PROMPT AND AFTERGLOW EMISSION FROM THE X-RAY–RICH GRB 981226
OBSERVED WITH BEPPOSAX

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ABSTRACT

We discuss observations of the prompt X- and γ-ray emission and X-ray afterglow from GRB 981226. This event has the weakest gamma-ray peak flux detected with the BeppoSAX Gamma-Ray Burst Monitor. It shows an isolated X-ray precursor and the highest X-ray to gamma-ray fluence ratio measured thus far with the BeppoSAX Wide Field Cameras. The event was followed up with the BeppoSAX Narrow Field Instruments, and the X-ray afterglow was detected up to 10 keV. The afterglow flux is observed to rise from a level below the sensitivity of the MECS/LECS telescopes up to a peak flux of (5 ± 1) × 10⁻¹³ ergs cm⁻² s⁻¹ in the 2–10 keV energy band. This rise is followed by a decline according to a power law with an index of 1.31 ± 0.44. We discuss these results in the light of the current GRB models.

Subject headings: gamma rays: bursts — gamma rays: observations — shock waves — X-rays: general

1. INTRODUCTION

Follow-up observations of arcminute positions of Gamma-Ray Bursts (GRBs) provided by the Wide Field Cameras on the BeppoSAX satellite (Jager et al. 1997; Boella et al. 1997a) have shown that in most cases a fading X-ray counterpart identified as the GRB X-ray afterglow is detected (Frontera et al. 2000a). The fading law is generally a smooth power law (e.g., Frontera et al. 2000b) except in two cases: GRB 970508 (Piro et al. 1998), in which a late-time outburst of about 10 s duration started about 6 × 10⁶ s after the main event, and GRB 970828 (Yoshida et al. 1999), in which a peak structure of 4000 s duration at 1.25 × 10⁵ s after the main event. Generally the afterglight curves extrapolated back to the time of the bursts, are in agreement with the tail of the GRB time profiles (Costa et al. 1997; Piro et al. 1998; Frontera et al. 2000b). This fact is considered as evidence that late afterglow emission and tail of the prompt GRB emission have the same origin (Frontera et al. 2000b). In the fireball model scenario (see, e.g., the recent review by Piran 1999), this means that both the tail of the prompt emission and the late afterglow emission can be due to an external shock produced by the interaction of a relativistically expanding fireball with the interstellar medium (ISM).

Of the promptly localized GRBs 80% show X-ray afterglow, about 50% exhibit also optical emission, and 30% show radio emission. Radio emission is generally accompanied by optical emission, except in two cases: GRB 990506 (Taylor, Frail, & Kulkarni 1999), from which also X-ray afterglow emission was observed with the RXTE/PCA experiment (Baccinale trigger 7549; Hurley 1999), and GRB 981226. For the latter event, in spite of several attempts to find the optical counterpart (Galama et al. 1999a; Rhoads et al. 1998; Bloom et al. 1998; Schaefer et al. 1998; Castro-Tirado et al. 1998; Wozniak 1998; Lindgren et al. 1998) none was identified. The best upper limit (R ~ 23 mag) to the optical flux of the GRB counterpart was reported by Lindgren et al. (1999). Frail et al. (1999a) reported the detection of a radio counterpart (VLA 232937.2–23553). The radio source peaked to 173 ± 27 μJy at 8.46 GHz at about 10 days after the burst. This time delay is typical of all previously studied radio afterglows. However, the source declined relatively fast, following a power-law decay (∝t⁻³) with δ_R = 2.0 ± 0.4 (Frail et al. 1999b). Two interpretations of this rapid decay have been proposed by Frail et al. (1999b): it is either the consequence of a jetted GRB or the result of a fireball shock in an ambient medium with variable density. An optical galaxy (R = 24.85 mag), consistent with the radio transient position, has been proposed as the host galaxy of GRB 981226 (Frail et al. 1999b).

GRB 981226 was also followed up with the BeppoSAX Narrow Field Instruments. A transient X-ray source was observed, which was proposed as the X-ray afterglow of GRB 981226 (Frontera et al. 1998). Here we report the properties of this afterglow emission along with those of the prompt X- and gamma-ray emission. We will discuss these properties in the light of the current models of GRBs.

2. OBSERVATIONS

GRB 981226 was detected with the BeppoSAX Gamma-Ray Burst Monitor (GRBM, 40–700 keV; Frontera et al. 1998).
1997; Amati et al. 1997) and WFC unit 1 (1.5–26.1 keV; Jager et al. 1997) on December 26 starting at 09:47:25 UT (Di Ciolo et al. 1998). Its position was determined with an error radius of 6′ (99% confidence level) and was centered at \( \alpha_{2000} = 23^h29^m40^s \), \( \delta_{2000} = -23^°55'30" \). A precursor is detected only in the WFC at 09:44:20 UT.

About 11 hr after the burst, the Narrow Field Instruments on-board BeppoSAX were pointed at the burst location for a first target of opportunity (TOO1) observation, from December 26.8785 UT to December 28.2986 UT. A new X-ray source was detected (Frontera et al. 1998) in the direction was offset by 7° with respect to the WFC axis. The MECS source count rates and spectra for TOO1 were pointed at the burst location (Jager et al. 1997), which implicitly subtracts the contribution of the background and of other point sources in the field of view.

The MECS source count rates and spectra for TOO1 were extracted, using the XSELECT package, from a \( \sim 3' \) radius region around the source centroid, while the background level was estimated from an annulus centered on the source with inner and outer radii of 4' and 8.5', respectively. The spectra from MECS 2 and 3 were equalized and co-added. Given the much lower exposure time, the source was much less visible in the LECS. We used for the source extraction from the LECS image the XIMAGE package (Giommi et al. 1991), which permits a more refined choice of the background region. The source counts were extracted from a square box centered on the source centroid consistent with the MECS centroid position and with side of 3′, while the corresponding background was extracted from a square annulus of inner side 3′ and outer side 12′, centered on the source. The uncertainties will be given as single parameter errors at 90% confidence level.

3. RESULTS

3.1. Prompt Emission

Figure 1 shows the measured time profiles of GRB 981226 in three energy channels after the background subtraction. In the γ-ray band (40–700 keV; middle panel), the GRB shows a single peak of about 20 s duration. A marginal evidence of the peak (2.9 \( \sigma \) total excess) appears in the high energy range (>100 keV; bottom panel). In the X-ray energy band (2–26 keV; top panel), the prompt emission starts about 180 s earlier with a precursor-like event of about 50 s duration. The X-ray main event exhibits two peaks, the first of which is coincident with that detected by the GRBM. The total duration of the X-ray main event is about 80 s. From the WFC images both precursor and main event are consistent with the same direction in the sky.

The spectral evolution of precursor and main event was studied by subdividing the GRB time profile into five temporal slices and performing an analysis on the average spectrum of each slice (see Fig. 1). We fit the spectra with a power law \( [N(E) \propto E^\alpha] \) and a smoothly broken power law (Band et al. 1993), both photoelectrically absorbed by a neutral hydrogen column density \( N_H \) (Morrison & McCammon 1983). The count statistics do not permit us to constrain \( N_H \) that was thus fixed to the Galactic value along the GRB direction (1.8 \( \times 10^{20} \) cm\(^{-2}\)). In Table 1 we show the results. Both laws fit the data. The Band law permits to determine the value of the peak energy \( E_p \) of the logarithmic power per photon energy decade (the \( \nu F_\nu \) spectrum). For the time slices A, C, D, where only upper limits to the gamma-ray flux were available, the upper limits of \( E_p \) were

### Table 1

| Time Slice | Model      | \( \alpha \)  | \( \beta \) | \( E_p \) (keV) | \( \chi^2 \) (dof) |
|------------|------------|--------------|------------|----------------|-----------------|
| A          | Power law  | -1.97 ± 0.41 | ...        | ...            | 1.32 (7)        |
|            | Band law  | -1.88 ± 0.21 | < -2.0     | < 4            | 1.16 (5)        |
| B          | Power law  | -1.66 ± 0.07 | ...        | ...            | 1.35 (7)        |
|            | Band law  | -1.25 ± 0.25 | -2.6 ± 0.7 | 61 ± 15        | 0.91 (5)        |
| C          | Power law  | -2.14 ± 0.14 | ...        | ...            | 0.85 (7)        |
|            | Band law  | -1.76 ± 0.38 | < -2.0     | < 7            | 1.2 (5)         |
| D          | Power law  | -2.17 ± 0.13 | ...        | ...            | 1.4 (7)         |
|            | Band law  | -1.83 ± 0.28 | < -2.0     | < 6            | 2.1 (5)         |
| E          | Power law  | -2.06 ± 0.16 | ...        | ...            | 1.36 (7)        |

* Band law refers to the smoothed broken power-law proposed by Band et al. (1993): \( \alpha \) and \( \beta \) are the power-law photon indices below and above the break energy \( E_o \) respectively. \( E_p = E_o (2 + \alpha) \).
Fig. 1.—Light curves of GRB 981226 in three energy bands, after background subtraction (see text). The zero abscissa corresponds to 1998 December 26, 09:47:25 UT. The time slices on which the spectral analysis was performed are indicated by vertical dashed lines. The X-ray precursor start time corresponds to $-180$ s.

The $\gamma$-ray (40–700 keV) fluence of the burst is $S_\gamma = (4 \pm 1) 	imes 10^{-7}$ ergs cm$^{-2}$, while the corresponding value found in the 2–10 keV band is $S_X = (5.7 \pm 1.0) 	imes 10^{-7}$ ergs cm$^{-2}$, with a ratio $S_X/S_\gamma = (1.4 \pm 0.4)$. The $\gamma$-ray peak flux, derived from the 1 s ratemeters, is $P_\gamma = 0.33 \pm 0.13$ photons cm$^{-2}$ s$^{-1}$, corresponding to $(6.5 \pm 2.6) \times 10^{-8}$ ergs cm$^{-2}$ s$^{-1}$, while the corresponding 2–10 keV peak flux is $P_X = 2.7 \pm 0.3$ photons cm$^2$ s$^{-1}$, corresponding to $(1.7 \pm 0.2) \times 10^{-8}$ ergs cm$^{-2}$ s$^{-1}$. The peak flux in gamma-rays is the lowest observed thus far with BeppoSAX.

3.2. Afterglow Emission

During TOO1, a previously unknown X-ray source, 1SAX J2329.6-2356, was detected in the MECS, almost at the center of the GRB error box, at celestial coordinates $x_{\alpha 2000} = 23^h 29^m 36.1^s$, $y_{\delta 2000} = -23^\circ 55' 58.3''$, with an error radius of 1' (Frontera et al. 1998). The MECS image obtained in the first part of TOO1 (exposure time of 26,950 s), when the source was stronger, is shown in Figure 3 (left). The source is also visible in the corresponding 0.1–2 keV LECS image (6880 s exposure time). The source was not detected in the TOO2, when the MECS exposure time was 25080 s (see Fig. 3, right panel).

Other count excesses, compatible with very weak celestial sources, are present in the TOO1 image. They are likely field sources, the number of which is in agreement with the
and E represent the power-law fits to WFC data, while that for slice B spectral fits to higher energies. (see also Table 1). The dashed lines represent the extrapolations of the burst time profile (energy flux in keV cm\(^{-2}\) s\(^{-1}\)). Continuous curves for slices A, C, D, and E represent the power-law fits to WFC data, while that for slice B represents the fit with a Band law (Band et al. 1993) to WFC + GRBM data (see also Table 1). The dashed lines represent the extrapolations of the spectral fits to higher energies.

log N–log S distribution of the 5–10 keV X-ray sources found by Fiore et al. (1999a) with BeppoSAX. Given its transient behavior, 1SAX J2329.6-2356 is likely the X-ray afterglow of GRB 981226. From the above log N–log S distribution, the chance probability for its coincidence with a background source is about 5 \times 10^{-3}.

3.2.1. Spectrum

We derived the average 0.1-10 keV count spectrum of 1SAX J2329.6-2356 over the first 15 hr of TOO1, when the source was brightest. We fit it both with a power law \([N(E) \propto E^{\alpha}]\) and a blackbody, photoelectrically absorbed by the Galactic column density along the GRB direction (see § 3.1). In the fits a normalization factor of 0.8 was applied to the LECS spectra following the cross-calibration tests between the LECS and MECS\(^{13}\). Both laws are acceptable descriptions of the data: \(\chi^2_\nu = 0.5\) (5 degrees of freedom [dof]) for a power-law and \(\chi^2_\nu = 1.3\) (5 dof) for a blackbody. However, in the case of the blackbody, for energies above 5 keV, the best-fit curve is constantly below the measured bins. This suggests that the power law provides a better description of the data. The best-fit power-law index is \(\alpha = -1.92 \pm 0.47\). We do not find evidence of a spectral evolution of the emission: the time behavior of the \((C(4–10\ keV)/C(1.4–4\ keV))\) hardness ratio is statistically consistent with a constant.

No evidence of the source is found in the 15–300 keV energy range: the BeppoSAX PDS instrument (Frontera et al. 1997) during TOO1 does not show any statistically significant count excess over the background level. Assuming the above power-law index, the 2 \(\sigma\) upper limit in the 15–60 keV energy band is \(5.5 \times 10^{-12}\) ergs cm\(^{-2}\) s\(^{-1}\), which is a factor of \(\sim 30\) higher than the extrapolated flux from the LECS + MECS spectrum. As mentioned above, no source excess is apparent in the MECS + LECS data during TOO2. Assuming the best-fit power-law index obtained from the TOO1 spectrum and the Galactic column density, we derived the following 2 \(\sigma\) upper limits to the source flux during TOO2: \(1.3 \times 10^{-13}\) ergs cm\(^{-2}\) s\(^{-1}\) and \(8.2 \times 10^{-14}\) ergs cm\(^{-2}\) s\(^{-1}\) in the 0.1–2 keV and 2–10 keV ranges, respectively.

3.2.2. Light Curve

The 2–10 keV MECS light curve of the afterglow in bins of 7000 s elapsed time is shown in Figure 4 (top). Its main feature is the weakness of the source in the first 7000 s bin, where its flux is below the MECS sensitivity limit (2 \(\sigma\) upper limit of \(1.5 \times 10^{-13}\) ergs cm\(^{-2}\) s\(^{-1}\) in the 2–0 keV energy band). Checks were done to verify whether this nondetection could be due to attitude malfunctions of the satellite. However we found that the source was correctly pointed since the beginning of the NFI TOO1. Afterwards the source flux increases by more than a factor 3 in about 10000 s \([(5 \pm 1) \times 10^{-13}\) ergs cm\(^{-2}\) s\(^{-1}\)]. After this peak flux the source starts fading. The light curve is also reported in the bottom panel of Figure 4 along with the WFC data points. The later fading of 1SAX J2329.6-2356 is apparent, that is well described by a power law, \(F(t) \propto t^{-\delta}\), with index \(\delta = 1.31 \pm 0.44\). In Figure 4 (bottom) we show the best-fit power law along with the slope uncertainty region (90% confidence level). From the best-fit light curve, the 2–10 keV afterglow fluence integrated over the time interval from the GRB end (80 s) to \(10^6\) s is \(S_n = (4.3 \pm 3.8) \times 10^{-7}\) ergs cm\(^{-2}\), with a ratio between X-ray afterglow fluence and the prompt \(E_{\gamma}\) of 1.1 \pm 0.9, versus a corresponding value of \((1.4 \pm 0.4)\) for the prompt emission (see § 3.1).

4. DISCUSSION

GRB 981226 shows the lowest gamma-ray peak flux among the bursts localized thus far with BeppoSAX. In the log N–log P distribution of the GRBs observed with

\(^{13}\) See F. Fiore, et al. at http://www.sdc.asi.it/software/cookbook.
BATSE (Paciesas et al. 1999), it is located near the faint end of the distribution. The burst is marked by three peculiarities, two of which have been seen for the first time:

1. Of the bursts localized by BeppoSAX, this burst is the richest in the X-ray band: the X-ray to gamma-ray fluence ratio of $1.4 \pm 0.4$ is the highest of all BeppoSAX bursts (Frontera et al. 2000b). The peak energy $E_p \sim 60$ keV is softer than that measured in other BeppoSAX bursts.

2. An isolated X-ray precursor occurs about 180 s before the main event (Figs. 1–2). Onset of X-ray emission before the gamma-rays has been observed in other GRBs (Laros et al. 1984; Murakami et al. 1991; in 't Zand at al. 1999; Feroci et al. 1999, private communication), but only one other isolated X-ray precursor, which started about 25 s before the start of $\gamma$-rays, has been reported thus far (Laros et al. 1984).

3. The X-ray afterglow light curve is peculiar. The afterglow emission is undetectable during the first 2 hr of the start of the NFI observations, after which it rapidly rises and then undergoes a decline in the typical power law fashion. Thus at least during the epoch 11–13 hr the afterglow is undetectable.

Item (2) is an uncommon feature of GRBs. Assuming the synchrotron shock model (e.g., Piran 1999), it implies an initial fireball expansion Lorentz factor smaller than that found in other GRBs (e.g., Frontera et al. 2000b).

Item (3) is the most interesting and mysterious aspect of this burst. In all SAX observed bursts to date, the afterglow emission at X-ray wavelengths begins more or less as soon as the main gamma-ray event ends. Also in the case of GRB 981226 we have evidence that the afterglow starts during the main event. Indeed the peak flux of the X-ray prompt emission ($\gtrsim 300$ $\mu$Jy) has the same order of magnitude as that ($173 \pm 27$ $\mu$Jy at 8.46 GHz) observed in the radio band $\sim 10$ days after the burst (Frail et al. 1999b). On the contrary, the X-ray flux measured by us about 13 hr after the main event is about 4 orders of magnitude lower than the radio peak flux. Now similar values of peak fluxes in X-rays and in the radio band are expected in quasi-adiabatic cooling shocks of relativistically expanding fireballs (Sari, Piran, & Narayan 1998). Thus a simplest conclusion is that the afterglow emission began immediately after the burst (phase E in Fig. 4), rather than 13 hr later, and then it was strongly reduced or completely ceased, and eventually restarted 13 hr after the burst. If we accept this explanation (but other possibilities cannot be ruled out), then we must explain the physical cause for this rather extended gap.

The afterglow emission is attributed to the forward shock, i.e. shock of the ambient gas particles swept up by the advancing blast wave. A cessation of X-ray afterglow would require that there be no ambient gas (or very reduced density) and the resurgence of the afterglow at 13 hr would then require increased density—in short, a cavity surrounding the explosion. The rapid decline of the X-ray and radio afterglow requires that the ambient density not be a constant but decreases with radius (Chevalier & Li 2000).

Indeed, one expects such a circumburst medium around massive stars to have a complicated geometry. For example, a star which exploded as a blue supergiant would have suffered two episodes of mass loss. During the first phase, the red supergiant phase, the wind speed is low leading to a rich circumstellar medium. During the next phase, the blue supergiant phase, the fast blue supergiant wind sweeps up the circumburst medium shaped by the red supergiant wind with the net result of a low-density cavity surrounded by a dense shell at the outskirts.

If one accepts this explanation then we have found an additional evidence linking GRBs to massive stars. In this scenario, we find a satisfying explanation also for item (1) and (2). The X-ray richness is because the blast wave picks up matter (baryons) as it tunnels through the envelope of the massive star. The resulting large baryon content leads to lower $E_p$ and hence more X-ray emission. We attribute the percursor emission to emission from shock breakout that is a natural consequence of models in which GRBs arise from the death of massive stars (MacFadyen et al. 1999).

The rapid decline in the radio and X-ray afterglow is because of the radial density gradient in the circumburst...
Fig. 4.—Top: 2-10 keV MECS light curve of 1SAX J2329.6-2356 in time bins of 7000 s each. Vertical bars represent ±1 σ errors. Bottom: 2-10 keV WFC and MECS data. Superposed on the data points is the power law curve (dashed line) obtained from the best fit to the late afterglow data, except the first bin with the upper limit. Also shown is the uncertainty region in the slope (1.31) derived from the best fit at 90% confidence level.
medium. Finally, the absence of an optical afterglow could well be due to extinction towards the GRB. If this GRB arises from the death of a massive star then most likely the progenitor was in a dusty region and hence the extinction.

We tend to exclude that the X-ray increase of the afterglow observed $\sim 13$ hr after the burst is a signature of a supernova emission. Given that the X-ray flux is similar to that measured for the X-ray counterpart of SN1998bw (Pian et al. 1999), one would expect a moderate distance for GRB 981226 ($z \lesssim 0.01$) and therefore a significant detection in the optical band even in the case of a large extinction.

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