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New Results on Cosmic Gamma-Ray Bursts

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Abstract Redshifts and/or long-wavelength counterparts have now been found for over 100 cosmic gamma-ray bursts, providing growing evidence that some bursts are associated with Type Ic supernovae. The BeppoSAX and HETE missions have also firmly established the fact that bursts are spectrally more diverse than previously suspected. Thus GRBs are slowly yielding many of their secrets. Two of the major remaining mysteries are first, what the nature of the short duration bursts is, and second, why some bursts have no detectable optical afterglows. The recently launched Swift GRB MIDEX mission is detecting bursts at a rate of about 100/year, and progress on these lingering issues is finally being made. Gamma-ray bursts are emerging as a powerful tool in many astrophysical disciplines.

Key words: gamma-rays: bursts

1 INTRODUCTION

With the realization that the long duration gamma-ray bursts are at cosmological distances, and with a growing understanding of their production mechanisms, gamma-ray bursts are well on their way to making the transition from an astrophysical curiosity to a unique tool. Much of this progress has been based on missions such as BeppoSAX, HETE (the High Energy Transient Explorer), and the interplanetary network, and it has occurred only over the last several years. In the next sections I will summarize what I believe to be the solid facts, and point out the open issues. However, the progress in this field is still very rapid. Since the 2004 Vulcano meeting, over 230 bursts have been detected, more than 60 afterglows have been observed in the X-ray, radio, and optical ranges, 10 new redshifts have been determined, and a giant magnetar flare has been observed which may provide an explanation for some short bursts. Every new event that is studied has the potential of putting a large piece of the puzzle into place. Thus a review article such as this one is destined to have a very short lifetime. This is particularly true in view of the start of operation of the Swift mission, which has ushered in a new era in GRB studies.

In this rapidly evolving field, some of the most up-to-date information is found on websites. A non-exhaustive list of them is: BATSE: www.batse.msfc.nasa.gov/batse/

BeppoSAX: www.asdc.asi.it/bepposax/
The Gamma-ray burst Coordinates Network: gcn.gsfc.nasa.gov/gcn/
Jochen Greiner's afterglow website: www.mpe.mpg.de/∼jcg/grb.html
HETE-II: space.mit.edu/HETE
INTEGRAL: integral.esac.esa.int/integral.html
The Interplanetary Network: ssl.berkeley.edu/ipn3/index.html
A Radio catalog of gamma-ray burst afterglows: www.aoc.nrao.edu/∼frail/grb_public.html
Swift: swift.gsfc.nasa.gov

Major GRB conferences are held roughly yearly. Four recent conference proceedings also contain a wealth of information (see the reference section for more information):

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Gamma-Ray Bursts in the Afterglow Era, L. Piro, L. Amati, S. Covino, and B. Gendre, eds.
Gamma-Ray Bursts: 30 Years of Discovery, E. Fenimore and M. Galassi, eds.
Supernovae and Gamma-Ray Bursters, K. Weiler, ed.
Cosmic Explosions, J. M. Marcaide and K. Weiler, eds.

The proceedings of the 2005 meeting on Gamma-Ray Bursts in the Swift Era are scheduled to appear in the AIP conference proceedings series in 2006.

2 CLASSES OF BURSTS

Gamma-ray bursts display a wide variety of spectral and temporal properties, and it is not immediately obvious whether the differences in these properties reflect different types of sources, different production mechanisms, or simply different viewing geometries. Figure 1 shows the time histories of short- and long-duration bursts. The GRB duration distribution spans five orders of magnitude (Figure 2). It is clearly bimodal, with short burst durations around 200 ms, and long burst durations around 10–20 s. The dividing line between the two is 1–2 s, and the short bursts not only tend to have harder energy spectra than the long ones, but also, tend to be somewhat deficient in low energy (1–10 keV) X-rays. These facts make them difficult to detect and image with proportional counters which operate at X-ray energies, and even with higher energy coded mask imaging systems which employ, say, CdTe. In the first case, there are relatively few photons, while in the second case, the high energy photons tend to traverse the coded mask. Thus very few short bursts have been localized rapidly and accurately, and few long wavelength counterparts to them have yet been identified (Hurley et al. 2002). However, the Swift and HETE missions have recently localized two short bursts which may prove to provide a breakthrough. Although there is no optical counterpart to the Swift burst, it lies close to a bright elliptical galaxy at $z = 0.22$ (Gehrels et al. 2005). In the case of the HETE burst, an optical counterpart has been identified, and it lies within a galaxy at $z = 0.16$ which has undergone recent star formation (Villasenor et al. 2005; Covino et al. 2006) At this point, though, almost everything that we know about GRB sources and production mechanisms still comes from observations of the long duration bursts and their counterparts. It seems likely that at least some of the short bursts do represent a separate class of event, possibly originating in the merger of a compact binary system (Perna and Belczynski, 2002; Gehrels et al. 2005), or giant magnetar flares (Hurley et al. 2005). Viewing angle effects (e.g. Yamazaki et al. 2004) are looking less likely.

In general, gamma-ray bursts –short or long– tend to have the hardest energy spectra of any known astrophysical object. They have been measured up to 18 GeV (Hurley et al. 1994), but this is just an experimental limit at present. The photon spectra are well described by the Band function (Band et al. 1993):

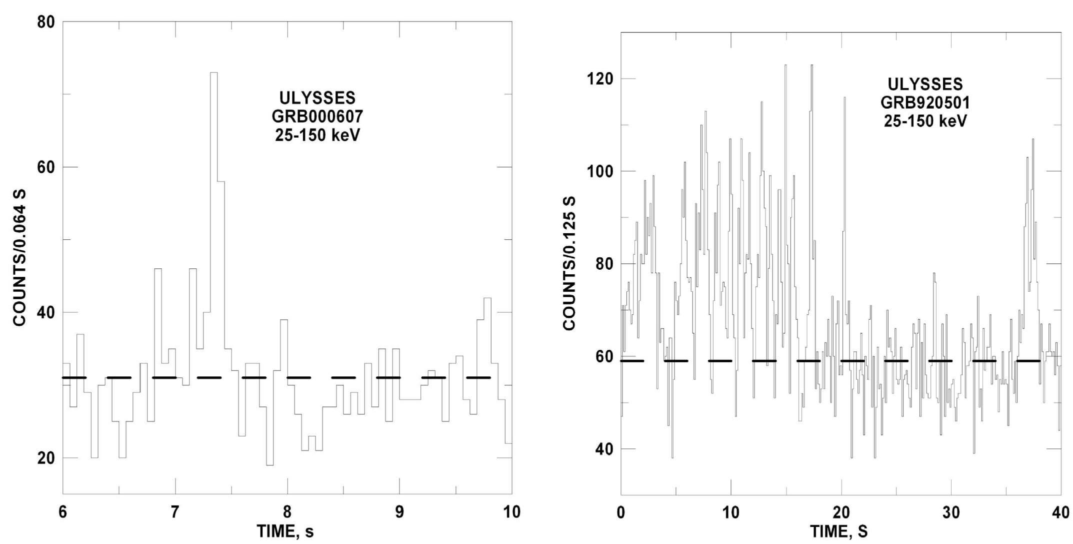

Fig. 1 Short and long duration gamma-ray bursts.

a power law with an exponential cutoff, which joins smoothly to a high energy power law. In an energy per decade or $\nu - F_\nu$ plot, this function has a peak (Figure 3), and for many years it was thought that all gamma-ray bursts had peak energies in the several hundred keV range. But the BeppoSAX mission revealed, among many other things, that there are also very soft spectrum bursts (Heise et al. 2001). The High Energy Transient Explorer (HETE) mission has now shown that burst spectra in fact form a kind of continuum, from events in which the peak energy is < 10 keV (now called X-ray flashes, figure 3), with no measurable gamma-ray emission, through X-ray rich events, with some gamma-ray emission, to the "classical" bursts with peak energies in the several hundred keV range, in roughly equal numbers (Sakamoto et al. 2005). It is generally thought that different types of sources are not required to explain this diversity (Sakamoto et al. 2004). Among the explanations that are invoked are explosions with less relativistic ejecta (Soderberg et al. 2004) and the viewing angle with respect to a jet (Lamb et al. 2005).

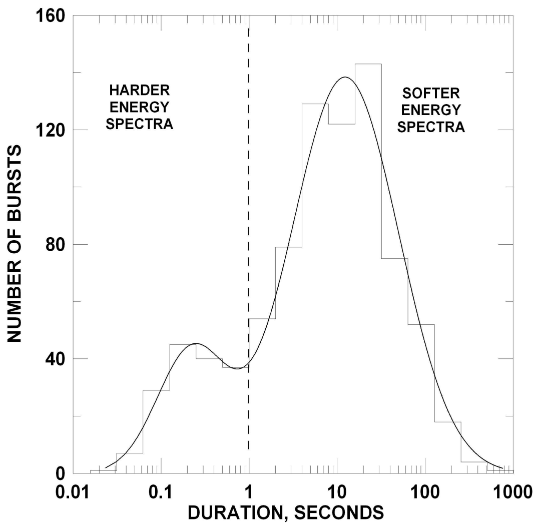

Fig. 2 The gamma-ray burst duration distribution (histogram) and a double lognormal fi t to it (smooth curve). This distribution is based on over 800 non-BATSE bursts. About 25% of all bursts are short-duration bursts.

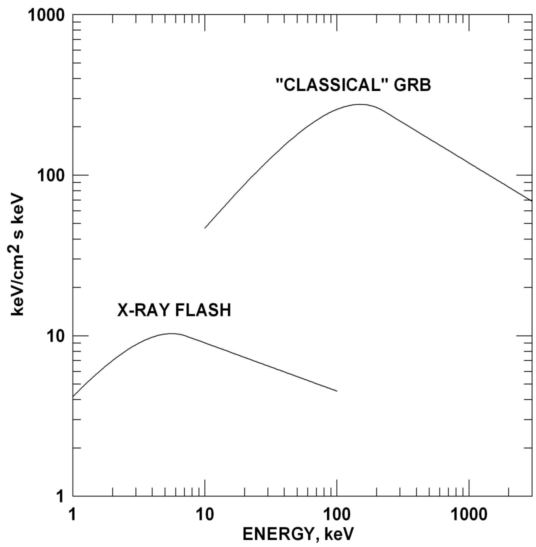

Fig. 3 Two gamma-ray burst energy spectra, in a $\nu - F_\nu$ representation. These presently represent the endpoints of the known distribution.

3 LONG-WAVELENGTH AFTERGLOWS

Thanks to BeppoSAX, and now also to the Swift mission (DePasquale et al. 2003, Gehrels et al., 2004) we know that virtually all of the long bursts display fading X-ray counterparts, which remain detectable for days to a week or so. This has led to the discovery of optical and radio afterglows (Masetti, 2004, Berger, 2004), as well as GRB host galaxies (Djorgovski et al., 2001). Figure 4 shows a compilation of numerous R-band afterglows. Not all bursts have measurable optical and radio afterglows, however. Initially, when BeppoSAX was operating, about 50% of all bursts had no detectable optical afterglows (DePasquale et al., 2003). The HETE mission, however, made it possible for astronomers to search GRB error boxes with shorter delays, reducing the percentage of "dark bursts". Swift has now reduced the delays still further. There are still long bursts with no measurable optical afterglows, but it is not clear whether, in all cases, the optical observations have been deep enough and rapid enough. If dark bursts do exist, however, the explanation could be that they suffer extinction in their host galaxies (Vergani et al., 2004), that their afterglows are intrinsically weak (DePasquale et al., 2003), or that they are at high redshift (DePasquale et al., 2003). So far, heavily extincted bursts and bursts with weak afterglows have indeed been found. However, the burst with the highest redshift found to date, GRB 000131 at $z = 4.5$, did not have an exceptionally weak afterglow (Andersen et al. 2000). The GRB redshift distribution is shown in Figure 5.

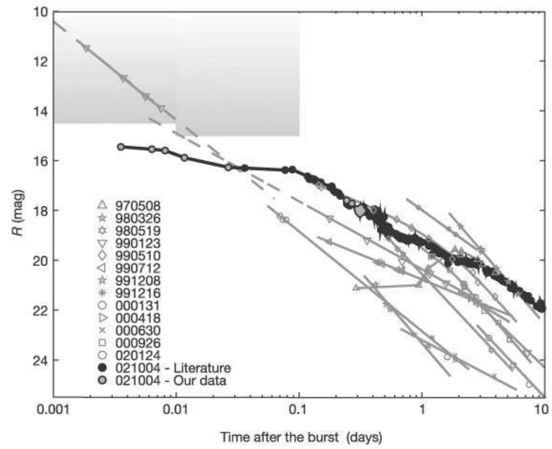

Fig. 4 From Fox et al. (2003). The R magnitudes as a function of time for 14 afterglows. The region in the lower left hand corner of the plot is where the dark bursts lie. The shaded regions at the top represent the areas where rapidly moving telescopes operate. Copyright Nature Publishing Group. Reproduced by permission.

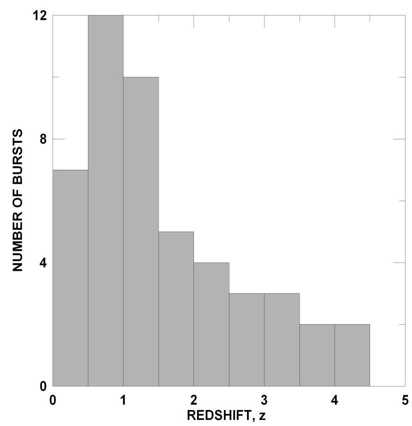

Fig. 5 The GRB redshift distribution of 49 GRBs. The lowest is $z = 0.1$, the highest is $z = 4.5$, and the average is $z = 1.6$.

4 GRB SOURCES AND ENERGETICS

Taking everything at face value, the isotropic gamma-ray energies of long bursts range from over 10^{51} to over 10^{54} erg. The most popular current model for releasing the energy involves a "collapsar", or hypernova (MacFadyen and Woosley 1999): the collapse of a massive ($\sim 30\,M_{\rm sol}$) star to a black hole surrounded by an accretion disk or torus. While this cannot liberate 10^{54} erg, it is likely, both from a theoretical and observational point of view, that the gamma-radiation is beamed into a several degree cone, reducing the total energy to a more manageable 10^{51}–10^{52} erg (Frail et al. 2001). The experimental evidence comes from the observation of "breaks" in the optical afterglow light curves, which are interpreted as being due to the slowing and expanding of a jet. An example is shown in figure 6. Beaming has several effects besides reducing the energy requirements. It also (in a model-dependent way) makes GRBs "standard candles" (Bloom et al. 2003). And, of course, it increases the total GRB rate, since for every burst that we observe, there are many more that we do not. However, this does not appear to contradict anything that we know about star formation and supernova rates. The long-wavelength afterglows are then produced in shocks

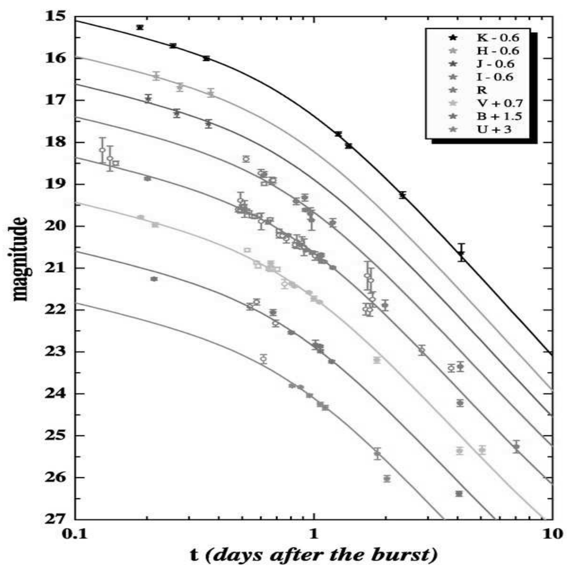

Fig. 6 From Klose et al. 2004. The fading optical afterglow of GRB 030226 in various colors. Note the change of slope.

as expanding shells of matter encounter an interstellar medium, or possibly a wind thrown off from the progenitor star in its final phases of evolution; this model, sometimes called the standard fireball model, was originally proposed before the cosmological nature of bursts had been determined (Mészáros & M. Rees 1993) and has been continually refined over the years. A competing, "cannonball" model, has also been proposed (Dado, Dar, and de Rujula 2002).

Table 1 shows how the total energy in a burst and its afterglow is distributed over the electromagnetic spectrum and beyond. This is a composite distribution calculated from many bursts, and is only approximate; as the neutrino and gravitational radiation components have never been measured, the total is not quite 100%. Note too that the radio emission during a burst has never been measured, but it is expected to be heavily absorbed, and therefore constitute a very small fraction of the total.

Table 1 Distribution of the GRB Energy

Component	During the burst	During the afterglow
γ-rays $>$ 25 keV	65%	7%
1–10 keV X-rays	7%	9%
Optical	0.1%	2%
Radio	?	0.05%
ν	?	?
Gravitational radiation	?	?

5 THE LONG GRB-SUPERNOVA CONNECTION

Over the past six years, the evidence has been growing for a connection between Type Ic supernovae and gamma-ray bursts. The first indication came from GRB 980425, which was roughly spatially and temporally coincident with a nearby supernova, SN1998bw (Galama et al. 1998). Evidence continued to build (Bloom et al. 1999) until, in 2003, the HETE spacecraft detected and rapidly localized GRB 030329 (Vanderspek et al. 2004), an intense, nearby ($z = 0.17$) burst. It has now become the most-studied and observed event, with well over 100 long-wavelength observations, and some 50 publications.

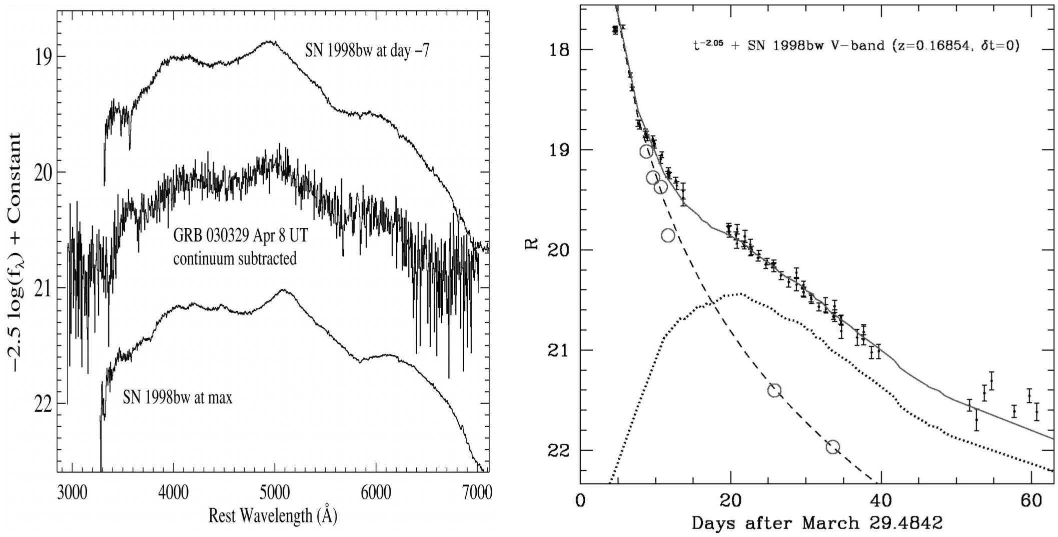

Fig. 7 Left: the optical spectrum of the afterglow of GRB 030329, compared to that of SN1998bw. From Stanek et al. 2003. Reproduced by permission of the AAS. Right: The afterglow lightcurve of GRB 030329, and its decomposition into a power law and a supernova component. From Matheson et al. 2003. Reproduced by permission of the AAS.

The evidence for a Type Ic supernova connection comes from the optical spectrum and afterglow light curve (Figure 7). The optical spectrum resembles that of SN1998bw, a Type Ic supernova, with broad lines characteristic of large expansion velocities (Stanek et al. 2003). The light curve can be decomposed into two components. The first is a power law decay characteristic of GRBs in general, while the second is the light curve of SN1998bw, scaled to the redshift of GRB 030329 and shifted in magnitude (Matheson et al. 2003).

Table 2 compares some basic properties of gamma-ray bursts and supernovae. The Universe- wide GRB rate depends on the beaming angle since, as noted above, for every burst that is observed, there are many more that are not. Nevertheless, it appears to be considerably smaller than the rate of Type Ic supernovae. Thus it seems at first glance that not all Type Ic's produce GRBs; however, in some beaming models, the two rates are indeed about equal (Lamb et al. 2005).

Table 2 GRBs and Supernovae Compared

	GRBs	Supernovae
Universe-wide rate	100–1000/day	100 000/day (all types)
		1000–10 000/day (Ic)
Rate per galaxy	$1/10^5$ y	1/100 y
Energy	10^{51}–10^{52} erg	10^{51}–10^{52} erg

6 SOME REMAINING MYSTERIES

While there are still many things to learn about GRBs, the following are some of the more mysterious aspects of them.

What are the short-duration bursts? Swift and HETE have provided the beginning of an answer to this question. In the case of the Swift burst, the progenitor may have been ejected from an early-type galaxy (Gehrels et al. 2005), while in the HETE case, it lies within a galaxy which is not an early type (Villasenor et al. 2005, Covino et al. 2006). Both galaxies lie at cosmological distances ($z = 0.22$ and 0.16, respectively), but are closer than the average long burst. They cannot be giant magnetar flares for reasons of energetics (Hurley et al. 2005), but this explanation still cannot be ruled out for all short bursts. The detection rate of short events is considerably lower than that of long events, so a complete understanding of the phenomenon may not be achieved quickly.

Are X-ray flashes and GRBs all part of the same family? Evidence is slowly emerging that they are (Sakamoto et al. 2004). The redshift of at least one XRF has been measured and it is $z = 0.251$; this has led to a determination of the energetics, and an indication that the mechanism is similar to that of classical GRBs (Soderberg et al. 2004).

Are there bursts with no detectable optical counterparts? The Swift mission should eventually provide an answer to this question. To date, over half of the Swift bursts have no optical counterparts, but most of these non-detections are not significant for one reason or another (burst location not suitable for follow-up, searches not deep enough, etc.). Most of the recent Swift bursts do have counterparts, which suggests that efficiencies are increasing and that the number of dark bursts will decrease to a fraction which is equal to that determined by HETE, or less.

Where are the high redshift bursts? GRBs can be detected to redshifts of 10 or more, if they are indeed created there (Lamb and Haiman 2004). Swift, HETE, BeppoSAX, and the IPN all have or had the sensitivity to observe them. But the record still stands at $z = 4.5$ (Andersen et al. 2000).

7 CONCLUSIONS

The remaining mysteries notwithstanding, cosmic gamma-ray bursts are now recognized as cosmological tools (Djorgovski et al. 2004). They can be used to study quantum gravity (Boggs et al. 2004), and blamed for mass extinctions (Kaye 2004). Among the current experiments and missions contributing to their study are Konus-Wind, Ulysses, the Ramaty High Energy Solar Spectroscopic Imager, the High Energy Transient Explorer, the International Gamma-Ray Astrophysics Laboratory, Mars Odyssey, Swift, and Suzaku. The coming years promise to be exciting.

Note added in proof: since this paper was written, there have been more observations of the short bursts and their counterparts, which strengthen the conclusion that these events are relatively nearby compared to the long bursts, and may be produced both in galaxies which are still undergoing star formation, and in galaxies which are not. Also, the previous record for the most distant long GRB ($z = 4.5$) has been broken by GRB 050904 ($z = 6.29$; Kawai et al. 2006). These observations do not alter the conclusions of this paper substantially.

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DISCUSSION

L. BURDERI's Comment: I just want to call everybody's attention to the LMXB systems in which accretion-induced collapse of the NS into a BH can be the mechanism that produces a fraction (significant?) of the short GRBs. Because of the virial theorem, during accretion you must deposit at least half of the accretable mass onto the primary (NS) and given that almost one solar mass is available for accretion in LMXBs, this makes the accretion-induced collapse of a NS into a BH quite a common endpoint of the evolution of LMXBs.

F. GIOVANNELLI: We have, if I am right, 79 GRBs for which the redshift of the host galaxy is known. My impression is that only in a very few of these cases the association of the GRB and the host galaxy is definitely certain (namely the GRB and the SN associations). For the other cases, indeed, we have the association on the basis that one galaxy is in the error box of the GRB. But there are other cosmic sources in these error boxes. Have you taken into account the possibility of an erroneous association? What is the probability of a wrong association?

HURLEY: Actually, in figure 5, I have shown only 49 redshifts. I have selected them because I feel that they are very secure identifications, and the probability that they are incorrect is really negligible. That is, they come from the observation of the afterglow itself, or the galaxy in which the afterglow is located. There are indeed other, less secure redshifts, but I have avoided using them.

N. REA: Very recently, Lazzati, Ghirlanda, and Ghisellini, reanalyzing the spectra of the BATSE short gamma-ray bursts, claimed that only 4% of the detected short GRBs could be due to SGR giant flares. Do you have any comment on this?

HURLEY: Since I wrote this paper, there has been considerable progress in identifying the sources of the short bursts, some of which appear to be due to compact object mergers. However, there is one event, GRB 050906, which does not fit this picture very well, and could be due to an extragalactic giant magnetar flare. If so, then this would be one out of five short bursts that have been studied by HETE and Swift, or about 20%. Considering the uncertainties in both estimates, they are probably consistent with one another. But it does look like only a small fraction could be due to giant flares, although I still believe that *some* of them do originate in this way.