view is extreme, but it is clear that too little is known about halogenation of organic matter in soil and the fate (and toxicity) of the resulting compounds. Myneni accomplishes the redirection of the scientific focus away from the toxicology of anthropogenic chemicals toward understanding the natural cycle of this very common element, chlorine, which is both a sweetheart and an affliction.

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PERSPECTIVES: ASTRONOMY

Demotion Looms for Gamma-Ray Bursts

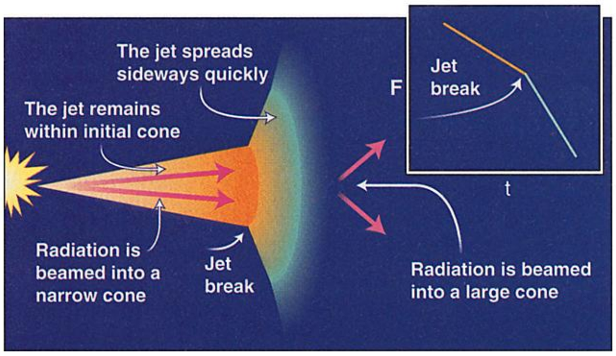
Tsvi Piran

Several times a day, a short burst of gamma rays (GRB) reaches Earth from outer space. The high-energy bursts last a few seconds and arrive from random directions in the sky. Because of their short duration, the exact location of the emitting sources could not be pinned down until the BeppoSAX satellite discovered in 1997 that GRBs are followed by an x-ray afterglow lasting several days. The exact positions given by the satellite enabled optical and radio astronomers to detect optical and radio afterglows lasting days to months. The host galaxies could be identified once the afterglows had faded.

Redshift measurements of the host galaxies revealed that GRBs are associated with an enormous energy output. In one extreme case, GRB990123, an energy output of more than 10^{54} ergs was estimated, comparable to the rest mass energy of a star. An energy output of this magnitude could not be explained with existing models, leading some researchers to talk about a GRB energy crisis.

It turns out that the reality is more mundane. Last November, three groups reported at a workshop at Woods Hole (*1*) that the initial energy estimates for GRBs were too high. The actual GRB energy is narrowly distributed around a "mere" $\sim 10^{51}$ ergs. The secret lies in beaming: The earlier energy estimates assumed isotropic emission, but GRBs form beams, some with an opening angle of only a few degrees. The wide distribution of observed fluxes and apparent luminosities results mostly from variations in these beaming angles.

According to the common fireball model (*2*, *3*), a GRB begins when a compact "central engine" accelerates relativistic flow to a velocity close to the speed of light. The kinetic energy of this flow is dissipated by shocks within the flow, producing the observed gamma rays. But these internal shocks do not dissipate all the available energy. External collisions with surrounding matter (interstellar matter or material ejected earlier from the progenitor) slow down the flow that still carries away a large fraction of the initial kinetic energy. The resulting external shocks produce the afterglow. Connaughton (University of Alabama, Huntsville) described observations showing the transition from a GRB phase to an afterglow phase in GRB991216, confirming this picture (*4*).



Beamed emission. A relativistic jet with a Lorentz factor γ and an opening angle θ moves forward until its Lorentz factor $\gamma = \theta^{-1}$. Then it expand sideways rapidly, resulting in a "jet break" in the light curve. A schematic light curve is depicted at the top right.

Relativistic time delays cause a jetted relativistic flow to move initially forward without sideways expansion. Later, during the afterglow phase, the flow slows down and then suddenly expands sideways (see the first figure). This transition produces a pronounced monochromatic "jet break" in the afterglow light curve, as observed in GRB 990510 (*5*, *6*). The timing of the jet break depends on the jet's opening angle—narrower jets have earlier jet breaks. Afterglows thus provide information on the opening angles of the jets.

An immediate prediction of this model is that we should observe orphan afterglows—optical or radio afterglows with no gamma-ray counterparts. This will happen when the narrow gamma-ray beam points away from us but the wider optical and radio emission can be seen on Earth. In fact, we expect to see far more orphan afterglows than bursts. Yet only one tentative observation has been reported so far. Vanden Berk (Fermilab, Batavia, IL) reported on the discovery of a mysterious optical transient in the Sloan Digital Sky Survey (*7*). The transient source was 100 times brighter than a supernova. It could be the first "orphan optical flash" because it was apparently not seen by the GRB detectors on the satellites BeppoSAX and Compton-GRO (which was still operational during this observation).

Sari (California Institute of Technology, Pasadena, CA) reported an analysis of the emitted gamma-ray energy for a sample of 17 bursts with known redshift. Sari and collaborators (*8*) have estimated the jet opening angles for these bursts from the afterglow data. When these angles were considered in the energy estimates, the gamma energy was narrowly distributed around $\sim 5 \times 10^{50}$ ergs. Panaitescu (Princeton University, Princeton, NJ) and Kumar (Institute for Advanced Study, Princeto, NJ) presented a different analysis (*9*). Using the multiwavelength afterglow light curves and spectra, they have modeled the afterglow emission and estimated the relativistic kinetic energy during the afterglow phase. They find that the kinetic energies are narrowly clustered around $\sim 3 \times 10^{50}$ ergs.

A third independent analysis supports these surprising results. Piro (Istituto di Astrofisica Spatiale, Rome) reported that the observed x-ray fluxes of 21 BeppoSAX afterglows at a given time after the burst are also narrowly distributed. We have found that according to the fireball model (*10*, *11*), these

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x-ray fluxes are directly related to the relativistic kinetic energy. This implies (*11*, *12*) that the narrowness of the x-ray flux distribution provides an upper limit to the narrowness of the underlying kinetic energy distribution.

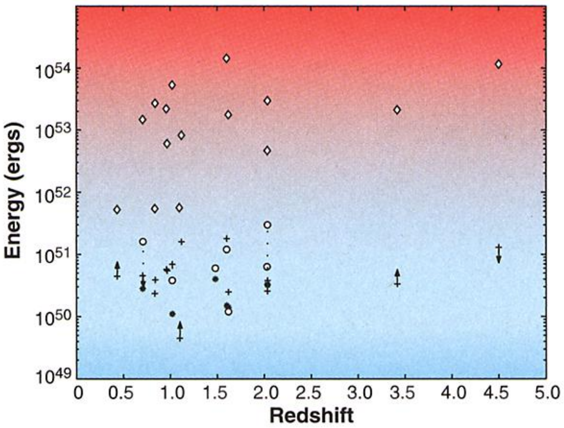
Some minor inconsistencies between the analyses remain. For example, Sari and collaborators (*8*) suggest that the gamma-ray energies vary by a factor of 2, whereas our analysis (*11*) suggests a factor of 10. But the overall picture that emerges is clear: The relativistic energy ejected by the central engine is rather constant and is comparable to the gamma-ray energy emitted during the GRB (see the second figure).

The results have several important implications. First, the revised energy estimates of $\sim10^{51}$ ergs are rather modest and are comparable to the energy released in a supernova explosion. Energetic considerations that previously disfavored some models, such as the magnetic pulsar model or the neutron star merger model, thus become irrelevant. A supermassive star is no longer required to account for the energy supply.

The constancy of the energy involved provides a severe constraint on the nature of these enigmatic explosions. It suggests (but does not require) that the gamma rays and afterglow tap the whole energy supply of the source. For instance, in the collapsar model for GRBs, the central engine is composed of a black hole and an accretion disk around it. This model has two energy reservoirs that can be tapped to launch a relativistic jet: the black hole's rotation energy and the gravitational energy of the disk. The nearly constant energy in GRBs implies that the mass accretion onto the black hole plus the possible conversion of the black hole's rotational energy to the kinetic energy of the jet do not vary much from one burst to another, in spite of the fact that both the disk mass and the black hole's spin are expected to vary widely in the collapse of massive stars.

The similarity between the gamma-ray energy and the afterglow's kinetic energy further implies that the gamma-ray emission mechanism must be very efficient. This is another strong constraint on GRB models, both on the nature of the "inner engine" and on the conditions within the gamma-ray–producing internal shocks.

Finally, the narrow beaming angles found in many bursts imply that the GRB rate is 500 times higher than observed. The observed GRB rate corresponds to about one burst per 10^7 years per galaxy, but the actual rate is likely to be almost one per 10^5 years per galaxy. This rate is so high that among every hundred supernova remnants (SNRs), we would expect one GRB remnant (GRBR) (*13*). Ayal and Piran (Hebrew University, Jerusalem) presented their estimate (*14*) that by taking into account the different topologies of GRBs and supernovae (two beams versus spherical expansion), we could distinguish GRBRs from SNRs within 150 to 3000 years after the burst. Radio observers should be able to find between 2 and 20 nonspherical GRBs within a 30 million light year radius around us.



Different energy estimates. The isotropic energy estimate (diamonds) from (*18*) assumes that the GRB is emitting isotropically in all directions. This estimate is highly variable and ranged from more than 10^{54} ergs to less than 10^{52} ergs. However, GRBs are beamed into arrow cones. When corrected for the beaming, the energy estimates are narrowly distributed. The gamma-ray energies from (*8*) (crosses) and (*9*) (circles) as well as the kinetic energy (stars) from (*9*) vary by less than one order of magnitude.

A major part of the meeting was devoted to the performance and recent results from the High Energy Transient Explorer (HETE), a new satellite dedicated to studying GRBs (*15*). HETE aims to localize GRBs and transmit their positions in real time to Earth, where optical and radio telescopes can quickly follow up with the search for afterglows. HETE has not yet reached its goal of localizing about 20 bursts per year. However, during the summer of 2001, HETE detected more than 200 x-ray bursts from two Soft gamma repeaters (a special kind of recurring GRBs). The first HETE afterglow, GRB010921, was discovered in September 2001, as discussed by Price and Kulkarni (California Institute of Technology, Pasadena).

Kawai (RIKEN, Wako, Japan) reported another HETE achievement. HETE has confirmed BeppoSAX's discovery of "x-ray–rich" bursts (*16*). The peak spectrum for these events is between 10 and 50 keV, and the duration distribution is very similar to that of long-duration GRBs. Kippen (University of Alabama, Huntsville) reported that about 25 to 30% of all BATSE long bursts are x-ray–rich. It remains unclear whether this is a new population of bursts—so-called "x-ray flashes"—or whether these bursts are generic GRBs located at redshifts of more than 5 whose gamma-ray emission has been redshifted into the x-ray band.

The realization that GRBs involve only 10^{51} ergs takes away from them the record of the most energetic explosions in the universe. With respect to energetics, GRBs tie with supernovae. However, supernovae release $\sim10^{49}$ ergs of radioactive Ni energy over a period of a few months and dissipate the remaining 10^{51} ergs of kinetic energy over $\sim$10,000 years. In contrast, GRBs convert the bulk of their energy to gamma rays within a few seconds. GRBs thus continue to hold the record as the brightest objects in the universe.

Lamb (University of Chicago, IL) (*17*) pointed out that the afterglow of a GRB is so bright that it would give an 18th to 20th magnitude optical signal even if the burst is as far away as a redshift of 10. These high-powered torches can be seen all across the universe, shining on everything between the burst and us. High-redshift GRBs (the current record holder, GRB000131, is at $z = 4.5$) could be the best tool to study the very early universe. The caveat is, of course, that this extreme brightness lasts only for a short time. One has to act fast to catch the afterglow early on. This is what HETE is all about.

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