COSMIC GAMMA-RAY BURSTS: THE REMAINING MYSTERIES

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ABSTRACT To anyone who has read a scientific journal or even a newspaper in the last six months, it might appear that cosmic gamma-ray bursts hold no more mysteries: they are cosmological, and possibly the most powerful explosions in the Universe. In fact, however, bursts remain mysterious in many ways. There is no general agreement upon the nature of the event which releases the initial energy. One burst at least appears to strain the energy budget of the merging neutron star model. There is evidence that another recent event may have come from a nearby supernova. Finally, while the number count statistics clearly show a strong deviation from the -3/2 power law expected for a Euclidean, homogeneous distribution, the distributions of some classes of bursts appear to follow a -3/2 power law rather closely. The recent data on bursts is reviewed, some of the mysteries discussed, and future experiments are outlined.

KEYWORDS: gamma-rays: bursts.

1. THE STORY SO FAR

Until about one year ago, the gamma-ray burst (GRB) distance scale was completely unknown, and, for most practical purposes, unconstrained. On February 28, 1997, the BeppoSAX spacecraft detected and rapidly localized a burst with the WFC, and, pointing the NFI instruments at the location, discovered its first fading X-ray counterpart (figure 1: Costa et al. 1997). Shortly thereafter, van Paradijs (1997) and his colleagues observed the region with an optical telescope, and discovered the first fading optical counterpart associated with a GRB. The X-ray and optical positions were confirmed by the Interplanetary Network (Hurley et al. 1997), and a twenty year search for GRB counterparts had come to an end.

Today we know that most, if not all GRB’s are accompanied by fading X-ray counterparts, and that approximately 50% of them also have fading optical counterparts. The fading generally can be described by a power law in time with an index \( \approx -1.5 \), although there are noteworthy exceptions (different power law indices, and fading behavior which is not a monotonic decrease).

The redshift of GRB970228 is still unknown. The first GRB redshift was measured, or more accurately, constrained, by Metzger (1997). From the observation of an absorption line system towards the source of GRB970508, he was able to show that \( z > 0.8 \). From the lack of a Ly \( \alpha \) forest, \( z < 2.2 \). This remains one of only three redshifts measured to date. The other two are \( z = 0.96 \) (Djorgovski et al. 1998) and...
FIGURE 1. BeppoSAX NFI images of the fading 2-10 keV X-ray source associated with GRB 970228, 8 and 48 hours after the burst, from Costa et al. 1997.

FIGURE 2. Flux of the fading radio counterpart to GRB970508 (Frail 1997). Note the presence of scintillations which damp out, followed by a smoother, monotonic decay.

The behavior of GRB afterglows can be understood in terms of the cosmological fireball model, in which a relativistic blast wave moving with a bulk Lorentz factor $\Gamma > 100$ impacts matter external to the burst source, resulting in the shock acceleration of particles and synchrotron emission (e.g. Wijers et al. 1997). Indeed, radio observations of GRB970508 by Frail et al. (1997) provide support for this picture. Figure 2 shows a VLA observation of the radio emission from the source as a function of time. The emission shows evidence for “scintillation”, which gradually disappears. The explanation (Goodman 1997) is analogous to the explanation for the fact that stars twinkle, while planets do not. In the GRB case the scintillation is caused by scattering in our galaxy’s interstellar medium, and it stops when the fireball has expanded to $\sim 3\mu$arcseconds. At this point, the expansion velocity has slowed to $\Gamma \sim 1$. 

$z=3.4$ (Kulkarni et al. 1998a).
2. NEUTRON STAR MERGERS AND HYPERNOVAES

One possibility for generating the GRB energy involves the merging of a neutron star in a binary system. The binary companion is either another neutron star or a black hole (Paczynski 1991). If the resulting gamma-radiation is not beamed, this need only occur once every $10^6$ years in every galaxy to explain the number of bursts observed. Such a merger will liberate $10^{52}$ erg of energy. Considering that the luminosity of the entire Universe is just $10^{53}$ erg/s, mostly in the optical band, this is indeed a phenomenal energy. The burst rate should roughly follow that of star formation, which is thought to peak around $z\approx 1.25$ (Madau et al. 1996). The timing would be approximately the following. Once two massive stars have formed, the first might go supernova in $\approx 10^7$ y, leaving behind a high mass X-ray binary system. The lifetime of this system would be short, only $\approx 10^5$ y, before the second star explodes as a supernova, leaving a binary neutron star system. This system will radiate its orbital energy away as gravitational radiation in several times $10^9$ y, resulting in a merger.

If this idea is basically correct, we might expect that many mergers will be associated with the small, low mass (and therefore intrinsically dim) galaxies which have undergone short bursts of star formation. In our own galaxy, there is some evidence that the binary pulsars have high velocities, $>200$ km/s. In the low mass galaxies where GRBs may be generated, a binary neutron star system can therefore achieve escape velocity, and in only $\approx 10^8$ y, it can reach a distance $\approx 30$ kpc from its host galaxy. Thus by the time the merger occurs, the system need not be in a galaxy at all.

There is, however, another possibility for the energy release. There is a strict upper limit to the amount of energy which can be released by two merging neutron stars: $E=mc^2 \approx 5\times10^{53}$ erg, and of course not all of this can go into the radiation which we observe. Some bursts, like GRB971214 ($z=3.4$: Kulkarni et al. 1998a) strain this energy budget if they are emitting isotropically. They may be caused by “hypernovae”, extremely energetic supernovae which result from the collapse of a 10 - 15 $M_\odot$ star to a black hole with an accretion disk which produces the energy for the burst.

Unlike the binary neutron stars, the massive stars which are the progenitors of hypernovae live only $\approx 10^6$ y, and do not travel far from their birthplaces. This leads to an observational test which can distinguish the two possibilities. Bursts generated by merging neutron stars should occur outside their host galaxies fairly often, while bursts generated by hypernovae should appear within them. So far, there is some observational evidence that favors the hypernova model, but this is based on only some 8 bursts, and more data will be required for a decisive test. Indeed, in these 8 cases, the host galaxies have not always been directly detected. In some cases, the presence of a host galaxy has been inferred from the flattening of the optical counterpart light curve (e.g. Groot et al. 1998), which is interpreted as due to the presence of an underlying galaxy which has too low a surface brightness to detect directly.
The approximate energy budget for a GRB, in either case, is given in Table 1. Starting from, say, $10^{52}$ erg, this table shows the amount of energy which goes into various emissions. Neutrinos are expected to carry away much of the intrinsic energy, but there are no measurements at present which constrain them significantly. Similarly, the optical and radio emissions during the burst could be significant, but they have not been measured.

Table 1. The Approximate GRB Energy Budget

| During the Burst | Afterglow |
|------------------|-----------|
| $\nu$ $> 10\%$?  | X-rays 10%|
| $\gamma$ rays: 70%| Optical: 2%|
| X-rays: 8%       | Radio: 0.05%|
| Optical: ?       | Radio: ?   |

3. Mysteries

Even though the GRB distance scale appears to be resolved, the source of the energy, as discussed above, remains a matter of some speculation. There are numerous other unknowns, too, three of which are now discussed.

3.1 Presence and absence of counterparts

Although virtually all GRB’s seem to have fading X-ray counterparts, less than 60% display fading optical counterparts, and perhaps only 33% display radio counterparts. Furthermore the presence or absence of an optical counterpart is not correlated with the GRB intensity or the intensity of the fading counterpart. The reason for this may be related to extinction (Reichart 1998). X-rays are attenuated roughly as $\nu^{-3}$, where $\nu$ is the frequency, while optical radiation is attenuated as $\sim \nu^1$. If the spectrum of a counterpart is redshifted, the ratio of optical to X-ray optical depths will go approximately as $(1+z)^4$, where $z$ is the redshift. Thus the optical light may be considerably attenuated with respect to the X-rays, even at modest redshifts. This is one more piece of circumstantial evidence that GRBs may originate close to the birthplace of their progenitors, in dusty, star-forming regions, and therefore be related to hypernovae rather than binary neutron stars.

3.2 A GRB-Supernova connection?

The search for the optical counterpart to GRB980425 revealed that the 8’ radius BeppoSAX WFC error circle (Soffitta et al. 1998) contained an optical transient
source which was in fact a supernova (figure 3: Galama et al. 1998). The supernova, 1998bw in the galaxy ESO 184-G82, is an unusual one (Filippenko 1998; Kulkarni et al. 1998b), and the galaxy is close, with a redshift of $z=0.008$ (Kay et al. 1998).

Pian et al. (1998) found two X-ray sources in the WFC error circle using the BeppoSAX NFI. One is variable, and the other is constant, but only the constant source has a position consistent with the supernova (Piro et al. 1998).

On the one hand, it would be tempting to believe that this is a hypernova and that the GRB-SN association is indeed true. On the other hand, though, bursts from supernovae were among the first theories proposed to explain GRB (Colgate 1974) and for twenty years, temporal and spatial coincidences between the two were searched for, with no positive results. This association is still debatable (Wang and Wheeler 1998; Kippen et al. 1998).

3.3 Euclidean and non-Euclidean GRBs

It is now well accepted that the log N-log S, or number count distribution of gamma-ray bursts as a whole deviates strongly from the $-3/2$ power law that one would expect if the sources were distributed homogeneously in Euclidean space. The fall-off is attributed to redshift effects. However, a number of authors have pointed out that certain categories of bursts, defined by their energy spectra and durations, for example, display nearly Euclidean distributions (Pizzichini 1995; Belli 1997; Tavani 1998). An example is shown in figure 4: the long duration, soft-spectra bursts and the short duration bursts follow a $-3/2$ power law more closely than the ensemble of all bursts. This is counterintuitive, since, in a cosmological distribution,
bursts with soft spectra would be expected to be more distant and display a strong deviation from a Euclidean distribution.

There are many possible solutions: selection effects, multiple populations, and/or strong luminosity and spectral evolution. It should also be noted that no short duration bursts have yet been associated with optical counterparts, so their distance scale could be quite different. In fact, they could even be galactic since, although their spatial distribution is isotropic, the agreement between their log N-log S distribution and a Euclidean distribution indicates that the population has not been fully sampled.

4. CONCLUSIONS

From this brief review, a number of important questions can be identified.

1. Are GRBs in their host galaxies, or outside them?

2. What is the distribution of their distances?

3. What is the intrinsic luminosity function for bursts?

4. Are there different classes of bursts, as the data seem to suggest?

5. What is the multiwavelength behavior of GRB light curves immediately after the burst?
Answering these questions will require hundreds of rapidly determined, small GRB error boxes, followed up by multiwavelength observations. Elsewhere in these proceedings (Hurley 1998), the missions capable of providing these error boxes have been summarized. In the immediate future, we have BeppoSAX, BATSE, and the 3rd Interplanetary Network. Around 1999, HETE-II should be launched; its nominal lifetime is 2 years. By 2003, a MIDEX mission dedicated to GRB studies may be in operation. INTEGRAL, in the years 2001-2003, will fill a void. Not only will it have an inherent GRB capability from the IBIS experiment, but also it can act as a point in a future interplanetary network. As such, it will serve the important role of maintaining interest and expertise in this important and exciting field.

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