Scientific Highlights of the HETE-2 Mission

D. Q. Lamb[a], G. R. Ricker[b], J-L. Atteia[c], C. Barraud[c], M. Boer[c], J. Braga[d], N. Butler[b], T. Cline[e], G. B. Crew[b], J.-P. Dezalay[c], T. Q. Donaghy[a], J. P. Doty[b], A. Dullighan[b], E. E. Fenimore[f], M. Galassi[f], C. Graziani[a], K. Hurley[g], J. G. Jernigan[g], N. Kawai[h], A. Levine[b], R. Manchanda[i], M. Matsuoka[j], F. Martel[b], G. Monnelly[b], G. Morgan[b], J.-F. Olive[c], G. Pizzichini[k], G. Prigozhin[b], T. Sakamoto[h], Y. Shirasaki[l], M. Suzuki[h], K. Takagishi[m], T. Tamagawa[n], K. Torii[n], R. Vanderspek[b], G. Vedrenne[c], J. Villasenor[b], S. E. Woosley[o], M. Yamauchi[m] and A. Yoshida[p]

[a]Department of Astronomy & Astrophysics, University of Chicago, Chicago, IL 60637, USA

[b]MIT Center for Space Research, Cambridge, MA 02139, USA

[c]Centre D'Etude Spatiale des Rayonnements, France

[d]Instituto Nacional de Pesquisas Espaciais, Sao Jose dos Campos, 12227-010, Brazil

[e]NASA Goddard Space Flight Center, Greenbelt, MD 20771

[f]Los Alamos National Laboratory, Los Alamos, NM, USA

[g]UC Berkeley, Space Sciences Laboratory, Berkeley, CA 94720, USA

[h]Tokyo Institute of Technology, Tokyo, Japan

[i]Department of Astronomy and Astrophysics, Tata Institute, Mumbai, 400 005, India

[j]NASDA, Tokyo, Japan

[k]Consiglio Nazionale Delle Ricerche, Italy

[l]National Astronomical Observatory, Tokyo, Japan

[m]Faculty of Engineering, Miyazaki University, Gakuen Kibanadai Nishi, Miyazaki, 889-2192, Japan

[n]Institute of Physical and Chemical Research (RIKEN), Tokyo, Japan

[o]Department of Astronomy & Astrophysics, University of California, Santa Cruz, CA 95064, USA

[p]Aoyama University, Tokyo, Japan

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 known redshifts. 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 established that the isotropic-equivalent energies and luminosities of GRBs are strongly correlated with redshift, implying 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 is also solving the mystery of "optically dark" GRBs, and revealing the nature of X-ray flashes.

1. Introduction

Gamma-ray bursts (GRBs) are the most brilliant events in the Universe. 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 Gamma-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 [39]. In 1997, results made possible by *Beppo*SAX [10] 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., [28]]. In 2003, results made possible by the High Energy Explorer Satellite 2 (HETE-2) [58] 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 2 1/2 years of operation (compared to 52 GRBs localized by *Beppo*SAX 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 9 *Beppo*SAX bursts with redshift determinations).
- HETE-2 has detected 16 XRFs so far (compared to 17 by *Beppo*SAX).
- HETE-2 has observed 25 bursts from the soft gamma-ray repeaters 1806-20 and 1900+14 in the summer of 2001; 2 in the summer of 2002; and 18 so far in 2003. It has discovered a possible new SGR: 1808-20.
- HETE-2 has observed ~ 170 X-ray bursts (XRBs) in the summer of 2001, > 500 in the summer of 2002, and > 150 so far in 2003 from ~ 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).

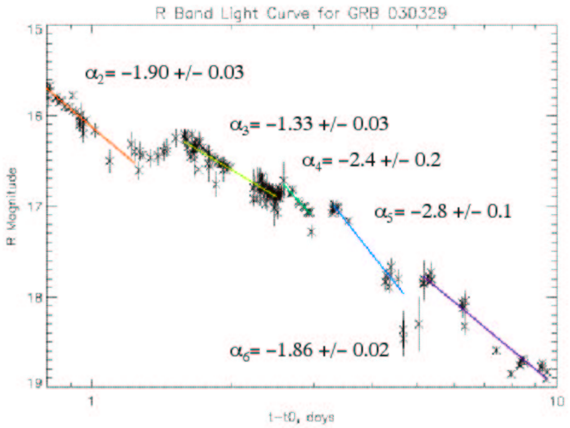

Figure 1. Successive rebrightenings of the optical afterglow of GRB 030329 during the 10 days following the burst. From [14].

- 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 hour “gap” immediately following the burst that existed in the *Beppo*SAX era. This has confirmed the existence of a very bright, distinct phase lasting ≈ 10 minutes.

- 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 essentially no 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.

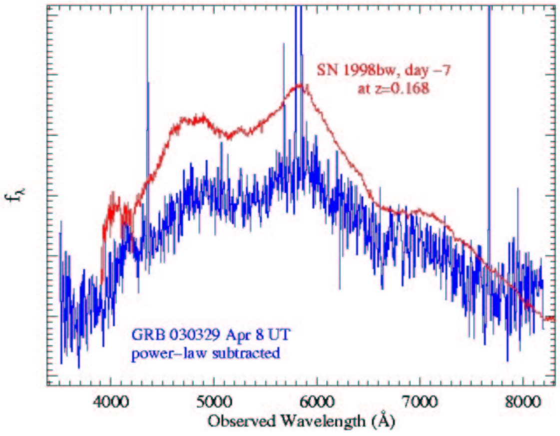

Figure 2. Comparison of the discovery spectrum of SN 2003dh seen in the afterglow of GRB 030329 at 8 days after the burst and the spectrum of the Type Ic supernova SN 1998bw. The similarity is striking. From [56].

- 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. [28]]. The detection and localization of GRB 030329 by HETE-2 [58] 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 $\sim 12^{\rm th}$ magnitude at 1.5 hours after the burst [43] – more than 3 magnitudes brighter than the famous optical afterglow of GRB 990123 at a similar time [1]. In addition, the burst source and its host galaxy lie very nearby, at a redshift $z = 0.167$ [22]. 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 bright spurred the astronomical community – both amateurs and professionals – to make an unprecedented number of observations of the optical afterglow of this event. Figure 1 shows the light curve of the optical afterglow of GRB 030329 1-10 days after the burst. At least four dramatic "re-brightenings" of the afterglow are evident in the saw-toothed lightcurve. These may be due to repeated injections of energy into the GRB jet by the central engine at late times, or caused by the ultra-relativistic jet ramming into dense blobs or shells of material [21]. If the former, it implies that the central engine continued to pour out energy long after the GRB was over; if the latter, it likely provides information about the last weeks and days of the progenitor star.

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 ten days after the burst, the spectral signature of an energetic Type Ic supernova emerged [56]. The supernova has been designated SN 2003dh. Figure 2 compares the discovery spectrum of SN 2003dh in 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 $\approx 36{,}000$ km s^{-1} – far higher than those seen in typical Type Ic supernovae, and higher even than those seen in SN 1998bw. It had been conjectured that GRB 980425 was associated with SN 1998bw [see, e.g., [19]], but the fact that, if the association were true, the burst would have had to have been $\sim 10^4$ times fainter than any other GRB observed to date made the association suspect. The clear detection of SN 2003dh in the afterglow of GRB 030329 confirmed decisively the connection between GRBs and core collapse SNe.

The association between GRB 030329 and SN 2003dh makes it clear that we must understand Type Ic SNe in order to understand GRBs. The converse is also true: we must understand GRBs in order to fully understand Type Ic SNe. It is possible that the creation of a powerful ultra-relativistic jet as a result of the collapse of the core of a massive star to a black hole plays a direct role in Type Ic supernova explosions [38], but it is certain that the rapid rotation of the collapsing core implied by such jets must be an important factor in some – perhaps most – Type Ic supernovae. The result will often be a highly asymmetric explosion, whether the result of rapid rotation alone or of the creation of powerful magnetic fields as a result of the rapid rotation [25].

The large linear polarizations measured in several bright GRB afterglows, and especially the temporal variations in the linear polarization [see, e.g., [50]], provide strong evidence that the Type Ic supernova explosions associated with GRBs are highly asymmetric. The recent dramatic discovery that GRB 021206 was strongly polarized [9] provides compelling evidence that GRB jets are in fact dominated by magnetic energy rather than hydrodynamic energy.

In addition, the X-ray afterglows of several GRBs have provided tantalizing evidence of the presence of emission lines of α-particle nuclei [46,6]. These emission lines, if confirmed, provide severe constraints on models of GRBs and Type Ic supernovae [see, e.g., [35]]. They may also provide information on the abundances and properties of heavy elements that have been freshly minted in the supernova explosion.

It is therefore now clear that GRBs are a unique laboratory for studying, and are a powerful tool for understanding, Type Ic core collapse supernovae. We discuss this in more detail below.

Confirmation by HETE-2 of the connection between GRBs and Type Ic 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

Nothing is known about the distance scale or the nature of short GRBs. *Beppo*SAX did not detect any short, hard GRBs during its 6-year mission, despite extensive efforts. HETE-2's localization of GRB 020531 is the first detection of a short GRB that has allowed rapid optical and X-ray follow-up observations.

The rapid HETE-2 and IPN localizations of GRB 020531 [32] made possible rapid optical (t = 2-3 hours) follow-up observations. No optical afterglow was detected [29,40,12]. Chandra follow-up observations at $t = 5$ days showed that $L_X(\text{short})/L_x(\text{long}) < 0.01 - 0.03$ [5]. These results suggest that real time or near-real time X-ray follow-up observations of short GRBs may be vital to unraveling the mystery of short GRBs.

5. "Optically Dark" GRBs

Only $\approx$ 35% of *Beppo*SAX 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.

Two 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., [28,49]].
- 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 [31].

A third explanation has also been mentioned:

- Some GRBs have afterglows that are intrinsically very faint [see, e.g., [18,42]].

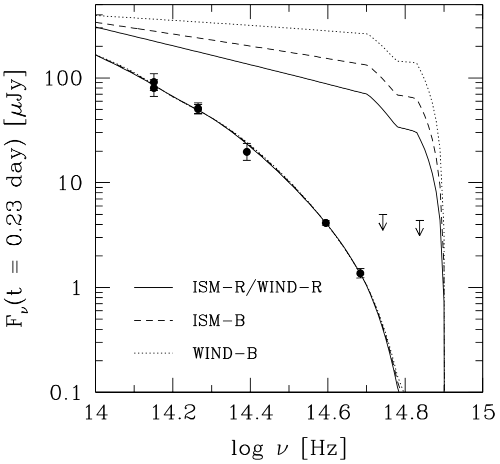

Figure 3. NIR and optical afterglow spectrum of GRB 030115, as determined from K, H, J, i*, and r* observations. The curve that goes through the data points is the best-fit model, assuming extinction by dust of the four theoretical afterglow spectra labeled "ISM-R, WIND-R, ISM-B, WIND-B." The amount 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 [33].

Rapid optical follow-up observations of the HETE-2–localized burst GRB030115 [24] show that the optical afterglow of this burst is by far the best case of case observed to date of a burst whose optical afterglow is extinguished by dust. Figure 3 shows the NIR and optical afterglow spectrum of this burst and the best-fit model, assuming extinction by dust [33]. 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 Figure 3 assumes z = 3.5, the largest

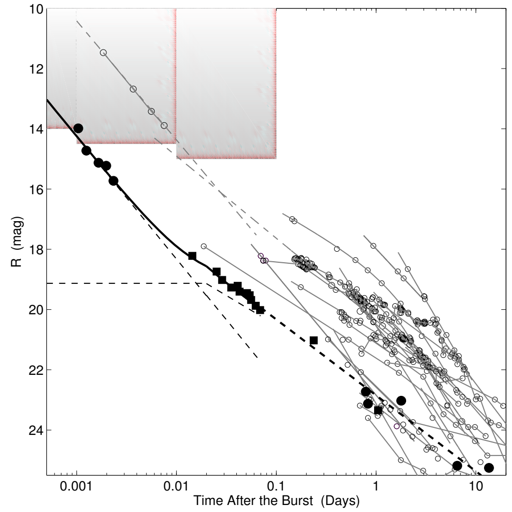

Figure 4. Light curve of the optical afterglow of GRB 021211, compared to those of other GRBs. The dashed curve in the upper left-hand corner of the figure shows the light curve of the optical afterglow of GRB 990123, while the dashed horizontal line in the left-hand middle of the figure shows the light curve of the optical afterglow of GRB 021004. 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 [16].

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.

Rapid optical follow-up observations [16,41,36, 60] of the HETE-2–localized burst GRB 021211 [11] show that the optical afterglow of this burst is intrinsically much fainter than those observed previously. Figure 4 shows the light curve of the afterglow of GRB 021211 [16]. The transition from the reverse shock component [53] to the forward shock component is clearly visible. Figure 4 also compares the afterglow of GRB 021211 to those of other GRBs. 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.

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 HETE-2–localized bursts (e.g., GRB020124) suggest that they too have afterglows that are very faint. GRBs with intrinsically faint afterglows may therefore account for a substantial fraction of bursts previously classified as "optically dark."

Figure 4 also shows for comparison the afterglow light curve of the HETE-2–localized burst GRB 021004. In the case of this burst, the early-time behavior of the afterglow was nearly flat – 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[15]. 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 hours after the burst that existed in the *Beppo*SAX era.

6. GRBs as a Probe of Cosmology and the Early Universe

HETE-2 has decisively confirmed the connection between GRBs and the deaths of massive stars, as we have seen. The earliest massive stars are thought to have formed at redshifts $z \approx 20$ [20,57] and died soon thereafter. Thus GRBs may mark the moment of "first light" and an end to the "dark ages" of the universe. Indeed, recent calculations suggest that 10-40% of all GRBs may lie at very high ($z > 5$) redshifts [31,8,4].

GRBs are far and away the brightest objects in the universe, with γ-ray luminosities that are frequently 10 billion times greater than the optical luminosities of the supernovae with which they are associated, or of their host galaxies. It is no surprise, then, that the bursts are easily detectable out to redshifts $z \approx 20$ by HETE-2.

Somewhat surprisingly, the infrared and near-IR afterglows of GRBs are also detectable out to very high redshifts [31]. The reason is that while the increase in distance and the redshift of

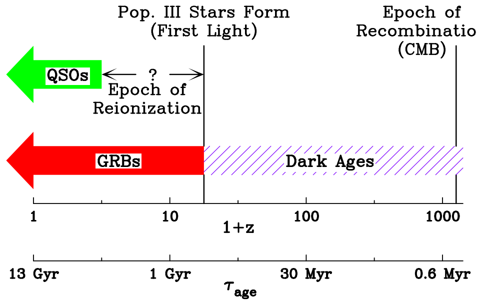

Figure 5. Cosmological context of VHR GRBs. Shown are the epochs of recombination, first light, and re-ionization. Also shown are the ranges of redshifts corresponding to the “dark ages”probed by QSOs and GRBs. From [29].

the spectrum tend to reduce the spectral flux in a given frequency band, cosmological time dilation tends to increase it at a fixed time of observation after the GRB, since afterglow intensities decrease with time. These effects combine to produce little or no decrease – and can even produce an increase – in the spectral energy flux of GRB afterglows beyond $z \approx 3$ [31,8]. Consequently, “optically dark,” but “near-infrared and infrared bright,” GRBs may be a powerful probe of cosmology and the early universe.

Figure 5 places GRBs in a cosmological context [29]. At recombination, which occurs at redshift $z = 1100$, the universe becomes transparent. The cosmic background radiation originates at this redshift. Shortly afterward, the temperature of the cosmic background radiation falls below 3000 K and the universe enters the “dark ages” during which there is no visible light in the universe. “First light,” which occurs at $z \approx 20$, corresponds to the epoch when the first stars form. Ultraviolet radiation from these first stars and/or from the first active galactic nuclei re-ionizes the universe. Afterward, the universe is transparent in the ultraviolet.

Important cosmological questions that observations of GRBs and their afterglows may address include the following [31]:

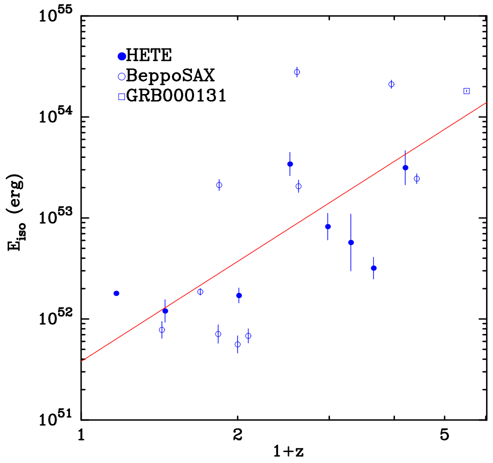

Figure 6. Distribution of *Beppo*SAX and HETE-2 GRBs with known redshifts in the $(1 + z, E_{\rm iso})$-plane, showing that $E_{\rm iso}$, the isotropic-equivalent γ-ray energy of GRBs, is strongly correlated with redshift (the chance probability of such a correlation is 1.5×10^{-3}. The best-fit slope of the correlation is +3.3 and the best-fit width of the smearing function (added in quadrature to the statistical uncertainties of the individual GRBs) is $\sigma_{E_{\rm iso}} = 0.6$. This result implies that *GRBs evolve strongly with redshift.* From [34].

- The moment of “first light” and the earliest generations of stars merely by the detection of GRBs at very high redshifts;

- The re-ionization of the universe by the shape of the red damping wing of the Gunn-Peterson trough due to Lyman α in the spectra of GRB afterglows.

- The history of metallicity growth in the universe – in the star-forming entities in which the bursts occur, in damped Lyman α clouds, and in the Lyman α forest – by observations of metal absorption line systems in the spectra of GRB afterglows; and

- The large-scale structure of the universe at very high redshifts ($z > 5$) by the clustering of Lyman α forest lines and the metal absorption-line systems in the spectra of their afterglows.

The recently announced results from the Wilkinson Microwave Anisotropy Probe indicate that re-ionization of the universe occurred at $z = 17 \pm 5$ [55], far earlier than previously thought. Such redshifts are far beyond those that can be probed using quasars or even Lyα-emission galaxies. In contrast, GRBs are expected to occur out to the redshifts ($z \approx 20$) at which the first stars formed, stars whose UV light evidently re-ionizes the universe. Thus, GRBs can be expected to provide a unique probe of the re-ionization of the universe and the moment of "first light."

HETE-2 has established that the isotropic-equivalent energies $E_{\rm iso}$ and luminosities $L_{\rm iso}$ of GRBs are strongly correlated with redshift [30] (see Figure 6). The observed correlation implies that *GRBs evolve with redshift* – bursts at $z = 5$ are $\sim$ 1000 times more luminous than those at $z = 0$! These results confirm clues to this effect from analyses of the BATSE catalog of GRBs, using the variability of burst time histories as an estimator of burst luminosities (and therefore redshifts) [13,47,48,37], and from an analysis of *Beppo*SAX bursts only [2].

The strong evolution of $E_{\rm iso}$ and $L_{\rm iso}$ with z also has profound implications for the nature of GRB progenitors and for the use of GRBs a a probe of cosmology and the early universe. The HETE-2 results suggest that GRBs at redshifts z = 10 - 20 may be much more luminous – and therefore easier to detect – than has been thought, making GRBs a more powerful probe of the very high redshift universe.

7. Nature of X-Ray Flashes and X-Ray-Rich GRBs

Two-thirds of all HETE-2–localized bursts are either "X-ray-rich" or XRFs, and one-third are XRFs (see Figure 7).[1] These events have received increasing attention in the past several years [23, 26], but their nature remains unknown.

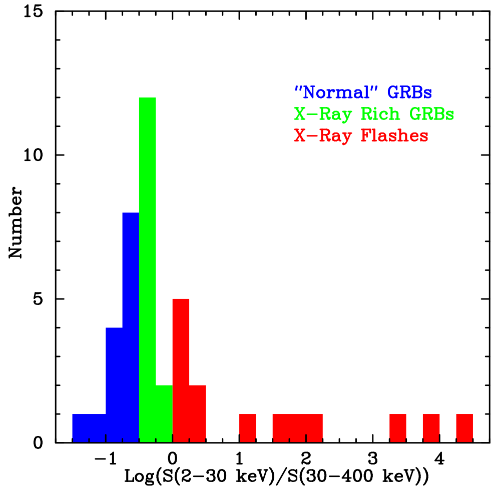

Figure 7. Hardness histogram for HETE-2 GRBs. Shown are GRBs (blue histogram), X-ray-rich GRBs (green histogram), and XRFs (red histogram). From [52].

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 [51] gave an upper limit $E^{\rm obs}_{\rm peak} < 5$ keV (99.7% confidence level) making this event one of the softest bursts seen so far by HETE-2. Follow-up observations made possible by the HETE-2 localization identified the likely optical afterglow of the XRF [54]. Later observations determined that the optical transient occurred in a star-forming galaxy at a distance $z = 0.25$ [54,7]; 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, [52] find that the XRFs, the X-ray-rich GRBs, and GRBs form a continuum in the $[S_\gamma(2-400\ {\rm kev}), E^{\rm obs}_{\rm peak}]$-plane (see Figure 8). This result strongly suggests that all of these events are the same phenomenon.

Furthermore, [34] have placed 9 HETE-2 GRBs with known redshifts and 2 XRFs with known redshifts or strong redshift constraints in the $(E_{\rm iso}, E_{\rm peak})$-plane (see Figure 9). Here $E_{\rm iso}$ is the

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

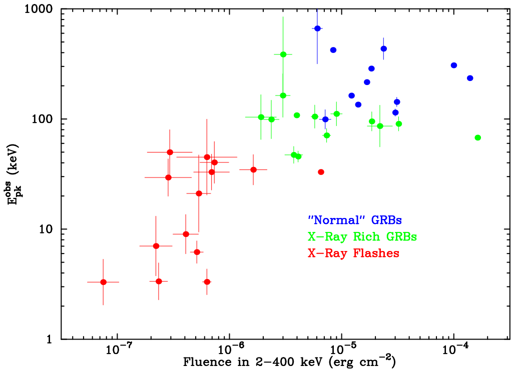

Figure 8. Distribution of HETE-2 bursts in the $[S(2-400\mathrm{keV}), E_{\mathrm{peak}}^{\mathrm{obs}}]$-plane, showing XRFs (red), X-ray-rich GRBs (green), and GRBs (blue). From [52].

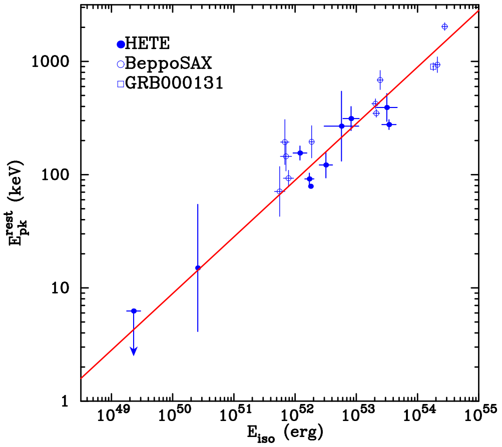

Figure 9. Distribution of HETE-2 and BeppoSAX bursts in the (E_{iso},E_{peak})-plane, where E_{iso} and E_{peak} are the isotropic-equivalent GRB energy and the peak of the GRB spectrum in the source frame. The HETE bursts confirm the relation between E_{iso} and E_{peak} found by Amati et al. (2002), and extend it by a factor $\sim$ 300 in E_{iso}. The bursts with th lowest and second-lowest values of E_{iso} are XRFs 020903 and 030723. From [34].

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. [2] 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 [51,34] provides strong evidence that XRFs and GRBs are the same phenomenon. However, additional redshift determinations are clearly needed for XRFs with 1 keV $< E_{\mathrm{peak}} <$ 30 keV energy in order to confirm these results.

8. 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 gamma-ray repeaters, and more than 700 X-ray bursts.

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 established that the isotropic-equivalent energies and luminosities of GRBs are strongly correlated with redshift, implying 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 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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