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INTEGRAL AND *XMM-NEWTON* OBSERVATIONS OF THE WEAK GAMMA-RAY BURST GRB 030227[1]

S. Mereghetti,[2] D. Götz,[2] A. Tiengo,[2] V. Beckmann,[3,4] J. Borkowski,[3] T. J.-L. Courvoisier,[3] A. von Kienlin,[5] V. Schoenfelder,[5] J. P. Roques,[6] L. Bouchet,[6] P. Ubertini,[7] A. Castro-Tirado,[8] F. Lebrun,[9] J. Paul,[9] N. Lund,[10] J. M. Mas-Hesse,[11] W. Hermsen,[12] P. R. den Hartog,[12] and C. Winkler[13]
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ABSTRACT

We present *International Gamma-Ray Astrophysical Laboratory* (*INTEGRAL*) and *XMM-Newton* observations of the prompt γ-ray emission and the X-ray afterglow of GRB 030227, the first gamma-ray burst for which the quick localization obtained with the *INTEGRAL* Burst Alert System has led to the discovery of X-ray and optical afterglows. GRB 030227 had a duration of about 20 s and a peak flux of ∼1.1 photons cm^{-2} s^{-1} in the 20–200 keV energy range. The time-averaged spectrum can be fitted by a single power law with photon index ∼2, and we find some evidence for a hard-to-soft spectral evolution. The X-ray afterglow has been detected starting only 8 hr after the prompt emission, with a 0.2–10 keV flux decreasing as t^{-1} from 1.3×10^{-12} to 5×10^{-13} ergs cm^{-2} s^{-1}. The afterglow spectrum is well described by a power law with photon index 1.94 ± 0.05 modified by a redshifted neutral absorber with column density of several 10^{22} cm^{-2}. A possible emission line at 1.67 keV could be due to Fe for a redshift $z \sim 3$, consistent with the value inferred from the absorption.

Subject headings: gamma rays: bursts — X-rays: general

1. INTRODUCTION

Our understanding of gamma-ray bursts (GRBs), one of the mysteries of high-energy astrophysics for more than 25 years, advanced dramatically after the discovery of their X-ray, optical, and radio afterglows (see, e.g., van Paradijs, Kouveliotou, & Wijers 2000). Currently, the multiwavelengths study of GRBs is providing a wealth of results relevant for several branches of astrophysics. Besides the study of the prompt emission, a rapid and accurate localization is crucial to pursue these objectives and fully exploit the information on the GRB afterglows and host environment. Such a capability was first achieved by the *BeppoSAX* satellite, which located more than 45 GRBs from 1997 to 2002 (see, e.g., Amati et al. 2002) and is currently provided by the *High Energy Transient Explorer 2*, a satellite specifically devoted to this task (Ricker et al. 2002).

The *International Gamma-Ray Astrophysical Laboratory* (*INTEGRAL*) satellite (Winkler et al. 1999) was successfully launched on 2002 October 17. The *INTEGRAL* payload consists of two γ-ray instruments operating in the ∼15 keV–10 MeV range: the Imager on Board the *INTEGRAL* Satellite (IBIS; Ubertini et al. 1999) and the Spectrometer on *INTEGRAL* (SPI; Vedrenne et al. 1999). Both are coded mask telescopes[14] optimized for angular and spectral resolution, respectively.

Although not specifically devoted to GRB studies, thanks to the large field of view and good imaging capabilities of its γ-ray instruments, *INTEGRAL* is able to localize GRBs at an expected rate of 1–2 per month (Mereghetti, Cremonesi, & Borkowski 2001a). The data are immediately transmitted to the ground, and it is possible to derive the coordinates of detected GRBs with very small delays. Automatic software, the *INTEGRAL* Burst Alert System (IBAS; Mereghetti et al. 2001b), has been developed at the *INTEGRAL* Science Data Center (ISDC; Courvoisier et al. 1999) to exploit these capabilities. As soon as telemetry reaches the ISDC, the IBAS software screens the data in real time looking for the presence of potential GRBs, performs a rapid imaging analysis of the candidates, and eventually distributes the positions of the GRBs via the Internet.

In line with prelaunch expectations, five GRBs have been detected to date in the field of view of the *INTEGRAL* instruments: GRB 021125 (Bazzano & Paizis 2002), GRB 021219 (Mereghetti, Götz, & Borkowski 2002), GRB 030131 (Borkowski et al. 2003), GRB 030227 (Götz et al. 2003a), and GRB 030320 (Mereghetti, Götz, & Borkowski 2003). Their positions have been determined with errors in the 2′–4′ range. Here we report on the observations of GRB 030227, the first GRB for which our prompt localization has led to the successful identification of X-ray (Loiseau et al. 2003) and optical afterglows (Castro-Tirado et al. 2003a; Soderberg et al. 2003).

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[2] Istituto di Astrofisica Spaziale e Fisica Cosmica, Sezione di Milano "G. Occhialini," CNR, via Bassini 15, I-20133 Milan, Italy; sandro@mi.iasf.cnr.it.

[3] *INTEGRAL* Science Data Center, Chemin d' Écogia 16, CH-1290 Versoix, Switzerland.

[4] Institut für Astronomie und Astrophysik, Universität Tübingen, Sand 1, D-72076 Tübingen, Germany.

[5] Max-Planck-Institut für extraterrestrische Physik, Postfach 1312, D-85741 Garching, Germany.

[6] Centre d'Etude Spatiale des Rayonnements, 9, Avenue du Colonel Roche, BP 4346, 31028 Toulouse Cedex 4, France.

[7] Istituto di Astrofisica Spaziale e Fisica Cosmica, CNR, via del Fosso del Cavaliere, I-00133 Rome, Italy.

[8] Instituto de Astrofísica de Andalucía (IAA-CSIC), P.O. Box 03004, 18080 Granada, Spain.

[9] Centre d'Etudes de Saclay, DAPNIA/Service d'Astrophysique, Batiment 709, Orme des Merisiers, Gif-sur-Yvette Cedex 91191, France.

[10] Danish Space Research Institute, Juliane Maries Vej 30, Copenhagen 0 DK-2100, Denmark.

[11] Centro de Astrobiología, Instituto Nacional de Técnica Aeroespacial (CSIC-INTA), Ctra. de Ajalvir, E-28850 Torrejon de Ardoz, Spain.

[12] Space Research Organization of the Netherlands, National Institute for Space Research, 3584 Utrecht, Netherlands.

[13] European Space Research and Technology Center, Research and Scientific Support Department, Keplerlaan 1, 2201 AZ Noordwijk, Netherlands.

[14] With the coded mask technique, it is possible to obtain images at energies at which photons cannot be easily reflected by interposing a partially absorbing mask between the source and a position-sensitive detector (see, e.g., Dean 1983).

2. *INTEGRAL* OBSERVATION

IBIS detected GRB 030227 with its low-energy detector ISGRI (*INTEGRAL* Soft Gamma-Ray Imager; Lebrun et al. 2001), an array of 128 × 128 CdTe crystals sensitive in the energy range from ~15 keV to 1 MeV. ISGRI has an effective area of the order of 1000 cm^2 and provides an angular resolution of ~12′ over a 29° × 29° field of view. Bright sources can be located with good accuracy (for example, the 90% confidence level [c.l.] error radius for a source with a signal-to-noise ratio of ~10 is as small as 1′). The SPI instrument observes with a coarser angular resolution (~2°) the same region of sky covered by IBIS, providing a better energy resolution (FWHM = 2.5 keV at 1 MeV). The detector consists of 19 Ge crystals cooled to 85 K, surrounded by a thick anticoincidence shield (ACS) of BGO scintillation crystals.

GRB 030227 was detected by the IBAS program based on the analysis of the IBIS/ISGRI data, consisting of positional, timing, and energy information of each detected photon. The IBAS alert message with the preliminary position of the burst (R.A. = $4^h57^m24^s$, decl. = +20°28′24″, J2000.0) was delivered to the IBAS Team at 08:42:38 UT on 2003 February 27, only 35 s after the start of the burst (most of this delay was due to buffering of the telemetry on board the satellite and to data transmission between the ground station and the ISDC). Unfortunately, the Internet message with these coordinates could not be distributed in real time.[15] Nevertheless, this information was distributed within less than 1 hr, after the GRB had been confirmed by an interactive analysis of the data (Götz et al. 2003a). Further analysis resulted in an improved localization at R.A. = $4^h57^m32\overset{s}{.}2$, decl. = +20°29′54″ (Götz et al. 2003b), with an error of 3′ dominated by systematic uncertainties. This position differs by only 50″ from that of the optical transient (Castro-Tirado et al. 2003a).

The IBIS/ISGRI light curve of GRB 030227 is shown in Figure 1*a*. The burst, which started approximately at 08:42:03 UT, had a typical fast rise and exponential decay profile, with a rise to the peak in 2 s and a decay well described by an exponential with *e*-folding decay time of 11 ± 1 s. The peak flux, integrated over 1 s, is 1.1 photons cm^{-2} s^{-1} in the 20–200 keV energy range. The fluence, in the same range and assuming the average spectrum discussed below, is 7.5 × 10^{-7} ergs cm^{-2}.

GRB 030227 was detected with a signal-to-noise ratio of ~20 at off-axis angles $Z = 5\overset{\circ}{.}3$, $Y = 6\overset{\circ}{.}9$. Since a fully calibrated response matrix valid at these off-axis angles is not yet available, we derived the spectrum of GRB 030227 by comparing its count rate in different energy bins to the corresponding values obtained from the Crab Nebula observed at a similar position in the field of view. With this procedure we extracted the average burst spectrum for the time interval 08:42:04–08:42:26 UT, which is well described by a single power law with photon index 1.85 ± 0.2 over the 20–200 keV energy range.

GRB 030227 was also detected by SPI with a significance of 7.7 σ in the 20–200 keV range and localized (R.A. = $74\overset{\circ}{.}766$, decl. = $+20\overset{\circ}{.}531$) only $0\overset{\circ}{.}36$ off the IBIS position, owing to the less accurate location precision of SPI.

A spectrum was extracted for a time interval of 18 s starting at 08:42:04 UT. The background was estimated from a time interval of 35 minutes around the GRB but excluding the time span of the event itself. A power law with photon index of 1.9 ± 0.3 and 20–200 keV flux of 4.7 × 10^{-8} ergs cm^{-2} s^{-1} gives a good fit to these data. These values are consistent with those obtained with IBIS, confirming that the method used in the IBIS spectral analysis does not introduce important systematic effects.

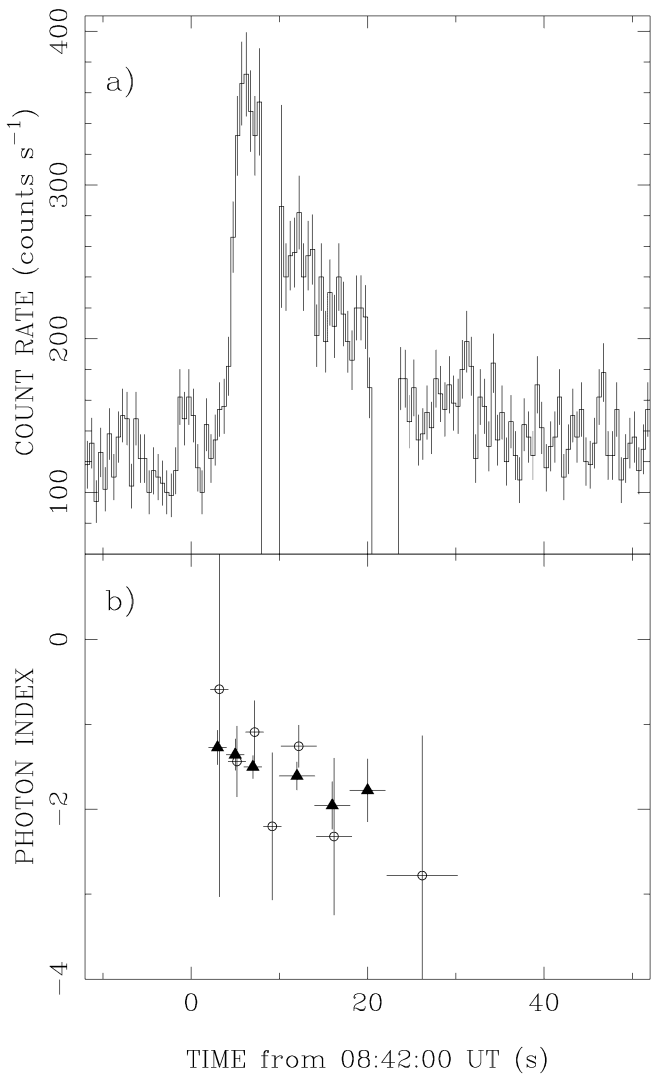

FIG. 1.—(*a*) IBIS/ISGRI light curve of GRB 030227 in the energy range 15–300 keV binned in 0.5 s intervals. The two small gaps at $t \sim 10$ and 20 s are artifacts due to telemetry saturation. (*b*) Power-law index as a function of time for IBIS (*triangles*) and SPI (*circles*). Error bars are at 1 σ.

To study the spectral evolution as a function of time, we defined a hardness ratio HR $= (H - S)/(H + S)$ based on the background-subtracted count rates in the ranges H = 40–100 keV and S = 20–40 keV. From the HR values of both SPI and IBIS, we found evidence for a hard-to-soft evolution. A time-resolved spectral analysis gave the power-law indices shown in Figure 1*b*, which confirm the indication of a possible spectral softening during the decaying part of the event.

The overall veto count rate of SPI's ACS showed no count rate increase that could be associated with the GRB. This is consistent with the fluxes quoted above and the low effective area of the ACS for directions corresponding to the SPI field of view (von Kienlin et al. 2001).

[15] The detection of GRB 030227 occurred during a calibration observation of the Crab Nebula. Since the instrument configuration during these observations caused some spurious IBAS triggers, the automatic delivery of the alerts to external clients had been temporarily disabled.

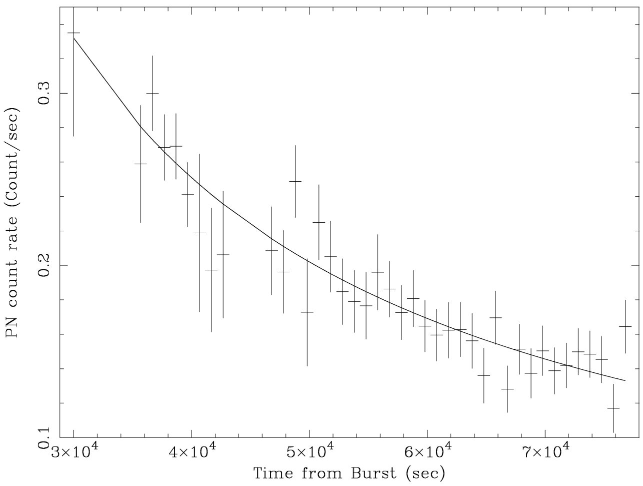

FIG. 2.—Light curve of the GRB 030227 afterglow fitted by a power-law function $F \propto t^{-\delta}$ with $\delta = 0.97$. All the points are from the PN, except for the first one obtained with the MOS (the remaining MOS points, consistent with the PN ones, are not plotted for clarity).

3. *XMM-NEWTON* OBSERVATION

XMM-Newton observed the position of GRB 030227 for ~13 hr, starting on February 27 at 16:58 UT. Because of the presence of a high particle background, the observation had to be interrupted twice, resulting in net exposures of 33 and 36 ks, respectively, in the PN and MOS cameras of the European Photon Imaging Camera (EPIC; Strüder et al. 2001; Turner et al. 2001). All the cameras operated in Full Frame mode and with the thin optical blocking filter. The data were processed using SAS version 5.4.1.

A bright and variable source was detected at R.A. = $04^h57^m33^s.1$, decl. = $+20°29'05''$ (error radius of 4″), well within the IBIS error circle of GRB 030227. The flux variability immediately suggested that this source was the GRB afterglow (Loiseau et al. 2003), as it was later confirmed by the discovery of a fading optical transient within its small error region. Figure 2 shows the background-subtracted PN light curve in the 0.2–10 keV energy range. The figure also shows the first flux measurement (at ~17:00 UT) obtained with the MOS camera, which started the observation earlier than the PN. The X-ray flux decay is well described by a power-law function, $F \propto t^{-\delta}$, with $\delta = 0.97 \pm 0.07$.

The source spectra were extracted from a circle of radius 40″ and rebinned to have at least 20 counts per channel and to oversample by a factor of 3 the instrumental energy resolution. For the PN, the background was extracted from a nearby rectangular region (1′.5 × 2′) in the same chip as the source and for the MOS from an annulus (radii of 1′ and 2′) centered on the source. All the errors on the spectral parameters given below are at the 90% c.l.

After checking that no significant variations in the best-fit parameters, except for the flux value, occurred during the observation, we performed a spectral fit of the whole PN data set. An absorbed power law gave an unacceptable fit (χ^2/degree of freedom [dof] = 272/209) with photon index $\Gamma = 2.04 \pm 0.05$ and $N_H = 3.6^{+0.3}_{-0.2} \times 10^{21}$ cm^{-2}, larger than the Galactic absorption in this direction ($N_H = 1.75 \times 10^{21}$ cm^{-2}; Hartmann & Burton 1997). An acceptable fit (χ^2/dof = 235/208; Fig. 3) could be obtained by fixing N_H to the Galactic value and adding a redshifted neutral absorption, $N_{H,z}$. This resulted in $\Gamma = 1.94 \pm 0.05$, $N_{H,z} = 6.8^{+1.8}_{-3.8} \times 10^{22}$ cm^{-2}, $z = 3.9 \pm 0.3$, and 0.2–10 keV observed flux $F_X = 8.5 \times 10^{-13}$ ergs cm^{-2} s^{-1}. As shown in Figure 4, the redshift is not strongly constrained, its value being correlated with that of $N_{H,z}$. The best-fit values are only slightly dependent on the assumed Galactic N_H value: by varying it by ±30%, acceptable fits were always obtained with $\Gamma \sim 2$, while the 90% c.l. range of z and $N_{H,z}$ varied by less than 35%.

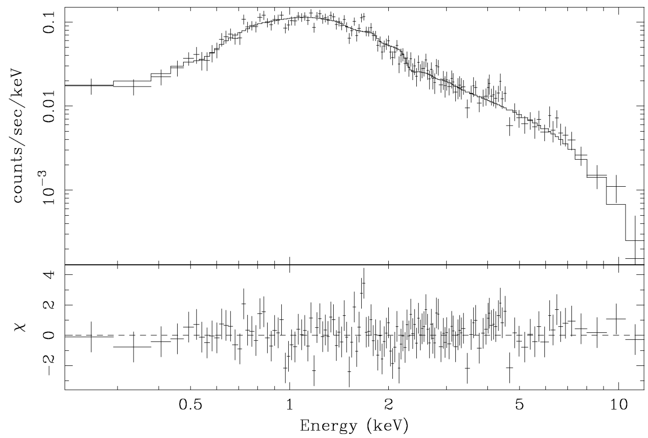

FIG. 3.—EPIC PN best-fit spectra of the afterglow of GRB 030227

Since the fit residuals of Figure 3 suggest the presence of possible lines in the spectrum, we tried to add Gaussian lines at different energies and with fixed widths, smaller than the instrumental resolution. The only possibly significant line was found at observed energy of $1.67^{+0.01}_{-0.03}$ keV. According to an *F*-test, this line is significant at the 3.2 σ level. However, such a probability value should be used with caution (Protassov et al. 2002), and we give it just to allow a comparison with other possible detections of lines reported for previous GRBs.

We also tried thermal models, both for the whole observation and for shorter time intervals, replacing the power-law component with a redshifted optically thin plasma model (MEKAL in XSPEC, with z linked to that of $N_{H,z}$). Keeping the elemental abundances fixed to the solar values resulted in unacceptable fits. Letting the abundances be free parameters, we obtained slightly better results (χ^2/dof = 260/207), with values of $N_{H,z}$ and z similar to the power-law case, and a temperature of ~25 keV. However, the corre-

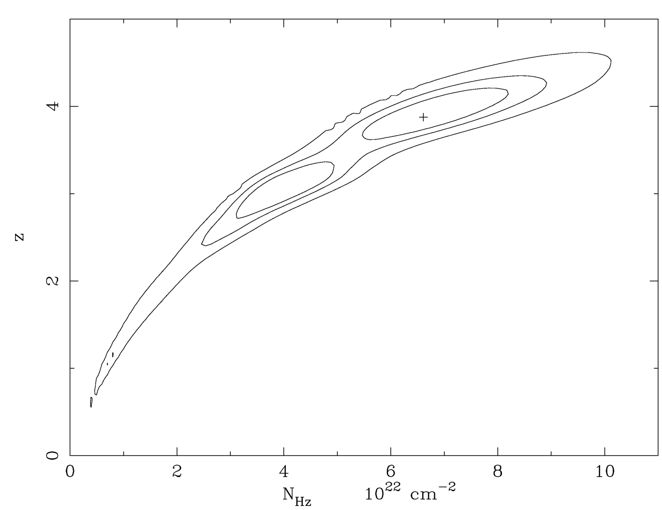

FIG. 4.—Confidence contours (68%, 90%, and 99% c.l.) of redshift and column density of the redshifted absorber from the fit of the whole PN data set.

sponding χ^2/dof values were always greater than in the power-law model.

Entirely consistent results were obtained with the MOS. As mentioned above, a short initial exposure was carried out only with the MOS, from 16:58 to 17:16 UT. These data do not provide enough statistics for a detailed spectral analysis, but they are consistent with the spectral parameters obtained for the rest of the observation. The corresponding flux is 1.34×10^{-12} ergs cm^{-2} s^{-1}.

4. DISCUSSION

The *INTEGRAL* data indicate that GRB 030227 belongs to the class of long GRBs. Its peak flux and fluence, converted to the 50–300 keV energy range used in the BATSE catalog, are, respectively, ∼0.6 photons cm^{-2} s^{-1} and $\sim 7 \times 10^{-7}$ ergs cm^{-2} (these values slightly depend on the extrapolation; for example, a break in the spectrum at 120 keV to a slope of 2.5 would reduce them by 15%). About three-quarters of the GRBs in the fourth BATSE catalog (Paciesas et al. 1999) have a higher peak flux, indicating that GRB 030227 is quite faint. The possible evidence for a hard-to-soft spectral evolution in GRB 030227 suggests that such a trend, already observed in samples of brighter GRBs (Ford et al. 1995; Preece et al. 1998; Frontera et al. 2000), may also apply to relatively faint bursts.

GRB spectra usually show a curvature requiring more complex models than a single power law. A broken power law, with a smooth transition between the low-energy (α) and high-energy (β) slope, provides in most cases an adequate empirical description of the data (Band et al. 1993). By fitting such a function to our data, no improvement of the fit was obtained. A spectral break, if any, could occur outside the energy range over which we detected GRB 030227, most likely above ∼100–200 keV as seen in most GRBs. Our photon index ∼1.9 lies in the lower tail of the distribution of values of α (Preece et al. 2000), indicating that GRB 030227 is relatively soft. An extrapolation of its spectrum to lower energies leads to a ratio of fluences in the 6–30 to 30–400 keV ranges of 0.45 (or more if there is a high-energy break). This would qualify GRB 030227 as an X-ray–rich GRB (Heise et al. 2001; Barraud et al. 2003). In this context, it is interesting to note that its optical afterglow is particularly faint, $R \sim 23.3$ at $t - t_o = 12$ hr (Gorosabel et al. 2003), comparable to the dimmest GRB afterglows found so far.

The fading behavior of the source detected with EPIC and its positional coincidence with the optical transient qualify it as the X-ray afterglow of GRB 030227. Among the afterglows detected so far by *XMM-Newton*, this is the brightest and the one observed with the shortest delay after the prompt event ($t - t_o = 8$ hr). Its EPIC spectrum has the highest statistical quality among the afterglows detected to date with *XMM-Newton*. A power law with a redshifted absorber provides a statistically acceptable fit to the spectrum. We found tentative evidence for an emission line at 1.67 keV. If this line is due to Fe, as it has been suggested for similar features observed in other afterglows (see, e.g., Piro 2002), the implied redshift of ∼2.7–3 (depending on the Fe ionization state) would be consistent with the value derived from the absorption. Other interpretations in terms of lighter elements are of course possible but somewhat arbitrary in the lack of an independent measure of z and/or other statistically significant lines.

Low-energy emission lines found in the initial part ($t - t_o \sim 11$–13 hr) of the GRB 011211 afterglow (Reeves et al. 2002, but see also Borozdin & Trudolyubov 2003) provide evidence for thermal emission from a plasma enriched in metals. Evidence for thermal emission in two other afterglows observed with *XMM-Newton*, GRB 010220 ($t - t_o \sim 15$ hr) and GRB 001025A ($t - t_o \sim 45$ hr), was reported by Watson et al. (2002a). On the other hand, the *XMM-Newton* spectra of the afterglow of GRB 020322 starting at $t - t_o \sim 15$ hr (Watson et al. 2002b) were adequately fitted with a power law. These results suggest that the presence of thermal components is not an ubiquitous property of all GRBs and/or it might be related only to some short-duration phases of the afterglows.

An upper limit to the redshift of $z \leq 3.5$ has been estimated from the absence of the onset of the Lyman forest blanketing in the optical data (Castro-Tirado et al. 2003b). This allows us to constrain the z-values derived by the X-ray spectral fitting (see Fig. 4), which is in any case greater than 1. The corresponding value of the local absorption $N_{H, z}$ of the order of a few times 10^{22} cm^{-2} supports the scenarios involving the occurrence of GRBs in regions of star formation (e.g., Galama & Wijers 2001).

Finally, we note that the rapid IBAS localization of GRB 030227 leading to the successful detection of its X-ray and optical afterglows, as well as the rate of ∼1 GRB per month in the IBIS field of view observed so far, demonstrate that *INTEGRAL* will efficiently complement other satellites specifically devoted to GRB studies. We also expect that particularly interesting results will be obtained for a few bursts falling in the central part of the field of view, which is covered also by the *INTEGRAL* monitors operating in the optical (*V* band) and in the X-ray range (4.5–35 keV).

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