

Letter to the Editor

The absorption properties of gamma-ray burst afterglows measured by BeppoSAX

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Abstract. We present an analysis of the X-ray absorption properties of 6 gamma-ray burst (GRB) afterglows measured with BeppoSAX. Between 8 hrs and 20 hrs after the initial GRB trigger, individual spectra can be described by a power-law with a photon index of ~ 2 and absorption, N_{H} , marginally consistent with the galactic value. Taken collectively, the data are inconsistent with zero N_{H} at the $>99.999\%$ confidence level. The data are only marginally consistent with a distribution of column densities varying as the total galactic N_{H} in the direction of each of the bursts ($\chi^2=9.6$ for 6 degrees of freedom). The data are consistent with cosmological models in which GRB occur within host galaxies. By simultaneously fitting a power-law spectral model with N_{H} fixed at the galactic value and additional, redshifted, absorption to all 6 afterglow spectra, the best-fit average N_{H} within the host objects is found to be $(1.01 \pm_{0.51}^{0.28}) \times 10^{22}$ atom cm^{-2} . This value is compatible with the host galaxy column densities inferred from optical data for GRB970508, GRB971214 and GRB980329, supporting the hypothesis that GRB occur within heavily absorbed star forming regions of their host galaxies.

Key words: gamma-rays: bursts – X-rays: general

1. Introduction

The BeppoSAX observation of gamma-ray burst (GRB) afterglows at X-ray wavelengths has ushered in a new era of gamma-ray burst studies. The breakthrough has been achieved using a conventional GRB detector in conjunction with a wide field X-ray camera and narrow field X-ray telescopes. The GRB detector verifies the nature of the burst and the wide field camera accurately determines its position, allowing a suite of highly sensitive, but narrow field instruments, to be slewed to the burst position within a matter of hours. The rapid dissemination of

arc-minute sized burst coordinates has resulted in the successful detection of afterglows at other wavelengths. Although the data are still preliminary, we may use this new information to investigate the burst progenitor, mechanism and burst site.

1.1. Burst astronomy with BeppoSAX

The narrow field instruments (NFI) on the Italian-Dutch satellite BeppoSAX (Boella et al. 1997a) have approximately 1° fields of view and include the imaging low- and medium energy concentrator spectrometers (LECS, 0.1–10 keV, Parmar et al. 1997; and MECS, 2–10 keV, Boella et al. 1997b). The NFI are co-aligned and are normally operated simultaneously. In addition, the payload includes two wide field cameras (WFC, 2–30 keV, Jager et al. 1997) which observe in directions perpendicular to the NFI and a gamma-ray burst monitor (GRBM, 40–700 keV, Feroci et al. 1997). These last two instruments allow the detection of X-ray transient phenomena and gamma-ray bursts.

After a GRBM trigger, WFC data are analyzed *post-facto* for a simultaneous X-ray event and, if one is found, a Target of Opportunity (TOO) declared. The burst location is quickly derived to an accuracy of a few arcminutes and the NFIs slewed to this position. The whole process takes ~ 8 hours. For some bursts several TOOs were scheduled, typically a few 10^4 s long, occurring ~ 0.3 days, days and several days after the initial trigger. For positive detections, the LECS and MECS uncertainty radii are typically $1'$. To date, there have been 12 such detections – GRB970111 (Feroci et al. 1998a), GRB970228 (Costa et al. 1997; Frontera et al. 1998), GRB970402 (Nicastro et al. 1998a), GRB970508 (Piro et al. 1998), GRB971214 (Antonelli et al. 1997), GRB971227 (Piro et al. 1997a), GRB980329 (in 't Zand et al. 1998), GRB970425 (Pian et al. 1998), GRB980515 (Feroci et al. 1998b), GRB980519 (Nicastro et al. 1998b), GRB980613 (Costa et al. 1998) and GRB980703 (Galama et al. 1998a) and of these, only 7 are statistically sufficient for spectral analysis.

The analysis that follows is limited to the first 6 bursts which are listed in Table 1. For completeness the table also includes a 7th burst (GRB970828) which, while not observed by BeppoSAX, was measured spectroscopically by ASCA (Yoshida et al. 1998).

All observed X-ray afterglows decay with time as $\sim t^{-1.3}$ and their spectra are well fit by an absorbed power-law of photon index, $\alpha \sim 2$. Some show outbursts of activity (Piro et al. 1998) and some evidence of spectral evolution (Piro et al. 1997b; Yoshida et al. 1998). By far the most interesting events are those for which an optical transient has also been detected. The additional optical information allows the X-ray data to be placed in context. For example, it is found that the spectral and temporal properties at optical wavelengths mirror those at X-ray wavelengths, ostensibly in agreement with the predictions of even the simplest fireball model. In addition, red-shifted emission and absorption features have been detected in the spectra of 3 optical afterglows (Metzger et al. 1997a; Kulkarni et al. 1998; Djorgovski et al. 1998b). The derived red-shifts are 0.835 (GRB970508), 3.42 (GRB971214) and 0.966 (GRB980703). In the cases of GRB971214 (Kulkarni et al. 1998), GRB980329 (Djorgovski et al. 1998a) and most recently GRB980703 (Djorgovski et al. 1998b), host galaxies have also been detected and probably in the case of GRB970228 (Sahu et al. 1997; Fruchter et al. 1998).

2. Data analysis

For each of the BeppoSAX afterglows listed in Table 1, events were extracted within radii of $8'$ (LECS) and $2'$ (MECS) of the best-fit source centroids. In cases where several TOO were made, the analysis was limited to the first TOO in order to maximize the signal-to-noise ratio and to minimize possible errors induced by the effects of spectral evolution, such as those reported for GRB970828 (Yoshida et al. 1998) and GRB970508 (Piro et al. 1997b). LECS and MECS spectral files, along with their associated responses and background files were simultaneously fit, keeping fitted parameters tied in both instruments. Because these events are weak, great care was taken in selecting blank sky regions for background subtraction. For all events, the 0.25, 0.75 and 1.5 keV count rates in the LECS standard background file were checked against the equivalent rates in the ROSAT all-sky background maps (Snowden et al. 1997). In one case (GRB970402), the background at the source was found to have a significantly different shape than the standard background (Nicastro et al. 1998a). Therefore, in this case the background was extracted from the same image at a position diametrically opposite from the source. In comparison with the standard background field, the differences in fitted spectral parameters were well within errors.

The LECS data were fit over the energy range 0.1–10 keV and MECS between 1.8–10.0 keV. It is known from inter-instrument spectral calibrations that there can be a position dependent error of $\lesssim 20\%$ in the relative flux normalizations between the LECS and MECS. This factor was included as a fixed multiplicative parameter during joint spectral fitting of

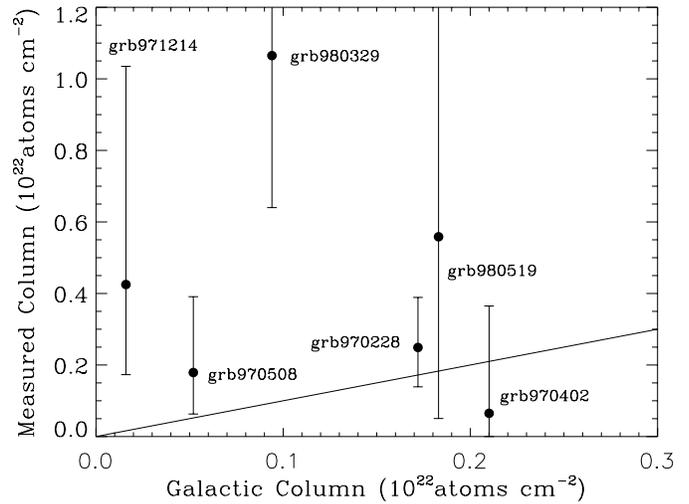


Fig. 1. The measured N_{H} for each of the afterglows considered in the text as a function of N_{gal} in the direction of the afterglow. The solid line shows the case if the measured columns are equal to the galactic values

LECS/MECS data. For all afterglows, an absorbed power-law gives the best fit to the individual spectra, with χ^2 typically ~ 1 per degree of freedom (dof). (We note that an unabsorbed black-body also gives almost equally good fits.) In the case of GRB970228, only data from the MECS3 unit was included in the fit, since the position of the burst is close to the window support rings of the MECS1 and MECS1 units (see Boella et al. 1997b). The best-fit parameters for each burst are listed in Table 1.

3. Results

From Table 1 it is apparent that the fitted photon indices are consistent with a constant mean value of 2.21 ± 0.20 . This supports a blastwave induced synchrotron or inverse Compton interpretation of afterglows (Waxman 1997; Meszaros & Rees 1997; Vietri 1997). In Fig. 1, the fitted hydrogen column density, N_{H} , for each burst is plotted against the galactic column density, N_{gal} , in that direction interpolated from the survey maps of Dickey & Lockman (1990). The estimated precision of the N_{gal} values is a few times 10^{20} cm^{-2} . Taken collectively, the derived N_{H} are inconsistent with zero column density, the χ^2 being 17.5 for 6 dof – thus excluding all but the most contrived of local models. The data are also marginally inconsistent with that of the total galactic column density along the line of sight of each burst ($\chi^2 = 9.6$ for 6 dof). Assuming, that bursts are cosmological in origin, we next tested whether the data could support an additional average absorption above N_{gal} (i.e., intrinsic to the source and/or host object). However, at cosmological distances the effective N_{H} is increased by $(1+z)^{2.6}$ (Morrison & McCammon 1983) since the spectral turnover is reduced by $(1+z)$ due to the red-shift. Therefore, we simultaneously included both the galactic absorption and an additional red-shifted absorption to represent intrinsic absorption within the environment local to the afterglow. In the model convention within XSPEC, this is

Table 1. GRB afterglow characteristics. The results of absorbed power-law model fits are listed. T_{start} is the time in hrs after the burst that the NFI began observing the afterglow, T_{exp} is the LECS/MECS exposure time in ks, OT denotes whether an optical transient is detected, N_{H} is the column density in units of 10^{21} atom cm^{-2} , α the photon spectral index, N_{gal} the galactic column density, and β is the power-law temporal decay index of the flux. Estimates of the red-shifts, z , based on optical and $\log N - \log F_{\text{peak}}$ data are given. All uncertainties are quoted at 68% confidence

Burst	T_{start} (hrs)	T_{exp} (ks)	OT	N_{gal}	N_{H}	α	χ^2/dof	β	z
GRB970228	8.0	5.5/14.3	Y	1.72	$2.5^{+1.4}_{-1.1}$	$1.96^{+0.19}_{-0.19}$	12/10	1.33 ± 0.12	$\sim 1^2$
GRB970402	8.0	11.6/34.2	N	1.67	$0.65^{+3.0}_{-0.65}$	$1.67^{+0.32}_{-0.57}$	6/8	1.57 ± 0.03^1	2.5^3
GRB970508	5.7	14.1/28.3	Y	0.52	$1.8^{+2.1}_{-1.1}$	$1.99^{+0.29}_{-0.07}$	24/22	1.1 ± 0.1	0.825^4
GRB970828	28.1	36.0	N	0.36	$3.5^{+2.2}_{-1.6}$	$2.7^{+0.5}_{-0.4}$	23/31	1.44 ± 0.05	...
GRB971214	9.7	3.2/6.9	Y	0.16	$4.3^{+6.1}_{-2.5}$	$2.03^{+0.51}_{-0.22}$	6/8	1.20 ± 0.02	3.43^5
GRB980329	7.0	15.8/39.2	Y	0.94	$10.7^{+7.8}_{-4.3}$	$2.63^{+0.41}_{-0.36}$	18/27	1.35 ± 0.03	...
GRB980519	9.7	23.1/78.2	Y	1.83	$5.6^{+10.2}_{-5.1}$	$2.52^{+0.70}_{-0.57}$	28/29	2.07 ± 0.11	...

¹ Assuming the afterglow X-ray emission begins ~ 100 s after the burst onset;

² Wijers et al. (1997);

³ Lipunov et al. (1998);

⁴ Metzger et al. (1987a);

⁵ Kulkarni et al. (1998)

designated $wabs * zwabs * zpower$. The values of z were fixed at the values given in Table 1. In cases where z has not been determined directly, the best estimated value is used, and if that does not exist (e.g., in the cases of GRB980329 and GRB980519) z is allowed to be a free parameter. If all the additional redshifted absorptions are constrained to have the same value, the resulting best-fit has a χ^2 of 94.3 for 98 dof for an average additional red-shifted N_{H} of $(1.01^{+0.28}_{-0.51}) \times 10^{22}$ atom cm^{-2} . Fixing the red-shifted column density to zero and re-fitting, results in a χ^2 of 101.1 for 99 dof. Thus, the addition of this column is significant under an F test at the $>92\%$ level. Since the predicted spectrum in blast wave models varies little from event to event (e.g., Wijers et al. 1997), we next tied the spectral slopes. Re-fitting resulted in a χ^2 of 100.4 for 104 dof for an average red-shifted N_{H} of $(8.7^{+3.4}_{-4.8}) \times 10^{21}$ atom cm^{-2} and best-fit α of $2.02^{+0.10}_{-0.12}$.

We note that for strong sources such as the Crab, the uncertainty in the fitted N_{H} values is a few 10^{20} atom cm^{-2} , due largely to uncertainties in low energy calibration. However, for weak sources, such as afterglows, the uncertainty is dominated by the uncertainty in background subtraction. From studies of weak sources we estimate this to be $\lesssim 25\%$ of the statistical error.

4. Discussion

The general properties of afterglows are in remarkable agreement with the predictions of even the simplest fireball models (Meszaros & Rees 1997) in which a relativistic blast wave radiates its energy as it decelerates by plowing through the surrounding medium. As the fireball slows down, the peak of the emitted radiation shifts in time to lower energies producing the observed power-law decays in the X-ray, optical and radio (e.g., Waxman 1997; Wijers & Galama 1998 and references therein). The diversity in afterglow behavior is most easily explained by beaming and/or the differences in radiative losses at early

times (Meszaros et al. 1998; Wijers & Galama 1998). However, afterglows are only detected optically about half of the time, leading to the suggestion that there must be significant extinction at the source. The extinction is generally believed to be in the form of dust whose existence has been inferred by the observed reddening in the optical spectra of GRB971214 and more recently, GRB980329. In addition, the detection of the [O II] 3728Å emission line and also an [Mg I] absorption line (Metzger et al. 1997a) in GRB970508 indicates the presence of a relatively dense medium (Metzger et al. 1997b). Given that the estimated redshifts for afterglows lie in the range 1–3.5, when star formation was at its peak (e.g., Madau et al. 1998) and that the progenitors of GRB970508, GRB971214, GRB980329 and GRB980702 appear to be well located inside their respective host galaxies, it seems likely that GRB are associated with star forming regions. This is supported by the high effective temperature implied by the relative strengths of the [O II] and [Ne III] lines observed in the optical spectra of GRB970508 and suggests the presence of a substantial population of massive stars and thus active star formation (Bloom et al. 1998).

The apparent longevity of the observed afterglows and the observation of X-ray precursors by *Ginga* (Murakami et al. 1991) support a “dirty” fireball model (Rees & Meszaros 1998). Although both hypernova and neutron star merger models can satisfy energetics requirements $>10^{53}$ ergs s^{-1} , we would expect a fraction of neutron star mergers to take place well outside their host galaxies - purely due to the high proper motion acquired in two consecutive supernova explosions. The fact that the observed optical transients of 4 (and possibly 5) bursts are well located within small host galaxies, is suggestive and would tend to favor hypernova models. In these models (Woosley 1993; Paczynski 1998), a very massive ($\sim 10M_{\odot}$) star collapses, producing a “dirty” fireball ~ 300 times more luminous than a supernova ($\sim 10^{54}$ erg). This large amount of energy is obtained from the rotational energy of a Kerr black-hole formed in the

core collapse. Since such massive stars die young ($\sim 10^6$ yrs) and therefore close to where they were born, a natural consequence is that GRB trace the star formation rate and should be associated with high density, dusty regions. The available data support this. For example, by comparing the color spectra of GRB971214 and GRB970508, Halpern et al. (1998) calculate that an additional N_{H} of $(1.5\text{--}2.3) \times 10^{21}$ atom cm^{-2} is required at the distance of GRB971214 to explain the extreme reddening of the spectrum. Reichart (1998) has shown that in order to reconcile the optical decay and spectral profiles, there must be a red-shifted source of extinction at the burst site of 1.9×10^{21} atom cm^{-2} . He further argues that this absorber is probably the host galaxy of GRB971214 at a z of 1.89. Taylor et al. (1998) argue from radio observations of GRB980329 that an additional N_{H} of 10^{21} atom cm^{-2} is required at the source to explain why the afterglow is bright at radio wavelengths (e.g., Galama et al. 1998b), but optically dim (Palazzi et al. 1998). This value is also consistent with that derived from optical reddening measurements (Palazzi et al. 1998).

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