In this paper we present BeppoSAX and XMM-Newton observations of two long gamma-ray bursts (GRBs), the X-ray–rich event of 2001 December 11 (GRB 011211) and the hard and very bright event of 2001 November 21 (GRB 011121). In both events we find evidence of a late X-ray burst taking place several minutes after the prompt emission. In the November burst the spectrum of the X-ray burst is much softer than that of the preceding prompt stage and consistent with the spectrum of the afterglow at 1 day. In addition, the tail of the X-ray burst and the light curve of the afterglow at 1 day are connected by a single power law \( \sim (t - t_0)^{-3} \), when \( t_0 \) corresponds with the onset of the X-ray burst. These evidences suggest that the late X-ray burst represents the onset of the afterglow. A similar conclusion is drawn for the December burst. The temporal and spectral behavior of the X-ray and optical afterglows indicate that the fireball evolution in the December burst takes place in an interstellar medium (ISM) environment. In contrast, in the November burst the wind case is revealed by an X-ray decay slower than that observed in the optical \( (\delta_X = 1.29 \pm 0.04 \mathrm{ vs.} \ 1.66 \pm 0.06) \). The wind profile should change into a constant-density profile at large radius in order to reconcile late-time radio data with a jet. Two other results are obtained for this burst. An X-ray burst precedes the much harder GRB by about 30 s. Contrary to the prediction of simple models of precursor activity for collapsars, the precursor’s spectrum is not consistent with a blackbody. Finally, a substantial absorption column \( \left[N_H = (7 \pm 2) \times 10^{22} \mathrm{ cm}^{-2}\right] \) is detected during the early part of the prompt emission. This is much greater than that of the wind, and it is thus likely associated with the region surrounding the burst.

Subject heading: gamma rays: bursts

1. INTRODUCTION

Gamma-ray bursts (GRBs) and their afterglows are well explained by the fireball model, in which a highly relativistic outflow from the central source produces the observed emission (Meszáros 2002 and references therein). On the other hand, this outflow from the central source produces the observed emission of the progenitor. The first is to single out spectral and temporal features that are produced in the vicinity of the central source and that can bear direct information on it. This is, e.g., the case of line features (e.g., Piro et al. 2000; Lazzati et al. 1999; Rees & Mészáros 2000; Reeves et al. 2002) or supernova (SN) features (e.g., Galama et al. 1998; Pian et al. 2000; Bloom et al. 1999; Stanek et al. 2003; Hjorth et al. 2003). Shock breakout at the surface of an exploding massive star is likely to produce a thermal X-ray precursor. The case of a SN was originally explored by Klein & Chevalier (1978). More recently, several authors have discussed the case of collimated fireballs erupting from the stellar surface (MacFadyen & Woosley 1999; Ramirez-Ruiz et al. 2002; Waxman & Mészáros 2003).

In the second approach, clues on the progenitor are inferred from the properties of the environment surrounding the GRB. This is the case, e.g., of measurements of X-ray (and optical) absorption in the prompt and afterglow phases (e.g., Piro 2004; Stratta et al. 2004; Amati et al. 2000; Lazzati & Perna 2002; Frontera et al. 2000a) and the location of optical transients (Bloom et al. 2002). Density profiles derived from afterglow modelling are particularly intriguing, in that the majority of events are consistent with a constant density environment, and only in very few cases a wind profile is preferred (e.g., Chevalier & Li 2000; Panaiteascu & Kumar 2002). This is at odds with the simple expectation of massive star progenitors. Recently, Chevalier et al. (2004) proposed a solution to solve this discrepancy, arguing that a region of constant density would be produced at the boundary of the wind with the molecular cloud surrounding the progenitor.

In this paper we present BeppoSAX (Piro et al. 1995; Boella et al. 1997a) and XMM-Newton (Jansen et al. 2001) observations of two long GRBs, the very bright event GRB 011121 and the X-ray–rich GRB 011211, hereafter called the November and December bursts, respectively. Observations, data analysis, and results are presented in \S 2.
These events show interesting and peculiar features, bearing implications on the environment and the progenitor of GRB. In the November burst we find X-ray bursting precedes the hard prompt event by 30 s. The origin of this feature is puzzling and it is discussed in § 3 in the framework of fireball precursors and progenitor precursors.

One intriguing property found in both events is a late bursting in X-rays taking place several minutes after the GRB trigger. We discuss this feature in § 4, showing its connection with the late afterglow and arguing that it represents the onset of the external shock producing the afterglow.

The possible presence of a jet break in the X-ray light curves is analyzed in § 5. We then model the afterglow evolution taking into account the X-ray measurements to derive information on the density profile (§ 6). This is particularly important in the case of the November burst, because this is one of the few events in which a wind profile is strongly preferred to a constant density medium (Price et al. 2002). The other cases include GRB 970508 (Panaitescu & Kumar 2002) and GRB 040106 (Gendre et al. 2004; see also Chevalier et al. 2004).

Broadband modelling of the November burst from radio to X-ray bands is carried out in § 7, in which the discrepancy posed by a jet evolution with the late radio data is outlined and reconciled in the framework of a wind termination shock. The implications of the measurement of X-ray absorption in this burst are presented and discussed in § 8. A summary of the results and conclusions of the paper is finally given in § 9. In this paper we adopt a cosmology with $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 65$ km s$^{-1}$ Mpc$^{-1}$. Errors on spectral parameters correspond to the 90% confidence level ($\Delta \chi^2 = 2.7$).

2. OBSERVATIONS

2.1. The November Burst GRB 011121

GRB 011121 was simultaneously detected by the BeppoSAX GRBM and WFC at 18:47:11.6 UT on 2001 November 21 (Piro 2001a; note the revised trigger time). A description of the two instruments is given in Feroci et al. (1997) and Jager et al. (1997), respectively. In Table 1 we summarize peak fluxes and fluences in different energy ranges. The fluence in the 2–700 keV range corresponds to an isotropic energy of $2.8 \times 10^{52}$ ergs at the redshift of the burst (z = 0.36; Infante et al. 2001; see below). The ratio of X-ray to gamma-ray fluence (peak) are $S_{2-26}/S_{40-700} = 0.14$ ($F_{2-26}/F_{40-700} = 0.08$). This event was the second-brightest GRB observed by BeppoSAX in gamma rays (after GRB 990123) and in X-rays (after GRB 010222). Both the duration of the event (about 75 s with the GRBM and 120 s with the WFC) and the hardness ratio are typical of long, normal GRBs. However, by analyzing the light curves (Figs. 1 and 2) we note the following sequence of events:

1. X-ray bursting activity precedes the hard main pulse of the GRB by $\sim$30 s. It is composed of two pulses, with a softness ratio $\approx 20$ times greater than that of the GRB (bottom panel of Fig. 1). The first pulse is followed by a second more intense and softer pulse, which decays just before the onset of the hard GRB. In coincidence with the X-ray bursting, a faint signal is

| Flux, Fluence, or Spectral Ratio | GRB 011121 | GRB 01121 |
|---------------------------------|------------|-----------|
| $F_{40-700}$                     | $7.3 \times 10^{-6}$ | $5 \times 10^{-8}$ |
| $F_{2-26}$                      | $6 \times 10^{-7}$ | $1.4 \times 10^{-8}$ |
| $F_{2-10}$                      | $3 \times 10^{-7}$ | $0.7 \times 10^{-8}$ |
| $S_{40-700}$                    | $1 \times 10^{-6}$ | $5.1 \times 10^{-6}$ |
| $S_{2-26}$                      | $1.4 \times 10^{-5}$ | $2.2 \times 10^{-6}$ |
| $S_{2-10}$                      | $0.7 \times 10^{-5}$ | $1.1 \times 10^{-6}$ |
| $S_{2-6}/S_{40-700}$            | $0.14$      | $0.5$     |
| $F_{2-26}/F_{40-700}$           | $0.08$      | $0.3$     |

**Notes.**—Subscripts indicate the energy range, expressed in keV. Peak fluxes are calculated with a bin size of 8 s. Flux values are given in ergs cm$^{-2}$ s$^{-1}$, and fluence values are given in ergs cm$^{-2}$.
TABLE 2
X-RAY SPECTRAL FITS TO BeppoSAX WFC+GRBM AND MECS+LECS OF THE 2001 NOVEMBER 21 BURST

| Slice                 | $T_1, T_2$ (s) | Instrument | $F_{2-10\text{ keV}}$ (ergs cm$^{-2}$ s$^{-1}$) | $F_{40-700\text{ keV}}$ (ergs cm$^{-2}$ s$^{-1}$) | $N_H$ (10$^{22}$ cm$^{-2}$) | $\alpha$ | $\chi^2/\nu$ |
|----------------------|---------------|------------|-----------------------------------------------|-----------------------------------------------|-------------------------------|----------|------------|
| Precursor 1.......... | -28; -16      | WFC+GRBM   | $1.3 \times 10^{-8}$                          | $2.8 \times 10^{-8}$                          | $3.0^{+3.5}_{-3.0}$            | 1.0 ± 0.11 | 25.5/26    |
| Precursor 2.......... | -16; -6       | WFC+GRBM   | $4.1 \times 10^{-8}$                          | $3.5 \times 10^{-8}$                          | 4.0 ± 3.0                      | 1.25 ± 0.10 | 18.9/26    |
| Rise ................ | -6; 9         | WFC+GRBM   | $8.2 \times 10^{-8}$                          | $1.8 \times 10^{-6}$                          | 4.5 ± 2.5                      | 0.37 ± 0.03 | 18.5/27    |
| Gamma peak........... | 9; 13         | WFC+GRBM   | $1.2 \times 10^{-7}$                          | $6.6 \times 10^{-6}$                          | $3.7^{+3.3}_{-3.1}$            | 0.12 ± 0.05 | 31.1/27    |
| Intermediate......... | 13; 18        | WFC+GRBM   | $1.6 \times 10^{-7}$                          | $4.6 \times 10^{-6}$                          | 9.5 ± 3.5                      | 0.33 ± 0.04 | 19.0/27    |
| X-ray peak........... | 18; 24        | WFC+GRBM   | $2.2 \times 10^{-7}$                          | $2.2 \times 10^{-6}$                          | 6.8 ± 2.2                      | 0.58 ± 0.04 | 21.6/27    |
| Quick tail........... | 24; 31        | WFC+GRBM   | $1.2 \times 10^{-7}$                          | $1.0 \times 10^{-6}$                          | <1.0                          | 0.58 ± 0.03 | 40.6/27    |
| Slow tail............ | 31; 45        | WFC+GRBM   | $4.0 \times 10^{-8}$                          | $4.8 \times 10^{-7}$                          | <1.0                          | 0.47 ± 0.04 | 33.5/26    |
| Slower tail........... | 45; 150       | WFC+GRBM   | $7.9 \times 10^{-9}$                          | $8.0 \times 10^{-8}$                          | 5 ± 4                          | 0.57 ± 0.04 | 20.1/26    |
| Intermediate......... | 150; 239      | WFC+GRBM   | $2 \times 10^{-9}$                            | $7 \times 10^{-9}$                            | 0 fix                          | 0.8 ± 0.15 | 36.7/27    |
| Rebursting........... | 239; 308      | WFC+GRBM   | $8.9 \times 10^{-9}$                          | $9.3 \times 10^{-9}$                          | $1^{+3}_{-2}$                  | 1.15 ± 0.15 | 32.0/26    |
| Slow tail............ | 308; 716      | WFC        | $1.2 \times 10^{-9}$                          | ...                                           | $5^{+1}_{-1}$                  | 1.3 $^{+1}_{-1}$ | 22.8/25    |
| Afterglow............ | (76; 120) $\times 10^{4}$ | LECS+MECS  | $4 \times 10^{-13}$                           | ...                                           | <10                            | 1.6 ± 0.7 | 11/18      |

**Notes.**—Energy spectral index values are given in the $\alpha$ column. $N_H$ is in the rest frame of the burst. Errors are at the 90% confidence level for one interesting parameter. Fluxes are derived from the best-fit model.

recorded in the 40–700 keV range (see the left inset in the middle panel of Fig. 1);

2. a hard main pulse ($-5$–$30$ s) characterized by the typical behavior of a GRB, i.e., spectral hardening in the rising part and hard-to-soft evolution in the decaying part;

3. a hard tail ($30$–$240$ s) with a temporal slope of about 1.4;

4. a late X-ray burst ($240$–$310$ s; see the rightmost insets in the top and middle panels of Fig. 1) with a softness ratio $\approx 10$ times larger than that of the preceding phase;

5. a slow X-ray tail ($310$–$716$ s).

To study in detail these features, we have carried out a time-resolved spectral analysis of the combined WFC and GRBM data. The results are presented in Table 2 and Figure 3. With regard to the X-ray bursting preceding the proper GRB and to the late X-ray burst we note the following.

1. X-ray bursting preceding the proper GRB. We have analyzed separately the spectra of the two pulses. Both are soft, being fitted by a power law with an energy index $\alpha = 1.0 \pm 0.11$ and $\alpha = 1.25 \pm 0.10$ for the first and second pulse, respectively.

Fig. 3.—Spectral evolution for the 2001 November 21 burst. We plot a selection of spectra (\nu F_{\nu}) as a function of time: (a) precursor pulse 1, (b) precursor pulse 2, (c) gamma-ray peak, (d) slower tail, (e) late X-ray burst, (f) afterglow (see Table 2). (a)–(c) WFC and GRBM data; (f) LECS and MECS data. The continuous line is the best-fit absorbed power-law model. The column density in the best-fit model from LECS and MECS data is equal to the galactic value. Note in particular the sharp transition from a soft to hard spectrum from the precursor phase to the GRB phase, an opposite transition to a soft spectrum, when the late X-ray burst event sets in (e), and the similarities of the spectra of the precursor (a and b), the late X-ray burst (e), and the late afterglow (f).
At the onset of the gamma-ray pulse, the spectrum changes abruptly to $\alpha = 0.1$, with the peak of the energy output changing from the X-ray band to above 1 MeV (Fig. 3). Hereafter we will refer to this event as X-ray “precursor” to underline its observational peculiarity with respect to the hard main pulse of the GRB. The $2–700$ keV fluence is $2 \times 10^{-6}$ ergs cm$^{-2}$ corresponding to an isotropic energy $E_{\text{prec}} = 6 \times 10^{50}$ ergs, i.e., $\approx 2\%$ of the isotropic energy of the proper GRB.

2. Late X-ray bursting. The prompt event is very hard and is followed by a hard tail with a moderate hard-to-soft evolution ($\alpha \approx 0.1 – 0.6$) until the late X-ray burst takes place. In this event, the spectrum switches to a soft shape ($\alpha = 1.15 \pm 0.15$), keeping this spectral shape in the subsequent tail and, as shown below, in the follow-up observation performed around 1 day after the burst. The isotropic energy contained in this event is $\approx 3\%$ of that of the proper GRB.

Finally, we find that the spectra in the early part of the burst, when fitted with a power law, require a significant absorption $N_H = (7 \pm 2) \times 10^{22}$ cm$^{-2}$ at the redshift of the burst. A fit with the smoothly broken power law proposed by Band et al. (1993) gives very low values of $E_0$ (below 10 keV), a model spectrum rising with energy below $E_0$, and the same spectral index of the power law fit above $E_0$. Basically, this model tries to reproduce the curvature produced at low energy by absorption. In addition, $\chi^2$ values are typically worse than those derived from a simple power law with absorption.

2.1.2. Follow-up Observations: BeppoSAX NFI

The prompt localization of this burst (Piro 2001a, 2001b) triggered several follow-up observations, including one by BeppoSAX itself. This was performed with the narrow-field instruments MECS and LECS starting 21 hr after the burst. The two instruments are described in Boella et al. (1997b) and Parmar et al. (1997), respectively. It was the first target of opportunity (ToO) observation performed after a new attitude control mode, the so-called gyroless mode, was installed in 2001 October and was still being tested. The observation was divided into two parts, the first covering the period 21–33 hr and the second 52–60 hr after the burst. The total net exposure time was 33 ks in the MECS and 9 ks in the LECS. An additional observation was carried out 4.5 days after the burst, with a MECS net exposure of 22 ks and 11 ks with the LECS.

The fading X-ray afterglow of GRB 011211 (ISAX J113426–7601.4) was detected in the first part of the first observation with $F_{2–10\,\text{keV}} = 4 \times 10^{-13}$ ergs cm$^{-2}$ s$^{-1}$ at a position (J2000) R.A. = $11^h34^m25^s$, decl. = $-76^\circ01'22''$, with an error radius of $50''$ (Piro et al. 2001). This position is $25''$ away from the optical transient (Garnavich et al. 2003), well within the error box, verifying the good quality of the aspect reconstruction in this new pointing mode. In the other parts of the observation the source was not detected with an upper limit $\approx 10^{-12}$ ergs cm$^{-2}$ s$^{-1}$. A fit to the light curve with a power law $\Gamma^{-\delta_X}$ gives $\delta_X = 3.8 \pm 1.9$. The spectrum is fitted by an absorbed power law with energy spectral index $\alpha_X = 1.6 \pm 0.7$ and column density consistent with the galactic value (Table 2).

Observations of the optical counterpart revealed a rather nearby event ($z = 0.36$; Infante et al. 2001) and excess emission above the power law decay, attributed to a SN bump (Garnavich et al. 2003; Greiner et al. 2003). The latter authors report a break after 1.3 days, attributed to a collimated outflows. Radio and optical observations suggested a fireball in a wind medium (Price et al. 2002).

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2.2. The December Burst GRB 011211

GRB 011211 was detected by the BeppoSAX Wide Field Camera 1 (WFC; 2–26 keV) at 19:09:21 UT on 2001 December 11 (Gandolfi et al. 2001a). A detailed off-line analysis of the GRBM (40–700 keV) data showed a very shallow and long event (Frontera et al. 2002) with a duration of about 270 s, similar to that observed by the WFC (Fig. 4). In Table 1 we summarize peak fluxes and fluences in different energy ranges. The fluence in the 2–700 keV range corresponds to an isotropic energy of $3.6 \times 10^{52}$ ergs at the redshift of the burst ($z = 2.14$; Fruchter et al. 2001; see below). The ratio of X-ray to gamma-ray fluence (peak) are $S_{2–26}/S_{40–700} = 0.5$ ($F_{2–26}/F_{40–700} = 0.3$). These values are higher than in typical GRBs (Frontera et al. 2000a), classifying the event as an X-ray–rich GRB, i.e., in the region in between normal GRBs and X-ray flashes. This is also supported by a combined spectral analysis of the WFC and GRBM spectra of the main prompt pulse (0–400 s) with the Band model (Band et al. 1993), which gives $E_0 = 20^{+20}_{-12}$, $\alpha = 0.1^{+0.2}_{-0.4}$, $\beta = 1.1 \pm 0.2$, where $\alpha$ and $\beta$ are the energy spectral indices. Although the values of the spectral indices are consistent with those observed in normal GRBs (e.g., Frontera et al. 2000a), the peak energy $E_p = E_0(1 – \alpha) = 18$ keV is substantially lower than the average value of about 200 keV of the BATSE sample and in the range of values found in X-ray–rich GRBs (Kippen et al. 2001).

The prompt emission of this burst is characterized by peculiar features.

1. The event is long with a similar duration in the gamma-ray and X-ray ranges ($\Delta T \approx 400$ s; Fig. 4). In contrast, most of the BeppoSAX GRBs show a duration decreasing with energy as $\Delta T \approx E^{-0.5}$ (Piro et al. 1998a; Frontera et al. 2000a). Time-resolved spectral analysis shows that the peak energy evolves from 40 to 12 keV (Table 3; Fig. 5), while a much stronger variation of the peak energy, from $\approx 1$ MeV to $\approx 10$ keV, is usually observed in long, hard GRBs (Piro et al. 1998a; Frontera et al. 2000a).
2. The other interesting feature is the late X-ray burst detected by the WFC from 600 to 700 s (Figs. 4 and 6). This event is markedly distinct from the prompt phase by a gap in which no emission is detected with 3 σ upper limit ≈4 times lower than the flux of the late burst. It contains ≈4% of the fluence of the prompt event. As in the case of the November burst, its spectrum is similar to that of the late afterglow (described in the following section).

The possible presence of a transient absorption feature in the WFC afterglow was detected within the WFC error box at coordinates (J2000) R.A. = 11h15m16s, decl. = −21°55′45″ within an error box of radius 2′. Prompt dissemination of the coordinates (Gandolfi et al. 2001a, 2001b) triggered follow-up observations by several ground-based and space observatories, including XMM-Newton. An XMM-Newton ToO observation started on December 12.269 UT (11.4 hr after the GRB) and lasted for about 32 ks. The X-ray afterglow was detected within the WFC error box at (J2000) R.A. = 11h15m17s, decl. = −21°56′57.5″ with an error radius of 10′ (Santos-Lleo et al. 2001).

We have analyzed data from the European Photon Imaging Camera (EPIC), i.e., the MOS (Turner et al. 2001) and pn (Strüder et al. 2001) CCDs, by using different methods to verify the consistency of the analysis procedures. At the reduction level we used both pipeline processed data as available from the Science Operation Center (SOC) database and also independently reprocessed raw data. Source spectra were derived by using two different filter options. One, which accepts only single-pixel events, optimizes the energy resolution at the expense of source signal. The other, which also includes double-pixel events, increases the source signal. We found that all these different methods lead to consistent results. In the following we present the results derived by using the pipeline SOC-processed data with single- plus double-pixel event selection, thus optimizing the signal-to-noise ratio. The background was estimated from source-free regions close to the target and was fairly stable during the whole observation.

To extract source net spectra and light curves in both pn and MOS, we used circular regions of 30″ radius. In the first 5 ks the source in the pn image was located close to the edge of the gap between CCDs. For this period we also extracted the source counts from a circle of 10″, avoiding the edge of the

### Table 3

| Time interval | Instrument | 2–10 keV flux (ergs cm⁻² s⁻¹) | N_H (10²² cm⁻²) | α | β | Energy (keV) | χ²/ν |
|--------------|------------|-------------------------------|-----------------|---|---|-------------|--------|
| 0 s–300 s    | WFC+GRBM   | 2.4 × 10⁻⁹                   | ...             | 0.2 ± 0.2 | 1.3 ± 0.7 | 50 ± 50   | 47.9/57 |
| 300 s–400 s  | WFC+GRBM   | 3.5 × 10⁻⁹                   | ...             | 0.2 ± 0.2 | 1.3 ± 0.7 | 15 ± 10   | 47.9/57 |
| 575 s–675 s  | WFC+GRBM   | 9.5 × 10⁻¹                   | 0.26 fix        | 1.3 fix  | 10 ± 2.5  | 26.0/28  |
| 0 s–300 s    | WFC+GRBM   | 2.4 × 10⁻⁹                   | 40 ± 20         | 0.79 ± 0.05 | ... | ... | ... |
| 300 s–400 s  | WFC+GRBM   | 3.5 × 10⁻⁹                   | 60 ± 30         | 1.18 ± 0.12 | ... | ... | ... |
| 575 s–675 s  | WFC+GRBM   | 7 × 10⁻¹                     | 40 ± 9          | 1 fix    | ... | ... | ... |
| (41–46) × 10² | EPIC pn+MOS | 1.1 × 10⁻⁴                  | 1.09 ± 0.07     | ... | ... | ... | ... |
| (47–55) × 10⁴ | EPIC pn+MOS | 8.6 × 10⁻⁴                  | 1.20 ± 0.05     | ... | ... | ... | ... |
| (55–71) × 10⁴ | EPIC pn+MOS | 4.2 × 10⁻⁴                  | 1.17 ± 0.04     | ... | ... | ... | ... |

Notes.—Energy spectral indices are given in the α and β columns. N_H is in the rest frame of the burst. Errors are at the 90% confidence level for one interesting parameter.

*a* Band model with absorption column density fixed to the Galactic value.

*b* Joint fit to the 0–300 and 300–400 s data sets with a Band model with absorption column density fixed to the Galactic value.

*c* Power-law model with absorption column density fixed to the Galactic value.

![Fig. 5.](image-url) Spectral (νF_ν) evolution of the 2001 December 11 burst in the BeppoSAX GRBM and WFC with a Band model (Band et al. 1993) in time slices (a) 0–300 s (data points: filled circles; model: continuous line), (b) 300–400 s (data: open squares; model: dashed line), and (c) 575–675 s (data: crosses and upper limits; model: dotted line).

![Fig. 6.](image-url) X-ray light curve of the 2001 December 11 burst from BeppoSAX WFC (from 0.1 to 5000 s) and XMM-Newton pn (from 30,000 to 140,000 s) in the 2–10 keV range. The latter data are expanded in the inset. The continuous line is the best-fit power law to XMM-Newton data.
CCD. The spectrum was consistent with that derived with a 30″ radius but with \(\approx 40\%\) fewer counts. Increasing the extraction radius from 30″ to 40″ did not significantly increase the source signal, while the background nearly doubled. We thus adopted an extraction radius of 30″, which optimizes the signal-to-noise ratio. In this case the net source count rate is 0.117 \(\pm\) 0.005 counts s\(^{-1}\), and the background contribution in the source area is 6%.

The light curve of the X-ray afterglow is shown in Figure 6. It follows a power law template \(F \propto r^{-\delta}\) with \(\delta = 1.56 \pm 0.25\), consistent with the values derived by other authors from the same data set (Reeves et al. 2003; Jakobsson et al. 2003). There is marginal evidence (\(\chi^2 = 1.25\)) of excess variability in addition to the power-law decay, with an amplitude of \(\approx 10\%\) on a timescale of hours.

Spectral analysis has been carried out by splitting the observations into three consecutive intervals with exposure times of 5, 8, and 15 ks. We have performed a joint fit of pn and MOS data. The absorption column density was kept fixed to the Galactic one (\(N_\text{H} = 4.2 \times 10^{20} \text{ cm}^{-2}\)) after a first run of fit did not show any evidence for excess absorption. The results are shown in Table 3. All the spectra are well described (\(\chi^2 \lesssim 1\)) by a power law with an average energy index \(\alpha = 1.18 \pm 0.03\), with no evidence of variation of the spectral index. The issue of the presence of soft X-ray lines has been discussed in several papers (Reeves et al. 2002, 2003; Borodzin & Trudolyubov 2003; Rutledge & Sako 2003). In this paper we are interested in the spectral and temporal evolution of the continuum, so we will not discuss this issue further.

The optical afterglow was found 10 hr after the burst (Grav et al. 2001), and its fading afterglow behavior was confirmed by Bloom & Berger (2001); the optical flux decayed following \(\approx r^{-0.9}\) (Soszyński et al. 2001) between December 12.2 and December 13.3 with a break around 2 days after the burst (Holland et al. 2001). Absorption lines in the optical spectrum (Fruchter et al. 2001) indicated a redshift \(z = 2.14\).

3. THE ORIGIN OF THE X-RAY PRECURSOR IN THE NOVEMBER BURST

An intriguing feature that appears in the November burst is an X-ray burst preceding the main gamma-ray pulse by \(\approx 30\) s. It has roughly 2% of the total fluence. This event shows a remarkable behavior when compared to the proper GRB. Its spectrum is much softer. It is composed of a sequence of two pulses, with the second being more intense and softer than the first. This trend is abruptly reversed with the onset of the gamma-ray pulse. In a few seconds the softness ratio changes by almost 2 orders of magnitude (Fig. 1), with the peak energy ramping up from the keV band to above 1 MeV (Fig. 3).

While this behavior is highly suggestive of different physical mechanisms at work in the precursor and in the proper burst, a definite conclusion requires more observations and theoretical efforts. In the framework of the standard scenario, the prompt GRB phase is explained by the internal shock model (Rees & Mészáros 1994; Sari & Piran 1997). Detailed models have been developed to describe the temporal and spectral evolution of single and multipulse bursts as produced by shocks of relativistic shells with different Lorentz factors (e.g., Kobayashi et al. 1997; Daigne & Mochkovitch 1998). To our knowledge none is predicting a sequence made of X-ray pulses followed by gamma-ray pulses (see below for fireball precursors due to a different mechanism). However, considering the freedom of tuning the sequence of the ejection of the shells and their Lorentz factor, it is not excluded that a detailed model might account for the phenomenology observed in the November burst. Here we explore some alternative origin for the precursor.

Thermal precursors in GRBs have been discussed in several circumstances. So far, evidence of an X-ray precursor with a blackbody spectrum remains limited to a single event observed by Ginga (Murakami et al. 1991). In fact, in our case, a blackbody model does not provide an acceptable fit to the spectrum of the precursor, giving \(\chi^2 = 61/27\) and 76/27 for the first and second pulse, respectively. This is primarily due to the limited spectral extension of the blackbody, too narrow to account for a spectrum that extends from few to hundreds of keV. In contrast, a power law provides a good fit (see Table 2) with a spectral index \(\alpha = 1.25 \pm 0.1\), consistent with the spectrum observed in the afterglow phase.

The predicted precursors can be subdivided into two classes: fireball precursors (associated with the fireball transition from the optical thick to the optical thin regime) and progenitor precursors (associated with the interaction of the fireball with the progenitor itself). Fireball precursors are predicted in baryon-loaded fireworks (Mészáros & Rees 2000; Daigne & Mochkovitch 2002), magnetic outflows (Lyutikov & Usov 2000), and pure radiation fireworks (Paczynski 1986). Fireball precursors are expected to have a thermal spectrum and an observed temperature ranging from several MeV for clean fireworks (either magnetic or radiation dominated) to several tens of keV for baryon-dominated fireworks. Using \(R\), as the radius at which the main gamma-ray pulse is produced, the delay between the precursor and the main event is

\[
\Delta t = \frac{R}{2e \Gamma^2_0} \sim 0.2 R_{13} \Gamma^{-2}_{0.2} \text{s,} \tag{1}
\]

where \(\Gamma_0 = 100 \Gamma_{0.2}\) is the Lorentz factor of the fireball. The precursor of the November burst seems, therefore, to lack all the characteristic features of a fireball precursor: it is not thermal and it is too distant from the main event, unless an unusually low Lorentz factor or a large radius is inferred. The latter is the case of prompt emission produced by external shocks (Ruffini et al. 2002; Dermer et al. 1999), but then it would be difficult to explain the presence of the very short spikes (\(\approx 1\) s; see Fig. 1) present in the light curve (Fenimore et al. 1996; but see also Dermer & Mitman 1999).

Alternative precursors associated with a shock breakout in a massive star explosion were originally introduced in the framework of SNe by Klein & Chevalier (1978) and more recently discussed for GRBs by MacFadyen & Woosley (1999), Ramirez-Ruiz et al. (2002), and Waxman & Mészáros (2003). In this case the precursor is due to thermal radiation coming from the shocked stellar material that, just before the jet breaks out of the star, is exposed on the stellar surface. In this case as well, the spectrum is expected to be of thermal nature, even though it can be modified by interaction with the jet itself (Ramirez-Ruiz et al. 2002). If the jet is optically thin at the star’s surface and nonthermal particles are present, inverse Compton scattering can produce the observed nonthermal spectrum (D. Lazzati 2005, in preparation). Yet, the 30 s delay between the appearance of the precursor and the beginning of the prompt emission in the November burst are difficult to account for. It is possible (if not at all likely) that the jet acceleration is not complete at the star’s surface and that the jet reaches the stellar surface with a moderate bulk Lorentz factor and a large amount of internal energy (Zhang et al. 2003). Let us call \(R\), the star radius and \(\Gamma\), the Lorentz factor achieved by the
jet at the star’s surface. The delay between the precursor and the prompt emission is then given by
\[ \Delta t \sim \frac{R_c}{2c\Gamma^2} + \frac{R_c}{2c\Gamma_0^2} \sim 3R_{a,11}/\Gamma_0^{-2} + 0.2R_{a,13}/0.2 \text{ s}. \] (2)

Again it is clear that a time interval as long as 30 s calls for nonstandard parameters, such as a large stellar radius and/or a moderate Lorentz factor.

4. THE LATE X-RAY BURST AND THE BEGINNING OF THE AFTERGLOW

In this section we discuss the late X-ray bursting observed in the December and November bursts at \( t = 600 \) and 240 s, respectively. Correcting for the redshift, they correspond to a similar \( t \approx 185 \text{ s} \).

The similarity between the spectrum of these events with that of the afterglow observed during the follow-up observations with XMM-Newton and BeppoSAX is particularly compelling. Furthermore, in the November burst the spectrum of the late X-ray burst was markedly softer than that of the preceding emission. This behavior is strikingly similar to that observed in other bursts, and the only difference is the onset of the X-ray bursting (Frontera et al. 2000a). For example, in GRB 970228 soft bursting activity started 35 s after the main hard pulse. The spectrum was similar to that observed in the late-afterglow observations (Frontera et al. 1998). This has been associated with the transition from the prompt hard phase to the afterglow (Frontera et al. 2000a; Sari & Piran 1999, hereafter SP99). It is therefore tantalizing to identify the late X-ray bursting as the onset of the external shock. Such an interpretation and the consequences it bears are not straightforward.

The onset of external shocks depends on the dynamical conditions of the fireball, and, in particular, two regimes can be identified depending on the “thickness” of the fireball (SP99). In the thin-shell regime, the reverse shock crosses the shell before the onset of the self-similar solution (i.e., when an ISM mass \( m = M_0/\Gamma_0 \) is collected, where \( M_0 \) and \( \Gamma_0 \) are the rest mass and asymptotic Lorentz factor of the fireball, respectively). As a consequence, the onset of the afterglow coincides with the deceleration time:

\[ t_{\text{aft}} = \begin{cases} 
\left( \frac{3E}{32\pi nm_\text{p}c^2\Gamma_0^3} \right)^{1/3}, & \text{ISM,} \\
\frac{E}{4\pi \times 10^3 A c^2 \Gamma_0^3}, & \text{wind,} 
\end{cases} \] (3)

where \( E \) is the kinetic energy of the fireball, \( n \) the density of the ISM, \( A_s = |M_0/(10^{-5} M_\odot \text{ yr}^{-1})|/|n_\text{p}/(10^3 \text{ km s}^{-1})| \), \( M_0 \) is the mass-loss rate, and \( v_\text{w} \) is the wind velocity.

In this case the peak of the afterglow is well separated from the prompt phase (SP99) as long as the prompt phase is identified with internal shocks. Moreover, the evolution of the afterglow after the peak is well described by a power-law decay, if the time is measured starting from the explosion time, that is very well approximated by the time at which the first prompt phase photons are collected. In the case of a thick shell, the reverse shock has not crossed the shell when the critical mass \( m = M_0/\Gamma_0 \) has been collected, and therefore the external shock remains energized for a longer time. The peak of the afterglow emission therefore coincides with the shell crossing time of the reverse shock:

\[ t_\Delta = \Delta/c = T, \] (4)

where \( T \) is the duration of prompt phase and \( \Delta \) is the thickness of the shell. It is immediately obtained that the early afterglow emission is mixed with the late GRB one. In addition, the afterglow decay will be well described with a single power law only if the time is measured starting from the time at which the inner engine turns off, roughly coincident with the GRB duration. Mathematically, a shell is defined as thick if (SP99)

\[ T_2 \left( \frac{n}{E_{52}} \right)^{1/3} \Gamma_0^{8/3} > 2.9 \quad \text{ISM} \]

\[ T_2 A_1 \Gamma_0^4 \frac{E_{52}}{\Delta_{52}} > 0.006 \quad \text{Wind} \] (5)

and thin otherwise.

For \( n = 1 \) and \( \Gamma_0 = 1 \), the thin shell condition is satisfied for both bursts, while for \( A_s = 0.003 \) (see below) and \( \Gamma_0 = 100 \) the thin shell is also satisfied for the wind best-fit case for the November burst. However, the strong dependence on \( \Gamma \) of equation (5) allows for solutions in which a thick-shell approximation is valid. We now present some evidence supporting this case. The decay part of the late X-ray burst cannot be connected to the 1 day afterglow emission with a single power law \((t - t_0)^{-\delta_X}\) when \( t_0 \) corresponds to the GRB onset (e.g., Fig. 6). However, this is the case (Fig. 7) when \( t_0 \) is set equal to the onset of the late X-ray burst. The best-fit slopes are \( \delta_X = 1.33 \pm 0.07 \) (\( \chi^2/\text{dof} = 39/30 \)) and \( \delta_X = 1.29 \pm 0.04 \) (\( \chi^2/\text{dof} = 31/16 \)) for the December and November bursts, respectively. The errors of the decay slopes include systematic errors derived by changing \( t_0 \) by \( \pm 10 \text{ s} \).

This observation seems, therefore, to favor a situation in which the shell is thick (and therefore either the case of a dense medium or the case of a relatively large Lorentz factor \( \Gamma > 100 \)). The fact that the afterglow peak is well separated from the gamma-ray phase would imply a long energy release by the inner engine, lasting longer than the observed gamma-ray phase. This can be obtained if the efficiency of conversion of the kinetic energy into gamma rays decreases with time (e.g., because of a smaller dispersion of the Lorentz factor).

Alternative explanations would require an inhomogeneous fireball or external medium. In this case the late X-ray burst would not be identified with the afterglow onset but with an emission bump overlaid on the regular afterglow decay. In the X-ray regime, inhomogeneities in the external medium can hardly affect the light curve, since the relevant electrons are in the fast-cooling regime (Lazzati et al. 2002). Inhomogeneities in the fireball itself and/or a reenergization of the shock by a delayed shell are both possible explanations. The latter hypothesis was proposed by Panaitescu et al. (1998) to explain the later and longer rebursting event observed in GRB 970508 (Piro et al. 1998b). A major reenergization or hot spot is, however, necessary in order to obtain such a prominent bump in the light curve.

5. A POSSIBLE BREAK IN THE X-RAY LIGHT CURVES

According to Greiner et al. (2003), the optical light curve of the November burst shows a break at 1.2 ± 1.0 days, i.e., slightly after the beginning of the BeppoSAX NFI observation.
For the November burst we derive $\delta_{X1} = 1.22 \pm 0.09$ and $1.15 \pm 0.09$ for a sharp and shallow transition, respectively. The corresponding break times are $t_b = 0.7 \pm 0.3$ and $0.7^{+0.9}_{-0.4}$ days, consistent with optical results. This model gives $\chi^2$/dof = 23.5/15 and 25.7/15 with a marginal improvement (97%) with respect to the simple power law.

For the December burst we have limited the analysis to the case of a shallow transition, because the optical break takes place after the end of the XMM-Newton observation. We derive $t_b = 0.8^{+0.3}_{-0.3}$ days, consistent with the value derived from optical data, and $\delta_{X1} = 1.22 \pm 0.06$. This model gives $\chi^2$/dof = 34.9/29, with a very marginal (93%) improvement with respect to the simple power law.

We conclude that, although the X-ray light curves are consistent with the presence of a break as found in the optical band, the statistical evidence is not compelling.

6. THE FIREBALL EVOLUTION: CONSTANT DENSITY AND WIND ENVIRONMENTS

By using the parameters of the X-ray spectral and temporal evolution and taking into account the optical behavior, we now show that the afterglow emission in the December burst is consistent with an expansion in a constant-density medium. In contrast, a wind is required for the November burst. This analysis is carried out for $t \leq t_b$, when the expansion is described by a spherical fireball.

We recall that, according to the fireball model, the temporal and spectral slopes are linked through relationships that depend upon the kind of the expansion (spherical or jet) and the density of the medium (uniform or wind) (e.g., Sari et al. 1999; Chevalier & Li 2000). We computed the so-called closure relationships in all the relevant cases, considering at first only the X-ray spectral and temporal slopes. In both bursts, the only solution consistent with the data is the case of spherical expansion into either ISM or wind for a cooling frequency below the X-ray range. For the December burst the corresponding closure relation is $C = \delta_X - 3/2n_X + 1/2 = 0.08 \pm 0.09$, while for the November burst it is $C = 0.06 \pm 0.2$ or $0.38 \pm 0.6$, adopting the spectra index of the late X-ray burst or of the late afterglow, respectively.

The degeneracy of the solution wind versus ISM can be resolved by comparing the temporal decay slopes above and below the cooling frequency, i.e., in X-rays and optical. In a wind the temporal evolution in X-rays should be shallower than in the optical (D = $\delta_X - \delta_O = -0.25$), while the reverse holds for an expansion in an ISM (D = +0.25).

In the December burst $\delta_O = 0.95 \pm 0.02$ (Jakobsson et al. 2003) versus $\delta_X = 1.3 \pm 0.07$, which gives $D = 0.4 \pm 0.07$, consistent only with the ISM case. The value of the electron index distribution $p \approx 2.4$ derived from the temporal slopes implies optical and X-ray spectral slopes of $0.7$ and $1.2$, respectively, in good agreement with the observed values $\alpha_O = 0.66 \pm 0.13$ (Garnavich et al. 2003) and $\alpha_X = 1.18 \pm 0.03$. Guided by these results, we have applied a detailed modelling of the afterglow using the prescription given, e.g., in Panaitescu & Kumar (2000). In Figure 8 we present a model with $p = 2.45$, total energy $E_{53} = 0.9$, $e_c = 0.0025$ and $c_b = 0.01$ (the fraction of energy in relativistic electrons and magnetic field, respectively), density $n = 3$ cm$^{-3}$, and jet opening angle $\theta_j = 8^o$.

For the November burst only the wind case is compatible with the data, because $\delta_O = 1.66 \pm 0.06$ (Price et al. 2002) versus $\delta_X = 1.29 \pm 0.04$, yielding $D = -0.37 \pm 0.07$. This gives $p \approx 2.5$, with predicted spectral slopes in the optical (0.75) and in X-rays (1.25) consistent with the observed values.

The postbreak optical slope $\delta_{O2} = 2.44 \pm 0.38$ is consistent with the steep slope derived by fitting the BeppoSAX NFI data alone$^8$ ($\delta_X = 3.8 \pm 1.9$). In the December burst Jakobsson et al. (2003) found a break in the optical curve at $t = 1.56 \pm 0.02$ days with a postbreak slope of $\delta_{O2} = 2.11 \pm 0.07$.

We have therefore fitted again the early and late afterglow X-ray light curves employing the empirical formula (Beuermann et al. 1999)

$$F_X(t) = 2^{1/n}F_X(t_b) \left[ \left( \frac{t}{t_b} \right)^{n_{X1}} + \left( \frac{t}{t_b} \right)^{n_{X2}} \right]^{-1/n},$$  \hspace{1cm} (6)

where the parameter $n$ describes the sharpness of the transition. To limit the number of free parameters, we have analyzed the cases of $n = 10$ (sharp transition) and $n = 1$ (shallow transition). In addition, we have fixed the postbreak transition $\delta_{X2}$ to the values derived in the optical band. The results are shown in Figure 7.

$^8$ This is not sensitive to variations of $t_b$ of $\approx 100$ s.
7. THE LATE RADIO TO X-RAY AFTERGLOW DATA OF THE NOVEMBER BURST: A WIND TERMINATION SHOCK?

Following the result presented in § 6, we have carried out a detailed modelling of the broadband afterglow data of the November burst. We have first fitted the data at 1 day, i.e., when the expansion is described by a spherical fireball. Data points are the X-ray fluxes, optical fluxes, and the radio flux at 8.7 GHz, including the large uncertainty due to interstellar scintillation (ISS; Price et al. 2002). The total energy has been fixed to the observed value $E = 7.28$ and $p = 2.5$, as derived in § 6. With these constraints we find $A_e \sim 0.003$, $c_e \sim 0.01$, and $c_B \sim 0.5$. This solution is shown in the middle and left panels of Figure 9. Interestingly, if we relax the constraint on $E_{53}$, allowing for a small efficiency of the internal shock phase, no acceptable solution can be found, pointing to a large efficiency for the gamma-ray production.

However, if we blindly extrapolate the above-mentioned model to the radio band, assuming a jet evolution after 1.3 days, we cannot account for the late-time radio measurements (Price et al. 2002), which are far brighter than the prediction, even considering the ISS. This is due to the steep decrease of the model flux at around 10 days, when the injection frequency enters the radio band. This behavior cannot be changed by any other choice of model parameters without violating the constraints on the injection and cooling frequencies imposed by the optical and X-ray data. They require the injection frequency to be below the optical band and the cooling frequency to be in between the optical and X-ray bands. The extrapolated model is shown in the right panel of Figure 9 with a thin solid line; thin dashed lines account for possible flux variations induced by ISS (Walker 1998).

It should be kept in mind, however, that the $r^{-2}$ scaling for the density cannot hold out to very large radii, since the stellar wind does not expand in a vacuum but rather in a dense molecular cloud. The wind interaction with the molecular cloud gives rise to a complex discontinuity and shock structure recently discussed by Chevalier et al. (2004; see their Fig. 1). Given the paucity of data, we account for this by assuming a uniform density for the ISM after a given radius $r_w$. We find that the radio data at $t > 20$ days can be reproduced if a different scaling for the density becomes uniform at a radius $r_w = 3$ pc with a low density value $n = 10^{-5}$ cm$^{-3}$. The model is shown in all the panels of Figure 9.
with a thick solid line. In the radio band panel, the ISS fluctuation range is shown with thick dashed lines. Since the radio flattening occurs after the jet break, the exact value of $r_w$ depends on the details of the jet sideways expansion. The quoted number holds for a non–sideways-expanding jet, while smaller $r_w$ are relevant in an expanding case.

Following Chevalier et al. (2004) we find that the wind structure is consistent with what is expected from a fast, light Wolf-Rayet wind, which expands in and is confined by a high-pressure environment. In this case a large constant-density region is produced in the shocked wind. This and the low wind density inferred from our afterglow modelling give a wind with $M \sim 10^{-7} M_\odot \, yr^{-1}$ and $v_w \sim 3 \times 10^8 \, cm \, s^{-1}$.

8. THE ORIGIN OF THE X-RAY ABSORBER IN THE NOVEMBER BURST

A significant absorption with a column density $N_{H} = (7 \pm 2) \times 10^{22} \, cm^{-2}$ is detected during the prompt emission until $t = 25 \, s$ (Table 2). After this time, the column density decreases to a value consistent with zero, although some of the upper limits are still marginally consistent with the value observed in the early phase. An overall decrease of the column density is expected if the absorbing gas is contained in a region of a few pc around the burst because of ionization by hard photons (Perna & Loeb 1998; Lazzati & Perna 2002). We have at first explored the possibility that this absorption is produced by the wind. A simple general formula is derived in this case:

$$N_{H,22} = \frac{3 A_s}{r_{13}}$$

where $N_{H} = 10^{22} N_{H,22} \, cm^{-2}$ is the column density of the wind from a radius $r = 10^{13} r_{13} \, cm$ to infinity. For the typical radius at which the prompt emission is produced in the internal shock scenario, $r_{13} = 1$ and $A_s = 0.003$ equation (7) gives $N_{H,22} = 10^{-2}$. The column density of the wind is thus much lower than observed. We conclude that the absorbing medium is external to the fireball region, and it could be associated with a star-forming region embedding the GRB.

9. CONCLUSIONS

In this paper we have presented the spectral and temporal evolution of the prompt and afterglow emission of two bursts, the events of 2001 November 21 (GRB 011121) and of 2001 December 11 (GRB 011211). The results have relevant implications on the environment and the progenitor.

Both events show a late X-ray burst taking place hundreds of seconds after the prompt emission. This phenomenon might also be present in other bursts, particularly in some of the long-duration GRBs identified in an off-line analysis of BeppoSAX WFC data (in’t Zand et al. 2004). For the bursts presented in this paper we find that the spectrum of the late X-ray burst is substantially softer than the prompt emission and remarkably similar to the power law observed in the afterglow at later times. This behavior has been observed in several other bursts (Frontera et al. 2000a) but on shorter timescales, and it is attributed to the transition from the prompt emission to the early afterglow in the framework of the internal-external shock scenario (SP99). These two phases are typically separated by gaps with little or undetected emission, but there are cases where the two overlap (Piro et al. 2002; Soffitta et al. 2004). The tail of the early afterglow emission usually lies on the backward extrapolation of the power law decay observed a day after the burst. In the November and December burst we find that the tail of the late X-ray burst and the afterglow at 1 day are connected with a single power law, but only if $t_0$ is coincident with the onset of the late burst. This is what is expected in the case of a thick fireball, in which the afterglow decay is described by a single power law only if the time is measured starting from the time at which the inner engine turns off (SP99). We are thus led to the conclusion that the late X-ray burst represents the beginning of the afterglow. The fact that the afterglow peak is delayed from the gamma-ray phase would imply a long energy release from the inner engine, lasting longer than the observed prompt phase. This can be obtained if the efficiency of conversion into gamma rays decreases with time (e.g., due to a smaller dispersion of the Lorentz factor in the internal shock scenario).

An intriguing feature observed in the November burst is an X-ray burst preceding the hard pulse of the gamma-ray burst by $\sim 30 \, s$. Similar events have been observed in a few other bursts (in’t Zand et al. 1999; Frontera et al. 2000b). It contains roughly 2% of the fluence of the main event. The spectrum is not consistent with a blackbody and is well-fitted with a power law with energy index of 1.2 extending from 2 to 700 keV. The origin of this feature is puzzling. Precursors associated with shock breakout at the surface of the star have been discussed in the framework of the association of GRBs with massive star explosions. These events are expected to be of a thermal nature, although a modification to a nonthermal spectrum can be obtained through the interaction with a nonthermal component in the jet at the stellar surface. In this framework, the delay between the precursor and the prompt emission would require that the jet acceleration is not complete at the star surface and that the jet reaches the stellar surface with a relatively small bulk Lorentz factor.

The spectral and temporal behavior of the X-ray afterglow and the time decay of the optical afterglow indicate that the fireball expands in a constant-density environment in the December burst. From broadband afterglow modelling we derive $n = 3 \, cm^{-3}$, fireball total energy $E_53 = 0.9$, $c_e = 0.0025$ and $\alpha_p = 0.01$, and jet opening angle $\theta_j = 8^\circ$. In contrast, in the November burst a fireball expansion in a wind is clearly revealed by an X-ray decay (temporal slope $\delta_x = 1.29 \pm 0.04$) slower than the optical ($\delta_O = 1.66 \pm 0.06$). Broadband modelling of radio to X-ray data at 1 day requires a wind with a rather low density $A_s \approx 0.003$, a total isotropic energy similar to that observed in gamma rays (indicating a high efficiency for gamma-ray production), $c_e \approx 0.01$, and $\alpha_p \approx 0.5$. The X-ray data are consistent with (but do not require) a break at 1.3 days, as suggested by optical data (Greiner et al. 2003). However, the late-time radio data (Price et al. 2002) fall above the extrapolation of a collimated fireball in a wind. We find that this discrepancy can be solved if the density becomes uniform with $n = 10^{-5} \, cm^{-3}$ at a radius $r_w = 3 \, pc$. This wind structure is consistent with that expected from a Wolf-Rayet wind, which expands in and is confined by a high-pressure environment (Chevalier et al. 2004) like that expected in a star-forming region. In this case a large constant-density region is produced in the shocked wind. For the November burst we derive a wind with $M \sim 10^{-7} M_\odot \, yr^{-1}$ and $v_w \sim 3 \times 10^8 \, cm \, s^{-1}$.

Finally, a significant absorption with a column density $N_H = (7 \pm 2) \times 10^{22} \, cm^{-2}$ is detected during the prompt emission of the November burst until $t = 25 \, s$. After this time, the column density decreases to a value consistent with zero, although some of the upper limits are still marginally consistent with the value observed in the early phase. A decrease of the column density on a timescale similar to that observed is expected if the absorbing gas is contained in a region of a few parsecs
around the burst, due to ionization by hard photons (Perna & Loeb 1998; Lazzati & Perna 2002). Since the column density in the wind is much lower than observed, we conclude that the absorbing gas could be associated with the medium of the star-forming region embedding the GRB, which is also likely responsible for the termination shock in the wind structure discussed above.

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