Astrophysics 1996

by VIRGINIA TRIMBLE

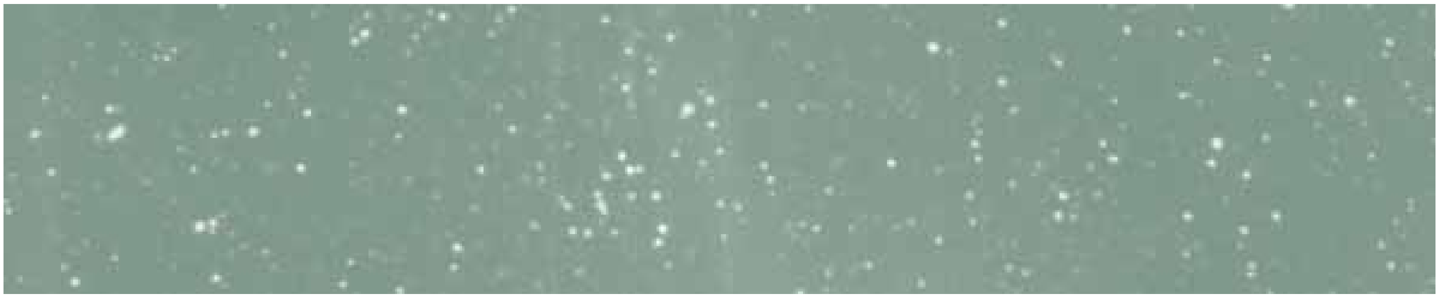
Highlights of fiscal 1996
included a plethora of peculiar planets,
gobs of geronto-galaxies,
and many things in between.

EXTRA-SOLAR-SYSTEM PLANETS

As the autumn 1995 leaves began to fall, we had firm evidence for 12 substellar objects in orbits around stars, three planets orbiting one short-period pulsar, discovered by Alex Wolszczan, and the nine orbiting Old Sol, with credits to Clyde Tombaugh (who died January 17th just as this was being written), Adams and Leverrier, William Herschel, and either Nicolas Copernicus or a Zinjanthropan named Og, depending on your point of view. Since then, the number has roughly doubled, with contributions coming from six of the (at least) seven possible ways of looking. And yet the solar system remains unique.

Some of the new discoveries are almost certainly true planets; others are probably brown dwarfs; and some occupy an uncertain territory between. How can you tell which is which? The table on the next page shows some distinguishing features (excluding great red spots and other birthmarks not visible at large distances). Naturally I like best the ones (formation mechanism and internal structure) that are hardest to determine outside the solar system. There must be some really good log-log plot on which one could display the old and new companions insightfully. This one probably isn't it, but

"I am the owner of the sphere, of the seven stars and the solar year."
—Ralph Waldo Emerson



is the best I have been able to think of—a plot of planet (etc.) mass vs. distance from the primary star in logarithmic units. The solar system, in addition to having more planets than anybody else, occupies unique territory in such a plot. Elsewhere, the planets with masses like that of the earth orbit pulsars, not aging low mass stars; the planets with masses like that of Jupiter are all closer (most much closer) to their parent stars than is our Jupiter; and brown dwarfs are (fortunately) like nothing in our family. Some of the uniqueness is a matter of time and technology. The sensitive searches are not yet old enough to have found orbit periods of a dozen years or more and are not yet sensitive enough to have picked up earth masses unless the central star carries a very precise clock with it.

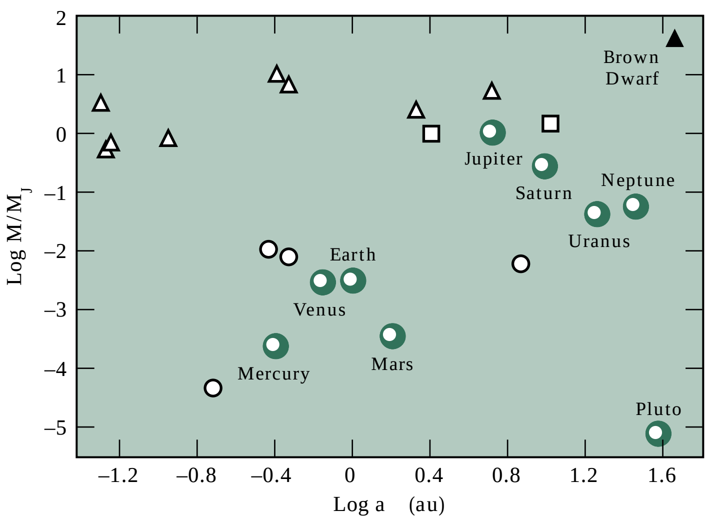
How have all these been found? First of the techniques to succeed was careful monitoring of rotation periods of pulsars. These periods are the steadiest clocks we know, and motions of a pulsar orbiting its center of mass with a companion produce measurable Doppler shifts. The Wolszczan trio has been augmented by timing residuals in the 0.7 second pulsar B0329+54, indicative of an Earth-mass (or larger) planet in a fairly eccentric, 16.9 year orbit. Because of the long period, orbit coverage is not yet complete enough to give the result a very high confidence level, and there is a hint of an additional, three-year period.

The second technique is direct imaging at optical or infrared wavelengths. This led to the candidacy of Gliese 229B for the title of "first companionate brown dwarf," with a probable mass of 20–60 Jupiters and an orbital radius of 44 times the earth-sun distance (astronomical unit), as projected on to the plane of the sky. GD 165B is the next strongest candidate for resolved, companion brown dwarf, while Gliese 105C* has been

*It would be perfectly reasonable for you to ask how stars get their names, and I promise to explain one of these issues. Meanwhile, think of them as like cats. Only the cat knows its own, true, ineffable name. Socks, Percival, Betelgeuse, and Ashurbanipal are random labels assigned so that we can talk about them. (Only optimists attempt to talk to either.)

How to Tell a Planet from a Brown Dwarf in Four Easy Lessons

Property	Planets	Brown Dwarfs
Mass	0.00001 to 10× Jupiter smaller is an asteroid	10 to 85× Jupiter bigger is a star
Orbit	fairly circular near equatorial plane of primary	optionally eccentric random orientation possible
Formation	in a disk around primary	separate condensation center
Internal Structure	core of rocks and metals surrounded by gases	chemically homogeneous degenerate gas (mostly hydrogen and helium)



Planets old and new, plotted in units of mass (relative to that of Jupiter) versus semi-major axis of the orbit (in astronomical units, the earth-sun distance), logarithmically in both cases. Green circles (including Pluto) indicate orbits of high excentricity. White triangles are the companions discovered from radial velocity measurements. Squares are astronometric companions (discovered from proper motion residuals), White circles are companions of pulsars, and the lonely triangle in the upper right corner is clearly a brown dwarf.

definitely promoted (or demoted?) to hydrogen-burning status, or class “star”. Numbers that come from this and most other methods are inherently lower limits to both mass and orbit size by a factor sin *i*, where *i* is an angle between our line of sight and the orbit plane.

Third comes optical or infrared spectroscopy, which, by demonstrating the presence of both methane and water-vapor (“steam”) lines in the atmosphere of Gl 299B put it definitely at a temperature less than 1000K, where no true stars live. Another spectral signature, the presence of lithium, has, in the same time frame, served to put a handful of single, non-companion, objects into the brown dwarf box. Brown dwarfs and low mass stars mix themselves fairly thoroughly over an eon or two, and lithium fuses at such low temperatures that it can remain in the star only if there is no serious hydrogen fusion anywhere therein.

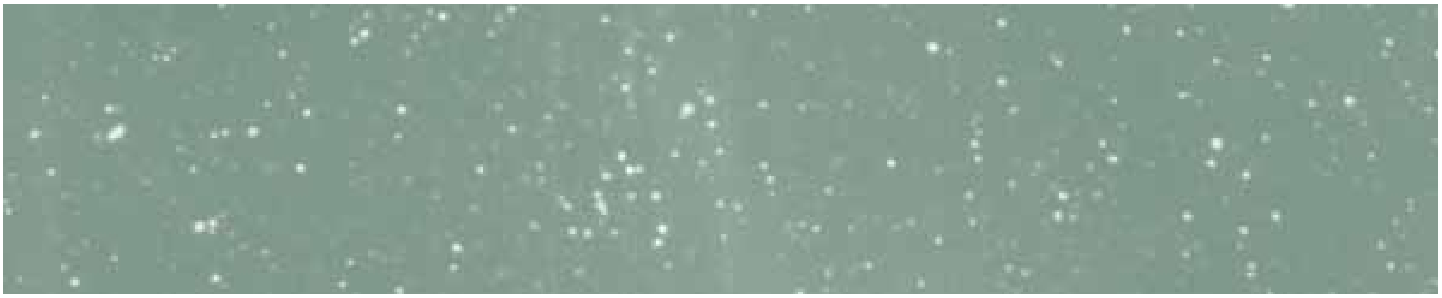
The fourth technique, looking for Doppler shifts in optical spectra of likely parent stars, has been the most spectacularly successful. Most astronomers can probably remember exactly where they were when they first heard the name 51 Peg in October 1995 (and most non-astronomers will wonder what a 51 Peg is, but we have agreed not to ask that question this week). The star had been on two monitoring programs, so that its 4.23 day orbit period, mass limit of 0.5 Jupiters, and so forth, were quickly confirmed. It has been joined, so far, in the published additional literature, by five additional massive planets, only one of which, 47 UMa is far enough away from its parent star to feel like Jupiter (chilly). The others, sometimes called hot Jupiters, are not at any risk of boiling away or being torn apart, but formation in situ seems improbable. Never mind. We have ways to drag planets inward (probably as many models as hot Jupiters at the moment). Three or more additional companion brown dwarfs found in separate, but similar surveys have also surfaced in the past year or two. Because the planet searches could easily have found brown dwarfs (but did not), and not conversely, one is tempted to conclude that planets are genuinely the more common sort of entity. Products of these radial velocity searches are now common enough for statistical arguments to apply to values of sin *i*, and we can say that most are truly of low mass, and not just artefacts of orbit orientation.

Paul Butler, left, and Geoff Marcy in the Keck control room. Their search for extrasolar system planets has been the most successful to date, partly because they have had the insight to use an iodine gas cell as a source of comparison lines to guarantee accurate, repeatable velocity measurements and partly because they have worked very hard.

Method five is the oldest of all, the search for small wiggles in the motion of stars across the sky (“proper motion residuals” is the approved term if you want to talk about them in public). The demise some years ago of two putative companions to Barnard’s star left the technique in mild disrepute, but (as Jack Benny said about “The Horn Blows at Midnight”) there is a whole new generation coming along that will never know. Anyhow, Lalande 21185 probably has one or two planets with Jupiter-like masses and large orbits.

The sixth possibility is to see transient fading when a planet in a nearly edge-on orbit passes across the face of its parent star. One report of such an event in the brightness of CM Draconis implies a planet with a size close to that of Jupiter and an orbit period of at least a few months.

In addition to merely shouting Eureka, astronomers can actually say a couple quantitative things about planets and brown dwarfs. First, although we now count them as “many,” they are nevertheless sparse enough on the



sky that they are not a major contributor to local dark matter. Second, they seem to tie up rather well with increasing evidence for dusty disks around many very young stars and protostars. Such disks probably really do form families of planets around many solar-type stars.

Oh. Did you want to hear about the seventh method for discovering planets? That's when something lands in your fish pond and somebody gets out and tells you that he is from the planet Alpha Venega, which orbits the third star on the left.

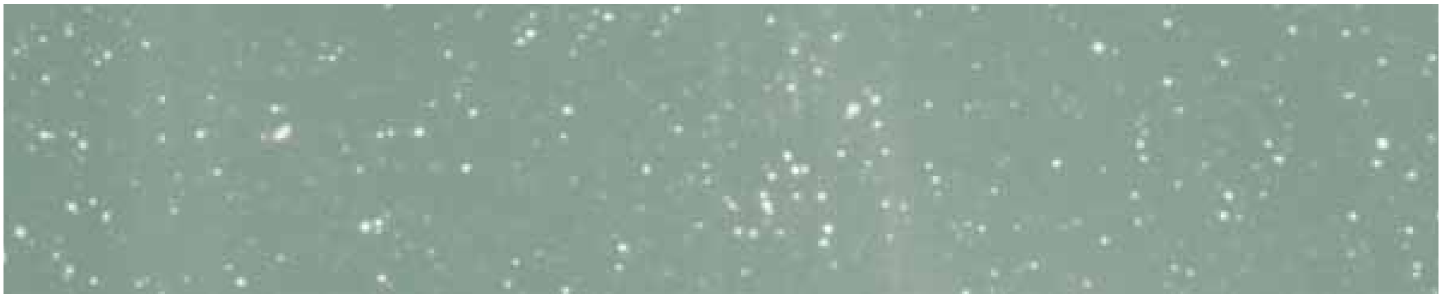
STAR-FORMING GALAXIES AT HIGH REDSHIFT

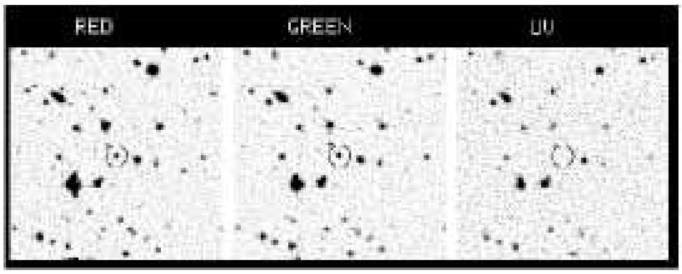
A year or two ago, this section would have been called (in fact was called) "primordial galaxies," and there weren't any. Now that the title has changed, there are an enormous number. This really is, in part, a result of looking at the problem in a slightly different way. But it comes mostly from a sudden flood of new images and spectra, many the products of the Hubble Space Telescope and the Keck I telescope. The objects so imaged are not, in fact, very much like either the galaxies we see here and now or what we were expecting long ago and far away. By way of reminder, light travels at the speed of light, and so distant things are necessarily seen as they were when the light left. Unfortunately, both "distant" and "when" if you want units like furlongs or miles and seconds or years are both model dependent. (This is a technical term, meaning that the numbers depend a lot on your choice of the expansion rate of the universe, its deceleration rate, etc, not just an all-purpose insult). The observed quantity is redshift of spectral lines, $z = \Delta\lambda/\lambda$. Yes, z can be bigger than one; no this does not violate special relativity or anything else sacred; and no, there is no unique way to turn z into a velocity. "Distant" in this context means $z \gtrsim 2$–3, corresponding to the era when the temperature of the 2.7K radiation was 8–11K.

A prototypical primordial galaxy was supposed to be the forerunner of a giant elliptical or the bulge of a big spiral (like the Milky Way), experiencing its first vigorous burst of star formation, so that ultraviolet radiation from hot, massive stars would ionize lots of gas. Most gas in galaxies is hydrogen, and so the expected signature was (redshifted) Lyman alpha emission, the line at 1216 Å emitted when the electron falls back from $n = 2$ to $n = 1$. The vast majority of searches for such emission have failed, except when the target area was close to a previously-identified quasar or radio galaxy, with a known redshift. The traditional excuses have been either that the ultraviolet line was absorbed by dust or that galaxy formation wasn't done in the hypothesized way. The answer is (as is frequently the case), some of each. Most of the new, high redshift galaxies and parts of galaxies are not strong Lyman alpha emitters. In addition, they don't look much like proto-ellipticals or proto-bulges. Most are compact and not enormously bright, and one's impression is that they are either bits and pieces that will eventually merge to make galaxies of recognizable types or that they are highly localized regions of star formation in something that will later "turn on" all over. Typical star formation rates are a few solar masses per year.

The winning technique also relies on the properties of hydrogen, but absorption rather than emission. Just shortward of the ionization limit at 912 Å, hydrogen is very opaque indeed, to the point where wavelengths $\lesssim$ 900 Å, at rest relative to us, used to be called the "unobservable ultraviolet." At redshifts $z \geq 3$, 912 Å begins to move into the color bands that we can observe from the ground (and into the standard color filters of HST). Thus, if you have a number of images of the same part of the sky, taken through infrared, red, yellow, blue, and ultraviolet filters, galaxies at large redshift may be quite bright and even quite blue in the first four images, but they will disappear completely in the fifth, U, image. For still larger redshifts, this "ultraviolet dropout" moves into blue and even yellow parts of the spectrum.

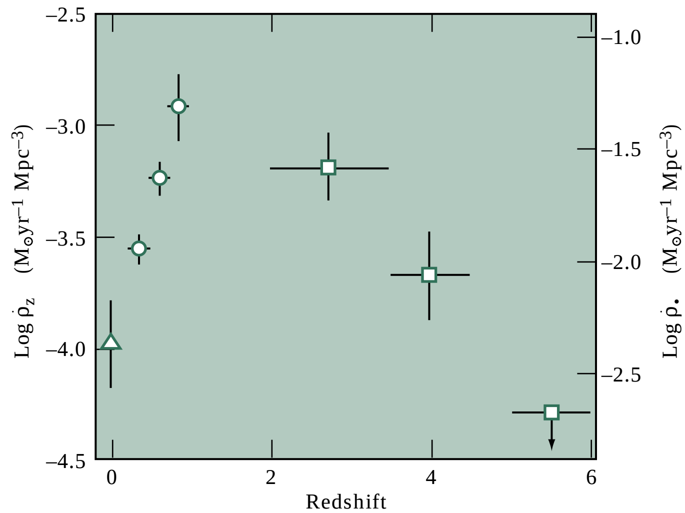
Ultraviolet dropout was pioneered by Charles Steidel and his colleagues at Caltech, looking first at the environs of known quasars and then at apparently blank bits of sky. They confirmed their estimated redshifts with Keck spectra and pronounced them good. The quintessential bit of "blank sky" is the Hubble Deep Field, a few square minutes in a region where HST's view is never





A graphic illustration of the "ultraviolet dropout" method of locating high redshift galaxies. The object in parentheses in each of the three images is quite conspicuous through both red and green filters (and in fact somewhat brighter in the green, indicating that it is intrinsically fairly blue), but completely absent in the right-hand ultraviolet image. This means that its redshift is large enough for the absorption edge due to neutral hydrogen to have been shifted into the U passband. (Courtesy Charles Steidel, California Institute of Technology)

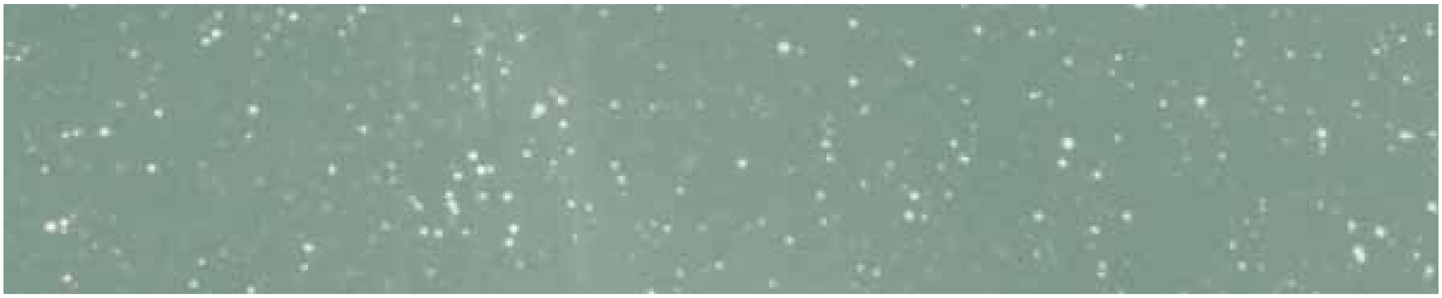
Charles Steidel



The rate of formation of massive stars (or of new heavy elements in massive stars) as a function of redshift as derived from numbers and brightnesses of high-redshift, star-forming galaxies. The upper limit at z = 5.5 comes from the paucity of V-band drop-outs in the Hubble Deep Field. [From Piero Madau in Star Formation Near and Far, Proc. 7th Annual Astrophysics Conference in Maryland, Eds. S. S. Holt and G. L. Mundy, (AIP, New York), in press.]

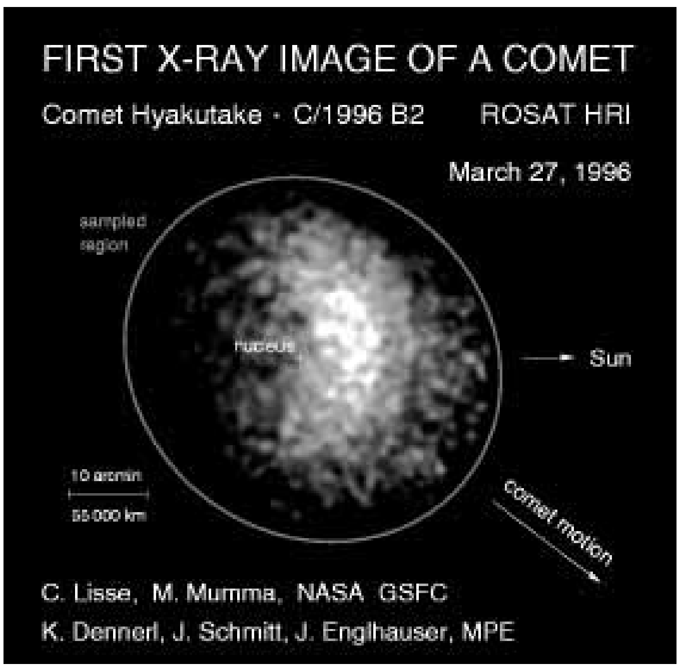
blocked by earth or sun, chosen precisely because it hosts nothing very bright in ordinary photographs (or even infrared, X ray, or radio images). Robert Williams, the current director of the Space Telescope Science Institute, made two rather brave decisions. First, to use a very large number of HST orbits to image this scrap of sky at several wavelengths. And, second, to release the data for public analysis immediately. Since the December 1995 release, preprints, papers, and pontification have proliferated. Real redshifts for uv-drop-out galaxies are accumulating rapidly as well. Redshifts up to $z \approx 4$ are well represented, and some candidates for z = 5–6 remain to be confirmed.

Important conclusions are (a) star formation is underway at or before $z = 4$ and is truly rampant at z = 1–3; (b) the earlier epoch of star formation made ellipticals and bulges, while the peak near $z = 1$ was making disk and irregular galaxies; (c) high z morphologies include some smooth-ish spheroids, some disks (but none with grand design spiral arms), and lots of "other," that is shapes implying interactions, mergers, and the like; and (d) the history of star formation correlates well with the history of how the universe became enriched in the heavy elements that only massive stars can make. Progress is also being made (but not to the point where I can list the answer) on some old questions about when and how galaxies came to be clustered, whether all ellipticals come from the merger of disk galaxies, and on the role in the great scheme of things of the large number of faint, blue, galaxies that turn up when you start trying to count absolutely everything in sight.



IN AND AROUND THE SOLAR SYSTEM

The Galileo mission to Jupiter (which dropped a probe into the interior in 1996) is still busily imaging its satellites. Two of my favorite results are (a) that high speed winds and turbulence persist so far down into the Jovian atmosphere that the primary energy source must be heat escaping from the interior (earth's winds, waves, and weather are, of course, driven by energy from the sun) and (b) that the moon Ganymede has a partially molten interior, its own dynamo magnetic field, and changing surface features that act a bit like plate tectonics and continental drift on earth.



Comets are, of course, things you go outdoors on a clear evening to see. Thus, as Hyakutake crossed the skies a year or so ago, I habitually asked colleagues, "Have you seen the comet?" Imagine my surprise when Joachim Trümpler of the Max Planck Institute in Munich e-said, "Yes. In X rays." Sure enough, the ROSAT X-ray satellite had detected the first known cometary emission. A couple of previous visitors have since been recovered in archival data. The emitting region is always more or less crescent shaped, and the hot gas responsible seems to be the result of solar wind particles hitting the gaseous front of the comet.

Life in or on a Martian meteorite? When I was a child, the phrase "I don't think so" was an expression of genuine doubt. Very occasionally, the real world intrudes into my office sufficiently to make me aware that this is no longer entirely the case, and I have been looking for a context in which to attempt the new meaning.

IN AND AROUND THE MILKY WAY

"I want one too," astronomers who study our own Galaxy have been saying about black holes ever since evidence began to mount up that they are common at the centers of other galaxies (some, though not all of which are quasars and other sources of excitement). The case for something very compact and as massive as a million or so stars at our center has grown gradually stronger over the years. The alternative has always been some other very compact, rather dark configuration, like a cluster of neutron stars. The alternative has now been ruled out by the completion of a pair of projects to measure velocities along the line of sight and in the plane of the sky of stars very near the galactic center. No cluster of stars could be compact enough to live inside the volume with the large velocity dispersion. The remaining alternatives are, therefore, a tight cluster of small black holes or one big one. In a logical universe, people who dislike the whole idea of black holes and don't want any in the real world would vote for the single big one, while enthusiasts should favor the cluster of little ones; but I suspect that an actual opinion poll would turn out the other way around.

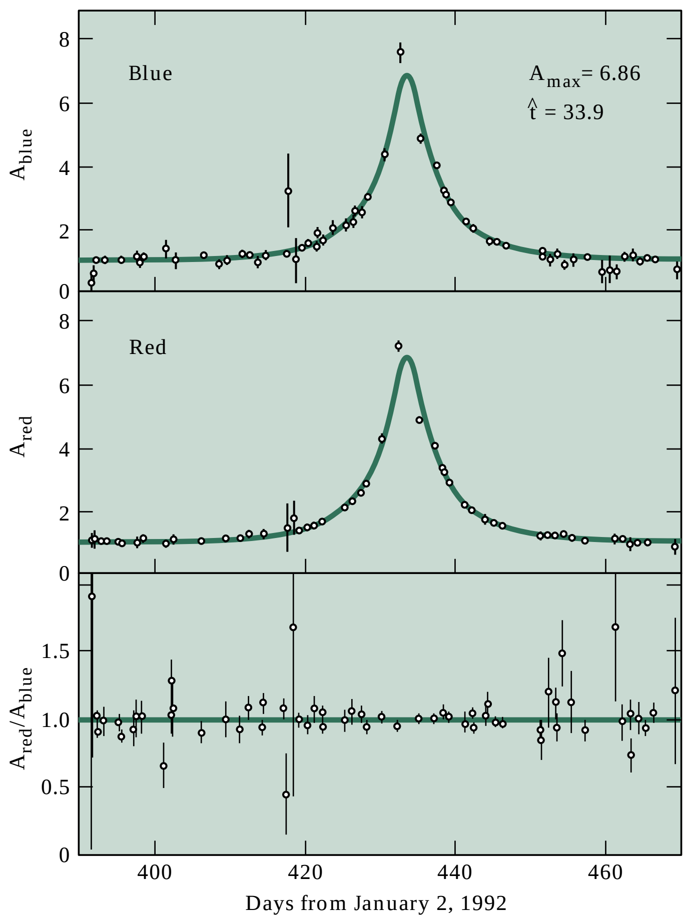
Up until the other day (it was a Saturday in December 1995, in fact), an X-ray burster was an X-ray burster and an X-ray pulsar was an X-ray pulsar, and Mark Twain hadn't met either one of them.* Although both are

The author is, of course, aware that the line is stolen from Kipling, not Twain, and that the two knew each other reasonably well. This is called literary license.

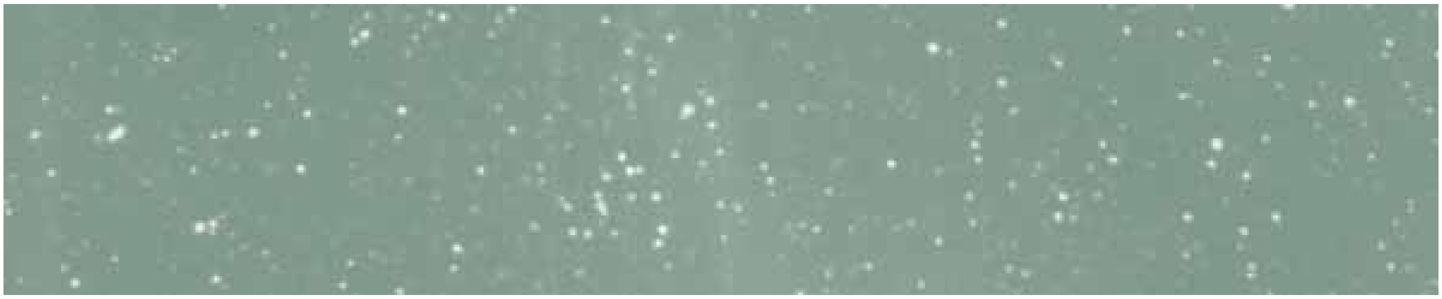
neutron stars, pulsars are regular variables at the rotation period of a star with a magnetic field sufficiently strong to channel accreting gas ("accretion powered pulsars") or outflowing relativistic fluids ("rotation powered pulsars") into the vicinity of their magnetic poles, leading to a corresponding modulation of the outgoing radiation. Such strong fields ($\approx 10^{12}$ G) are associated with neutron stars early in their lives (or at least in their lives as accretors). Bursters, on the other hand, are nonperiodic, though with characteristic time scales, and are the result of sporadic accretion or sporadic explosive fusion of helium accumulated on neutron star surfaces. The previously known examples were all low-mass X-ray binaries, meaning that the gas donors were solar-type stars or smaller and that the neutron star fields were less than about 10^{10} Gauss, leaving the stars with fairly uniform surfaces.

On December 2, 1995, the Compton Gamma Ray Observatory spotted the first source that does both. Now called GRO Jl744-28 (dial this at your peril), it showed periodic modulation at about 0.5 seconds but also about 200 irregularly timed bursts of 8 to 30 seconds or more in the first nine days, and an orbit period of 11.8 days. It has turned off and back on again a time or two in the intervening 1.2 years and has become a bit of a nuisance, nearly saturating the CGRO burst detectors and keeping them from seeing more interesting (or anyhow more mysterious) gamma-ray bursts of other kinds. A number of modelers concur that the bursts are of the variable accretion type, though they disagree about whether it is the accretion rate, the magnetic field strength, or some other combination of properties that must be very finely tuned to allow both kinds of variability in a single source.

We have worried before in these pages (*Beam Line* Vol. 22, No. 3, Fall 1992; Vol. 25, No. 1, Spring 1995) and elsewhere about the age of the universe, how well it is known, and whether it presents problems for people who think they know other things about the universe, like the Hubble constant or the density. Most discussions focus on clusters of old stars (globular clusters) found in the halo of our galaxy. A few have considered the decay of uranium and thorium to lead in the solar system and how long ago the U and Th must have formed to make things come out right. If the synthesis had happened in a single burst of star formation, we would be home clear. But galaxies don't work that way, and the



The first microlensing of a star in the Large Magellanic Cloud found by the MACHO group, in January 1992. The top two panels show the brightness versus time over about two months in blue and red light. The bottom panel is the ratio of red to blue luminosity. The time symmetric profiles (best seen in the fitted curves in the top two panels) and the invariant color shown in the bottom panel are signatures that distinguish lensing events from intrinsic variability of stars. (Courtesy Kim Griest, University of California, San Diego)



"time back to first synthesis" depends a good deal on what you assume about the history of star formation.

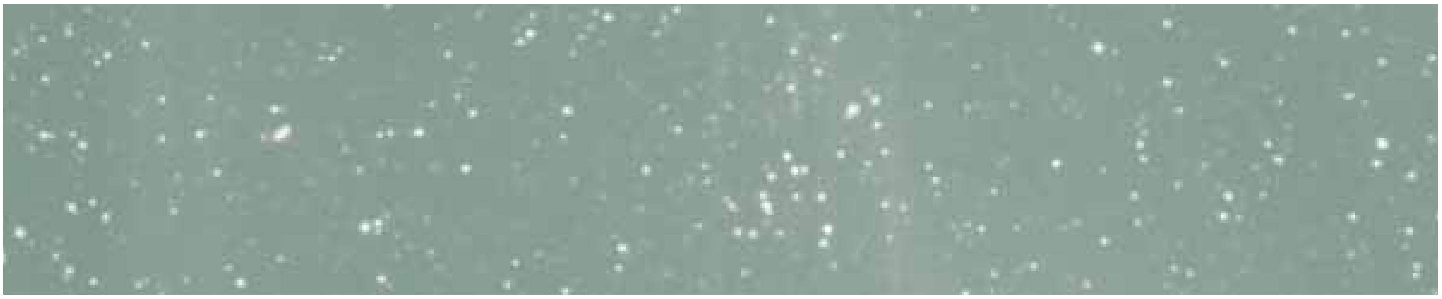
Residual uranium and/or thorium would be a better cosmic chronometer if the solar system were older (though of course we would probably not be around to worry about the problem). The detection of thorium in one old (halo, population II) star is, therefore, a major advance. The discoverers cannot say anything about the amout of Pb^{208} that much of the Th^{232} has decayed into. But they can measure the thorium/europium ratio and (reasonably) assume that it is smaller than the production ratio because some of the thorium has decayed, and the europium has not. The implied stellar age is 15.2 ± 3.7 billion years, much the same sort of number that has come out of other considerations. We hope that the discoverers are busily writing observing proposals to look for thorium in a few additional very old stars!

Gravitational microlensing by (probably) stars or substellar objects in the halo of the Milky Way starred in a couple of press releases during the year. The official two-year sample has 7 ± 1 events in the direction of our neighbor, the Large Magellanic Cloud. Mercifully, only the first year's data (three events) appeared in the refereed literature during the official year, and this spares me from having to decide whether to be complacent, puzzled, or panic-stricken by the set of seven durations and amplitudes and their possible decodings into masses, velocities, and locations of the stars(?) responsible. All three reactions and some others have appeared in preprints-by-pundits. The problem is that the simplest possible interpretation of the events puts the lensing objects in a mass range of 10 to 50 percent the mass of our sun, where they ought to be detectable by other methods (and are not).

IN AND AROUND THE UNIVERSE

The amount of deuterium left from nuclear reactions in the hot, dense early universe (a.k.a. Big Bang or Tremendous Space Kablooie) is very sensitive to the density of stuff involved in the reactions. Qualitatively, this is easy to see. If there are lots of protons and neutrons around, the average deuteron will easily find some and burn through to helium. If not, not. The community has lived fairly happily for a decade or two with the ratio of deuterium to ordinary hydrogen being something times 10^{-5} (implied by the local interstellar gas and by the gases in Jupiter's atmosphere). What one really wants, of course, is the ratio in gas that hasn't had stars and galaxies monkeying around with it. Certain clouds responsible for absorption lines in the spectra of distant quasars are a reasonable candidate, and the year has seen a sort of tug of war between groups of observers, each with an accompanying entourage of theorists, who have found clouds with D/H around 10^{-5} and groups who have found clouds with D/H about a factor of 10 bigger. The debate is still at the scientific duel stage (scurrilous adjectives at 10 paces). I suppose the wise thing is to bet on the less interesting answer, since then one will have either the satisfaction of being right or the satisfaction of learning something new and exciting about the universe. This is sort of like choosing a book you have to read anyhow if you are trying to read yourself to sleep. At least one objective is bound to be accomplished.

Supernovae in very distant galaxies ought to be useful probes of something or other. Perhaps one could use them to measure the Hubble constant, or the slowing of the cosmic expansion, or the geometry of the universe, or to test even more fundamental points like whether the universe is really expanding at all. The general idea was published the year the author's parents were married, and the first serious search for supernovae at redshifts of 0.1 or more started nearly a decade ago. It found one event. And then, with a new search, there were two. Now, suddenly, they are being published by the dozen in Circulars of the International Astronomical Union. The current record redshift is 0.75, more than enough for any of the cosmological tests you might want to perform. A good many foothills remain to be got out of the way before the mountains can be moved, but we can already rule out a couple of variant universes (for instance with redshifts proportional to age rather than distance and redshifts caused by photons simply losing energy as they travel). This is one area I definitely want to keep an eye on in 1997–98.



AND ALL THE REST

The literature of astronomy has not quite reached the 200,000 papers per year attributable to physics, but it's getting there. Every paper is, presumably, a highlight at least to its authors, and my choice of items here and in the longer paper from which this is drawn is necessarily arbitrary, biased, and various other words you might think of (especially if your particular favorite topic isn't here). And there is still more coming, so stay tuned to your favorite preprint shelf, whether wooden or Webbed.

Suggestions for Further Reading

THESE ITEMS AND MANY DOZENS OF OTHERS from the 1996 astronomical literature are discussed by Virginia Trimble and Lucy Ann McFadden in *Publications of the Astronomical Society of the Pacific* for February 1997. Lucy Ann did the solar system part, and Virginia is to blame for nearly all the rest. For more about Mark Twain and Rudyard Kipling, see C. C. Park "The River and the Road" in *American Scholar*, Vol. 66, No. 1, 1997, p. 43.

DATES TO REMEMBER

Jun 29–Jul 2	20th Anniversary Symposium: 20 Beautiful Years of Bottom Physics, Chicago, IL (Dan Kaplan, Department of Physics, Illinois Institute of Technology, Siegel Hall, 3301 S. Dearborn, Chicago, IL 60616 or b20@hepl.iit.edu)
Jul 3–9	High Energy Physics International Euroconference on Quantum Chromodynamics: QCD 97: 25th Anniversary of QCDS, Montpellier, France (QCD Secretariat, Laboratoire de Physique Mathematique et Theorique, Universite Montpellier II, Place Eugene Bataillon, F-34095 Montpellier Cedex 05, France or qcd@lpm.univ-montp2.fr)
Jul 7–11	7th International Symposium on Heavy Flavor Physics, Santa Barbara, CA (flavors@hep.ucsb.edu)
Jul 28–Aug 1	18th International Symposium on Lepton-Photon Interactions (LP 97), Hamburg, Germany (LP97 Coordinator, DESY, D-22603 Hamburg, Germany or LP97@desy.de)
Aug 4–15	25th SLAC Summer Institute on Particle Physics: Physics of Leptons, Stanford, CA (Lilian DePorcel, Conference Coordinator, SLAC, Box 4349, Stanford, CA 94309 or ssi@slac.stanford.edu)
Aug 4–Sep 5	Aspen Workshop on New Physics at LEP2 and the Tevatron, Aspen, CO (Aspen Center for Physics, 700 W. Gillespie, Aspen, CO 81611 or jane@acpl.zgsw.com)
Aug 19–26	International Europhysics Conference on High-Energy Physics (HEP 97), Jerusalem, Israel (D. Lellouch, Scientific Secretary, Weizmann Institute, Rehovot, Israel, or hep97@www.hep97.ac.il)
Sep 1–12	CERN Accelerator School (CAS 97): Accelerator Physics, Gjovik, Norway (Mrs. S. Von Wartburg, CERN Accelerator School, AC Division, 1211 Geneva 23, Switzerland or suzanne.von.Wartburg@cern.ch)