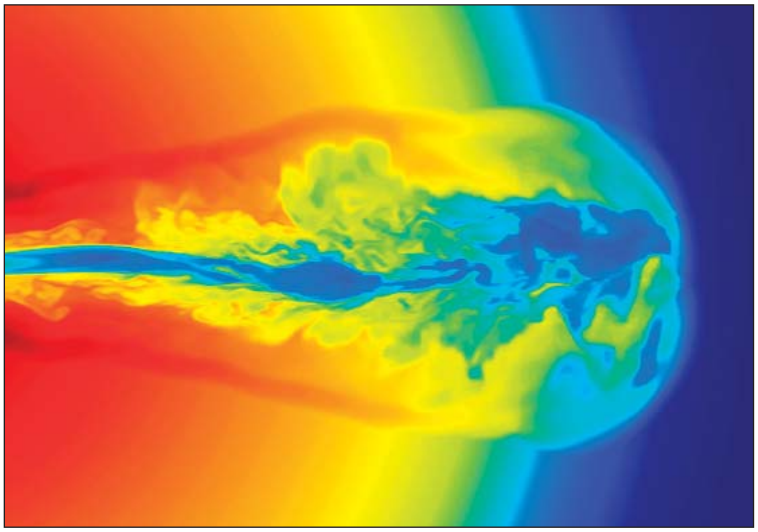
ASTRONOMY

Long Gamma-Ray Bursts

Andrew MacFadyen

About once a day, explosions from the depths of the cosmos bathe Earth in blasts of low-energy gamma rays. These gamma-ray bursts (GRBs), discovered by military satellites in the late 1960s, are the most luminous explosions in the universe. The common long-duration variety is believed to mark the death of a star many times more massive than our Sun and the birth of a black hole (or exotic neutron star). Supernova SN2003dh, discovered on 29 March 2003 beneath the fading glare of a long GRB, confirms this picture (*1, 2*).



A relativistic jet breaks out of the surface of a massive star. In this computer simulation, the surface of the star is marked by the thick blue contour. The colors represent density, with red the highest density and blue the lowest. The blue stream is a jet of low-density material traveling almost at the speed of light. This material is thought to produce the GRB after the jet and the surrounding turbulent flow escape the star.

GRBs are short nonthermal flashes of ~100-keV gamma rays. About two-thirds of all GRBs have mean durations of 35 s. These "long" GRBs have softer spectra than their short-duration cousins (*3*). They may vary on millisecond time scales, shut off for a few seconds and then turn back on, or last longer than 2000 s. Given their rapid variability (on a microsecond time scale) and large energy (~10^{52} ergs), it is likely that a compact object of stellar mass powers the GRB explosion.

In 1966, Colgate predicted that GRBs were caused by the emergence of a shock wave from a star during a supernova explosion (*4*). The details of his model turned out to be incorrect, but long GRBs are now believed to be indeed caused by the death of massive stars. However, these stars do not explode in the way that ordinary stars do. They produce asymmetric outflows traveling almost at the speed of light. Such ultrarelativistic outflows are required to produce the observed nonthermal spectrum and rapid variability.The kinetic energy of the explosive outflow from a long GRB is thought to be ~10 times that of a supernova. A key question is why much of this energy is concentrated in a small mass (10^{-5} solar masses) in a GRB instead of in several solar masses in a supernova. In both GRBs and supernovae, much more energy (10^{53} ergs) may be released as neutrinos and gravitational waves. Detailed knowledge of the partitioning of energy among photons (from gamma rays to radio wavelengths), neutrinos, and gravitational waves is critical to fully understanding long GRBs.

Observable long GRBs occur about once every 10 million years per galaxy. However, x-ray observations indicate that GRBs are beamed like a flashlight, so that we only see the one in several hundred pointed in our direction. Hence the true rate, including the GRBs pointed away from us, is one per 10,000 years per galaxy. Given that supernovae occur about once every 100 years per galaxy, roughly 1 in 100 supernovae results in a long GRB. The GRB might, for example, be caused by the formation of a black hole (collapsar) (*5, 6*), a highly magnetized neutron star (magnetar) (*7, 8*), or a supermassive spinning neutron star (*9*).

According to the collapsar model for long GRBs (*5, 9*), some rotating massive stars (with masses of more than ~25 times the solar mass) fail to explode in the way thought to produce normal neutron stars. Instead, the core of the star collapses to form a black hole. If the star spins sufficiently rapidly when it collapses, the gas in the star forms an accretion disk and swirls into the new black hole. The release of gravitational energy is thought to power a jet-like outflow along the rotational axis of the star. In addition, the disk may sustain magnetic fields that can extract rotational energy directly from the black hole.

Because there is no centrifugal barrier along the rotation axis of the star, the polar regions drain quickly into the black hole. As accretion disk energy is deposited in this low-density channel by magnetic processes, perhaps aided by neutrino annihilation, a fast collimated outflow forms. The stellar gas that remains along the poles is shock-heated, and much of it is pushed sideways. Eventually the jet breaks out of the star and accelerates to ultrarelativistic speeds (see the figure) (*10*). Much of the gas attempting to accrete is expelled from the accretion disk because it cannot cool (*6*). The outflowing gas and the shock waves from the jet explode the star.

The collapsar model predicts an exploding star with every long GRB. Because hot gas flowing off the accretion disk can form ^{56}Ni, some of these explosions should be observable as supernovae beneath the glare of the fading optical counterpart to the GRB. The star must have been small in radius when it died, so that the relativistic jet can escape the star while it is still powered by the accretion disk. Such a star should appear as a type Ib or type Ic supernova. supernova SN2003dh was a type Ic supernova (*1, 2*).

It is also possible that a highly magnetized, rapidly spinning neutron star is formed (*9*). This magnetar may act like a supercharged pulsar that accelerates a magnetically dominated flow. In both the collapsar (black hole) and magnetar (neutron star) scenarios, the jet may be composed of extremely relativistic particles that manage to escape the star and travel far away before internal collisions dissipate energy and emit the observed gamma rays. Alternatively, the outflow may be a mag-

The author is in the Department of Theoretical Astrophysics, California Institute of Technology, Pasadena, CA 91125, USA. E-mail: andrew@tapir.caltech.edu

CREDIT: WEIQUN ZHANG/UNIVERSITY OF CALIFORNIA AT SANTA CRUZ netically dominated plasma that dissipates energy through plasma instabilities.

Any model for long GRBs must explain the large amount of ^{56}Ni inferred to have been produced in the supernovae SN2003dh and SN1998bw. The type Ib and Ic supernovae observed so far shine principally because of radioactive decay of this isotope. In the collapsar model, ^{56}Ni is thought to be produced from gas that is ejected in a wind from the accretion disk (*6*). This wind is separate from the relativistic jet and flows at large angles (30°) from the pole. The jet itself does not synthesize sufficient ^{56}Ni and does not contain much mass.

The main problem in observing GRBs has been their short duration. It is difficult to point many telescopes at them fast enough to measure their luminous output at all wavelengths when the burst is brightest. GRBs can only be detected from space, because gamma rays are absorbed by the atmosphere. Their position in the sky must be determined accurately and quickly so that other satellites and Earth-based telescopes can search for their emission. The HETE-II satellite is providing valuable localizations of GRBs, including GRB030329. The SWIFT satellite, scheduled for launch in spring 2004, promises to revolutionize the field by simultaneously observing GRBs in many wavelengths (gamma ray through optical) soon after it detects them.

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Short Gamma-Ray Bursts

Stephan Rosswog

More than 35 years after their initial discovery, gamma-ray bursts (GRBs) remain one the most exciting and mysterious events in our universe. GRBs are flashes of energetic photons that outshine, for a short moment, the whole rest of the gamma-ray sky. They are classified as "short" or "long" depending on whether their duration is shorter or longer than 2 s. A wealth of information about long GRBs has been gathered, including afterglows at different wavelengths, redshifts, host galaxies, and indications that the bursts occur close to star-forming regions (*1*). In contrast, information about short GRBs is so far restricted to gamma rays alone.

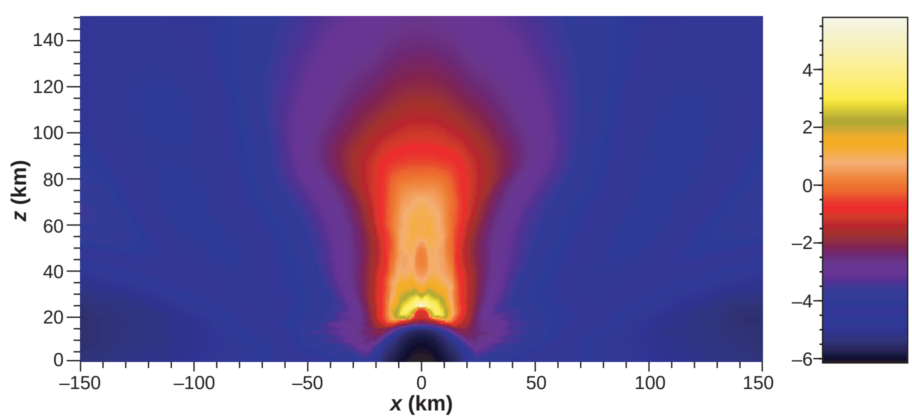
In principle, the two classes of GRBs could be caused by two different types of progenitors, or they could have the same kind of progenitor, which acts in two different ways depending on its initial conditions (such as its initial rotation). It is more likely that each class of GRB has a different kind of progenitor, because there are substantial differences apart from the duration of the burst. For example, the number of subpulses that constitute the light curve of a GRB is different for short and for long bursts (*2*). The spectra of short GRBs are harder (*3*); that is, they have a larger fraction of high-energy photons, their peak energy is larger (*4*), and they evolve differently in time (*2*). The peak energies of the spectra are influenced by the cosmological expansion—that is, for more remote bursts, one would expect lower peak energies—and by the speed with which the radiation-producing matter is ejected from the central engine. Therefore, a higher peak energy of the short bursts could mean either that their central engines produce higher outflow velocities or that they occur on average closer to Earth. Statistical arguments (*5*) also point to a relatively local origin of the short GRB class.

Compact binary mergers—the coalescence of either two neutron stars or of a neutron star and a low-mass black hole—have long been the standard model for the central engine of GRBs (*6*–*8*). Such mergers provide huge energy reservoirs of several 10^{53} ergs and would yield a natural explanation for the shortest time scales observed in GRBs. More recently, the association of long GRBs with supernovae has been substantiated (*9*). Compact binary mergers are now thought to power only short GRBs.

If the gamma-ray emission were beamed into a narrow jet, we could detect a short GRB only if it is by chance directed toward Earth, and we would miss most bursts that occur in the universe. This would mean that the "true" event rate is much higher than our observed one. The estimated compact binary merger rates are high enough to explain all short GRBs, even if the gamma-ray emission is strongly beamed. Because of the long time from the birth of the binary system to its death in the final coalescence, GRBs resulting from compact binary mergers are expected to occur relatively late in the life of the universe. Fryer *et al.* (*10*) estimate that they occur at 0.5 to 0.8 times the cosmological redshift of long GRBs, providing further support for a relatively local origin of short GRBs.

Generally, it is assumed that whatever the exact progenitor system, it will produce a "fireball" consisting of electron-positron pairs, photons, and some baryons. To explain the spectra of GRBs, the final fireball has to reach ultrarelativistic velocities. This is only possible if the fireball contains less than 10^{-5} solar masses of baryonic material; otherwise, only nonrelativistic outflow will result.

By which mechanism can the hot merger remnant deposit the required energy in a volume that is almost devoid of baryons? Candidates are the annihilation of neutrino-antineutrino pairs (*6*) and magnetic processes.



A possible mechanism for short GRBs. The annihilation of neutrino-antineutrino pairs above the remnant of a neutron star merger drives relativistic jets along the original binary rotation axis. Only the upper half-plane is shown; the *x* axis lies in the original binary orbital plane. The dark oval around the origin is the newly formed, probably unstable, supermassive neutron star formed in the coalescence.

The author is in the School of Engineering and Science, International University Bremen, Bremen, Germany. E-mail: s.rosswog@iu-bremen.de