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Cosmic Gamma-Ray Bursts: The Big Picture

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Abstract The observational properties (time histories, energy spectra, and spatial distribution) of cosmic gamma-ray bursts and their multi-wavelength afterglows are reviewed. Although one class of burst (the long bursts) can be attributed to the collapse of massive stars, the origin of another class (the short bursts) is still mysterious. This is only one of several questions which remains to be answered. However, despite our incomplete understanding, it is clear that this phenomenon has finally entered the mainstream of astrophysical research, and has numerous applications to other studies.

Key words: gamma-rays: bursts

1 INTRODUCTION

Cosmic gamma-ray bursts are the brightest, if not the most energetic, explosions in the universe. They are observed at cosmological distances, out to redshifts of 4.5. This places them at somewhat smaller distances than those of the most distant quasars, but there is no reason why they could not be observed to much greater distances, if indeed they are generated there. Their practical uses are wide-ranging, including such diverse topics as tracing star formation rates in distant galaxies and probing the reionization epoch, as well as the study of quantum gravity and relativistic shocks, to name just a few. For the first 25 years after the announcement of their discovery (Klebesadel, Strong, & Olsen 1973) it was not at all obvious that gamma-ray bursts were anything but a relatively weak Galactic phenomenon, possibly involving single neutron stars. A paradigm shift came in 1997, with the discovery of the first X-ray (Costa et al. 1997), optical (van Paradijs et al. 1997), and radio (Frail et al. 1997) counterparts to bursts. In the 6 years that have followed, gamma-ray bursts have evolved from a curiosity into a subject of mainstream astrophysical research. The story of how this happened has been told in two recent books (Katz 2002; Schilling 2002), so it will not be summarized here. This review will concentrate on the observational properties of bursts, and what appear today to be the most promising theoretical explanations of these properties.

2 OBSERVATIONAL PROPERTIES OF THE PROMPT EMISSION

A gamma-ray burst (GRB) may last between 10 ms and 1000 s or so, with a typical value being around 10 s (Fig.1). During that time, it may be the brightest object in the gamma-ray sky.

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Most of its electromagnetic energy comes out in gamma-rays with energies greater than around 25 keV. A striking feature of the GRB duration distribution is that it is bimodal (Fig.2), with one group having durations of a few hundred milliseconds, and the other, about 20 seconds. Virtually everything that we know about bursts and their counterparts comes from observations of the "long" class. No counterpart to a short burst has yet been observed.

The spatial distribution of burst sources is completely isotropic, and the number-intensity distribution is consistent with a non-Euclidean population (Paciesas et al. 1999), as would be expected from cosmological sources. No convincing evidence has been found to date which would imply that a single source has ever emitted more than one burst (Hakkila et al. 1998).

GRB energy spectra are diverse, but at their hardest they are perhaps *the* hardest of all known astrophysical objects. They have been measured from ~ 2 keV to 18 GeV. The latter is only an instrumental limit, and there is no indication that spectra are falling off at the highest energies. Indeed, there is tantalizing evidence that spectra extend to TeV energies (Atkins et al. 2000). At the soft end of the GRB spectra, there are events which display almost no emission above several 10's of keV. These are referred to as "X-ray flashes" or "X-ray rich GRB's" (Heise et al. 2000). They are identical to GRBs in all other properties. Fig.3 compares the general shape of GRB energy spectra with those of other well-known astrophysical X- and gamma-ray emitters.

Very recently, polarization has been detected in the gamma-radiation from a burst (Coburn & Boggs, 2003). The burst was GRB021206 (whose time history appears in Fig.1), and the level of polarization was 80%, which suggests the presence of an ordered magnetic field.

3 GAMMA-RAY BURST AFTERGLOWS

As the gamma-ray emission ends, afterglows begin at various times, depending on their wavelengths, and fade at different rates. In some very intense bursts, a gamma-ray afterglow is clearly observed, which remains detectable for $\sim$1000 s (e.g. Burenin et al. 1999). There is evidence that this is in fact a common feature of all bursts (Connaughton 2002), although it is harder to detect in weak events. The emission fades as a power law with various indices, but a rough average might be ~ -1. Soft X-ray ($1-10$ keV) afterglows commence as the gamma-ray burst progresses or ends (Frontera et al. 2000), and fade as a power law with index ~ -1.5. They remain detectable for several weeks with sensitive instruments such as *Chandra* and XMM-*Newton*. Optical afterglows are observed for roughly half of all the long duration bursts. In one case, intense (9th magnitude) optical emission has been observed which was simultaneous with the burst (Akerlof et al. 1999). However, although many searches have been carried out, this remains the only example of simultaneous optical emission (e.g. Williams et al. 1999). More commonly, weaker ($\sim$ 17th magnitude) optical emission is discovered in the hours following the burst, and it fades as a power law (index ~ -1.3), or a broken power law, with time, but often with significant fluctuations. An example is shown in Fig.4. It is not unusual for the optical afterglow to initially outshine the host galaxy in which it originates. It is possible to track the afterglow for weeks or even months with the most sensitive telescopes. Finally, radio afterglows are similarly observed for about half of the long bursts, and they become detectable with telescopes such as the VLA several days after the burst, at levels of several tenths of a milliJansky. In some cases, they can be observed for a year or more (e.g. Frail et al. 2000).

3.1 Gamma-ray burst host galaxies

In almost all cases where an optical or radio counterpart to a GRB is found, a host galaxy is identified, and in most of those cases, a redshift can be measured. A typical magnitude is $m_R = 25$. The closest burst comes from a redshift of 0.16 (with one possible exception,

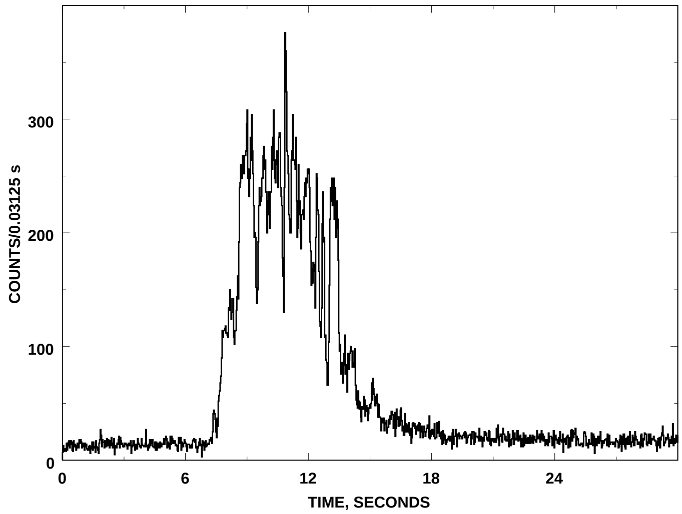

Fig. 1 The gamma-ray burst of December 6 2002. The data are from the Ulysses GRB experiment, in the 25 – 150 keV energy range.

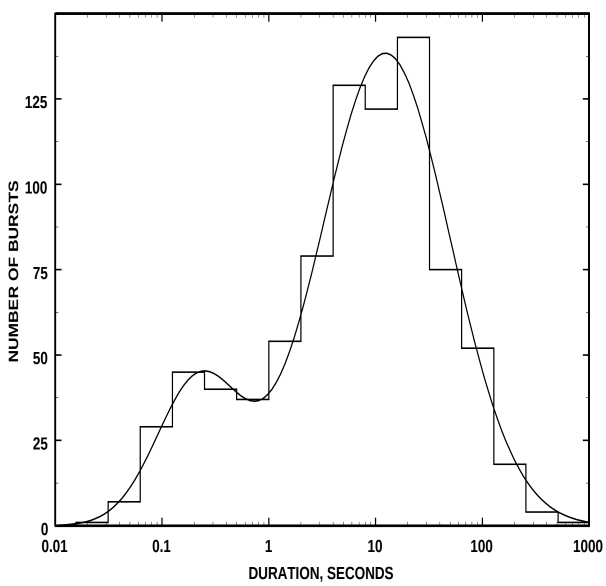

Fig. 2 The duration distribution for over 800 GRBs, from Hurley (1992) and a fit using the sum of two lognormal functions.

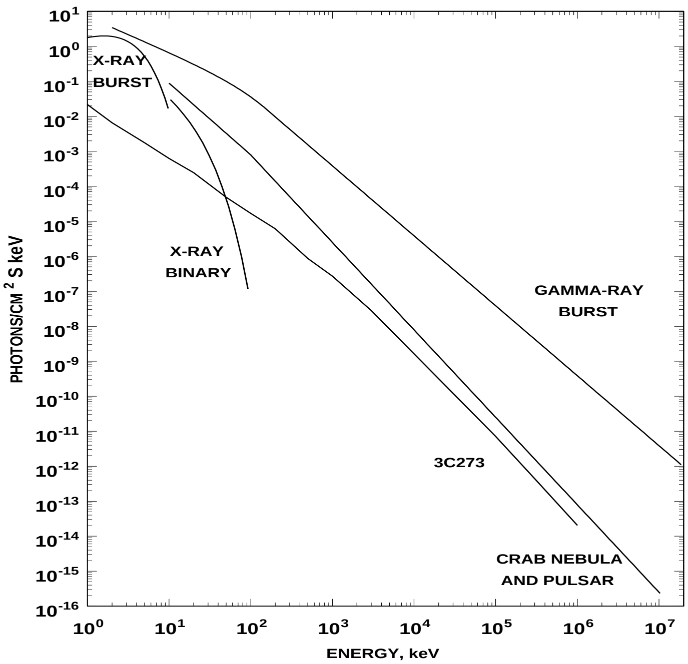

Fig. 3 GRB energy spectra compared to the spectra of X-ray burst sources (blackbody), X-ray binaries (optically thin thermal bremsstrahlung), 3C 273 (from Turler et al. 1999), and the Crab nebula and pulsar (broken power law). Although the latter spectrum has been observed at energies well above those of GRBs, it tends to be softer. The GRB spectrum shown here uses the function of Band et al. (1993). Short GRBs tend to have harder spectra than long ones.

discussed below), and the farthest, 4.5. The distribution of GRB redshifts is shown in Fig.5. The host galaxies are normal, which is to say that they are not active galaxies, and that it would be difficult, perhaps impossible, to identify them in a random sample of galaxies at similar redshifts. The gamma-ray burst sources are found within the host galaxies, sometimes within regions which can be identified as undergoing star formation. Reviews of host galaxy properties have appeared in Hurley, Sari, & Djorgovski (2002), and Bloom (2002).

4 THE SHORT EXPLANATION

The following picture is based on observations of the long GRB's, their afterglows, and their host galaxies. A GRB occurs in the star-forming region of a galaxy at a redshift of about 1. In currently popular models, it is caused by the collapse of a massive star (≈ 30 solar masses) which has exhausted its nuclear fuel supply. The star collapses to a black hole threaded by a strong magnetic field, and energy is extracted through the Blandford-Znajek (1977) mechanism. This energy goes into accelerating shells of matter, once part of the massive star, to ultra-relativistic velocities (Lorentz factors of several hundred). These shells collide with one another as they

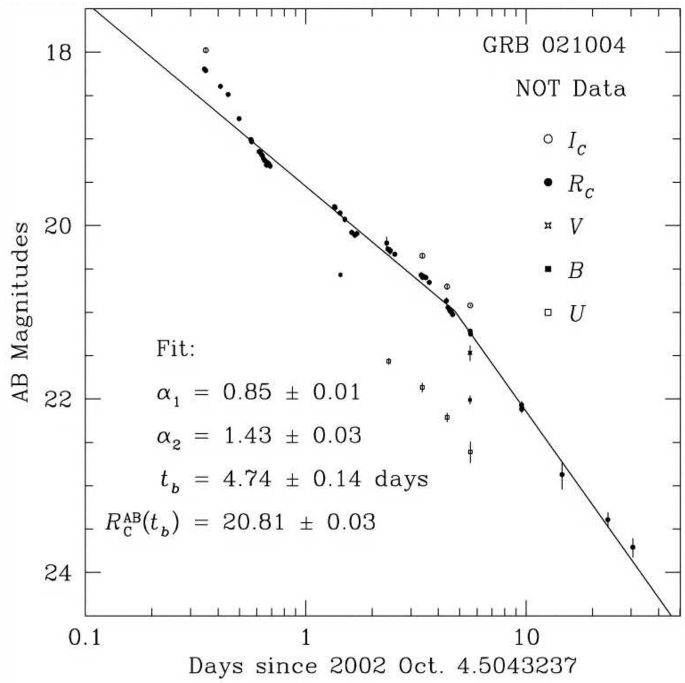

Fig. 4 The afterglow light curve of GRB021004, fit by a broken power law. Note the bump at the start of the curve. The data were taken at the Nordic Optical Telescope (Holland et al. 2003), and are reproduced by permission of the AAS.

move outward, producing "internal" shocks. The shocks accelerate electrons, and the electrons emit synchrotron radiation. In the observer's frame, the radiation appears in gamma-rays. The fact that the gamma-rays are polarized is most easily explained by the presence of a large-scale, ordered magnetic field, roughly at equipartition strength (Coburn & Boggs 2003).

The break which is observed in the optical light curves is evidence of beaming; it signals the expansion of a jet whose opening angle is initially only several degrees (Frail et al. 2001). The total energy emitted in this stage is $\sim 5 \times 10^{50}$ erg. As the shells continue to move outward, they eventually reach a region of enhanced density. This could be either the interstellar medium, or a region which originated due to a wind from the massive star in its final stages of evolution. As the shells impinge on this region, they produce "external" shocks, which give rise to long-wavelength afterglows. There is about an order of magnitude less energy in the afterglow than in the burst itself. Depending on their specific properties, irregularities, or "bumps" in the optical lightcurve can be interpreted as being caused by regions of enhanced density, a supernova-like component in the explosion, or as the result of microlensing.

The model described above is known as the "standard fireball model". Such models had been discussed extensively long before the GRB distance scale was known, but the establishment of a cosmological distance scale for bursts brought them into sharp focus (Meszaros 2002). To be sure, there are competing models (e.g., Dado et al. 2003) as well as variations on this theme. In those cases where afterglows are not detected, the host galaxies cannot be identified, and it

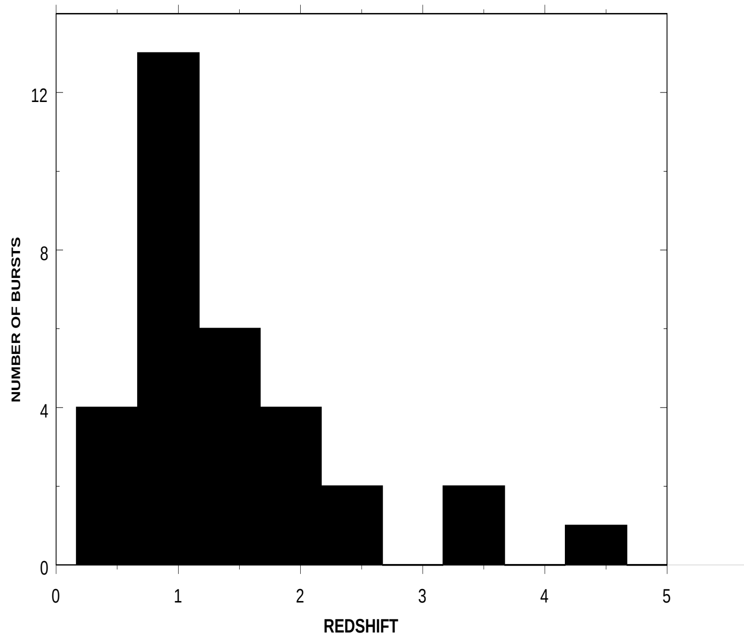

Fig. 5 The redshift distribution of gamma-ray burst sources.

is almost impossible to demonstrate that the GRB is due to the collapse of a massive star, as opposed to the merger of two neutron stars, for example.

Because the gamma-rays are beamed, we detect only a small fraction of them. This implies that the Universe-wide GRB rate is at least 1000 per day.

4.1 Loose ends

The discovery of long-wavelength counterparts and the measurement of host galaxy redshifts solved a long-standing GRB mystery. But other questions have now arisen. Some of the new mysteries are listed below.

1. What is the nature of the short bursts? One possibility is that they arise from the merger of two compact objects, rather than the collapse of a massive star (e.g. Perna & Belczynski 2002, and references therein). If this is the case, some of these systems might be expected to travel outside their host galaxies before merging, because they may receive substantial kick velocities. If so, it is conceivable that these GRBs might not produce long-lived afterglows because the IGM might be too tenuous to form strong shocks on. Thus short bursts could also be dark bursts. In any case, it is certainly true that no counterparts to short GRBs have been identified to date (e.g. Hurley et al. 2002).

2. Why have no radio and/or optical counterparts been found for approximately one-half of the long GRBs? In a few cases, the explanation could simply be that the counterpart searches have not been deep enough and/or rapid enough even to identify "normal" afterglows (that is,

afterglows which have about average intensities). But this is not the whole explanation. Other possibilities are that some bursts are heavily obscured by dust in the star-forming regions of their host galaxies, or are at very high redshifts (and therefore their optical afterglows are brighter in the IR). One fact which has emerged from studies of bursts localized in near real-time by the HETE spacecraft is that some afterglows fade very quickly and/or are intrinsically weak to begin with (Fox et al. 2003; Li et al. 2003).

3. What is the nature of X-ray flashes? Some GRB spectra are soft, and have no detectable emission above several 10's of keV. XRFs were discovered in the data of the BeppoSAX spacecraft (Heise et al. 2000), and continue to be observed by HETE. They appear to be identical to GRBs in all respects, except for the lack of gamma-rays. About 30% of all GRBs fall into this category.

4. What is the relation between GRBs and supernovae? The first experimental evidence that the two phenomena were related came from GRB980425, which was roughly spatially and temporally coincident with SN1998bw (Galama et al. 1998). The very low redshift of the host galaxy (0.008) would have suggested that any GRB from it would be extremely intense; in fact, GRB980425 was quite weak. But further evidence for an association comes from features in the optical light curves of GRB afterglows (Bloom et al. 1999). The best evidence to date, however, is from the study of GRB030329, a GRB discovered by the HETE spacecraft and studied extensively in the optical. The optical spectrum of the afterglow (Stanek et al. 2003) bears a striking resemblance to that of SN1998bw.

5 CONCLUSIONS

Multi-wavelength measurements are the key to understanding cosmic gamma-ray bursts. Ideally, they should commence as the burst starts, and continue throughout the afterglow phase, from radio to gamma-ray wavelengths. The HETE mission has made it possible for the first time to obtain near real-time, precise GRB positions, and significant advances have followed as a result. INTEGRAL is now doing the same. The Swift mission will be launched in 2004. Swift should detect over 100 bursts/year, localize them in near real-time, and conduct X-ray and optical observations of the counterparts within minutes. These observations should resolve many of the outstanding issues, and usher in a new era in GRB astrophysics.

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