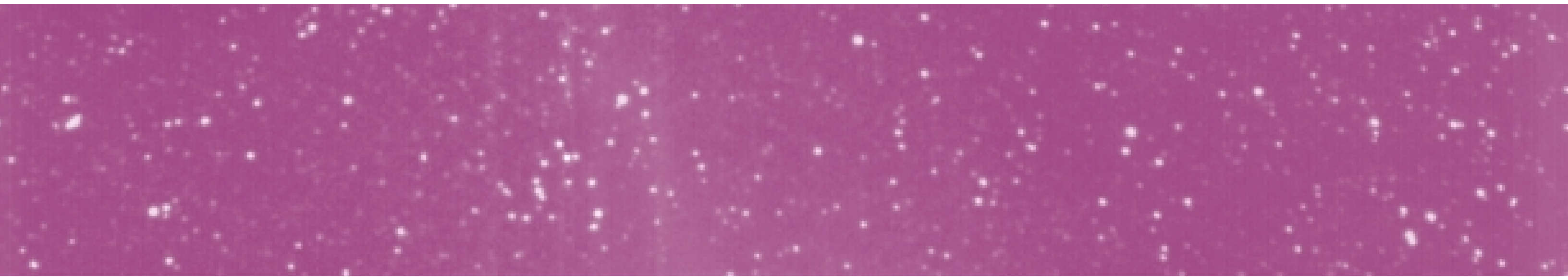
Unfortunately, construction of the great mural quadrant at Uraniborg was not complete until after he had looked at the events of 1572 and 1577 with less innovative instrumentation. With the rigid mounting of his giant quadrant against a wall, he acquired stability (and so eventually positional accuracy) as good as the 0.5 arc minute resolution of human sight, as a compensation for being able to observe only transits across the northern meridian. Stjerneborg even had its major measuring devices underground, to avoid wind flexure. Working from latitude 55°N, Tycho had also the disadvantage of a relatively short baseline, but the advantage of some very long winter nights, over which both upper and lower culmination of circumpolar stars could be measured. The supernova happily flared up in November to make this work out.

And, of course, other astronomers with less precise instrumentation and perhaps less steady hands were not idle during these years. Thus Galileo, in his 1632 *Dialog*



Earth-rotation (geocentric) parallax of a circumpolar object seen from high northern latitudes. Over a 24-hour period, the apparent position of the source traces out an ellipse relative to the direction of the Earth's rotation axis, N. For Tycho, at latitude 55 degrees north, the half-baseline b is only about 3658 km, and the angle, θ, for the moon 32.7 arcminutes. Since Tycho could measure this angle for the moon (the ellipse is skinnier because the moon is not far north in the sky, but its semimajor axis is the same), he knew that the nova of 1572 and the comet of 1577 must be further away, since he could not see any parallactic shift through the night.

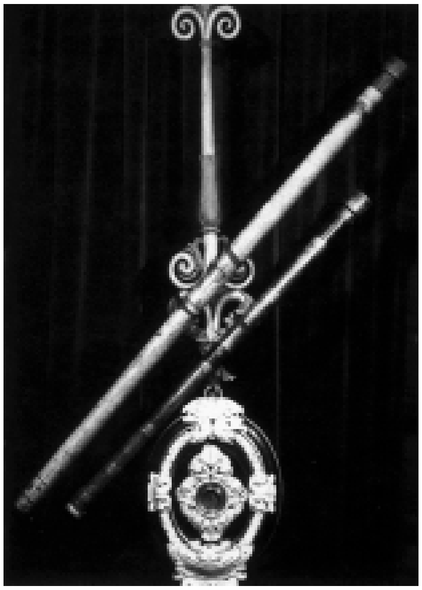
(written to persuade his non-specialist but educated contemporaries of the truth of the Copernican picture) found it necessary to discuss at length which observations of the nova were most trustworthy and how one



might estimate the parallax, or a limit, by a suitable weighting of the best data. Not surprisingly, he voted with Tycho and against a bunch of people like Hainsel whom you are not expected to have heard of. This Galilean passage would probably also be the right place to begin a study of statistical astronomy. Do not worry, by the way, that the cost and effort to build Uraniborg were wasted. It was here, looking for the geocentric parallax of Mars, thinking it closer by a factor 16 than we now know, that Tycho collected the sequence of Martian data from which Kepler could work out his three laws of planetary motion.

Galileo seems to have approached science with a perspective very different from Tycho's. Hearing about the first, Dutch, telescope, he built an 8-power and used it to look at anything and everything. He continued omnivorous observation through several larger and more carefully shaped lens pairs, and became the first (or second or third) human being to see the moons of Jupiter, the resolution of the Milky Way into stars, the phases of Venus, mountains on the moon, and sunspots rotating across the solar surface.

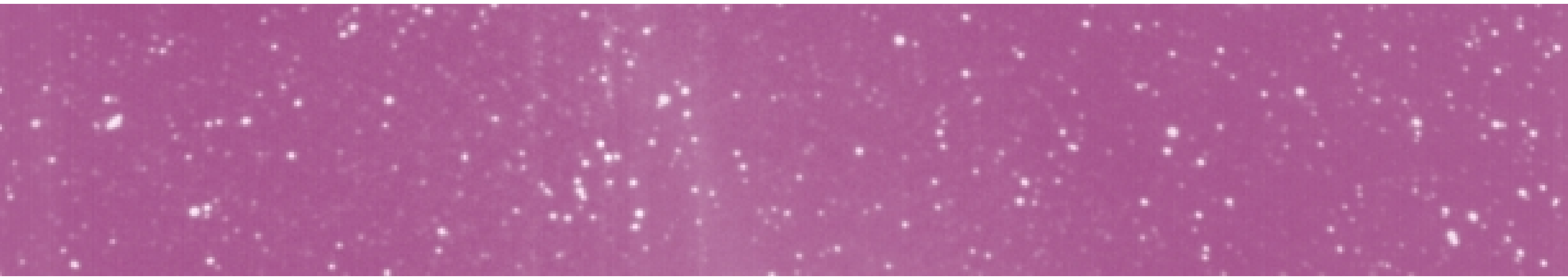
We then enter some decades of confusion, in which "observers," using hand-held or casually mounted telescopes looked at surface features, while "measurers" with carefully machined quadrants and such determined positions of things with naked-eye sightings along their brass circles. Telescopes improved a good deal (technology-driven science), while positions (discovery-driven science) did not. Clearly what was needed was a marriage of the two attitudes. Achievement of this can perhaps be credited to Ole Roemer, who built the first precision-mounted telescope, a transit circle, at Copenhagen, after taking up the directorship there in 1681. He came with credentials of both sorts, having both (a) participated in Cassini's 1672 campaign to measure the geocentric parallax of Mars, clearly a "discovery motivated" project (which probably succeeded), and (b) shown that light is fast but not infinitely fast, from accurate timing of the occultations of the moons of Jupiter by their parent. The latter, while motivated by needs of navigation, was enabled by improvements in clock design.



Several museums in Italy house telescopes said to have been assembled, used, or blessed by Galileo (I have seen the one in Padua). Some were meant to be held up to the eye; some are on tripods; and this one appears to have an early alt-azimuth mounting.

Next up to bat were Samuel Molyneux (a London amateur with some money and a house big enough to build a telescope inside, looking straight up to the zenith), his assistant James Bradley (who understood what was needed), and George Graham (who knew how to build widgets and make them work). Together, they give birth to the zenith sector, mounted against the chimney, and set out to find the heliocentric parallax of Gamma Draconis, which transits very close to straight overhead for London observers.

They expected to find the star farthest north of its average position near the winter solstice and farthest south near the summer solstice. Instead, as December melted into March, they found the star moving south, hesitating, and moving back to its maximum northern extent in September. And the swing was a full 20 arcseconds either direction, definitely three months (90 degrees) out of phase with what they had expected. The collaborators thought at first that they had detected changes in the direction of the earth's axis of rotation, but a couple more annual cycles and data on a few more stars, along, it seems with Bradley's observations of weather vanes on boats as they changed direction on a windy day, led them to the correct explanation,



aberration of starlight. In one step, Bradley et al. had provided the first direct demonstration of the Copernican picture, pinned down the speed of light (quite close to Roemer's value), and shown that all previous star catalogues would have errors up to ±20 arcseconds in position, depending on the location of the stars and the time of year they had been observed. Incidentally, you can see bright stars in the day time with a telescope, though not from the bottom of a well without one.

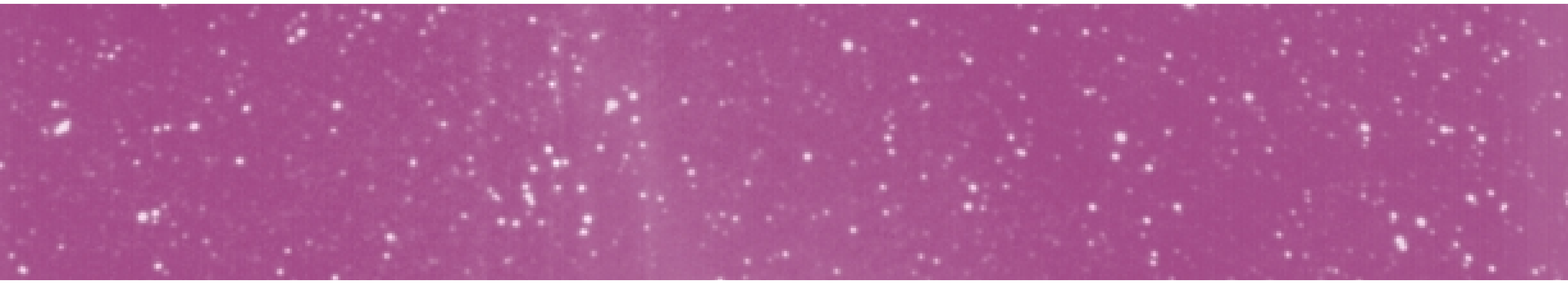
PARALLAX, SPECTROSCOPY, AND IMPROVED PHOTON DETECTORS

William Herschel discovered Uranus because he had a very good telescope and lots of patience. But he went on to be the next major assailant on the parallax problem. Thinking that all stars were intrinsically the same brightness, he carefully recorded pairs that looked different, expecting them to be at very different distances and so ideal for parallax measurements. Twenty years of patient watching led to discovery of positional shifts all right, but the stars were going around each other, showing the universality of Newtonian gravitation on a grander scale than the mere solar system and giving birth to binary star astronomy.

The grail still glimmered ahead, and, once again, telescopes were designed and built with the discovery of heliocentric parallax as their main goal. Two of the three winners, Wilhelm Struve of Dorpat (Tartu, Estonia) and Friedrich Wilhelm Bessel of Konigsberg, Germany, had commissioned instruments from the same builder, Joseph Fraunhofer. The telescopes were not identical, but both were designed to make repeated and repeatable measurement of the angular separation between stars close together on the sky but at very different distances. Struve looked at Vega, Bessel at 61 Cygni (fainter appearing, but actually closer), and the third winner, Thomas Henderson of Cape of Good Hope, at Alpha Centauri, then as now the second closest star to us (the closest is the sun). He had a less finely tuned instrument, but had picked the optimal target. The reports were publish in 1837–1839.

Meanwhile, Fraunhofer had improved another technology to "see what he could see." Newton separated white light into colors and put them back together again (the hard part, Nature had been making rainbows at least since the time of Noah), but saw only a continuous spectrum, because his aperture was a round hole. In 1802, Wollaston (of the prism) tried a narrow slit and spotted seven dark lines crossing the rainbow, which he supposed were to divide the primary colors. Fraunhofer's 1817 inventory was 600, the most conspicuous of which he lettered A to K. He also recognized that his D was the same color (wavelength) as an emission feature seen in many flame spectra. This counts as the beginning of astronomical spectroscopy, though Fraunhofer, dying in 1826, saw neither the fruition nor the triumph of his instruments in recognizing parallax. Definitive identification of D with sodium and other solar features with other elements came from Bunsen and Kirchhoff in 1859, an example of technology improved for other purposes (both were laboratory scientists) yielding astronomical fruits quickly.

The history of astronomical photography, like that of telescopes, begins with a borrowed technique, and the first daguerreotype of the sun dates from 1845 (work of Foucault and Fizeau, known mostly for laboratory physics). The Harvard College Observatory archives include an 1857 (probably collodion) plate of the Pleiades. It shows three stars. Dry plates from the 1870s onward made it possible to record at the telescope images and spectra you could then measure at leisure back home, including the flash spectrum of the solar chromosphere during an eclipse, moving asteroids and comets, and the variable brightnesses of pulsating stars (though



recognition of the 30 Hz Crab Nebula pulsar required another generation of detector electrification).

As early as 1912, however, C. E. Kenneth Mees, the first research director at Eastman Kodak, initiated work leading to special series of spectroscopic plates to meet astronomical needs. The sensitizing dyes and emulsion-making techniques that resulted from this led to Tri-X and other fast films, Technical Pan with its wide wavelength response and fine grain, and red and infra-red sensitive emulsions later used to penetrate camouflage, spy at night, and detect subtle changes in vegetation color that signal disease and other stresses.

THE TWENTIETH CENTURY

In the 1890s, astronomers interested in variable stars were still arguing about whether you learned more from photographic images or from careful visual comparisons, through suitable telescopes, of course, of the target star with constant neighbors. Much of the problem was that the emulsions of the day recorded mostly blue light, while the eye is at its best in the yellow-green, so that how much the brightness of a star changed really did depend on observing method. Amateur astronomers today (who monitor most of the variables that get monitored at all) still use visual telescopic methods, but also modern electronic detectors and, occasionally, film.

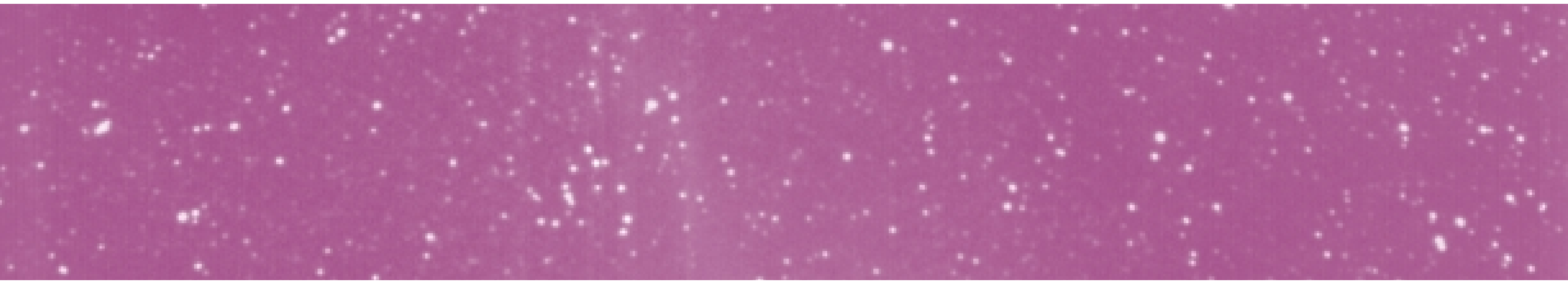
The photographers, with a range of filters and Mees's red and panchromatic emulsions, of course won over the visual observers on the professional side. But they did not have the only permanent floating crap game for long. The photoelectric effect must have been discovered in time for Einstein to explain it in 1905–1906, but it was not part of many applications yet in 1915, when Joel Stebbins followed an eclipse of the binary star Delta Orionis with a selenium photometer.* Delta Ori thereby became the first spectroscopic, eclipsing binary to have its orbit determined by both techniques, and Stebbins was one of the first two astronomical photometrists.

To bring optical and near infrared detectors down to the present, we can recall that CCDs arose in industry but have been improved (especially, thinned to broaden their wavelength coverage) specifically for astronomy. Frank Low developed his infrared bolometer to look at the skies (with great success, and a remote descendent is being adapted for non-destructive testing). More recent entries in the still-difficult IR regime are InSb (pronounced inz-bee) and HgCdTe (MerCadTell) arrays, which arose in the military-industrial complex. They are being incorporated into astronomical cameras and spectrographs as fast as industry can produce them, indeed somewhat faster. We currently have a bottle neck in arrays, and being sure you are going to get "a good chip" is a big step en route to astronomical progress today. Here the available technology is clearly driving what astronomy can do.

The first two radio telescopes were built by people who wanted to discover something—the source of noise in trans-Atlantic radio telephony in the case of Karl Jansky in 1932 and "more about what Jansky had seen" in the case of Grote Reber, who, a couple of years later, built the second radio telescope on his own time, in his own back yard.

Then there was a war, whose remains included a large number of radar dishes, S, X, and other band receivers, and people who had learned how to use them. A small subset, in England and Australia, turned the dishes up at the sky (the horizon no longer being interesting, and the ground even less so). What they saw was so spectacularly unexpected that improvements in sensitivity and angular resolution became drivers for rapid technological development. In particular, multi-baseline interferometry and aperture synthesis were first reduced to practice to sharpen radio images. Much of the mathematics, while obviously inherent in laboratory experiments with visible light dating from the nineteenth and early twentieth centuries, was first reduced to practice

**Selenium is actually a photoconductor, that is, a metal in which absorption of a photon puts an electron into the conduction band, decreasing resistence. Stebbins'device was, therefore, the remote ancestor of the CCD, or charge coupled device (detector of choice in most of optical astronomy today). In between both photoelectric and photoconducting detectors have been in use.*



to sharpen radio images. Much of the mathematics of reconstructing an image from portions of its Fourier transform (that is what an interferometer gives you) was also worked out in the first instance by radio astronomers.

Optical interferometry, tried by Albert Michelson at Mt. Wilson in the 1920s, again without phase preservation by Hanbury-Brown and Twiss in Australia in the late 1950s, and now bordering on the routine, at least for small, closely-spaced mirrors, has a mostly-astronomical history. Significantly, Hanbury-Brown was (and is) a radio astronomer most of his life. In contrast, adaptive optics (where you wiggle a mirror—generally not the giant primary of your telescope—to undo the wiggles introduced by air), though first proposed by an astronomer (Horace Babcock, in the 1950s) was developed under Air Force classification to a much higher standard than astronomers had been able to achieve. Declassification had led to AO programs at nearly all large telescopes. Because not all interesting patches of sky include a star bright enough to be the reference source for adaptive optics, laser guide stars (reflected patches from the sodium ion layer high in the atmosphere) are being used or considered many places. The laser is another "we thought of it, but you did it" technology. Back in the 1930s, Donal H. Menzel, calculating the absorption of radiation by diffuse gas remarked that you might, if enough atoms were in an excited level, actually get amplification rather than absorption. He was right. Indeed there are natural, interstellar masers (and possibly lasers) as well as laboratory ones.

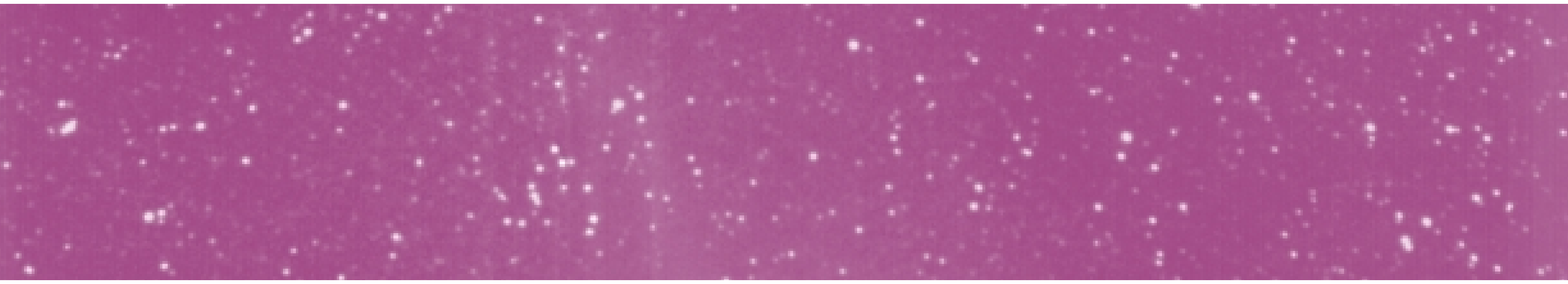
The beginnings of X-ray and gamma-ray astronomy present an interesting contrast, although both require getting above most of the earth's atmosphere and so now rely on rocket launches, remotely descended from the German V-2 (another of the spoils of war). But apart from the rocket flights that looked at the sun in the 1940s, the first X-ray astronomy was done by people who know how to build X-ray detectors, and simply wanted to look at the skies to see what might be there. Much of the credit rightly goes to Riccardo Giacconi, who persuaded the sponsors that X-ray flourescence of sunlight from the lunar surface would be detectable, thus providing a motivation for a 1962 rocket flight. The fluorescence was eventually seen more than 25 years later, but, meanwhile the rocket-borne detector saw a really bright source, Scorpius X-1, that happened to be close in the sky to the moon that day. The first gamma-ray telescope, on the other hand, was sent aloft (on a balloon) specifically to look in the direction of Cygnus A, a radio source in a distant galaxy that, it was then supposed, might actually be a galaxy-anti-galaxy pair in collision. If so, then the flux of annihilation gammas would have been truly enormous. It wasn't, and several more generations of detectors flew on balloons and rockets before the first astronomical source registered (it was the Crab Nebula, also the first identified X-ray source and radio source outside the solar system).

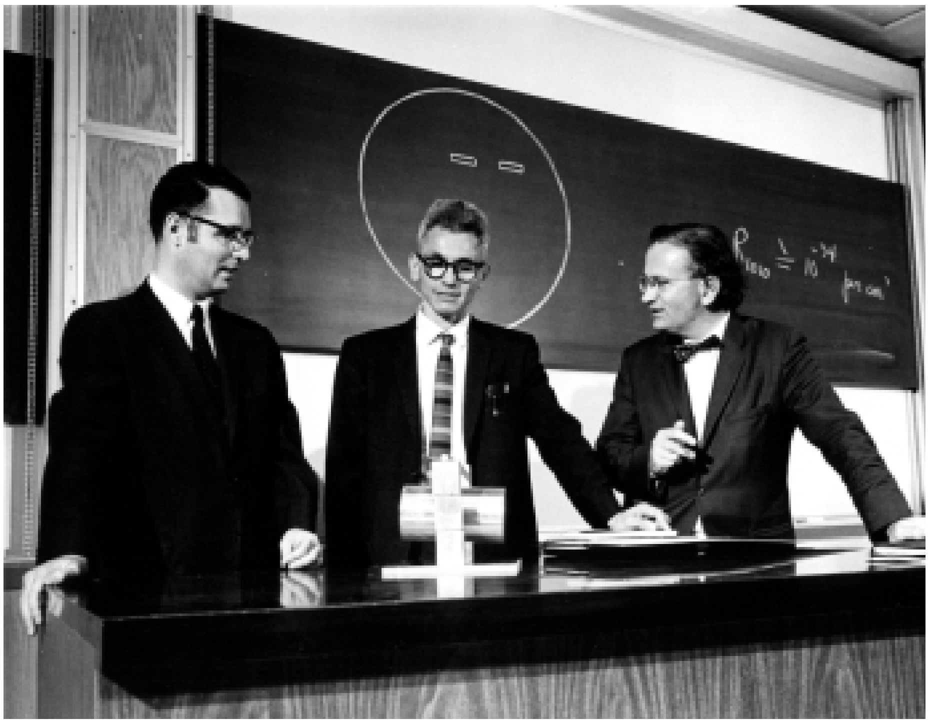
The beginnings of neutrino astronomy and gravitational radiation astronomy are also, at least approximately, one of each. A later issue of the *Beam Line* will remind you of how Raymond Davis, Jr., then of Brookhaven National Laboratory, set out with the specific goal of seeing neutrinos from the nuclear reactions inside the sun. It took about a decade, but he succeeded, in the process figuring out chemical methods (like rescuing 25 argon atoms from 100,000 gallons of cleaning fluid) that had never been needed before.

At about the same time, Joe Weber set out, using techniques he had learned as a radio engineer, to build and operate the best detector for gravitational radiation he could think of simply to see what there was to see.

Before going on to look ahead a few years, two general points are worth noting. The first is that new ways of doing something are, very often, at the beginning enormously inferior to what has been around for a good long while. Stebbins's early photometer could not record even the fainter naked-eye stars. And the first CCD images looked like a bad case of acne overlain by dandruff. Indeed a good deal of tidying up of "bad pixels" is still needed to produce the glorious Hubble Space Telescope pictures you see at every turn.

Second, just what James Bradley's family thought of his observing the same star over and over again (up to





Somewhere on the campus of the University of Maryland in 1969, Joe Weber speaks at a press conference, organized by the university, upon instructions from the Chairman of the Physics Department, Howard Laster (with plain black tie), and with the support of the Director of the Astronomy Program, Gart Westerhoud (with bow tie). On the demonstration table is a scale model of the original, 26-in. diameter bar detector (the acoustic isolation of the model is poor). On the board is a cross section of the bar, acting as a halo for Weber. The announcement was picked up by a number of newspapers, and Weber used to describe the coverage as “having appeared on the obituary page of the New York Times,*” where they often tucked science items in those days. Weber still had and occasionally wore the striped silk tie at the time of his death.*

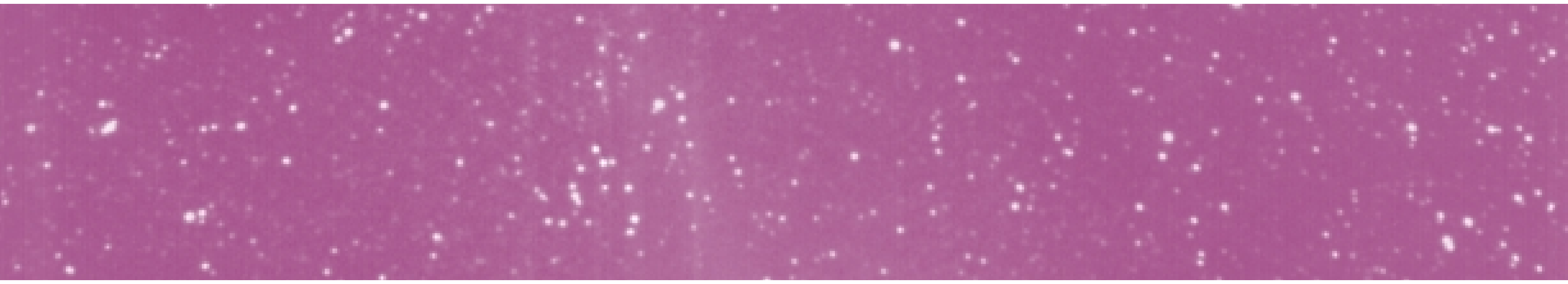
16 times a night), night after night, year after year, is known only to the ghosts that flit around their graves. But no important new technology has been developed in modern times (and the same is probably true of major theoretical advances) except by someone who took the project more seriously and worked on it more intensively than his friends and relations thought entirely reasonable.

TECHNOLGIES WAITING TO HAPPEN

The Compleat Astronomer would like to know the direction of arrival, the time of arrival, and the precise energy (wavelength) of every photon that ever hits the earth’s atmosphere. Increasingly, this has meant enormous, and enormously expensive facilities, like the Next Generation Space Telescope (2007 or thereabouts), ALMA (the Atacama Large Millimeter Array), and LIGO (the Laser Interferometric Gravitywave Observatory), also multi-year to decade projects. For these and others like them, the wishes and widgets continuously reshape each other. NASA has invented the word “rescope” to describe this. Building consensus for such things requires meetings convened over may years, whose proceedings you can read, so I mention here a handful of smaller gems.

The award for widget of the year in 1999 went to two solid state devices that are a first step toward recording direction, arrival time, and energy simultaneously (prevented by the two-dimensional nature of most detectors). These were a superconducting tunnel junction (STJ) and a cryogenic-transition edge senser spectrophotometer (TES). Both initially looked to see whether the color of the optical emission from the pulsar in the Crab Nebula changes through its period (not much). Matching a spectrograph to the image size from a very large, but short focal-ratio telescope might seem to require microminiaturization. Immersing the grating in some substance, like glycerol, whose index of refraction is very close to that of glass also works.

X- and gamma-ray astronomy have always suffered from the difficulty in forming images. If you measure



direction of arrival with some sort of collimator, then you buy angular precision at the expense of a decent size field of view. The more recent X-ray satellites (Chandra and XMMNewton) form real images with grazing-incidence optics (sometimes gold plated). A giant step beyond is grazing-incidence interferometry for X-rays. This could, someday, yield micro-arcsecond resolution to image the horizon of galactic and extragalactic black holes. Meanwhile, the grating that is the surface of an old LP record can be used to focus keV X-rays by placing two of them only a few microns apart. The collecting area is therefore rather small per record pair, but there must be an awful lot of surplus LPs these days.

MACHO, the most extensive of the surveys for gravitational lensing by compact objects in the halo and disk of the Milky Way, closed its dome essentially on schedule in January 2000, but successor programs are starting up. AGAPEROS is the seductively named succesor to EROS, a contemporary of the MACHO project, and there are several others.

The experience of processing the billions of star brightness measurements that were the raw data of MACHO (etc) has expanded estimates of what can be done in this direction, from space as well as from the ground. For instance, two mission proposals (in the medium cost, 1/3 billion dollar range) aim to locate from space and follow large numbers of fairly distant supernovae and use them to measure the cosmological parameters (this is SNAP) and to catch transits by earth-sized planets orbiting stars in our part of the galaxy. Even if such planets should prove to be fairly common, you have to watch a great many stars to catch a few transits, because most orbits will not be seen exactly edge-on. And, of course, the star will be dimmed to about 0.99999999 of its normal brightness, requiring some fairly stable calibrations (this is Kepler). Think of it as having $1,000,000 in pennies, and somebody takes one away.

Perhaps the largest barrier to improvements in astronomical technology is that the community does not reward suffiiently the people who contribute. They are hardly ever fist authors on the papers reporting major discoveries from the devices to which they gave birth, they win few major prizes, and sometimes even face difficulties in acquiring degrees and tenure. Thus we increasingly buy the skills we need from industry. This tends to drive cost up and involvement down and other branches of science have a better record in rewarding and valuing their living instrument builders, which astronomy might do well to learn from.

MEHR LIGHT

MY SECRET HISTORICAL WEAPON in the past year has been a Russian-language biographical dictionary, with about 1000 entries, from the Greeks well into the twentieth century. Compiled by Igor G. Kolshinskij, Alla Korsum, and M. G. Rodriguez, it was published in Kiev in 1986 and originally cost 2 rubles, 20 kopeks.

A valuable source on photometers, CCDs, and all is G. H. Rieke, **Detection of Light** (Cambridge University Press, 1994).

Technology transfer from astronomy to other sciences and industry was discussed in the last two of the “Decade Reports,” on astronomy and astrophysics commissioned by the National Research Council. The 1991 version was called **The Decade of Discovery** and chaired by John Bahcall. The 2001 version was coordinated by J. H. Taylor and C. F. McKee and has just about been released under the title **Astronomy and Astrophysics in the New Millennium**. The relevant chapter in 1991 was written by yours truly, the 2001 version probably by Stephen Strom and David Hollenbach.

Karl Hufbauer’s **Exploring the Sun: Solar Science Since Galileo** (1991, Johns Hopkins University Press) is complementary to Michael Hoskin’s **The Cambridge Concise History of Astronomy** (1999, Cambridge University Press). And someday (perhaps about 2003) there will be a two-volume biographical encyclopedia of the history of astronomy edited by Thomas Hockey (Springer).