

Berkeley, pop-up fabrication involves micromachining structures that resemble the hatches on ships. First, the structure, lying flat and replete with hinges, is patterned. Next, the layer beneath the structure and around the hinges is etched away. Pop-up structures can be engineered to spring upright spontaneously once the underlying layer disappears. But for their triode, shown in the accompanying figure, the Agere researchers chose instead to raise the three electrodes by hand under a microscope.

Other ideas

The Agere team developed the triode as a proof of concept, rather than as a production prototype. The triode shows the expected field-emitting behavior and amplifies the grid current by a significant, but modest, factor of four. However, the team couldn't run the triode in AC mode as a

microwave generator because too much current is lost each cycle to capacitance that strays into the circuit from the base of the device. With an optimized choice of materials, a triode of about the same dimensions should, the Agere team calculates, operate close to 200 MHz.

In the vacuum tube marketplace, pentodes and induction-output amplifiers, not triodes, are the biggest money earners. The Agere team has already built a pentode, but the biggest challenge remains: to build a microwave device that can operate at the 1–2 GHz frequencies used in wireless communications.

The basic concept behind the Agere triode, controlling the flight of ballistic electrons in minuscule settings, offers other possibilities. David Garner of University College London envisions creating a tiny UV light source

by sending a beam of electrons through a low density gas, such as nitrogen. Ionized by the electrons, the atoms would deexcite by emitting UV photons, just like a fluorescent light bulb. Dan Nicolaescu of Romania's National Institute for Research and Development in Microtechnologies has proposed using electrons from a cold cathode to measure magnetic fields. Deflected by the Lorentz force, field-emitted electrons could hit one of several anodes, depending on the magnitude of the field. **CHARLES DAY**

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X-Ray Spectrum Challenges Models of Gamma-Ray Bursts

Astrophysicists have been studying gamma-ray bursts (GRBs) for more than 30 years, but they still don't fully understand the cataclysmic cosmic processes that give rise to these brief showers of energetic gamma rays.¹ One technique for learning about the explosions (see also page 24 in this issue) is to study the emissions of the x-ray, optical, or radio afterglows that follow the GRBs: Afterglows can reveal details of the temperature, ionization, composition, and other features of the material illuminated by the bursts.

This past April, James Reeves and colleagues at the University of Leicester, UK, presented an unusually detailed emission spectrum² of the x-ray afterglow following the gamma-ray burst GRB011211, so named because it was observed on 11 December 2001. The paper has generated a lot of questions, according to Reeves, with scientists puzzling over how to reconcile the data with their favored theories of GRB formation.

The first GRB was detected on 2 July 1967 by US surveillance satellites built to ensure that the Soviet Union was not testing nuclear weapons in space in violation of the Nuclear Test Ban Treaty. Thirty years later, the Italian–Dutch satellite BeppoSAX recorded a GRB with a redshift of about 0.8, confirming that the bursts were of cosmological origin, not confined to our galaxy (see *PHYSICS TODAY*, July 1997, page 17, and the article by Neil Gehrels and

▶ The debate is heating up: Does the progenitor of these powerful explosions collapse in one step or two?

Jacques Paul in *PHYSICS TODAY*, February 1998, page 26).

A GRB releases a staggering amount of energy, perhaps as much as 10^{44} – 10^{45} joules. It is generally agreed that GRB energy is released in a pair of jets. Because the bursts are jetted, we see only a fraction of the GRBs emitted in the universe on any given day. To estimate how often GRBs occur, one needs to know the solid angle subtended by the jets. Typical theoretical models give a value of 0.01–0.1 steradians. Combining this value with observed occurrences of GRBs, one concludes that there are, roughly speaking, hundreds of bursts every day.

Modeling bursts

The duration of the prompt gamma-ray luminous phase of a GRB can range from 0.001 to 1000 seconds. Most of the bursts are “long,” with durations of more than 2 seconds. The long bursts are the only ones for which afterglows have been observed. Short bursts display qualitatively different energy spectra with relatively more high-energy gamma rays. The spectral differences between the short and long bursts, and the different timescales associated with them, hint that they may originate from different physical mechanisms.

Models for gamma-ray bursts fall

into two main sets. One set posits that GRBs are generated by the coalescence of two compact objects, such as two neutron stars or a neutron star and a black hole. In the second set of models, the progenitor whose catastrophic collapse leads to a GRB is a single massive object.

For about five years, a consensus has been growing that neutron-star-binary mergers or similar processes are not the cause of long-duration GRBs. As early as 1997, the Hubble Space Telescope showed long-duration GRBs occurring near the optical disks of galaxies. Such observations argue against merger scenarios if, as many believe, the gradual decay of the binary orbits occurs over billions of years. Over that long span, the binary system should drift far from the galactic plane. Because of the drift, coalescing neutron-star binaries would emit GRBs in a region of space with interstellar matter too diffuse to allow for x-ray afterglow emission. Thus, other strikes against the coalescence picture are the x-ray spectrum Reeves and colleagues observed and iron x-ray fluorescence earlier researchers saw. Optical afterglows have generally been observed in relatively young, star-forming regions of galaxies, a further argument against coalescence models.

The timescale associated with the catastrophic final phase of binary merging is much shorter than the several-second timescale of long-duration GRBs and single progenitor models.

The different timescales suggest that binary merging may be the cause of short-duration GRBs while single massive objects yield the longer bursts. Positions of observed short-duration GRBs have not been fixed, nor have afterglows been observed, so binary mergers are viable candidates for those bursts.

Some observational evidence directly links long-duration GRBs to supernovae. The gamma-ray burst GRB980425 exploded at just about the same time and place as the supernova SN 1998bw. Many in the astronomical community think the two explosions were related. However, each of the two events was unusual in its own way: The supernova was extremely bright and was a strong radio source; the GRB was weak. So the community continues to ponder just what happened on 25 April 1998. Teams led by Shri Kulkarni (Caltech) and by Kris Stanek (Harvard-Smithsonian Center for Astrophysics) and Peter Garnavich (University of Notre Dame) have obtained characteristic light curves that provide evidence for a supernova underlying GRB011213.³

In single-progenitor models, the catastrophic death of a massive object yields an initial explosion that ejects highly relativistic jets. The initial burst of gamma rays is probably the result of internal shocks that arise from colliding ejecta. Eventually the ejected particles encounter external matter and generate the shock waves ultimately manifested as afterglows. Understanding just how the shocks make the GRB and afterglows does not tell much about how the initial jets were created, says Stan Woosley (University of California, Santa Cruz), who in 1993, proposed that a “collapsar” is the progenitor of GRBs. In the collapsar model, a star of 20–30 solar masses loses some of its outer gases in the course of its evolution, then the remaining central core rapidly collapses to form a black hole. The afterglow arises once the material ejected during the core collapse encounters the previously ejected stellar material.

Many who theorize about GRBs favor a one-step collapse process along the lines of the collapsar model. Some, though, endorse scenarios that involve two distinct collapses, as was first suggested in 1999 by Mario Vietri (University of Rome III) and Luigi Stella

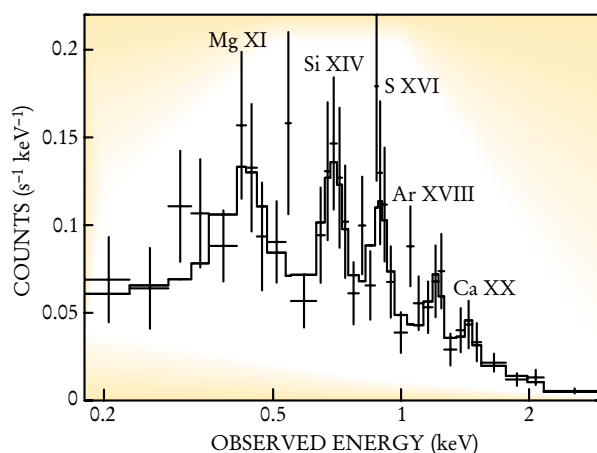


FIGURE 1. X-RAY AFTERGLOW spectrum measured by James Reeves and colleagues (University of Leicester) integrated over the first 5000 seconds of their observation. The Roman numerals indicate ionization states of the elements shown. The known energies of the five displayed peaks need to be reduced by a redshift of 1.88 to agree with the data. Comparing the recessional velocity deduced from this redshift with that implied by the 2.140 redshift of the gamma-ray burst that preceded the afterglow, Reeves and company conclude that, relative to the burst, the x-ray emitting material is moving toward us at about 1/10 light speed. Relative element abundances, deduced from peak intensities, are consistent with relative solar abundances. (Adapted from ref. 2.)

(Astronomical Observatory of Rome).⁴ In their two-step model, a massive, rotating star ejects matter as it collapses to form a rotating neutron star. The rotation of the neutron star protects it from immediately condensing to a black hole, but in time, the rotational

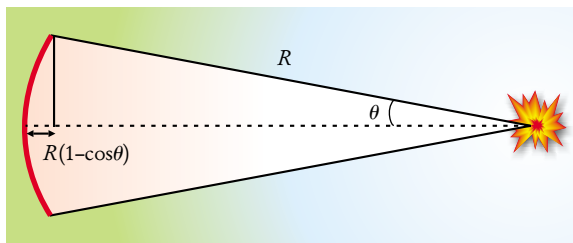


FIGURE 2. AFTERGLOWS ARE EMITTED over a section of a sphere (red) of half-opening angle θ , located a distance R from the gamma-ray burst. Thus, different bits of x-ray-emitting material are located at various distances from us. The diagram illustrates the geometric part of the argument whose conclusion is that material ultimately shocked into emitting x rays was ejected from a massive progenitor some 10–100 hours before the gamma-ray burst.

energy dissipates. After a period of weeks or more, a second collapse forms a black hole. The second collapse is the one accompanied by a GRB.

Reeves and company’s analysis of their spectral data has received attention in large part because of the challenge it poses to both one-step and two-step modelers. Charles Dermer of the Naval Research Laboratory notes that the Reeves group’s paper “necessitates a whole series of new calculations.” An understanding of GRB formation, Dermer continues,

may shed light on a number of important astronomical questions concerning, for example, black-hole formation, the death of stars, the star-formation history of the universe, and the equation of state of neutron stars.

An argument for two steps

A little more than 11 hours after BeppoSAX observed GRB011211, the European Space Agency’s XMM-Newton orbiting x-ray telescope began observing the burst’s x-ray afterglow. It was the data taken by XMM-Newton that was analyzed by the Reeves group. They found that significant x-ray line emission occurred during the first 10 000 seconds of the 27 000-second observation, with line intensity diminishing over time.

Figure 1 shows the emission spectrum integrated over the first 5000 s of the run. Reeves and colleagues concluded that the data suggest emission from an optically thin plasma with a temperature of 5×10^7 K and a luminosity of 7×10^{38} watts. By comparing the redshift z of the elemental line energies in the x-ray spectrum with the redshift of the burst obtained from the optical afterglow, they determined that the material emitting x rays was flowing outward from the source of the GRB at 8.6% of light speed. Combining this speed with the luminosity and temperature of the x-ray emitting plasma they studied, the group estimated the emitting material’s mass and kinetic energy. The derived mass is about 1/10 that of the sun, and the kinetic energy about 10^{44} joules, values consistent with single progenitor models with jetted GRBs.

Reeves and colleagues assume that the 10 000 s duration of the emission lines is fully attributable to the difference in light transit time between the farthest and closest bits of an emitting shell segment. Figure 2

shows that if a segment has half-opening angle θ in the rest frame of the GRB, the distance separating the closest and farthest parts of a shell of radius R is $R(1 - \cos\theta)$. Time dilation reduces the emission duration by a factor of $1 + z$ in the frame of the GRB. So equating $10\,000\text{ s}/(1 + z)$ with $R(1 - \cos\theta)/c$ and assuming a half-opening angle of 20° , typical of many jetting models, they calculate a radius of about 10^{13} m .

The matter forming the shell that ultimately emits x rays travels at about $1/10$ light speed and covers a distance of roughly 10^{13} m before being shocked into emitting the x-ray afterglow. Thus, conclude Reeves and colleagues, there is evidence for a two-step process with substantial delay between an initial event in which stellar material is thrown out and a second that leads to the GRB. The delay one deduces depends on the half-opening angle of the jet: Typical values lead to a time delay of about four days, significantly less than that indicated in the original Vietri and Stella model. Assuming isotropic emission yields a lower bound to the time delay of about 10 hours.

Rebuttal for one step

A basic incompatibility may exist between conventional two-step models and the data presented by the Reeves group. "Unless the time delay between explosions is several months," explains Woosley, "you can't get the gamma rays out." The material in the vicinity of the burst is too dense to allow the gamma rays to escape in the 11 hours or less that separated the afterglow of GRB011211 from the burst itself. That is, the few-day separation between explosions suggested by the Reeves group seems unreasonably short. On the other hand, the timescale for a neutron star to lose its rotational support against collapse, due to interactions with the local magnetic field or gravitational instabilities, is on the order of seconds at most. A few days is orders of magnitude greater than this natural time scale. It is thus difficult, say proponents of one-step models, to imagine a model that, without contrivance, allows for both gamma-ray escape and a delay of a few days between explosions.

Modeling difficulties notwithstanding, don't the data presented by Reeves and company suggest a two-step process? Martin Rees of King's College, Cambridge, UK, is not convinced. "The key question," he says, "is whether the distance [separating the x-ray emitting material and the

GRB] is what you infer assuming light-travel time delay." There may be a way of continuously energizing a supernova's ejecta so as to create a thermal x-ray source of long duration. After all, the afterglow may be initiated by a shock to an external medium, but within the shell where this shock occurs is a region full of plasma and high magnetic fields. Gas in this extreme environment, suggests Rees, could interact with debris from the GRB and be heated so that it radiates. The Reeves team did consider models in which x-ray reflection was the source of the spectral lines they saw, but such reflection models fit their data poorly; a thermal model worked better. Admits Woosley, "I don't have a model that I'm enthusiastic about."

None of the spectral lines observed by Reeves and company is more than about three standard deviations above background. What makes the sale for the significance of the spectrum is the fact that its several lines are all consistent with a single redshift and temperature. Even so, the statistical significance of the spectrum taken as a whole has been questioned.⁵

Binary collisions redux

For a number of years, astrophysicists have accumulated a body of evidence arguing against binaries as the engines powering long-duration GRBs. But Andrew King and colleagues in the theoretical astrophysics group at the University of Leicester have pro-

posed a variation of collapsar models that has, literally at its core, a binary collision.⁶ The group's model melds the GRB profile of single-precursor, single-step models with the characteristic delay of two-step models. Binaries may be back.

The upcoming launch of NASA's Swift satellite in September 2003 may lead to rapid change in the GRB field. Swift will be able to point its telescopes at a GRB within minutes of the burst's detection, allowing for the first observations of short-duration burst afterglows and views of unprecedentedly bright afterglows for long-duration GRBs.

STEVEN K. BLAU

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