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Perspective

Afterglows from the largest explosions in the universe

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The distinction of "largest explosions in the universe" has been bestowed on cosmic gamma-ray bursts. Their afterglows are brighter than supernovae and therefore are called hypernovae. Photometry and spectroscopy of these afterglows have provided major breakthroughs in our understanding of this mysterious phenomenon.

Supernovae are commonly believed to be the most energetic explosions in the universe. Now this distinction has been bestowed on another phenomenon: hypernovae, fading afterglows of gamma-ray bursts (GRBs). Discovered more than three decades ago, the nature of GRBs remains mysterious. Astronomers have obtained rigorous distance estimates only in recent years, placing GRBs firmly into the realm of cosmology. Redshift measurements suggest very large distances, making GRBs the most powerful catastrophic energy releases known to mankind. Gamma-ray detectors aboard satellites near Earth and in interplanetary space witness the unique high-energy firework display once per day, but the cause of these explosions is still unknown. Recent x-ray, optical, and radio observations have led to important breakthroughs in our understanding of GRBs, although much remains to be learned from and about these tremendous explosions.

About once every second a massive star somewhere in the universe completes its life with the vast firework display of a core-collapse supernova. The formation of a new black hole or compact neutron star is heralded by an energy release of $\approx 10^{53}$ erg. More than 99% of this energy is carried away by neutrinos within a few seconds. Roughly 1% (10^{51} erg = 1 foe) of the energy is converted into the kinetic energy of the ejected stellar envelope, and even less (0.01 foe) is emitted as optical light on a time scale of months. But energy is enough to power spectacular optical displays. So, what could be more impressive than a supernova?

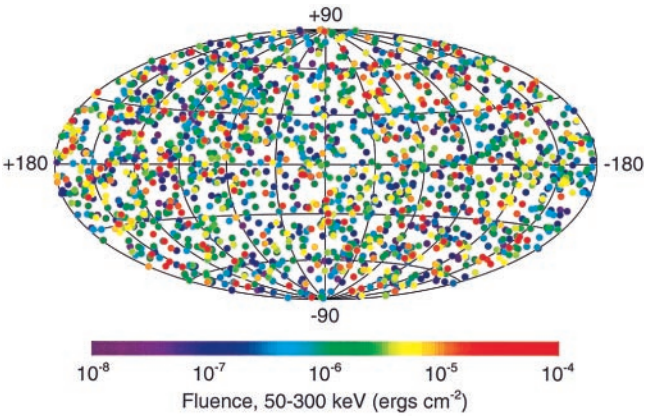

FIG. 1. Distribution on the sky of 1,825 GRBs observed by BATSE. The map shows burst locations (without indicating position uncertainties) in galactic coordinates. There are no preferred directions, either of galactic or extragalactic significance. Color code indicates total burst energy. Bursts are distributed isotropically, independent of their brightness, duration, spectrum, or any other characteristic.

Gamma-ray bursts were discovered in the late sixties by the U.S. Vela satellites (1). They are short flashes of almost pure high-energy emission (x-rays and gamma-rays) that occur randomly on the sky (Fig. 1), and which, apparently, do not emit more than once. Typical durations are of the order of seconds, but can range from a few milliseconds to well over 1,000 sec. They are extremely bright, outshining all other objects on the gamma-ray sky, but their spectra are featureless and reveal little about the underlying physical processes of the GRBs. Integrating their spectra over energy and time yields large fluences (received energy per unit area), but does not determine the total burst energy until the distance is also known.

Because of the intrinsically poor angular resolution of gamma-ray detectors, burst locations are usually too inaccurate for unambiguous identification of quiescent counterparts. For example, positions from the Burst And Transient Source Experiment (BATSE), launched in 1991 aboard the Compton Observatory, have typical uncertainties of several degrees. A network of detectors in interplanetary space and around Earth (IPN) triangulates GRBs with arcminute accuracy, but this process takes days, hours at best. Inspection of these coarse locations with ground-based telescopes is unlikely to result in an unambiguous counterpart identification, simply because there are too many candidate sources in such large areas on the sky.

In the eighties a new method for pinpointing GRBs (2) considered the possibility of optical emission occurring simultaneously with the gamma-rays. Searches were conducted with archival photographic plate collections for such optical transients (OTs) in the vicinity of GRB positions. This approach was based on the assumption that GRBs emit repeatedly. Although a few interesting, bright candidate OTs were indeed identified (2), a variety of problems with photographic data prevented an unambiguous counterpart identification. It became clear that simultaneous optical imaging was required to catch the optical display of a GRB, if it existed. To this end, a protocol (3) has been developed to determine coarse burst locations within seconds of their triggering the BATSE detectors. This information is then routed via the GRB Coordinate Network (3) through the internet to specifically designed wide-field-of-view telescopes at the Lawrence Livermore (LOTIS; ref. 4; see also: http://hubcap.clemson.edu/~ggwilli/LOTIS/; Fig. 2) and Los Alamos National Laboratories (ROTSE; refs. 5 and 6; http://www.umich.edu/~rotse/), and elsewhere in the world. Despite sustained experimental efforts optical afterglows were not detected with these telescopes until very recently (7).

GRB identification from optical afterglows finally succeeded in 1997, when the x-ray analog of OTs (a fading x-ray flux from GRB970228) (http://www.tesre.bo.cnr.it/Sax/) was detected by the Italian-Dutch x-ray satellite Beppo-SAX (8). Localization is significantly easier in the x-ray range of the spectrum; Beppo-SAX was able to provide arcminute positions within hours of the GRB. This allowed ground-based telescopes to search for OTs, and one was indeed found (9). Further studies with the Hubble Space Telescope, the Keck telescopes on Hawaii, and others identified a fuzzy emission region surrounding the OT as the host of this burst, but it was not possible to determine whether or not it was a galaxy.

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FIG. 2. Four wide-field-of-view (17.6 × 17.6 degrees) cameras of the Livermore Optical Transient Imaging System (LOTIS) (4) survey the sky for OTs from GRBs at a site near Livermore, CA. A similar system, ROTSE (5, 6), operates at a site near Los Alamos, NM.

Although their statistical properties long supported the notion that bursts occurred at cosmological distances, this distance scale was finally established by a burst on May 8, 1997. A faint, extended object was identified as the host, which showed clear evidence for absorption lines, revealing it had a lower redshift limit of $z = 0.835$ (10). On December 14, 1997, another burst (GRB971214) showed absorption lines at $z = 3.42$ (11), and another event (GRB980703) had associated absorption features at $z = 0.966$ (12), indicating that GRBs are, along with quasars, the most distant objects in the universe. Of course, such large distances imply large energies. In fact, the assumption of isotropic emission implies burst energies in excess of 100 foe (comparable to supernova energies, but predominantly released in the gamma band), and the optical afterglows were also much brighter than those of supernovae. Hence the name hypernova was proposed (13).

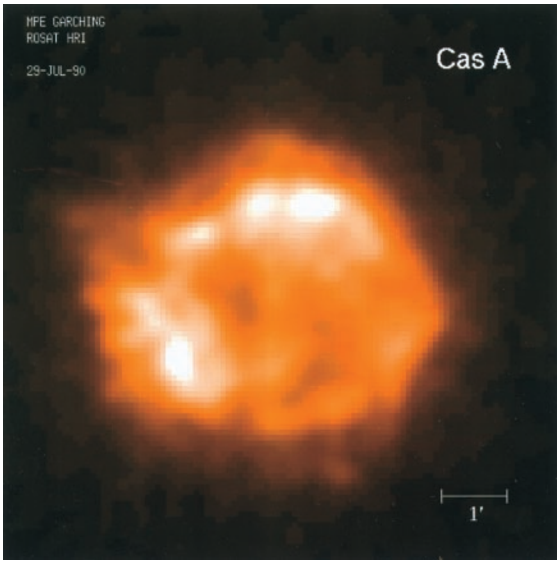

FIG. 4. The x-ray image (obtained with the German x-ray satellite ROSAT) of the Galactic SNR Cas A (25), the result of a supernova explosion that occurred ≈300 years ago at a distance of 3 kpc from Earth. Shocks propagating forward into the interstellar medium and back into the supernova ejecta cause the observed soft x-ray emission. GRBs are relativistic analogs of supernova remnants.

Collapsars and Opaque Fireballs

On April 25, 1998 a burst coincided in time and location with the unusually bright type Ic supernova SN1998bw (14) located in the outer regions of a nearby spiral galaxy at $z = 0.008$, suggesting a possible connection between stellar evolution and the burst phenomenon. Two teams (15, 16) independently suggested that an extremely energetic explosion produced by the collapse of a massive star was responsible for this unusual supernova/GRB pair. The large energy required to understand the supernova is in contrast to generic expectations for the explosion of such massive

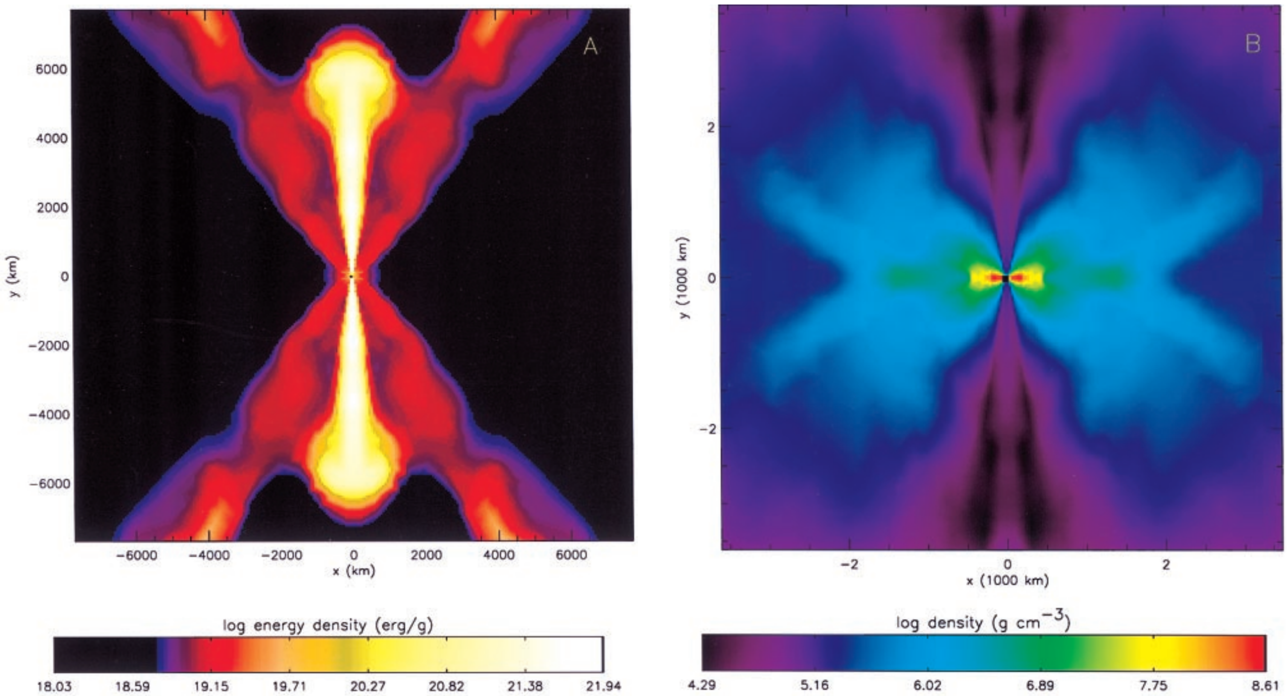

FIG. 3. Two-dimensional hydrodynamic simulations (18) show the formation of a low-density region above the poles of a rotating black hole formed in the collapsar model. (*A*) The energy density in the jets and surrounding area ≈1 sec after its initiation. The jet has moved to a distance of ≈10,000 km, and its opening angle is of order 10 degrees. (*B*) The density contours ≈16 sec after the onset of collapse. The yellow/red region shows the dense accretion disk around the black hole.

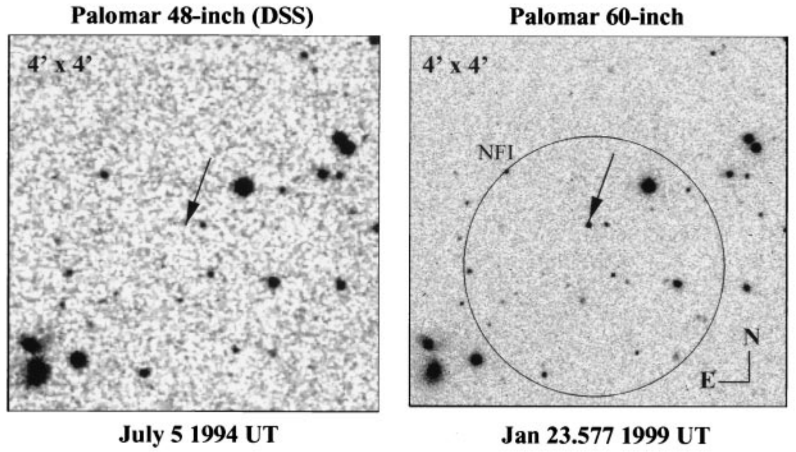

FIG. 5. Palomar discovery image of the OT from GRB990123 (26) (*Right*). A faint host candidate was detected on the Digital Sky Survey (DSS) (*Left*). The OT had a magnitude $R \approx 18.2$ approximately 2 hr after the GRB. The host galaxy candidate has $R \approx 21.3$, relatively bright in comparison to other GRB host galaxies. Observations with MDM and Keck, however, showed that this "galaxy" is only statistical noise.

stars and may suggest a new class of stellar explosions: collapsars (17). In this scenario the formation of a black hole in the stellar core is accompanied by the formation of an accretion disk and a bipolar jet. Numerical simulations (18) show the formation of a low-density funnel along the rotational axis of the system, along which the subsequently formed jet propagates as a collimated flow (Fig. 3). After the shock breaks through the collapsing envelope of the star the flow in the jet becomes highly relativistic, with Lorentz factors exceeding 10.

The collapsar is only one of several ways a rapidly spinning black hole with a surrounding accretion disk can be formed. Other models leading to black-hole accretion disk systems involve common envelope phases in close binary systems, or the direct merger of a black hole–neutron star (BH/NS) or neutron star–neutron star (NS/NS = DNS, double neutron star) system because of energy loss by gravitational radiation. Although the accretion disks in collapsars may be quite massive (several solar masses) (19), those formed in a DNS merger are expected to be much less massive (20). These differences may be reflected in the observed bimodal GRB duration distribution.

The amount of energy that can be extracted from these systems is a fraction of Mc^2 that depends on the accretion geometry and the rotation state of the black hole. For a nonrotating black hole surrounded by a one-solar-mass accretion disk, the energy reservoir is 6% of $M_d c^2$ (where M_d = disk mass), which amounts to 100 foe. For a maximally rotating black hole the mass-to-energy conversion efficiency increases to 42%, thus there is plenty of energy to power GRBs at cosmological distances. An even larger amount of energy may be available to a GRB if magnetic coupling through the Blandford–Znajek mechanism (21) taps directly into the rotational energy of the black hole. With the additional (and likely) possibility of beaming, there might be sufficient energy to account for even the brightest bursts at cosmological distances.

Dumping a large amount of energy into a small spatial volume in a short time inevitably leads to an opaque "fireball" (22), because the large number density of photons implies a very large cross section for photon–photon pair creation of electron–positron pairs. The result is an optically thick lepton/photon region that rapidly accelerates to relativistic speeds. Baryons trapped in this fireball quench gamma-ray emission, and the original energy is converted to kinetic energy of a rapidly expanding plasma cloud. Eventually this energy leads to the GRB and its afterglow through hydrodynamic shocks in the expanding medium or through the collision between the fireball and any pre-existing medium surrounding the burst source. The physical situation is similar to that encountered in galactic supernova remnants (SNRs) (Fig. 4), except that GRB fireballs provide a laboratory for extreme relativistic physics. Simple theoretical models of afterglow emission from these fireballs provide good fits to the observations (23, 24), and it is possible to derive some key parameters for the central engines as well as some properties of the burst environments.

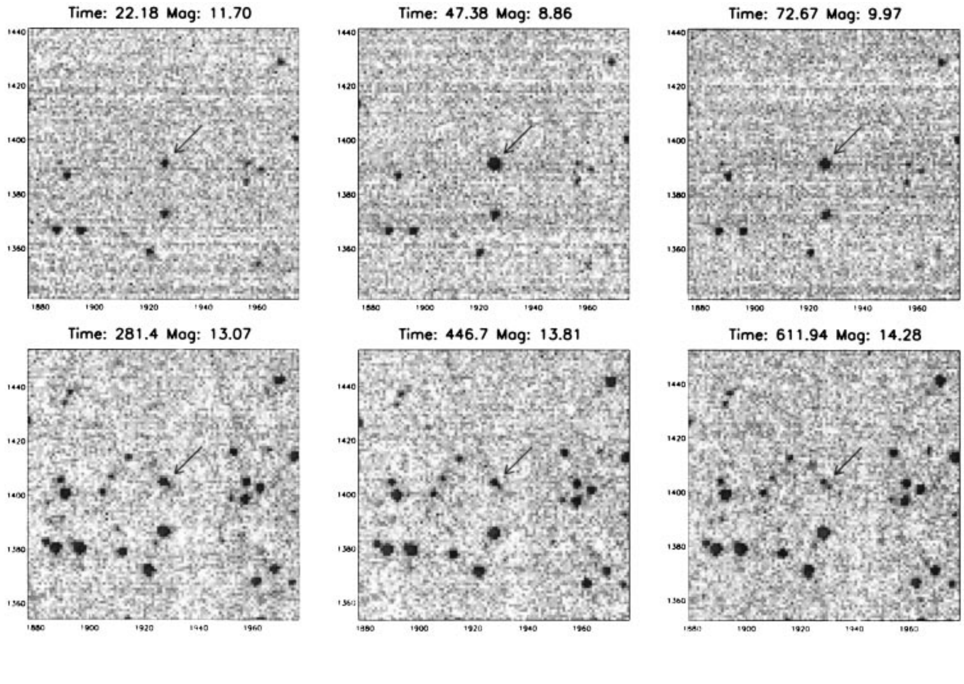

FIG. 6. The ROTSE-I wide-field-of-view cameras operated by Los Alamos National Laboratory caught an incredibly bright ($R \approx 9$) OT simultaneously with GRB990123 (6). First exposure began 22 sec after the burst trigger. The light curve is complex, showing an increase by 3 magnitudes between the first and second image (5-sec exposures each), reaching a peak brightness of $R \approx 9$. Without lensing and beaming corrections the optical flux corresponds to 2×10^{16} solar luminosities. Total optical output thus would be $\approx$1 foe, compared with roughly 1,000 foe for the GRB itself.

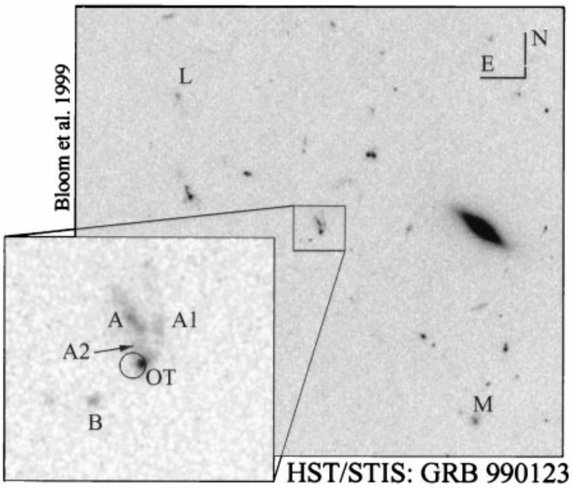

FIG. 7. The Hubble Space Telescope image of the optical afterglow of GRB990123, obtained 16 days after the burst. The bright spot is the fading OT, located outside of a faint ($V \approx 25$) galaxy. This host galaxy is probably a normal, star-forming galaxy at a redshift $z = 1.6$ (29).

Studies of the GRB host galaxies suggest that they are normal star-forming galaxies, and not those with active nuclei. The estimated star formation rates in these hosts, together with other evidence from x-ray spectra and photometry of the afterglows suggests that GRBs may be directly associated with star-forming regions. If that turns out to be correct, astronomy would have a powerful new tool for the study of structure formation in the universe, a tool that could reach further back in time than quasars do.

A Lensed GRB?

On Jan. 23, 1999 a very bright burst (GRB990123) was observed by the instruments aboard the Compton Observatory and Beppo-SAX, showing gamma-ray activity with a duration of more than 100 sec. The quality of the x-ray position from SAX enabled the discovery (26) of a rapidly fading OT on images taken at the Palomar 60-in telescope (Fig. 5). These observations also showed a potential host galaxy (with a magnitude in the R-band of $\approx$21) separated from the OT ($R \approx 18$, at that time) by $\approx$2 arcsec. ROTSE caught the burst a mere 22 sec after the trigger (6). The holy grail of OT searches was found (Fig. 6): a simultaneous OT/GRB.

The peak magnitude of this OT was approximately $V \approx 9$ (visible with binoculars if you knew where to look and were fast enough to point in that direction). This GRB ranks in the top 1% of more than 2,000 BATSE bursts judged by either peak flux or fluence. Initially, the relatively bright ($R \approx 21$) host galaxy, as seen at Palomar, suggested that this GRB must have been very close. But spectra taken with the Keck II 10-m telescope (27) showed absorption lines at $z = 1.61$: the burst must be at or beyond that distance.

Given the distance of the GRB, how could it be so bright? It was suggested (28) that the $R \approx 21$ galaxy is in fact a foreground object, causing gravitational lens amplification of the GRB and its optical afterglow. This idea is appealing because the inferred GRB energy is $\approx 2 \times 10^{54}$ erg (or 2,000 foe), much larger than most current models can account for. Amplification by lensing (a factor 10^4, or 10 magnitudes), combined with significant beaming, would significantly reduce the energy requirements. The lensing hypothesis suffered a major setback when observations with the MDM 2.4-m telescope and the Keck-I telescope did not find galaxies (and specifically the $R \approx 21$ galaxy) within a few arcsec of the OT; the earlier detection turned out to be a statistical fluke.

However, the real, $V \approx 25$, host galaxy of GRB990123 eventually was found in images taken by the Keck-I 10-m telescope and the Hubble Space Telescope (29) (Fig. 7). The OT is located about 10,000–20,000 lightyears (assuming a redshift of $z = 1.6$) away from the host, which refutes the possibility that GRBs are related to galactic nuclear activity.

Conclusions

Despite these breakthroughs in GRB observations, many questions remain about the nature of the underlying processes and the evolutionary sequences leading up to the creation of the central engine driving these outbursts. The idea of a relativistic analog of a supernova remnant goes a long way to explain the current observations, but we still have to improve our knowledge of the hidden central engine. The ultimate goal of understanding this engine may be accomplished through simultaneous optical observations, which is the goal of dedicated experiments such as LOTIS (4), ROTSE (5, 6), and others under development throughout the world.

The study of GRBs is currently in a super-charged phase, with progress occurring rapidly. By the end of 1999 NASA plans to launch the HETE satellite (http://space.mit.edu/HETE/), which will produce a significant number of rapid x-ray localizations, much like those currently produced by SAX. NASA just selected five new missions for further study in the medium-class Explorer (MIDEX) program, including the Swift GRB explorer. If selected for flight, Swift (a Gamma/X/Optical-Observatory) (http://swift.gsfc.nasa.gov/) would continue this line of study with greater sensitivity and more frequent burst detections.

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