Observations of Gamma-Ray Bursts by HETE-2


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Abstract

The High Energy Transient Explorer 2 (HETE-2), launched in October 2000, is currently localizing gamma-ray bursts (GRBs) at a rate of \(\sim 20 \text{ yr}^{-1}\), many in real time. As of August 2003, HETE-2 had localized 43 GRBs; 16 localizations had led to the detection of an X-ray, optical, or radio afterglows. The prompt position notification of HETE-2 enabled probing the nature of so-
called “dark bursts” for which no optical afterglows were found despite of accurate localizations. In some cases, the optical afterglow was found to be intrinsically faint, and its flux declined rapidly. In another case, the optical emission was likely to be extinguished by the dust in the vicinity of the GRB source. The bright afterglows of GRB021004 and GRB030329 were observed in unprecedented details by telescopes around the world. Strong evidence for the association of long GRBs with the core-collapse supernovae was found. HETE-2 has localized almost as many X-ray rich GRBs as classical GRBs. The nature of the X-ray rich GRBs and X-ray flashes have been studied systematically with HETE-2, and they are found to have many properties in common with the classical GRBs, suggesting that they are a single phenomenon.

1. Mission overview

The primary goals of the HETE mission are the multiwavelength observation of GRBs and the prompt distribution of precise GRB coordinates to the astronomical community for immediate follow-up observations [30]. To achieve these goals, HETE-2 is equipped with one gamma-ray (French Gamma Telescope; FREGATE [3]) and two X-ray detectors (Wide-Field X-ray Monitor; WXM [17] and Soft X-ray Camera; SXC [41]), which share a common field of view of \( \sim 1.5 \) steradians, and, together, are sensitive to photons in the energy range of 2 keV to over 400 keV. The two X-ray detectors are coded-aperture imagers. Once a GRB is detected by HETE-2, sophisticated on-board processing software allows
the location to be calculated on board in real time, and it is then immediately broadcasted to the ground in VHF. A network of the secondary ground stations, which are distributed around the equator to have nearly uninterrupted contact with HETE-2, receives the localization alert and transmits to the MIT mission operation center. The GRB coordinates are then distributed to the interested observers through the GRB Coordinates Network (GCN). After the observation data products are downlinked via the primary ground stations, ground post-burst analyses will provide refined localizations. The typical accuracy (90% error radius) is 30 arcmin (WXM real-time flight localization), 10 arcmin (WXM ground analysis), and 2 arcmin (SXC ground analysis) [38].

HETE-2 was launched successfully on October 9, 2000 0538(UT) with a Pegasus Rocket on the ocean near the Kwajalein Atoll of the republic of Marshall Islands at the center of the Pacific Ocean. The orbit is semicircular low-earth orbit with the apogee of 635 km and perigee of 595 km, and inclination of 1.95°. The orbit life is sufficiently long to support its planned mission life of two years with possible extension of extra few years. The operational status of the HETE-2
Table 1. Scientific Instruments of HETE-2.

<table>
<thead>
<tr>
<th></th>
<th>FREGATE</th>
<th>WXM</th>
<th>SXC$^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Built by</td>
<td>CESR</td>
<td>RIKEN, LANL</td>
<td>MIT CSR</td>
</tr>
<tr>
<td>Instrument type</td>
<td>NaI(Tl); cleaved Scintillator (Xe 1.4 atm) (15 µm pixel)</td>
<td>1-dim PSC</td>
<td>CCD</td>
</tr>
<tr>
<td>Energy Range</td>
<td>6–400 keV</td>
<td>2–25 keV</td>
<td>1.3–14 keV</td>
</tr>
<tr>
<td>Resolution</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Timing</td>
<td>10 µs</td>
<td>1 ms</td>
<td>1.2 s</td>
</tr>
<tr>
<td>Spectral</td>
<td>25% (20 keV)</td>
<td>22% (8 keV)</td>
<td>∼300 eV</td>
</tr>
<tr>
<td>Angular</td>
<td>–</td>
<td>±11' (at 8 keV)</td>
<td>±33''</td>
</tr>
<tr>
<td>Effective Area$^a$</td>
<td>120 cm$^2$</td>
<td>350 cm$^2$</td>
<td>37 cm$^2$</td>
</tr>
<tr>
<td>Coded Mask</td>
<td>N. A.</td>
<td>1/3 open</td>
<td>1/5 open</td>
</tr>
<tr>
<td>Sensitivity (10 σ)</td>
<td>3 × 10$^{-8}$</td>
<td>8 × 10$^{-9}$</td>
<td>3 × 10$^{-8}$</td>
</tr>
<tr>
<td>(erg cm$^{-2}$s$^{-1}$)</td>
<td>(8 keV–1 MeV)</td>
<td>(2 keV–10 keV)</td>
<td>(1.4–10 keV)</td>
</tr>
<tr>
<td>Field of View</td>
<td>3 str</td>
<td>1.6 str</td>
<td>1.3 str</td>
</tr>
</tbody>
</table>

$^a$ Total effective area on the detector surface. $^b$ Current values after loss of the optical blocking filters.

mission at the present time is still excellent.

On orbit, the HETE spacecraft point preferentially in the anti-solar direction for optimal exposure of the solar panels to the Sun. As a result, most bursts detected by HETE are found at least 120 degrees from the Sun and, therefore, in prime position for observations by ground-based optical observers. The scientific instruments operate during orbit twilight and night, when the Earth is not blocking their view. Head-nodding was implemented in the spring of 2002, which has enabled HETE-2 to maintain real-time aspect during the full moon, and to point away from Sco X-1 and the X-ray sources in the Galactic bulge during the period May–July, thereby markedly reducing the X-ray background and the rate of non-GRB triggers.

The WXM instrument and flight software are working well. Forty GRB localizations have been sent out within 1–2 hours, and 12 real-time GRB localizations have been sent out. Operational efficiency continues to be excellent, despite the loss of one of the four cameras (“YB camera”) in January 2003, resulting from an impact by a micrometeorite or space debris, which reduced the field of view of the WXM by ≈ 20%. The loss of optical blocking filters four months af-
Fig. 3. Skymaps for GRB021211 and GRB030115. Rapid and accurate localization by the HETE-2 WXM plus SXC led to the identification of the optical transient (“O.T.” in the map) or the infrared transient (“I.R.T” in the map).

ter launch due to higher than predicted concentrations of oxygen at the altitude of the HETE-2 orbit had limited the capability of SXC. However, new software uploaded to the SXC in the summer of 2002 brought the localization capabilities of the SXC back to near pre-launch expectations.

Fifteen GRBs have been localized to 2 arcminute precision by the SXC plus WXM within \( \sim 1-2 \) hours of the trigger. These localizations are accurate enough to allow large telescopes to search for optical counterparts at faint limiting magnitudes. Fourteen of fifteen SXC plus WXM localizations have led to the identification of a counterpart at optical, X-ray, and/or radio wavelengths.

2. Scientific Highlights of HETE-2

2.1. “Optically Dark” GRBs

Only \( \approx 35\% \) of BeppoSAX localizations of GRBs led to the identification of an optical afterglow. In contrast, 13 of the 15 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.

Following explanations of “optically dark” GRBs have been 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., [20], [29]).
- 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 [21].

• Some GRBs have afterglows that are intrinsically very faint [see, e.g., [9], [27]].

HETE-2 localized burst GRB030115 [18] is by far the best case of a burst whose optical afterglow is extinguished by dust. Rapid follow-up observations of this burst revealed an infrared afterglow [15],[23], while the optical afterglow was very dim, and yet its host galaxy was visible in optical.

In some cases, the optical afterglows are found to be intrinsically dim. Near-real time optical followup observations [7],[26],[24],[42] of an X-ray rich gamma-ray burst GRB021211, which was localized by HETE-2 in real time [6], showed that its afterglow was bright at R ≈ 14 at t ≈ 100 seconds after the GRB, but quickly faded and was very much fainter at t > 60 minutes than that have been observed previously. Without the prompt, accurate localization of HETE-2, the optical transient would not have been discovered, and this GRB would have been categorized as a “optically dark” GRB. 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.” No such case has been identified yet.

2.2. Detailed light curve study

The early discoveries of optical transients also enabled the study of their light curves in details, which were not possible before. In the light curve of the optical afterglow of GRB021211 from 104 seconds after the start of the burst to ≈ 170 minutes after the burst [24], the transition from the reverse shock component [33] to the forward shock component is clearly visible. Comparison with light curves with other GRBs shows that the light curve of the afterglow of GRB021211 tracks that of the afterglow of GRB990123 but is three magnitudes fainter. GRB021004 and GRB030329 were observed by tens of telescopes around the world thanks to the very early discovery of bright optical afterglows. Deviations from the simple power-law description of the decay are common. Continuous energy injection is discussed to account for the plateau in the very early light curve of the afterglow of GRB021004 [8]. Repeated breaks, flattenings, and rebrightenings have been found in the light curve of GRB030329 afterglow, which can be caused by the additional repeated injections of explosion energy, and/or variation in the circumstellar density. Evidence for the supernova components was found
to emerge in the optical spectrum of the GRB030329 afterglow [11], establishing the association of (at least some of) the long GRBs with the core-collapse type supernovae.

2.3. **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. [20]]. In particular, detection of a powerful type Ic supernova SN1998bw positionally and temporally coincident with GRB980425 have been often discussed as evidence for the GRB-SN association [see, e.g., [10]]. However, the low redshift of SN1998bw ($z \approx 0.008$) implied that the gamma-ray luminosity of GRB980425 was $\sim 10^4$ times fainter than any other GRB observed to date. If their association is real, GRB980425 may not be a typical cosmological gamma-ray burst.

The detection and localization of GRB 030329 by HETE-2 [39] led to a dramatic confirmation of the GRB – SN connection. GRB 030329 was among the brightest 1% of GRBs ever seen (see Fig. 4.). Its optical afterglow was $\sim 12^\text{th}$ magnitude at 1.5 hours after the burst [28] – more than 3 magnitudes brighter than the optical afterglow of GRB 990123 (which is famous for its bright optical flash) at a similar time [1]. In addition, the burst source and its host galaxy lie very nearby, at a redshift $z = 0.167$ [12]. Given that GRBs typically occur at $z \sim 1 - 2$, the probability that the source of an observed burst should be as close as GRB 030329 is one in several thousand.

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. More than 170 GCN Cir-
culars have appeared so far, reporting optical, IR, and radio observations of the afterglow.

About ten days after the burst, the spectral signature of an energetic Type Ic supernova emerged [36] on top of the usual GRB afterglow continuum of non-thermal synchrotron emission. The underlying supernova has been designated SN 2003dh. The spectrum of SN 2003dh is strikingly similar to that of the Type Ic supernova SN 1998bw, which was putatively associated with GRB980425. 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.

Time evolution of the spectral features and the intensity of SN 2003dh also resemble those of SN 1998bw at similar time interval (in the redshift-corrected source frames), showing that the two supernovae evolved in time in nearly identical ways [14],[16].

It had been conjectured that GRB 980425 was associated with SN 1998bw, 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.

We note, however, that evidence for association with supernovae has been found only with the “long soft” GRBs. We have no clue for “short hard” GRBs, which constitutes \( \sim 20\% \) of the GRB population and for which no optical afterglows have been found.

2.4. X-ray Flashes

HETE-2 is detecting X-ray flashes (XRFs), which are similar to regular “classical” GRBs in many ways except that XRFs have larger fluence in the X-ray band (2–30 keV) than in the gamma-ray band (30–400 keV). XRFs have received increasing attention in the past several years [13] [19].

XRFs have \( t_{90} \) durations between 10 and 200 sec [37]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 \( \sim -2.5 \), respectively, which are similar to those of GRBs, but that the XRFs had spectral peak energies \( E_{\text{peak}}^{\text{obs}} \) that were much lower than those of GRBs [19]. The only difference between XRFs and GRBs therefore appears to be that XRFs have lower \( E_{\text{peak}}^{\text{obs}} \) values. It
Fig. 5. WXM spectrum of XRF 020903; the spectrum has a peak energy $E_{\text{peak}}^{\text{obs}} < 5$ keV, making it one of the softest events observed so far by HETE-2. From [32].

Fig. 6. (right) The energy resolved light curves of GRB020903 in 1.0 second resolution. The two spectral regions are shown in the dotted lines.

has therefore been suggested that XRFs might represent an extension of the GRB population to bursts with low peak energies.

Some of the possibilities popularly discussed are: i) XRFs represent a very high-z population of GRBs with its photon energies redshifted down into the X-ray range; ii) XRFs have jets with intrinsically lower Lorentz factor; iii) lower Lorentz factor components of structured jets are seen as XRFs; and iv) XRFs have lower relativistic beaming due to large off-axis viewing angles. 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 low energy threshold of WXM, SXC (2 keV) and FREGATE (6 keV), and the effective areas at X-ray energies of these instruments make HETE-2 ideal for detecting and studying XRFs. Unlike previous missions (Ginga, BATSE, and BeppoSAX), HETE-2 has the ability to trigger on and localize XRFs, and can carry out detailed studies of their spectral properties using FREGATE and the WXM.

2.4.1. XRF020903

One of the softest event HETE-2 localized is XRF020903: The upper limit $E_{\text{peak}}^{\text{obs}} < 5$ keV (99.7% confidence level) makes this event one of the softest bursts seen so far by HETE-2, and no photons were significantly detected above $\sim$
Fig. 7. Distribution of the fluence ratio of 2–30 keV to 30–400 keV in the logarithmic scale. The dashed lines are the borders of hard GRB/X-ray rich GRB, and X-ray rich GRB/XRF.

10 keV [32] (see its spectrum in Fig. 5.) The light curve (6.) exhibits a double-peak structure, and the burst duration is shorter at higher energies. These are commonly seen in “classical” long GRBs. Follow-up observations made possible by the HETE-2 localization identified the likely optical afterglow of the XRF [34]. Later observations determined that the optical transient occurred in a star-forming galaxy at a distance $z = 0.25$ [35],[5]; both of these properties are typical of GRB host galaxies.

2.4.2. General properties

The fluence ratio distribution between 2–30 keV ($S_X$) and 30–400 keV ($S_\gamma$) is shown in Fig. 7. for a sample of HETE-localized bursts which have sufficient photon statistics in WXM and/or FREGATE for spectral analysis. Here we define XRFs, X-ray rich GRBs, and hard GRBs as those events for which $\log(S_X/S_\gamma) > 0$, $-0.5 < \log(S_X/S_\gamma) \leq 0$, and $\log(S_X/S_\gamma) \leq -0.5$ respectively. According to this working definition, the HETE-2 localized bursts are classified to approximately equal numbers of hard GRBs, X-ray rich GRBs and XRFs.

When the 30–400 keV fluence is plotted against the 2–30 keV fluence (Fig. 8.), we find that not only the XRFs have lower gamma-ray fluence, but also they tend to have lower X-ray fluence among the entire sample. Accordingly, the spectral peak energies ($E_{\text{peak}}$) and the peak flux in the gamma-ray band (50–300 keV) shows a strong correlation (Fig. 9.). We find that the spectral properties
Fig. 8. Distribution of HETE-2 bursts in the \((S_X,S_\gamma)\)-plane. \(S_X\) and \(S_\gamma\) are the energy fluence in the 2–30 keV and the 30–400 keV energy ranges respectively. The marks below the dashed lines are XRFs, the marks above the dot-dashed lines are hard (classical) GRBs, and the marks between are X-ray rich GRBs.

Fig. 9. Distribution of HETE-2 bursts in the peak photon flux (50–300 keV) vs. \(E_{\text{peak}}\) plane. The flux is measured as the average over the 1 s at the peaks. A strong correlation is seen despite the fact that these bursts are sampled from various redshifts.
Fig. 10. Distribution of HETE-2 and BeppoSAX bursts in the \((E_{\text{iso}}, E_{\text{peak}})\)-plane, where \(E_{\text{iso}}\) and \(E_{\text{peak}}\) are the isotropic-equivalent GRB energy and the peak of the GRB spectrum in the source frame. The HETE bursts confirm the relation between \(E_{\text{iso}}\) and \(E_{\text{peak}}\) found by Amati et al. [2], and extend it by a factor \(\sim 300\) in \(E_{\text{iso}}\). The bursts with the lowest value of \(E_{\text{iso}}\) is XRF020903. The dashed line is \(E_{\text{src}, \text{peak}} = 89 \left(\frac{E_{\text{iso}}}{10^{52} \text{ erg}}\right)^{0.5}\).

of XRFs and “X-ray rich” GRBs form a continuum with those of ordinary GRBs and suggest that XRFs may represent a further extension of this continuum. XRF 020903 lies on the hard/soft fluence correlation for the other GRBs and X-ray-rich GRBs, and appears to extend by a decade the hardness-intensity correlation [25].

This correlation is not easy to understand, since the GRBs and XRFs plotted here are supposedly sampled from a wide range of redshifts from \(z < 0.5\) to \(z > 3\); the effect of distance (redshift) on the observed flux, which should be much larger than that on \(E_{\text{peak}}\), would weaken the intrinsic correlation.

In fact, the properties in the source frame of the GRBs have a surprisingly tight correlation. Using twelve BeppoSAX GRBs with measured redshifts, Amati et al. [2] showed that the spectral peak energy at the source frame \(E_{\text{src}, \text{peak}}\) and the isotropic-equivalent radiated energy \(E_{\text{iso}}\) are tightly correlated, and follows a relation \(E_{\text{src, peak}} \propto E_{\text{iso}}^{1/2}\). With the 10 HETE GRBs/XRFs with measured redshifts (Fig. 10,) we have confirmed this relation. Furthermore, we extended this relation by three orders of magnitude in \(E_{\text{iso}}\).

These results provide strong evidence that XRFs, X-ray-rich GRBs form a continuum, and are a single phenomenon. The extended Amati et al relation \((E_{\text{peak}} \propto E_{\text{iso}}^{1/2})\) suggest that the \(E_{\text{src, peak}}\) and \(E_{\text{iso}}\) are controlled by some single pa-
rameter, which differentiate XRFs and GRBs. Understanding this key parameter should certainly lead to the understanding of the energetics and radiation mechanism of GRBs. There are several theoretical proposals for the the nature of XRFs: “off-axis jet” model ([43]; [44]), “structure jet” model ([31], “unified jet” model ([22]), and so on. In order to understand the nature of GRBs and XRFs, it is essential to obtain larger sample of XRFs and GRBs with measured redshifts. In particular, additional redshift determinations are clearly needed for XRFs with $1 \text{ keV} < E_{\text{peak}} < 30 \text{ keV}$ in order to confirm these results and to test the theories.

3. Conclusion

HETE-2 has provided accurate and rapid localizations of gamma-ray bursts (GRBs), and has contributed in establishing the association of long soft GRBs with core-collapse supernovae. The early afterglows in the first two hours have been measured for the first time with the HETE-localized GRBs, and have provided the information on the environment and the energetics of GRBs. It is also solving the mystery of “optically dark” GRBs, and revealing the nature of X-ray flashes (XRFs). The relation between the spectral peak energy and the isotropic-equivalent radiated energy (both in the source frame) have been confirmed for GRBs and extended for XRFs. These new results from HETE-2 have shown that XRFs provide unique insights into the structure of GRB jets, the rate of GRBs, and the nature of Type Ic supernovae.

The wide energy coverage (2–400 keV) of HETE-2 makes it ideal for detecting and studying most of XRFs and hard GRBs at the same time. In contrast, BAT on *Swift* has a nominal energy range of 15–150 keV, and will have difficulty for determining the spectral peak energy $E_{\text{peak}}$ for very soft XRFs and very hard GRBs. While Swift is expected be a very powerful observatory for detecting numerous GRBs and studying their afterglows, HETE-2 is complementary to *Swift*. The scientific discoveries that HETE-2 has made need to be confirmed and proceeded with further operation of HETE-2 in synergy with *Swift* in the coming years.

References

[38] Tamagawa, T. et al. 2003, this proceedings.