Part I

Can't You Keep Einstein's Equations Out of My Observatory?

by VIRGINIA TRIMBLE

Fish and guests start

to smell after three days.

—Old Country Saying

ALL SPECIES ARE ADAPTED to the environment that has been around for a while (some admittedly better than others). This includes *Homo scientificuss* and its subspecies *H. scientificuss* astronomische. Thus even we, committed though we are to Progress and Advancement, tend to resist changes in our surroundings. Such resistance is by no means completely foolish. Most of the inventions patented never worked very well; most new ideas are wrong; and most of the people who tell you how to improve your research want to start without the second law of thermodynamics. Hence, betting against neat, new things is nearly always the winning strategy. But when you lose, you lose spectacularly, and virtually all the achievements of astronomy over the last few centuries can be traced pretty directly to changes in technology, demographics, or theoretical constructs.

New widgets include amplifiers, detectors, telescopes, launch vehicles, computers, and much else. The community constantly recruits not just new people but new kinds of people. And I hope at some future time to explore how we have (often reluctantly) incorporated these. Today (Wednesday), however, the focus is on interchanges of ideas between astronomy and other parts of science. An oral presentation of some of the material, at the 150th anniversary meeting of the American Association for the Advancement of Science,

was originally entitled "How physics came to visit and tried to take over the house," but I soon realized that the real situation is a good deal more complex. Notice, however, that even the name of the society includes "defend our territory" words as well as "reach out" words.

Both the domains of thought and the specific ideas within each of the following sections are as chronological as I could make them (which isn't very). And the approach is relentlessly Whiggish, making use of highly collimated hindsight, emphasizing contributions that we perceive as moving the subjects forward, and drawing distinctions between disciplines that probably did not exist when some of the ideas were being formulated.

NEWTONIAN GRAVITATION

Sir Isaac, in assembling his theory of universal gravitation, made direct use of astronomical observations of the motions of the moon and planets. He promptly returned the favor by providing the first estimates of the mass of the sun: 29.7 earth masses in 1687 and 226.512 earth masses in 1713. Notice he shared the fondness of modern, calculator-owning freshpersons for carrying around more (in)significant figures than necessary! The correct value is actually 332.9 earth masses, but nearly all of Newton's error the first time out arose from using a distance to the sun that was not the best available even then, not from the content of his theory. Astronomers soon fell in with the idea, and improved "solar masses" came from Lalande (a cataloguer of stars) in 1774 and Encke (who found an interesting comet) in 1831. Estimates for the masses of Jupiter and the other planets with satellites followed and gradually improved in parallel as the distance scale for our solar system improved.

The next step obviously was masses for other stars, but this required recognizing that many of them orbit in gravitationally bound pairs. John Michell, the English polymath, had said so on statistical grounds as early as 1767. He was perhaps more ignored than disbelieved, and the recognition of the reality of bound systems had to wait for William Herschel's efforts to measure stellar parallax. He thought that close star pairs in the sky were accidental projections. But, after more than twenty years of looking for changes in separation angles due to the motion of the Earth (parallax), he concluded that the real motions were orbital and the pairs not accidents.

Masses for stars followed slowly (most visual binaries have orbit periods of many years, and you need a distance estimate as well). And, meanwhile, Herschel held to the view that only solid bodies could exert gravitational forces and therefore the sun, though perhaps gaseous on its surface, must have a cooler, solid interior, of which we catch glimpses through the sunspots. He also expected that interior to be inhabited, and was by no means alone in either opinion. A gaseous (and uninhabitable) sun had to await advances in spectroscopy and thermodynamics, which brought their own controversies and misunderstandings.

CERES, STATISTICS, AND THE PERSONAL EQUATION

The discovery of Ceres in 1801 (by Giuseppe Piazzi, a Sicilian astronomer) was very nearly followed by the undiscovery of Ceres, when it disappeared behind the sun with too little of its orbit observed to permit calculating where it should reappear. Carl Friedrich Gauss came to the mathematical rescue, with an improved method of orbit computation that made use of what we now call the method of least squares to incorporate discordant data. And to this day, the least squares method is the only bit of statistics the average astronomer has heard of. We nearly all think Gauss invented the idea, which is also only approximately true.

The personal equation is a statistical idea that arose within astronomy and has not, so far as I know, ever seemed applicable anywhere else in science, though it turns up occasionally in detective fiction. It arose from the method by which positions of stars in the sky used to be measured. Start with a telescope that is free to swing in only one direction, perpendicular to the horizon, in the north-south ("meridian") direction. Then the precise time a star passes through the center of your field

of view provides its east-west position (right ascension) and the distance above the horizon at which it passes provides the north-south position (declination), at least after a bit of additional arithmatic. Standard operating procedure involved two astronomers, one with a list of stars to be observed, an accurate clock, and a pencil to keep records, and the other with his eye to the telescope, to say "now" each time the next star passed the cross-hairs in his eyepiece. Feel free to replace the pencil by a pen in this narrative and "now" by "nunc" or some other one-syllable equivalent.

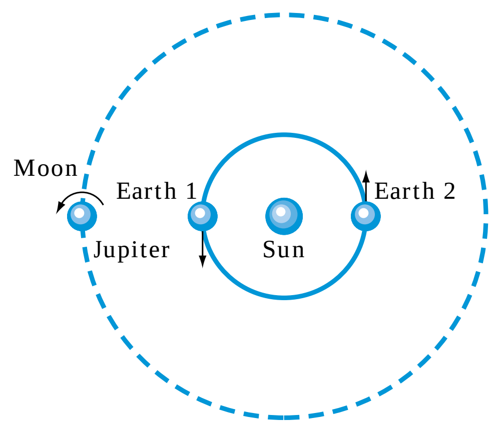
Comparison of positions obtained by different astronomers at different observatories soon showed that the identity of the record-keeper didn't matter very much, but the identity of the now-sayer did, especially for the east-west coordinate. In the words of a 1926 text: "Even the best observers habitually note the passage of a star across the fixed wires of the reticule slightly too late or too early, by an amount which is different for each observer. This *personal equation* is an extremely troublesome error, because it varies with the observer's physical condition and also with the nature and brightness of the object. Faint stars are almost always observed too late in comparison with bright ones . . . " Thus Prof. Apple's right ascensions for a given set of stars could easily be systematically larger or smaller than Dr. Berry's by several seconds of arc, enough to matter in many applications of positional astronomy.

In the end, the way around the problem of the personal equation was that of Rutherford, "Don't do better statistics. Do a better experiment." Other measurable quantities that, over the years, have revealed systematic offsets from one observer to another include stellar and galactic brightnesses, Doppler shifts, and classifications of stars and galaxies. And increased automation and mechanization, from photoelectric detectors to automated neural networks, have gradually made results more repeatable and impersonal (which is not quite the same as more correct). There must surely be similar cases in other sciences (the average number of species assigned to a newly-discovered genus?), and examples would be appreciated.

THE SPEED OF LIGHT, MAXWELL'S EQUATIONS, AND THE REST MASS OF THE PHOTON

Ole or Olaus* Roemer (1644–1710) actually participated in 1672 in one of the sets of observations that put the sun much further away than the distance Newton chose to use in the first edition of *Principia*, but astronomers know him as the first person to measure a reliably-finite value for the speed of light. Even before universal gravitation, Roemer had enough confidence in the uniformity of nature to suppose that the orbit periods of Jupiter's moons were constant from year to year. He thus attributed late and early sightings of their eclipses by Jupiter to light having more or less distance to travel,

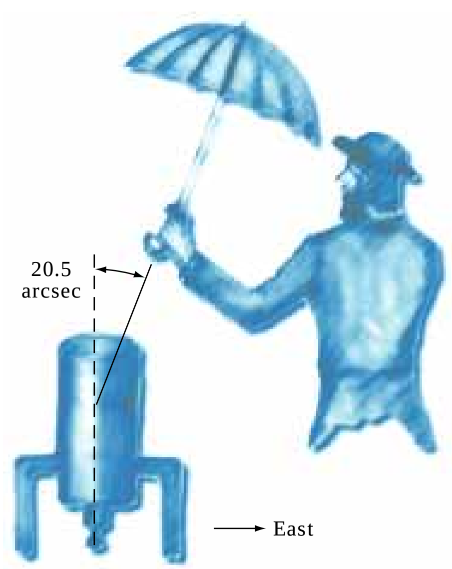
**Or any of several other spellings, but it doesn't matter which you choose because the sound is one of those Danish phonemes not available to the rest of us. It is, as Victor Borge said, a long way from "ugghrl" to "thhhh." Incidentally, Roemer also invented the transit circle and meridian circle instruments whose use revealed the "personal equation" of the previous section, and the mercury thermometer, whose use was germane to the discovery of the "mechanical equivalent of heat" of the next section.*



Each of the four Galilean moons of Jupiter is eclipsed once every 1.7 to 16.7 days. When the Earth is at E_1, we see the eclipses occurring too early by about 8.5 minutes. You can't quite observe Jupiter when we are at E_2 (the sun is in the way), but the eclipses will seem to be occurring somewhat too late any time we are in that part of the orbit. The Earth's orbit is really only one-fifth the size of Jupiter's, not about one-third as shown.

depending on the relative orbital positions of the planets. The data available to him slightly over-estimated the range of early-to-late and slightly underestimated our distance from the sun, leading to a number for c within ten percent of the current best value (which can never be improved again, since it is now a definition!).

Halley (who also had a comet) updated Roemer's numbers in 1694, and uninterest flowered for another generation. Then James Bradley found the same sort of number by a very different method. Bradley (like Herschel) was looking for stellar parallax, but discovered the oddly-named aberration of starlight. Think of photons as raindrops descending upon a moving observer. The angle you have to tilt your umbrella (telescope) forward to catch the drops (photons) is the ratio of your speed to the speed of light. Bradley saw this 20.5 arcsec tilt in 1725, had understood it by 1729, and, armed with a better idea of the size of the solar system and the Earth's speed in it, improved on Roemer's number for c.



An astronomer unclear on the concept of aberration of starlight attempts to shield his telescope from photons by holding an umbrella over it at an angle of 20.5 arcsec to the vertical. 20.5 arcsec = 10^{-4} radians = v_e/c, where v_e is the Earth's orbital velocity.

Notice that sufficiently accurate versions of Roemer's and Bradley's observations could, in principle, take the place of the Michelson-Morley experiment, because one can carry them out with the Earth's orbital velocity making various angles with the incoming light. In fact, the physicists finally took over, and the first laboratory value of c came from Fizeau in 1849. It was about as good as the astronomical ones, but improved methods, from Cornu, Foucault, and (of course) Albert Abraham Michelson quickly took the lead in providing additional significant figures (1850+) and, eventually, evidence for non-dependence on the motion of source or observer (1887+).

Meanwhile, back at the Cambridge ranch, James Clerk Maxwell was busy writing down the four equations, knowledge of which is frequently taken as the minimum requirement for calling yourself a physicist. Constancy of c is built in, along with the absence of magnetic monopoles. Astronomers quickly came to terms with the former; the latter you may well wonder about. We quite blithely ascribe polarization of radio (etc.) radiation to synchrotron emission in magnetic fields strung out for kiloparsecs and more along the arms of spiral galaxies and the jets and lobes of quasars. If an experimental physicist wise in the ways of laboratory plasmas comes along and asks where are (or at least were) the electric currents that sustain (or at least produced) these magnetic fields, the answer is quite often, "eh?" On the other hand, you get back the curious fact that the rest mass of the photon must be less than 10^{-47} to 10^{-57} g, in order for fields to persist over large scales from Jupiter to a galaxy.

The corresponding limit on the mass of the graviton (from the existence of gravitationally-bound superclusters of galaxies at least 100 million parsecs across) is about 10^{-63} g. Both are considerably smaller than laboratory limits, and occasional free spirits have taken them as real, non-zero masses.

WHAT MAKES THE SUN SHINE?

The source of solar and stellar energy was the most important unsolved problem in astronomy/astrophysics

for half a century or more, 1880±10 to 1938±2. Of course, it couldn't be a problem until conservation of energy was recognized as **a** universal phenomenon, which it was not by Galileo or Newton or even William Herschel (though he speculated on the role of chemical interactions in the atmosphere above the solid(!) surface of the sun).

Energy conservation became part of laboratory physics sometime between 1798, when Benjamin Thompson (Count Rumford) reported to the Royal Society (London) on "Experimental inquiry concerning the source of heat excited by friction" and 1849, when James Joule reported to them "On the mechanical equivalent of heat." The German physician Julius Robert Mayer is generally credited with the first proposal of energy conservation in full generality in 1841. By this time, the Earth was already at least tens of millions of years old, according to Hutton, Lyell, and other uniformitarian* geologists who had thought about how long it must have taken to build up sedimentary rocks, make the oceans salty, and so forth. Chemical reactions, which might sustain the sun for a few thousand years, were, therefore, never serious contenders, except on Archbishop Ussher's chronology, and, even then, the end would be at hand.

In fact, Mayer soon proposed a solution to the solar problem he had identified. It was gravitational potential energy, liberated by infalling meteors. Independently, the Scots engineer John James Waterston recognized the problem of solar energy in 1843 and proposed as a solution the continuous contraction of the sun, following on from its origin in a Kantian rotating nebula. Mayer's paper was rejected by the Academy in Paris, Waterston's by the Royal Society in London.

A contracting star can live about GM^2/RL years on gravitational potential energy, a number that should obviously be called the Mayer-Waterston time scale, but is actually called the Kelvin-Helmholtz time scale, for those who put forward the same ideas in about 1854 (Kelvin with meteors initially, Helmholtz with overall contraction). Both had encountered Waterston's work, in a two-page abstract arising from an 1853 meeting of the British Association for the Advancement of Science and containing both the meteoric and the contraction possibilities. Kelvin and Helmholtz were, therefore, presumably at least guided by their predecessors, but they had better credentials, better press agents, and better formal mathematics at their disposal.

There followed a brief era of good feeling, in which most geologists squeezed hard on their layers of sediment to compress them within 20–40 million years, though a few refused, including T. C. Chamberlin of Chicago (whom we recognize as the first half of the Chamberlin-Moulton hypothesis for the origin of the solar system, once a popular competitor to Kantian contraction). Chamberlin and Kelvin faced off at the 1900 meeting of the American Association for the Advancement of Science, neither, of course, changing his mind.

In any case, the solar boat was soon set further rocking, this time by the biologists, who had taken the ideas of Darwin to heart (and head). They insisted on at least 10^9 years for evolution from slime molds to Kelvins. The physicists clambered back aboard starting in 1905, when Rutherford and Boltwood (independently) reported rock ages of many gigayears after considering the decay of uranium and thorium to lead. The numbers settled down around $3–4\times10^9$ yr in 1913, when Soddy weighed in with the concept of isotopes.

A PAIR OF JEANS (Sir James)

You might think at this point that we are well poised to romp home with Eddington, Bethe, and all to hydrogen fusion as the primary source of stellar energy. But real events took several detours, which it would not be fair to blame entirely on James Jeans.* Jeans was, however, the person who most strongly insisted that the real age of stars and stellar systems was more like $10^{12–13}$

**Uniformitarianism is not, at least in intention, a religion, but just the notion that we see in continuous operation now all the important processes that have shaped the Earth. The opposite is catastrophism, and, as usual, the truth is somewhere in between.*

**After all, it was Eddington who declared that the sun was made mostly of iron, silicon, and oxygen, so that radiation pressure and gas pressure were equal at its center.*

years than 10^{9-10}. This "long chronology" arose when Jeans tried to account for the relaxed appearance of stars, clusters, and (after 1925) galaxies and for the observed distribution of the shapes of orbits of binary stars. The binary star case, at least, was an example of the theorem that most mistakes are made before you ever put pencil to paper. Jeans postulated that all binaries had formed with circular orbits, which were gradually distorted into ellipses by encounters with other stars. Stars are VERY far apart, and so this will take a VERY long time: in fact, just about the time Jeans calculated. Like most British astronomers of his and later generations, he had a background in formal mathematics, and did not often make mistakes after putting pencil to paper. Modern observations of binary systems of different ages show, however, that they form with eccentric orbits that are gradually circularized by tidal interactions between the stars.

Meanwhile, however, Jeans' time scale led him to require a source of stellar energy in which mass was completely annihilated and 100 percent of mc^2 made available. That physics knew of no process to do this was not, to him, a fatal objection. Indeed, at the time, experimental physics was not very clear on how to liberate any form. of "subatomic energy" except through spontaneous radioactivity.

There were even times when the long chronology seemed to be winning. Rutherford's definitive 1929 statement on the age of earth rocks from uranium decay (3.4 Gyr) includes the remark that this number proves the sun must be making uranium more or less currently, since the total solar age is 100 times longer. Similar remarks appear in other papers and books by both physicists and astronomers up until about 1935 when the "short" time scale of a few $\times 10^9$ yr triumphed. This seems to have come from approximate agreement among (a) the age of the Earth, (b) the expansion time scale of the Universe, and (c) the time stars could live on nuclear transformations without annihilation. Even Jeans capitulated, in the last, 1944, edition of one of his popular books.

E. A. Milne, whom we have not met before in these pages, was an equal muddier of the waters of stellar physics in the 1920s and 30s, and his ideas are even harder for the modern reader to appreciate than those of Eddington and Jeans. Leon Mestel has made the intriguing suggestion that it would all have been sorted out much sooner if Karl Schwarzshild had survived the Great War and had been available to bang their recalcitrant heads together.

BACK ON TRACK

A second seeming detour was actually the path back to the main highway. This was the association of the stellar energy problem with that of the origin of the elements. Heroes of the tale include Aston with his mass spectrograph (1922+), Atkinson and Houtermans with cyclic nuclear reactions that both built up heavy elements and released a few MeV per nucleon (1929), and Gamow, Condon, and Gurney with barrier penetration. They and others are hymned at greater length in an earlier *Beam Line* (Spring 1994, Vol. 24, No. 1), ending with two choruses by Hans Bethe, the first dated 1939 (when he wrote down most of the details of the hydrogen fusion reactions that we now call the CN cycle and proton-proton chain), the second dated about 1990 (when he added his voice to the choir proclaiming that the solar neutrino deficit is a problem in weak interaction physics, not in astronomy or argon chemistry).

Nucleosynthesis (the formation of complex atoms from simple ones) and the production of energy in stars are now solved problem, though much input was required from nuclear physics and from the area of spectroscopy, to which we will turn in Part II in the Winter issue.