use of the biggest telescopes in the world by several groups in the United States and Europe. The break came in 1987–1988, when the colors of G" were recognized to be markedly bluer than all surrounding field stars. This was quite a result in itself because G", with a magnitude between 25 and 26, has a photon flux comparable to that of a candle on the surface of the moon seen at the Earth. If G" was the optical counterpart of 1E0630+178, then the optical to x-ray flux ratio was similar to Vela's, strengthening the case that the source was a neutron star.

Final confirmation of this link came, unexpectedly, in 1992, starting with observations by the Roentgen Satellite (ROSAT), the German, United States, and United Kingdom x-ray satellite, which found the x-ray flux from 1E0630+178 to be pulsed, with a periodicity of about 0.25 s. This clinched the case for a neutron star and provided a tool for further identification. At that time, NASA had recently launched the Compton Gamma Ray Observatory (CGRO), and its high-energy detector, the Energetic Gamma Ray Experiment Telescope (EGRET), keeping Geminga under constant scrutiny, quickly saw the same pulsation in gamma ray photons. The case for the identification of the x-ray–emitting neutron star 1E0630+178 with Geminga was closed.

The accuracy of the data made it possible to measure the change of pulsation period with time, a result of the slowing of the neutron star's rotation, and it was then possible to predict the period of Geminga during the 1975–1982 COS-B measurements, and even during the 1972–1973 SAS-2 studies. When those data were revisited, the pulsation was readily apparent, although with much worse statistics; it can be firmly stated that the pulsation could not have been deduced from the early observations because of the paucity of the gamma ray photons.

The ratio of the observed gamma ray flux to the global energy output of a neutron star with Geminga's rotation characteristics (its period and period derivative) showed that the object could not be at a distance much in excess of 1000 light years—it must be very local, in other words. Because neutron stars generally have high space velocities (hundreds of kilometers per second), it seemed likely that the proper motion of G" could be detected, if indeed this was the optical counterpart of Geminga. Comparison of 1984 and 1987 images with one image from the European Southern Observatory's (ESO's) New Technology Telescope (NTT) on 4 November 1992 revealed a very rapid motion of 170 marc sec year^{-1} across the sky. This finding confirmed that G" is a nearby, intrinsically underluminous object (compared to a normal star) and confirms it as the optical identification of Geminga, whose neutron star nature had been established through the x-ray and gamma ray pulsations.

The Geminga story is a nice example of the power of multiwavelength astronomy for neutron star work. It is the only identification of a neutron star through its gamma ray emission, making it a unique example among the more than 550 radio pulsars now known. In the last couple of years, however, the synergism of the contemporaneous ROSAT and CGRO missions, with help from the most powerful ground-based optical telescopes, has added to the database of isolated neutron stars. So far, ROSAT has now found nearly 20 such sources in soft x-rays, in most cases their emission being explicable as thermal radiation from hot neutron star surfaces. In gamma rays, the CGRO has observed, as well as the Crab, Vela, and Geminga pulsars, pulsed emission from PSR 1706-44, PSR 1055-52, and PSR 1509-58. For all of them, the high-energy emission is a significant fraction of the total; for PSR 1055-52, it may be the dominant energy output.

In the optical domain, observations of the Crab, Vela, and Geminga have been complemented with the secure identification of PSR 0540-69, the first isolated neutron star seen in the Large Magellanic Cloud. More recently, tentative identifications have been proposed for PSR 0656 + 14 (one of the ROSAT objects) and for PSR 1509-58, a high-energy emitter. The latter is of special interest: It has the highest period derivative (slowing down of its rotation) and the highest magnetic field among all neutron stars. A recent deep observation, again with ESO's NTT, found an excellent candidate for the optical counterpart, of 22nd magnitude. If confirmed by timing measurements, this result would require a serious reassessment of pulsar emission theory. Even more interesting are the conclusions reached by comparing the preferred energy output with the age of the objects. Two monotonic trends are apparent: As neutron stars get older, they increase their gamma ray output and decrease the fraction of their luminosity emerging in visible light.

Taking Stock of Gamma Ray Bursts

Dieter H. Hartmann

Astrophysical gamma ray bursts (GRBs), discovered by chance some 20 years ago, are baffling; they are brief, energetic, unpredictable, variable, and do not repeat. For the past 3 years, the Burst and Transient Source Experiment (BATSE) on board the orbiting Compton Gamma Ray Observatory (CGRO) has detected on average one cosmic GRB per day, an event rate almost matched by the publication rate in the field. To help readers take advantage of this active corner of the scientific stock market, I shall discuss the reasons for the GRB boom and some possible pitfalls.

Burst durations range from hundredths of a second to a thousand seconds, with recent convincing evidence for a bimodal duration distribution (*1–3*). Photon energies are typically 1 MeV, with significant emission above 100 MeV but little in the x-ray band. Bursts occur randomly in time and position on the sky; they are distributed isotropically in direction and do not repeat [three sources are known to have had repeated outbursts, but spectrally and in mean photon energy, these three do not resemble classical GRBs and are thought to constitute the distinct class of Soft Gamma Repeaters (SGRs)].

Light curves of GRBs show significant count rate variations on time scales as short as milliseconds; this represents a light travel distance of only 300 km, indicating that the emission is from rather compact astrophysical sites. Burst spectra are in general featureless, but in some cases, low-energy (10- to 100-keV) absorption features have been seen. If interpreted in terms of magnetic resonances in the photon-electron interaction, field strengths of some teragauss are implied, similar to what is inferred in radio pulsars, which are rapidly rotating neutron stars. There is occasional evidence of emission features at about 400 keV, which can be interpreted as the 511-keV electron-positron annihilation line redshifted by the gravitational field of a solar mass neutron star. The existence of these lines has been controversial, but they lent weight to GRB models involving neutron stars.

The spatial distribution of the 10^8 to 10^9 galactic neutron stars, inferred from pulsar studies, resembles the disk of stars but with a larger scale height, say 500 pc. Because the burst distribution shows no sign of the

The author is in the Department of Physics and Astronomy, Clemson University, Clemson, SC 29634.

Milky Way disk, it seems that observed bursts must be no more than 1 kpc from the sun, within which volume the neutron star distribution is approximately uniform. In a magnitude-limited sample of a uniform population, the number of bursts should be proportional to the −3/2 power of the observed brightness, which, before BATSE, was indeed observed. Moreover, the small number of neutron stars within 1 kpc necessitates burst recurrence to maintain the observed event rate.

It was widely expected that BATSE, with its superior sensitivity, would see more distant GRBs and reach beyond the scale height of galactic neutron stars; the Milky Way should be revealed, and deviations from the −3/2 number-brightness relation should show up. Less than a year after launch, this was clearly not what was observed. The brightness distribution indeed fell away from the −3/2 law, with fewer faint sources, but no concentration of sources toward the galactic plane was seen; the burst distribution remained isotropic on the sky. These two facts effectively destroyed the old paradigm (*4*) because the pattern of bursts does not match any conceivable galactic disk population. Even models putting the bursts in the galactic dark matter halo do not work (*5*): Although the halo is roughly spherical, our viewpoint is about 8.5 kpc from the galactic center, so the observed distribution would still be anisotropic. The BATSE surprise cast grave doubts on all galactic burst models. Data for the first set of 260 bursts are now publicly available (*6*).

If GRB sources are not local neutron stars but instead are distributed throughout the universe, isotropy is guaranteed and the geometry of the expanding universe could cause a reduced number of fainter (more distant) bursts. Cosmological models have a long history but had never been widely popular because the bursts would have to be so much more energetic. If GRBs are cosmological, the BATSE results along with observations by the Pioneer Venus Orbiter (PVO) require that the maximum redshift reached by BATSE is of order unity (*7*), and the required event rate translates into one burst per typical galaxy per million years.

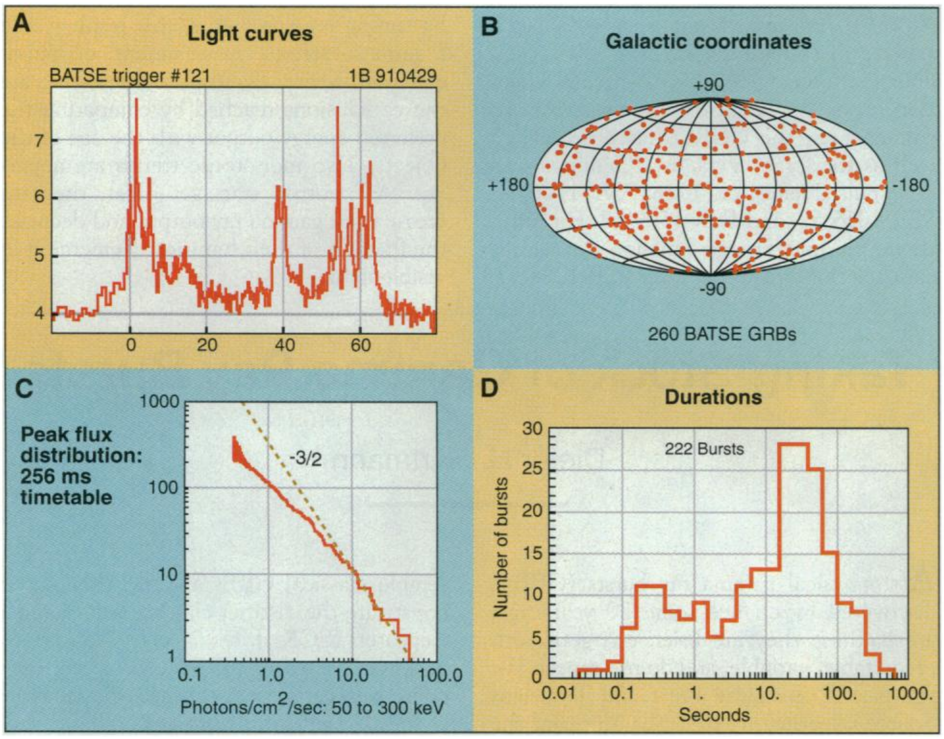
A currently popular model, though certainly not the only one, involves the merging of two compact objects, say two neutron stars, generating in excess of 10^{53} ergs, predominantly in the form of neutrinos. To account for the observed burst brightnesses, a mere 0.1% of that energy must somehow be converted into photons with energies of about 1 to 100 MeV. Neutrino-antineutrino annihilation can do the job, but if even a small amount of baryonic material is present in the emission region, which is likely for a merger of neutron stars, most of the burst energy will be converted to bulk motion of the baryons, quenching gamma ray emission. Conceivably, then, GRBs may represent a delayed energy release from the interaction of the fireball debris with the surrounding medium (*8*).

Studies of our own galaxy suggest a neutron star merger rate of up to one per 10^5 years or so, which seems fine. But if cosmic fireball emission is strongly beamed, a higher merger rate is needed, and strong beaming may be implied by the detection by the Energetic Gamma Ray Experiment Telescope instrument on CGRO of a few burster photons above 1 GeV in energy. The escape of such high-energy photons suggests either large Lorentz factors in the emitting system or geometric beaming such that the angle-dependent threshold for photon-photon pair creation is increased. Burst redshifts are unknown, so cosmological models are hard to verify; so far, the data are consistent with cosmological distributions, but certainly do not require it.

A galactic origin for GRBs is not being abandoned lightly, and several groups are considering novel halo models. New pulsar observations have indicated that some neutron stars may be born in the halo (*9*), and if, like disk neutron stars, these objects are born with high velocities, they could give rise to a very extended halo, reaching into the domain of the local group of galaxies and form a large and uniform population of potential GRB sources. At first, the BATSE data were consistent with these extended halo models (*10*), but by now, the constraints derived from over 700 GRBs are so tight that even these solutions are unlikely (*11*).

A different proposal comes from Lamb's group, who have divided GRBs into two distinct classes, according to brightness and variability (*12*). Analysis of the angular distribution of the two classes with respect to a galactic reference frame shows evidence for significant anisotropy in one of the classes (*13*). The analysis indicates a galactic disk origin, with the suggestion of an association with the galaxy's spiral arm structure (*13*). This group concludes that essentially all bursts have a galactic origin, as has also been argued by Atteia and Dezalay (*14*) from the brightness distribution of BATSE bursts.

But is it reasonable to expect more bursts in the spiral arms? The distribution of the more than 500 known pulsars—young neutron stars—shows no sign of the spiral arm structure. Neutron stars, because of their high velocities, are expected to migrate quickly from the disk, so old neutron stars, to form a disk-related burst population, must somehow be triggered into activity only when they are near the disk. Accretion of interstellar matter could provide a natural trigger (*13*), but with the exception of HII regions, none of the gaseous or



Four views of gamma bursts. The time evolution of a gamma ray burst is shown in the light curve (**A**). Bursts are isotropically distributed across the sky (**B**). The distribution of gamma ray burst brightness follows a −3/2 power law for a narrow range and falls off elsewhere (**C**), The distribution of pulse durations is bimodal (**D**). [Adapted from (*6*)] stellar tracers of galactic structure show any strong spatial coherence resembling spiral arms. It would be surprising if GRBs turn out to be better spiral arm tracers than other galactic populations. Because of these reservations, one may look again at the observational evidence. A classification of bursts based on peak photon fluxes instead of peak count rates caused the evidence for anisotropy to disappear (*15*). Moreover, the BATSE team applied the analysis of Lamb and Quashnock (*12, 13*) to new GRB data and found that the anisotropy was reduced and the multipole vector had changed direction (*16*). Support for a purely galactic burst origin hypothesis seems therefore much reduced. The possibility that bursts originate much closer to home—in the local interstellar medium or in the Oort cloud of solar system comets—has been considered, and although such ideas are not altogether ruled out, many observational facts argue against them (*11*).

Whether bursts repeat is a crucial issue; on the cosmological hypothesis, they are rare events in isolated galaxies and should certainly not repeat. However, GRB positions are in general known only to an accuracy of a few degrees, so burst recurrence can be investigated only by statistical techniques. If all or some GRBs repeat, their angular distribution would show clustering on scales on the order of the detector resolution function, which could be detected as an enhancement in the two-point correlation function or as an excess of pairs with small angular separations. There is evidence for a statistical excess of bursts at small separations (*17, 18*), which would indicate recurrence and rule out cosmological models, but there is also an excess correlation on scales near 180° (*19*), which could be caused by systematic position errors or could simply be a statistical fluke. In any case, analysis of a larger data set (743 events) shows no sign of any excess, at large or small scales (*11*). For now, it appears that the classical belief in no burst repetition remains secure.

An important observational "fact" favoring the neutron star model has been the presence of cyclotron lines in some bursts; the Japanese x-ray satellite Ginga revealed harmonic structure in multiple-line features (*20*) whose near integer ratios supported the picture of cyclotron resonances in strong magnetic fields. Models with line-forming regions near the surfaces of neutron stars and with magnetic fields of about 10^{12} G, required the neutron stars to be about 1 kpc away. Taking account of instrumental differences between BATSE and Ginga, it is estimated that BATSE should see lines in about five bursts per year; to date, no such lines have been found, although not for lack of trying.

The lack of detected transient emission in all but the MeV band has stymied attempts to identify GRB counterparts at other wavelengths. The degree size error boxes of GRB locations make the search for counterparts a needle in a haystack problem, except that we do not know what the needles look like. Optical transients found on archival plates near present-day GRB locations were once thought promising but have led nowhere, and the x-ray satellite ROSAT surveyed several GRB error boxes but found no quiescent x-ray sources; the lack of x-rays is a severe constraint on local neutron star models. Schaefer (*21*) pointed out that any low-energy x-ray emission from GRBs close to the galactic plane would be strongly absorbed if the source were outside the galaxy but much less affected if it were in the solar neighborhood. Plans are under way to search for this effect.

Distances to galactic radio pulsars are routinely estimated from frequency-dependent signal propagation delays caused by free electrons in the interstellar medium, and if GRBs generated any radio emission, similar distance determinations might be possible. For cosmological bursts, delays would come from intergalactic electrons, electrons in our galaxy and the host galaxy, and perhaps electrons in the burst emission region itself; if radio delays were found to be in excess of the known contribution from our own galaxy, an extragalactic origin would be implied. Radio waves from high redshift GRBs might be delayed by as much as an hour (*22*), enough time to point a terrestrial radio telescope toward the burst position. The BATSE team in collaboration with Cline and Barthelmy at the Goddard Space Flight Center is now setting up a response network that should allow ground-based pointings in coincidence with the burst, at least those that last for, say, 10 s or more, which is a substantial fraction of all bursts.

Burst taxonomy has been attempted since their discovery but has not met with much success except for the three clearly distinct SGRs, which show soft spectra, short durations, and obvious recurrence. The prototypical SGR, the 5 March 1979 event, is now known to be associated with a supernova remnant in the Large Magellanic Cloud, and the most prolific, SGR 1806-20 (over 100 outbursts) (*23*), is almost certainly associated with the supernova remnant G10.0-0.3 (*24*). Two out of three SGRs are now known to be associated with young galactic supernova remnants, which perhaps makes it harder to buy into the cosmological picture for classical GRBs, except that the connection, if any, between the SGRs and classical GRBs remains questionable.

I assume that this summary has left the reader as confused as most of those trying to understand GRBs. The old paradigm may be dead, but not quite, and the new paradigm, though it emerged with shining armor, has soft spots. There are many transient phenomena in astronomy, from novae and supernovae to x-ray bursts, SGRs, and GRBs; all but the classical GRB phenomenon seem to be reasonably well understood. The debate is on the basic question of whether GRBs are as near as 10^{16} cm or as far as 10^{26} cm, a range of 10 orders of magnitude. The implied energies differ by 20 orders of magnitude and thus imply vastly different physical mechanisms. There is no tell-tale feature in the light curves or spectra that allows an easy answer.

This broker is at a loss advising you where to invest your money. At present there seems to be no good strategy; perhaps patience would be good, or investment in many places to spread the risk. Either way, the game is fun and the author is almost certain that whatever the solution turns out to be (some day), we shall learn from the experience. I recommend that you do invest in GRBs, but do not let anyone promise you the sky.

References

1. C. Kouveliotou *et al.*, *Astrophys. J.* **413**, L101 (1993).
2. K. Hurley, in *Proceedings of the 2nd Huntsville Gamma Ray Burst Workshop*, G. J. Fishman *et al.*, Eds. (American Institute of Physics, New York, in press).
3. ———, in *Gamma Ray Bursts*, W. Paciesas and G. J. Fishman, Eds. (American Institute of Physics, New York, 1992), p. 3.
4. C. A. Meegan *et al.*, *Nature* **355**, 143 (1992).
5. S. Mao and B. Paczynski, *Astrophys. J.* **389**, L13 (1992).
6. G. J. Fishman *et al.*, *Astrophys. J. Suppl. Ser.*, in press
7. E. E. Fenimore *et al.*, *Nature* **366**, 40 (1993).
8. P. Meszaros and M. Rees, *Astrophys. J.* **405**, 278 (1993).
9. P. A. Harrison, A. G. Lyne, B. Anderson, *Mon. Not. R. Astron. Soc.* **261**, 113 (1993).
10. D. H. Hartmann *et al.*, *Astrophys. J. Suppl. Ser.*, in press.
11. D. H. Hartmann *et al.*, in (*2*).
12. D. Q. Lamb, C. Graziani, I. A. Smith, *Astrophys. J.* **413**, L11 (1993).
13. J. Quashnock and D. Q. Lamb, *Mon. Not. R. Astron. Soc.*, in press.
14. J.-L. Atteia and J.-P. Dezalay, *Astron. Astrophys.* **274**, L1 (1993).
15. R. Rutledge and W. Lewin, *Mon. Not. R. Astron. Soc.*, in press.
16. M. Briggs *et al.*, in (*2*).
17. J. Quashnock and D. Q. Lamb, *Mon. Not. R. Astron. Soc.*, in press.
18. V. C. Wang and R. E. Lingenfelter, *Astropohys. J.* **416**, L13 (1993).
19. R. Narayan and T. Piran, *Mon. Not. R. Astron. Soc.*, in press.
20. T. Murakami *et al.*, *Nature* **335**, 234 (1988).
21. B. E. Schaefer, in *COMPTON Gamma Ray Observatory*, M. Friedlander, N. Gehrels, D. J. Macomb, Eds. (American Institute of Physics, New York, 1993), pp. 280 and 803.
22. D. Palmer, *Astrophys. J.* **417**, L25 (1993).
23. C. Kouveliotou *et al.*, *Nature* **362**, 728 (1993).
24. S. R. Kulkarni and D. A. Frail, *ibid.* **365**, 33 (1993).