



Scientific highlights of the HETE-2 mission

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Abstract

The High Energy Explorer Satellite 2 (HETE-2) mission has been highly productive. It has observed more than 250 γ -ray bursts (GRBs) so far. It is currently localizing 25–30 GRBs per year, and has localized 43 GRBs to date. Twenty-one of these localizations have led to the detection of X-ray, optical, or radio afterglows, and as of now, 11 of the bursts with afterglows have redshift determinations. HETE-2 has also observed more than 45 bursts from soft γ -ray repeaters, and more than 700 X-ray bursts.

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HETE-2 has confirmed the connection between GRBs and Type Ic supernovae, a singular achievement and certainly one of the scientific highlights of the mission so far. It has provided evidence that the isotropic-equivalent energies and luminosities of GRBs may be correlated with redshift; such a correlation would imply that GRBs and their progenitors evolve strongly with redshift. Both of these results have profound implications for the nature of GRB progenitors and for the use of GRBs as a probe of cosmology and the early universe.

HETE-2 has placed severe constraints on any X-ray or optical afterglow of a short GRB. It has made it possible to explore the previously unknown behavior of optical afterglows at very early times, and has opened up the era of high-resolution spectroscopy of GRB optical afterglows. It is also solving the mystery of “optically dark” GRBs, and revealing the nature of X-ray flashes.

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1. Introduction

γ -ray bursts (GRBs) are the most brilliant events in the Universe. They mark the birth of stellar-mass black holes and involve ultra-relativistic jets traveling at 0.9999 c. Long regarded as an exotic enigma, they have taken center stage in high-energy astrophysics by virtue of the spectacular discoveries of the past six years. It is now clear that they also have important applications in many other areas of astronomy: GRBs mark the moment of “first light” in the universe; they are tracers of the star formation, re-ionization, and metallicity histories of the universe; and they are laboratories for studying core-collapse supernovae.

Three major milestones have marked this journey. In 1992, results from the Burst and Transient Source Experiment (BATSE) on board the *Compton γ -ray observatory* ruled out the previous paradigm (in which GRBs were thought to come from a thick disk of neutron stars in our own galaxy, the Milky Way), and hinted that the bursts might be cosmological (Meegan et al., 1993). In 1997, results made possible by *BeppoSAX* (Costa et al., 1997) decisively determined the distance scale to long GRBs (showing that they lie at cosmological distances), and provided circumstantial evidence that long bursts are associated with the deaths of massive stars (see e.g., Lamb, 2000). In 2003, results made possible by the High Energy Explorer Satellite 2 (HETE-2) (Vanderspek et al., 2003) dramatically confirmed the GRB–SN connection and firmly established that long bursts are

associated with Type Ic core collapse supernovae. Thus we now know that the progenitors of long GRBs are massive stars.

The HETE-2 mission has been highly productive in addition to achieving this breakthrough:

- HETE-2 is currently localizing 25–30 GRBs per year.
- HETE-2 has accurately and rapidly localized 43 GRBs in 2½ years of operation (compared to 52 GRBs localized by *BeppoSAX* during its 6-year mission); 14 of these have been localized to <2 arcmin accuracy by the SXC plus WXM.
- 21 of these localizations have led to the identification of the X-ray, optical, or radio afterglow of the burst.
- As of the present time, redshift determinations have been reported for 11 of the bursts with afterglows (compared to 13 *BeppoSAX* bursts with redshift determinations).
- HETE-2 has detected 16 XRFs so far (compared to 17 by *BeppoSAX*).
- HETE-2 has observed 25 bursts from the soft γ -ray repeaters 1806–20 and 1900+14 in the summer of 2001; two in the summer of 2002; and 18 so far in 2003. It has discovered a possible new SGR: 1808–20.
- HETE-2 has observed \sim 170 X-ray bursts (XRBs) in the summer of 2001, >500 in the summer of 2002, and >150 so far in 2003 from \sim 20 sources. (We pointed HETE-2 toward the Galactic plane during the summer of 2002 and caught a large number of XRBs in order to calibrate new SXC flight software.)

Fourteen GRBs have been localized by the HETE-2 WXM plus SXC so far. Remarkably, all 14 have led to the identification of an X-ray, optical, infrared, or radio afterglow; and 13 of 14 have led to the identification of an optical afterglow. In contrast, only $\approx 35\%$ of *BeppoSAX* localizations led to the identification of an optical afterglow.

2. Scientific highlights of the HETE-2 mission

Confirmation of the GRB–SN connection is a singular achievement and certainly one of the scientific highlights of the HETE-2 mission. Other highlights of the mission include the following:

- HETE-2 made possible rapid follow-up observations of a short GRB, allowing severe constraints to be placed on the brightness of any X-ray or optical afterglow.
 - The rapid follow-up observations made possible by HETE-2 have opened the era of high-resolution spectroscopy of optical afterglows (e.g., GRBs 020813, 021004, and 030329).
 - Accurate, rapid HETE-2 localizations sent to ground-based robotic telescopes have made it possible to explore the previously unknown behavior of optical afterglows in the 3–20 h “gap” immediately following the burst that existed in the *BeppoSAX* era. This has confirmed the existence of a very bright, distinct phase lasting ≈ 10 min.
 - HETE-2 is solving the mystery of “optically dark” GRBs. As already remarked upon, the identification of an optical afterglow for 13 of 14 GRBs localized by the SXC plus WXM instruments on HETE-2 has shown that very few long GRBs are truly “optically dark.”
 - Optical and NIR follow-up observations made possible by HETE-2 have provided the best case to date of a GRB whose optical afterglow has been extinguished by dust, and several examples of GRBs with exceptionally dim optical afterglows. These GRBs would very likely have been classified as “optically dark” were it not for the accurate, rapid localizations provided by HETE-2.
- HETE-2 is revealing the nature of X-ray flashes (XRFs). Specifically, HETE-2 has provided strong evidence that the properties of XRFs, X-ray-rich GRBs, and GRBs form a continuum, and therefore that these three types of bursts are the same phenomenon.
 - HETE-2 results also show that XRFs may provide unique insights into the nature of GRB jets, the rate of GRBs, and the role of GRBs in Type Ic supernovae. In particular, the HETE-2 results provide evidence that GRB jets are uniform rather than structured. They also suggest that the jets are very narrow, and that the rate of GRBs may be much larger than has been thought.

3. GRB–SN connection

There has been increasing circumstantial and tantalizing direct evidence in the last few years that GRBs are associated with core collapse supernovae (see, e.g., Lamb, 2000). The detection and localization of GRB 030329 by HETE-2 (Vanderspek et al., 2003) led to a dramatic confirmation of the GRB–SN connection. GRB 030329 was among the brightest 1% of GRBs ever seen. Its optical afterglow was ~ 12 th magnitude at 1.5 h after the burst (Price et al., 2003) – more than three magnitudes brighter than the famous optical afterglow of GRB 990123 at a similar time (Akerlof et al., 1999). In addition, the burst source and its host galaxy lie very nearby, at a redshift $z = 0.167$ (Greiner et al., 2003). Given that GRBs typically occur at $z = 1–2$, the probability that the source of an observed burst should be as close as GRB 030329 is one in several thousand. It is therefore very unlikely that HETE-2, or even *Swift*, will see another such event.

The fact that GRB 030329 was very nearby made its optical afterglow an ideal target for attempts to confirm the conjectured association between GRBs and core collapse SNe. Astronomers were not disappointed. About 10 days after the burst, the spectral signature of an energetic Type Ic supernova emerged (Stanek et al., 2003). The supernova has been designated SN 2003dh. Fig. 1 compares the discovery spectrum of SN 2003dh in

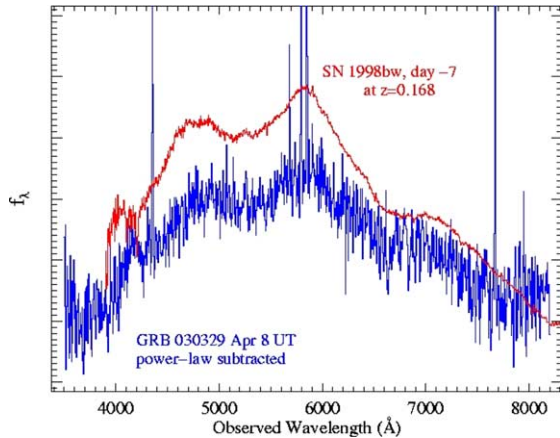


Fig. 1. Comparison of the discovery spectrum of SN 2003dh seen in the afterglow of GRB 030329 at 8 days after the burst and the spectrum of the Type Ic supernovae SN 1998bw. The similarity is striking (from Stanek et al., 2003).

the afterglow light curve of GRB 030329 and the spectrum of the Type Ic supernova SN 1998bw. The similarity is striking. The breadth and the shallowness of the absorption lines in the spectra of SN 2003dh imply expansion velocities of $\approx 36,000 \text{ km s}^{-1}$ – far higher than those seen in typical Type Ic supernovae, and higher even than those seen in SN 1998bw.

The clear detection of SN 2003dh in the afterglow of GRB 030329 confirmed decisively the connection between GRBs and core collapse SNe, and implies that GRBs are a unique laboratory for studying Type Ic core collapse supernovae. Confirmation by HETE-2 of the connection between GRBs and core collapse supernovae has also strengthened the expectation that GRBs occur out to redshifts $z \sim 20$, and are therefore a powerful probe of cosmology and the early universe.

4. Short GRBs

Assuming that short bursts follow the star-formation rate (as long bursts are thought to do), Schmidt (2001) has shown that the peak luminosities of short bursts are essentially the same as those of long bursts. Otherwise, little is known about the distance scale or the nature of short GRBs. *BeppoSAX* did not detect any short, hard

GRBs during its 6-years mission, despite extensive efforts. The rapid HETE-2 and IPN localizations of GRB 020531 (Lamb et al., 2004a) made possible rapid optical ($t=2-3 \text{ h}$) follow-up observations. No optical afterglow was detected (Lamb, 2002; Miceli et al., 2002; Dullighan, 2002). Chandra follow-up observations at $t=5 \text{ days}$ showed that $L_X(\text{short})/L_X(\text{long}) < 0.01-0.03$ (Butler et al., 2002). These results suggest that real time or near-real time X-ray follow-up observations of short GRBs may be vital to unravel the mystery of short GRBs.

5. “Optically dark” GRBs

Only $\approx 35\%$ of *BeppoSAX* localizations of GRBs led to the identification of an optical afterglow. In contrast, 13 of the 14 GRBs localized so far by the WXM plus the SXC on HETE-2 have optical afterglows. HETE-2 is thus solving the mystery of “optically dark” bursts.

Three explanations of “optically dark” GRBs have been widely discussed:

- The optical afterglow is extinguished by dust in the vicinity of the GRB or in the star-forming region in which the GRB occurs (see, e.g., Lamb, 2000; Reichart and Price, 2002).
- The GRB lies at very high redshift ($z > 5$), and the optical afterglow is absorbed by neutral hydrogen in the host galaxy and in the intergalactic medium along the line of sight from the burst to us (Lamb, 2000).
- Some GRBs have afterglows that are intrinsically very faint (see, e.g., Fynbo et al., 2001; Price et al., 2002; Lazzati et al., 2002).

Rapid optical follow-up observations of the HETE-2-localized burst GRB 030115 (Kawai et al., 2003) show that the optical afterglow of this burst is the best case observed to date of a burst whose optical afterglow is extinguished by dust. Fig. 2 shows the NIR and optical afterglow spectrum of this burst and the best-fit model, assuming extinction by dust (Lamb et al., 2004b). The amount of extinction by dust is a sensitive function of the redshift of the burst. Since the redshift of this burst has not been reported as yet, the case shown in Fig. 2 assumes $z = 3.5$, the largest red-

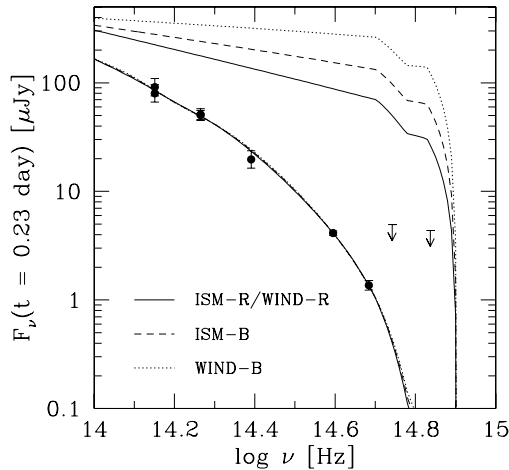


Fig. 2. NIR and optical afterglow spectrum of GRB 030115, as determined from K, H, J, i^* , and r^* observations. The curve that goes through the data points is the best-fit model, assuming extinction by dust of the four theoretical afterglow spectra labeled “SM-R, WIND-R, ISM-B, WIND-B.” The amount of extinction by dust is a sensitive function of the redshift of the burst. The redshift of this burst has not yet been reported; the case shown therefore assumes $z = 3.5$, the largest redshift allowed by the observations and the one that attributes the *least* amount of extinction by dust. The amount of extinction by dust in the optical is still substantial (from Lamb et al., 2004b).

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Rapid optical follow-up observations (Fox et al., 2003b; Park et al., 2002; Li et al., 2003; Wozniak et al., 2002) of the HETE-2-localized burst GRB 021211 (Crew et al., 2003) show that the optical afterglow of this burst is intrinsically much fainter than those observed previously. The transition from the reverse shock component (Sari and Piran, 1999) to the forward shock component is clearly visible in the light curve of the afterglow at about 20 min after the burst. Fig. 3 shows the light curve of the afterglow of GRB 021211 compared to those of other GRBs, including a two-component flare + afterglow fit for the early optical emission from GRB 021211 (Fox et al., 2003b) These observations show that the light curve of the afterglow of this burst tracks those of GRBs 990123 and 030329, but is *three and six magnitudes fainter* than them, respectively.

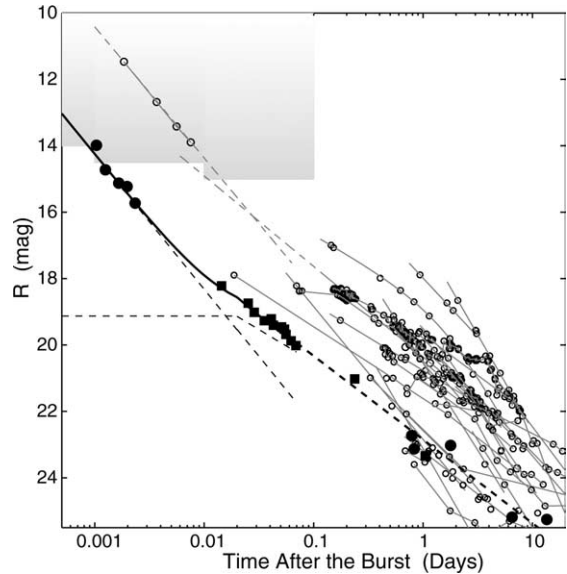


Fig. 3. Light curve of the optical afterglow of GRB 021211, compared to those of other GRBs. The dashed curve in the upper left-hand corner of the figure shows the light curve of the optical afterglow of GRB 990123. HETE-2 has shown that the optical afterglows of GRBs can exhibit a wide range of behaviors in the first few hours after the burst (from Fox et al., 2003b).

This burst would almost certainly have been classified as “optically dark” were it not for its accurate, rapid localization by HETE-2. Upper limits or measurements of the optical afterglows of other *BeppoSAX*- and HETE-2-localized bursts suggest that they too have afterglows that are very faint (see, e.g., Fynbo et al., 2001; Price et al., 2002; Lazzati et al., 2002). GRBs with intrinsically faint afterglows may therefore account for a substantial fraction of bursts previously classified as “optically dark.”

The temporal behavior of the optical afterglow of the HETE-2-localized burst GRB 021004 was nearly flat at early times – a behavior that is different than any seen previously and that suggests the “central engine” powering the GRB continued to pour out energy long after the burst itself was over (Fox et al., 2003a). Thus HETE-2 is making it possible to explore the previously unknown behavior of GRB afterglows in the “gap” in time from the end of the burst to 3–20 h after the burst that existed in the *BeppoSAX* era.

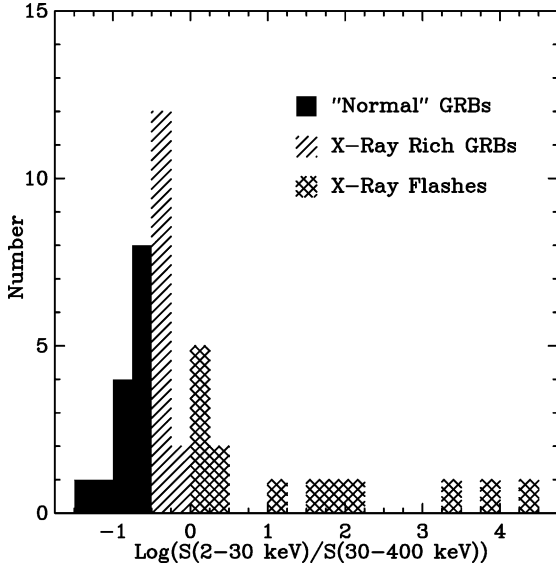


Fig. 4. Hardness histogram for HETE-2 GRBs. Shown are GRBs (solid histogram), X-ray-rich GRBs (hatched histogram), and XRFs (cross-hatched histogram) (from Sakamoto et al., 2004b).

6. Nature of X-ray flashes and X-ray-rich GRBs

As already discussed, the 1, 2, and 6 keV thresholds, and the effective areas at X-ray energies of the WXM, SXC, and FREGATE instruments make HETE-2 ideal for detecting and studying XRFs. Indeed, *two-thirds* of all HETE-2-localized bursts are either “X-ray-rich” or XRFs, and *one-third* are XRFs (see Fig. 4).¹ These events have received increasing attention in the past several years (Heise et al., 2002; Kippen et al., 2002), but their nature remains largely unknown.

XRFs have t_{90} durations between 10 and 200 s and their sky distribution is consistent with isotropy. In these respects, XRFs are similar to “classical” GRBs. A joint analysis of WFC/BATSE spectral data showed that the low-energy and high-energy photon indices of XRFs are -1 and ~ -2.5 , respectively, which are similar to those of GRBs, but that the XRFs had spectral peak

¹ We define “X-ray-rich” GRBs and XRFs as those events for which $\log[S_X(2-30 \text{ keV})/S_\gamma(30-400 \text{ keV})] > -0.5$ and 0.0 , respectively.

energies $E_{\text{peak}}^{\text{obs}}$ that were much lower than those of GRBs (Kippen et al., 2002). The only difference between XRFs and GRBs therefore appears to be that XRFs have lower $E_{\text{peak}}^{\text{obs}}$ values. It has therefore been suggested that XRFs might represent an extension of the GRB population to bursts with low peak energies.

Clarifying the nature of XRFs and X-ray-rich GRBs, and their connection to GRBs, could provide a breakthrough in our understanding of the prompt emission of GRBs. The spectrum of the HETE-2-localized event XRF 020903 is exceedingly soft (Sakamoto et al., 2004a). The upper limit $E_{\text{peak}}^{\text{obs}} < 5 \text{ keV}$ (99.7% confidence level) makes this event one of the most extreme XRFs seen so far by HETE-2. Follow-up observations made possible by the HETE-2 localization identified the likely optical afterglow of the XRF (Soderberg et al., 2002). Later observations determined that the optical transient occurred in a star-forming galaxy at a distance $z = 0.25$ (Soderberg et al., 2002; Chornock and Filippenko, 2002) both of these properties are typical of GRB host galaxies.

Analyzing 42 X-ray-rich GRBs and XRFs seen by FREGATE and/or the WXM instruments on HETE-2, (Sakamoto et al., 2004b) find that the XRFs, the X-ray-rich GRBs, and GRBs form a continuum in the $[S_\gamma(2-400 \text{ keV}), E_{\text{peak}}^{\text{obs}}]$ -plane (see Fig. 5). This result strongly suggests that these three kinds of events are the same phenomenon.

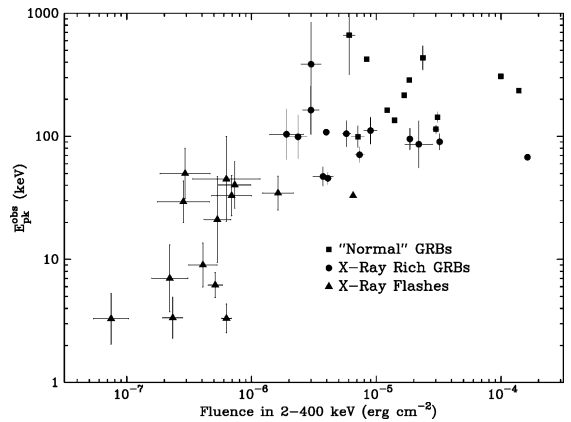


Fig. 5. Distribution of HETE-2 bursts in the $[S(2-400 \text{ keV}), E_{\text{peak}}^{\text{obs}}]$ -plane, showing XRFs (filled triangles), X-ray-rich GRBs (filled circles), and GRBs (filled squares) (from Sakamoto et al., 2004b).

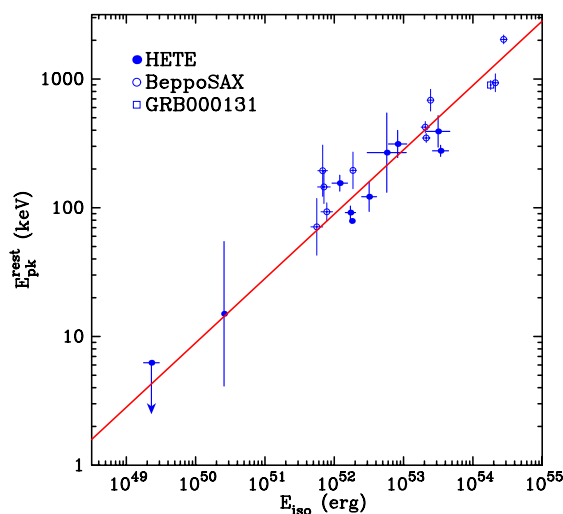


Fig. 6. Distribution of HETE-2 and *BeppoSAX* bursts in the $(E_{\text{iso}}, E_{\text{peak}})$ -plane, where E_{iso} and E_{peak} are the isotropic-equivalent GRB energy and the peak of the GRB spectrum in the source frame. The HETE bursts confirm the relation between E_{iso} and E_{peak} found by Amati et al. (2002), and extend it by a factor ~ 300 in E_{iso} . The bursts with the lowest and second-lowest values of E_{iso} are XRFs 020903 and 030723 (from Lamb et al., 2004c).

Furthermore, (Lamb et al., 2004c) have placed 9 HETE-2 GRBs with known redshifts and 2 XRFs with known redshifts or strong redshift constraints in the $(E_{\text{iso}}, E_{\text{peak}})$ -plane (see Fig. 6). Here E_{iso} is the isotropic-equivalent burst energy and E_{peak} is the energy of the peak of the burst spectrum, measured in the source frame. The HETE-2 bursts confirm the relation between E_{iso} and E_{peak} found by Amati et al. (2002) for GRBs and extend it down in E_{iso} by a factor of 300. The fact that XRF 020903, one of the softest events localized by HETE-2 to date, and XRF 030723, the most recent XRF localized by HETE-2, lie squarely on this relation (Sakamoto et al., 2004a; Lamb et al., 2004c) provides additional evidence that XRFs and GRBs are the same phenomenon. However, additional redshift determinations are clearly needed for XRFs with $1 \text{ keV} < E_{\text{peak}} < 30 \text{ keV}$ energy in order to confirm these results.

7. Conclusions

The HETE-2 mission has been highly productive. It has observed more than 250 GRBs so far. It

is currently localizing 25–30 GRBs per year, and has localized 43 GRBs to date. Twenty-one of these localizations have led to the detection of X-ray, optical, or radio afterglows, and as of now, 11 of the bursts with afterglows have redshift determinations. HETE-2 has also observed more than 45 bursts from soft γ -ray repeaters, and more than 700 X-ray bursts.

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