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Gamma-Ray Bursts as a Laboratory for the Study of Type Ic Supernovae

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HETE-2 has confirmed the connection between GRBs and Type Ic supernovae. Thus we now know that the progenitors of long GRBs are massive stars. HETE-2 has also provided strong evidence that the properties of X-Ray Flashes (XRFs) and GRBs form a continuum, and therefore that these two types of bursts are the same phenomenon. We show that both the structured jet and the uniform jet models can explain the observed properties of GRBs reasonably well. However, if one tries to account for the properties of both XRFs and GRBs in a unified picture, the uniform jet model works reasonably well while the structured jet model fails utterly. The uniform jet model of XRFs and GRBs implies that most GRBs have very small jet opening angles (∼ half a degree). This suggests that magnetic fields play a crucial role in GRB jets. The model also implies that the energy radiated in gamma rays is ∼ 100 times smaller than has been thought. Most importantly, the model implies that there are $\sim 10^4 - 10^5$ more bursts with very small jet opening angles for every such burst we see. Thus the rate of GRBs could be comparable to the rate of Type Ic core collapse supernovae. Accurate, rapid localizations of many XRFs, leading to identification of their X-ray and optical afterglows and the determination of their redshifts, will be required in order to confirm or rule out these profound implications. HETE-2 is ideally suited to do this (it has localized 16 XRFs in ∼ 2 years), whereas Swift is not. The unique insights into the structure of GRB jets, the rate of GRBs, and the nature of Type Ic supernovae that XRFs may provide therefore constitute a compelling scientific case for continuing HETE-2 during the Swift mission.

1.1 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. It is the last topic that we focus on here.

1.2 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., 2003a) led to a dramatic confirmation of the GRB – SN connection. GRB 030329 was among the brightest 1% of GRBs ever seen (see Figure 2). Its optical afterglow was $\sim 12^{\rm th}$ magnitude at 1.5 hours after the burst (Price et al., 2003) – more than 3 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 bright spurred the astronomical community – both amateurs and professionals – to make an unprecedented number of observations of the optical afterglow of this event. Figure 1.1 (left panel) 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 (Granot, Naka & Piran, 2003). 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

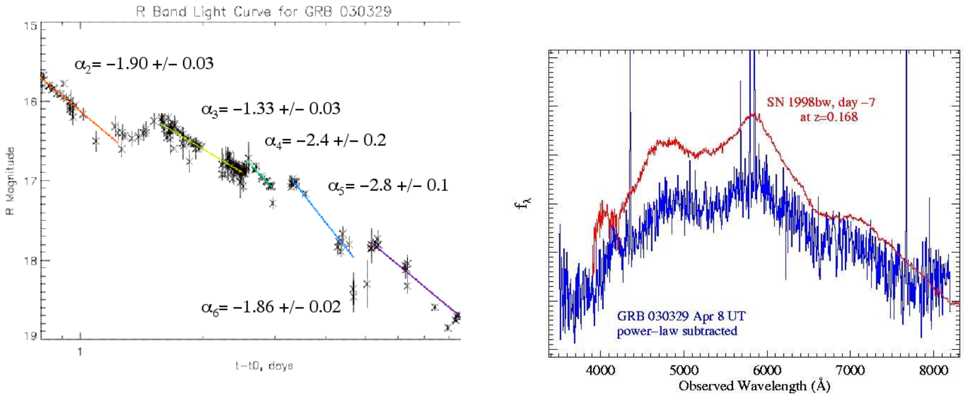

Fig. 1.1. Left panel: Successive rebrightenings of the optical afterglow of GRB 030329 during the 10 days following the burst. From (Fillipenko, 2003). Right panel: Comparison of the discovery spectrum of SN 2003dh seen in the afterglow of GRB 030329 at 8 days after the burst and the spectrum of the Type Ic supernova SN 1998bw. The similarity is striking. From Stanek et al. (2003).

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 (Stanek et al., 2003). The supernova has been designated SN 2003dh. Figure 1.1 (right panel) 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., Galama et al. (1998)], 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 (MacFadyen, Woosley & Heger, 2001), 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 (Khokhlov et al., 1999).

The large linear polarizations measured in several bright GRB afterglows, and especially the temporal variations in the linear polarization [see, e.g., Rol et al. (2003)], 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 (Coburn & Boggs, 2003) 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 (Reeves et al., 2002; Butler et al., 2003). These emission lines, if confirmed, provide severe constraints on models of GRBs and Type Ic supernovae [see, e.g., Lazzati, Ramirez-Ruiz & Rees (2002)]. 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.

1.3 Nature of X-Ray Flashes and X-Ray-Rich GRBs

Two-thirds of all HETE-2–localized bursts are either "X-ray-rich" or X-Ray Flashes (XRFs); of these, one-third are XRFs † (Sakamoto et al., 2003b). These events have received increasing attention in the past several years (Heise et al., 2000; Kippen et al., 2002), but their nature remains unknown.

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. Analyzing 42 X-ray-rich GRBs and XRFs seen by FREGATE and/or the WXM instruments on HETE-2, Sakamoto et al. (2003b) find that the XRFs, the X-ray-rich GRBs, and GRBs form a continuum in the $[S_\gamma(2-400 \text{ kev}), E^{\text{obs}}_{\text{peak}}]$-plane (see Figure 1.2, left-hand panel). This result strongly suggests that all of these events are the same phenomenon.

Furthermore, Lamb et al. (2003c) 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 Figure 1.2, right-hand panel). Here E_{iso} is the isotropic-equivalent burst energy and E_{peak} is the energy of the

† 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.

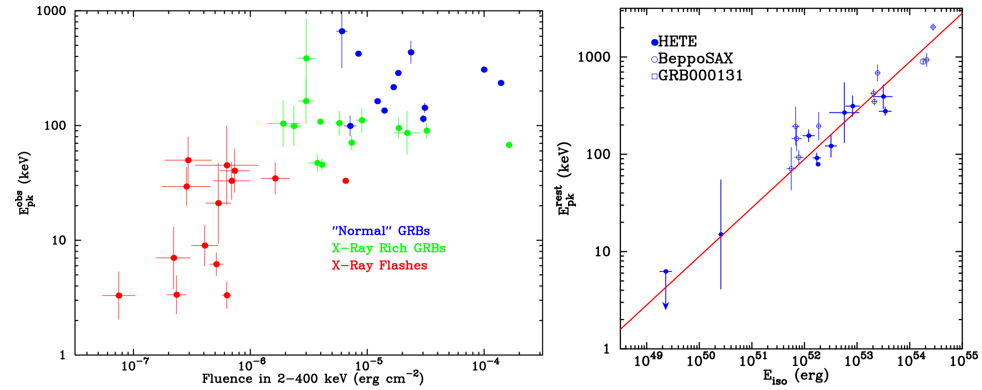

Fig. 1.2. Distribution of HETE-2 bursts in the $[S(2-400 \text{ keV}), E_{\text{peak}}^{\text{obs}}]$-plane, showing XRFs (red), X-ray-rich GRBs (green), and GRBs (blue) (left panel). From Sakamoto et al. (2003b). Distribution of HETE-2 and BeppoSAX bursts in the (E_{iso},E_{peak})-plane, where E_{iso} and E_{peak} are the isotropic-equivalent GRB energy and the peak of the GRB spectrum in the source frame (right panel). The HETE-2 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 the lowest and second-lowest values of E_{iso} are XRFs 020903 and 030723. From Lamb et al. (2003c).

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., 2003a; Lamb et al., 2003c) provides strong evidence that XRFs and GRBs are the same phenomenon. However, additional redshift determinations are clearly needed for XRFs with 1 keV $< E_{\text{peak}} <$ 30 keV energy in order to confirm these results.

1.4 XRFs as a Probe of Type Ic Supernovae

Frail et al. (2001; see also Bloom et al. 2003) have shown that most GRBs have a "standard" energy; i.e, if their isotropic equivalent energy is corrected for the jet opening angle inferred from the jet break time, most GRBs have the same radiated energy, $E_\gamma = 1.3 \times 10^{51}$ ergs, to within a factor of $\pm$ 2-3.

Two models of GRB jets have received widespread attention:

- The "structured jet" model (see the left-hand panel of Figure 1.3). In this model, all GRBs produce jets with the same structure (Rossi, Lazzati, & Rees , 2002; Woosley, Zhang, & Heger , 2003; Zhang & Mészáros , 2002;

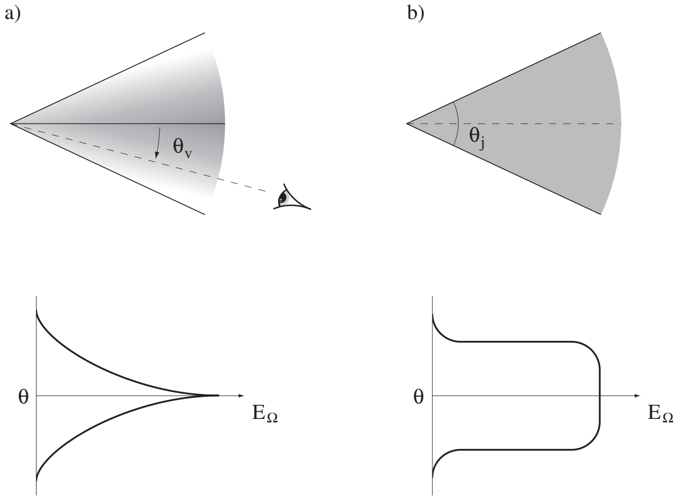

Fig. 1.3. Schematic diagrams of universal jet model and jet model of GRBs (Ramirez-Ruiz & Lloyd-Ronning, 2002). In the universal jet model, the isotropic-equivalent energy and luminosity is assumed to decrease as the viewing angle θ_v as measured from the jet axis increases. In order to recover the "standard energy" result (Frail et al., 2001), $E_{\rm iso}(\theta_v) \sim \theta_v^{-2}$ is required. In the uniform jet model, GRBs produce jets with a large range of jet opening angles $\theta_{\rm jet}$. For $\theta < \theta_{\rm jet}$, $E_{\rm iso}(\theta_v) =$ constant while for $\theta > \theta_{\rm jet}$, $E_{\rm iso}(\theta_v) = 0$.

Mészáros, Ramirez-Ruiz, Rees, & Zhang , 2002). The isotropic-equivalent energy and luminosity is assumed to decrease as the viewing angle θ_v as measured from the jet axis increases. The wide range in values of $E_{\rm iso}$ is attributed to differences in the viewing angle θ_v. In order to recover the "standard energy" result (Frail et al., 2001), $E_{\rm iso}(\theta_v) \sim \theta_v^{-2}$ is required (Zhang & Mészáros , 2002).

- The "uniform jet" model (see the right-hand panel of Figure 1.3). In this model GRBs produce jets with very different jet opening angles $\theta_{\rm jet}$. For $\theta < \theta_{\rm jet}$, $E_{\rm iso}(\theta_v) =$ constant while for $\theta > \theta_{\rm jet}$, $E_{\rm iso}(\theta_v) = 0$.

As we have seen, HETE-2 has provided strong evidence that the properties of XRFs, X-ray-rich GRBs, and GRBs form a continuum, and that these bursts are therefore the same phenomenon. If this is true, it immediately implies that the E_γ inferred by Frail et al. (2001) is too large by a factor of at least 100 (Lamb, Donaghy & Graziani, 2003). The reason is that the values of $E_{\rm iso}$ for XRF 020903 (Sakamoto et al., 2003a) and XRF 030723 (Lamb et al., 2003c) are $\sim$ 100 times smaller than the value of E_γ inferred by Frail et al. – an impossibility.

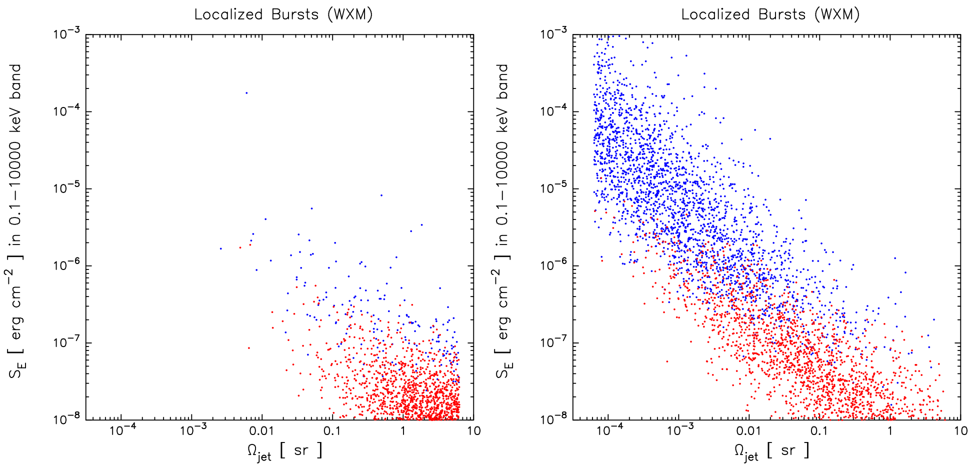

Fig. 1.4. Expected distribution of bursts in the $(\Omega_{\rm jet}, S_E)$-plane for the universal jet model (left panel) and uniform jet model (right panel), assuming that the Amati et al. (2002) relation holds for XRFs as well as for GRBs, as the HETE-2 results strongly suggest. From Lamb, Donaghy & Graziani (2003).

HETE-2 has also provided strong evidence that, in going from XRFs to GRBs, $E_{\rm iso}$ changes by a factor $\sim 10^5$ (see Figure 1.2, right-hand panel). If one tries to explain only the range in $E_{\rm iso}$ corresponding to GRBs, both the uniform jet model and the structured jet model work reasonably well. However, if one tries to explain the range in $E_{\rm iso}$ of a factor $\sim 10^5$ that is required in order to accommodate both XRFs and GRBs in a unified description, the uniform jet works reasonably well while the structured jet model fails utterly.

The reason is the following: the observational implications of the structured jet model and the uniform jet model differ dramatically if they are required to explain XRFs and GRBs in a unified picture. In the structured jet model, most viewing angles θ_v are $\approx 90°$. This implies that the number of XRFs should exceed the number of GRBs by many orders of magnitude, something that HETE-2 does not observe (see Figures 1.2, 1.4, and 1.5). On the other hand, by choosing $N(\Omega_{\rm jet}) \sim \Omega_{\rm jet}^{-2}$, the uniform jet model predicts equal numbers of bursts per logarithmic decade in $E_{\rm iso}$ (and S_E), which is exactly what HETE-2 sees (again, see Figures 1.2, 1.4, and 1.5) (Lamb, Donaghy & Graziani, 2003).

Thus, if $E_{\rm iso}$ spans a range $\sim 10^5$, as the HETE-2 results strongly suggest, the uniform jet model can provide a unified picture of both XRFs and GRBs, whereas the structured jet model cannot. This means that XRFs provide a powerful probe of GRB jet structure.

A range in $E_{\rm iso}$ of 10^5, which is what the HETE-2 results strongly suggest, requires a *minimum* range in $\Delta\Omega_{\rm jet}$ of $10^4 - 10^5$ in the uniform jet model. Thus the unified picture of XRFs and GRBs in the uniform jet model implies that there are $\sim 10^4 - 10^5$ more bursts with very small $\Omega_{\rm jet}$'s for every such burst we see; i.e., the rate of GRBs may be ~ 100 times greater than has been thought.

In addition, since the observed ratio of the rate of Type Ic supernovae to the rate of GRBs in the observable universe is $R_{\rm Type\ Ic}/R_{\rm GRB} \sim 10^5$ (Lamb, 1999), a unified picture of XRFs and GRBs in the uniform jet model implies that roughly *all* Type Ic supernovae produce high-energy transients (Lamb, Donaghy & Graziani, 2003). More spherically symmetric jets yield XRFs and narrow jets produce GRBs. Thus XRFs and GRBs provide a combination of GRB/SN samples that would enable astronomers to study the relationship between the degree of jet-like behavior of the GRB and the properties of the supernova (brightness, polarization $\Leftrightarrow$ asphericity of the explosion, velocity of the explosion $\Leftrightarrow$ kinetic energy of the explosion, etc.). GRBs may therefore provide a unique laboratory for understanding Type Ic core collapse supernovae.

A unified picture of XRFs and GRBs in the uniform jet model also implies that most Type Ic supernovae produce narrow jets, which may suggest that the collapsing cores of most Type Ic supernovae are rapidly rotating. Finally, such a unified picture implies that the total radiated energy in gamma rays E_γ is ~ 100 times smaller than has been thought (Lamb, Donaghy & Graziani, 2003).

As we have seen, the HETE-2 results provide strong evidence that XRFs and GRBs are the same phenomenon. But the profound implications of these results in terms of the structure of GRB jets, the rate of GRBs, and the nature of Type Ic supernovae, require incontrovertible evidence.

Obtaining the incontrovertible evidence needed to sustain (or refute) these implications will require accurate, rapid localizations of XRFs, leading to identification of their X-ray and optical afterglows and the determination of their redshifts. Until very recently, only one XRF (XRF 020903; Soderberg et al. 2002) had even a probable optical afterglow and redshift. The reason why is that, as expected in the uniform jet picture, the X-ray (and therefore the optical) afterglows of XRFs are $\sim 10^3 - 10^4$ times fainter than those of GRBs (Lamb, Donaghy & Graziani, 2003). But this challenge can be met: the recent HETE-2–localization of XRF 030723 represents the first time that an XRF has been localized in real time (Prigozhin et al., 2003); identification of its X-ray and optical afterglows rapidly followed (Fox et al., 2003c). This event may well be the Rosetta stone for XRFs.

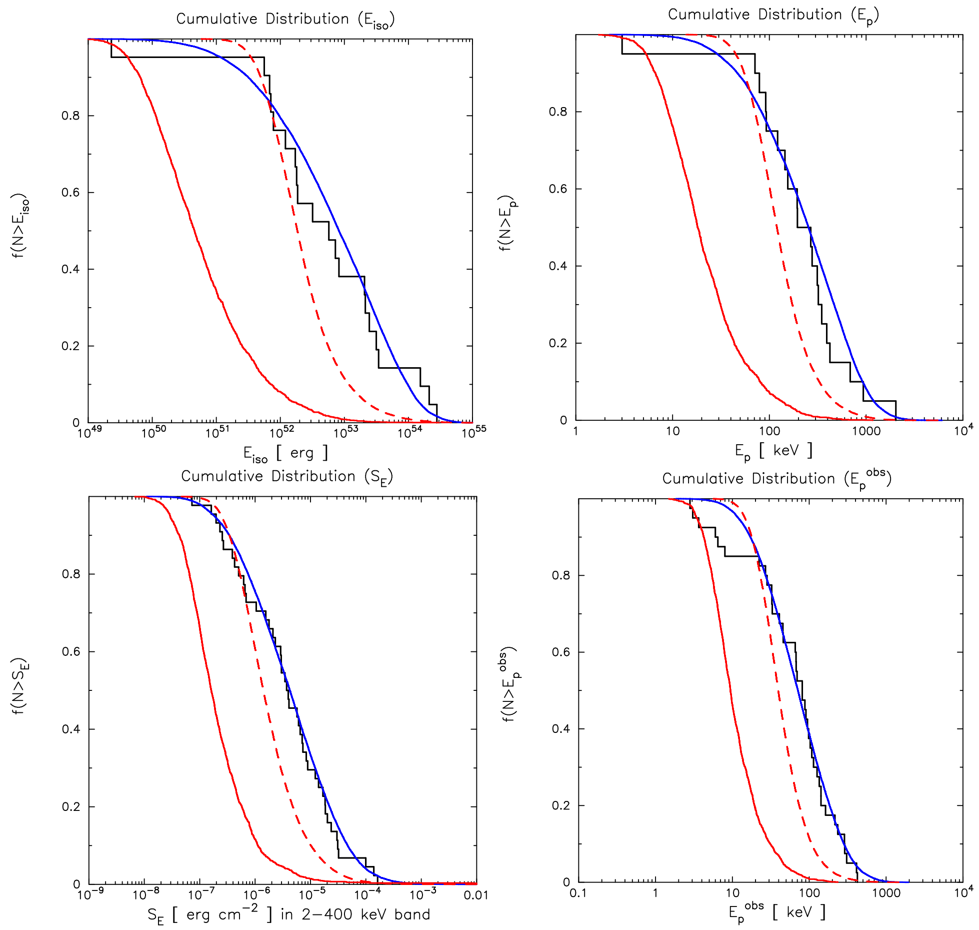

Fig. 1.5. Top row: cumulative distributions of $S(2-400\text{keV})$ (left panel) and $E_{\text{peak}}^{\text{obs}}$ (right panel) predicted by the structured (red) and uniform (blue) jet models, compared to the observed cumulative distributions of these quantities. Bottom row: cumulative distributions of E_{iso} (left panel) and E_{peak} (right panel) predicted by the structured (red) and uniform (blue) jet models, compared to the observed cumulative distributions of these quantities. The cumulative distributions corresponding to the best-fit structured jet model that explains XRFs and GRBs are shown as solid lines; the cumulative distributions corresponding to the best-fit structured jet model that explains GRBs alone are shown as dashed lines. The structured jet model provides a reasonable fit to GRBs alone but cannot provide a unified picture of both XRFs and GRBs, whereas the uniform jet model can. From Lamb, Donaghy & Graziani (2003).

The exciting recent results involving XRF 030723 highlight the fact that HETE-2 is ideally suited to obtain the evidence about XRFs that is required to confirm or rule out the profound implications about the structure of GRB jets, the rate of GRBs, and the nature of Type Ic supernovae described above. HETE-2 will obtain this evidence, if the HETE-2 mission is extended, whereas *Swift* cannot. HETE-2's ability to accurately and rapidly localize XRFs – and study their spectra – therefore constitutes a compelling reason for continuing HETE-2 during the *Swift* mission.

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