THE X-RAY AFTERGLOW OF GRB 000926 OBSERVED BY BeppoSAX AND CHANDRA: A MILDLY COLLIMATED FIREBALL IN A DENSE MEDIUM?

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ABSTRACT

We present X-ray observations of the afterglow of GRB 000926, performed around and after the break observed in the optical light curve 2 days after the burst. The steep X-ray light curve observed around the break confirms the presence of this feature in X-rays. However, the spectral and temporal properties are not consistent with a standard jet scenario based on synchrotron emission, requiring a more complicated model. We find that X-ray and optical data are compatible with a moderately collimated fireball (with opening angle $\theta \approx 25^\circ$) expanding in a dense medium ($n \approx 4 \times 10^4$ cm$^{-3}$). This produces two breaks in the light curve. The first, at $t \approx 2$ days, is due to jet behavior. The second, around 5 days, is attributed to the transition of the fireball to a nonrelativistic expansion. This transition predicts a flattening of the light curve, which explains the late X-ray measurement in excess above the extrapolation of the simple jet scenario, and is also consistent with optical data.

Subject heading: gamma rays: bursts

1. INTRODUCTION

Afterglows of gamma-ray bursts (GRBs) are typically characterized by a power-law behavior in time and in frequency, i.e., the observed flux $F \approx (t - t_0)^{-\alpha} \nu^{-\beta}$. This property is nicely accounted for by the fireball model, in which the afterglow is produced by the interaction of a relativistic expanding shell with an external medium (e.g., Wijers, Rees, & Mészáros 1997). The spectral and temporal slopes depend on the geometry (e.g., spherical versus jet; Sari, Piran, & Halpern 1999) and on the density distribution of the external medium (e.g., of constant density [hereafter ISM] versus wind; Chevalier & Li 1999). A change of the slope (i.e., a break) of the light curve is produced either when a spectral break (such as that associated with $\nu_c$, the cooling frequency of electrons) transits the observed frequency window, or when “bulk” variations, i.e., global changes of the kinematics or hydrodynamics of the fireball, take place. The latter is the case of jet expansion and also the transition from relativistic to nonrelativistic expansion (hereafter NRE). In contrast to the effect of spectral breaks, jet expansion and NRE produce achromatic breaks in the light curves. In a jet, this happens when the beaming angle of the fireball ($\approx \Gamma^{-1}$, where $\Gamma$ is the Lorentz factor) becomes similar to the opening angle of the jet, $\theta$ (Sari et al. 1999; Rhoads 1999), at the time $t_B$, 

$$t_B \approx (1 + z) \left( \frac{E_{53}}{n_6} \right)^{1/3} \left( \frac{0.1}{\theta} \right)^{8/3} \text{days},$$

where $n = n_6 \times 10^6$ cm$^{-3}$ is the density, and $E_i = E_{53} \times 10^{53}$ ergs s$^{-1}$ is the energy the fireball would have if it were spherically symmetric; i.e., in the case of a jet of solid angle $\Delta \Omega$, its energy would be $E = (\Delta \Omega/4\pi) E_i$.

On the other hand, the transition to NRE occurs when the blast wave has swept up a rest-mass energy equal to its initial energy (e.g., Wijers et al. 1997; Livio & Waxman 2000, hereafter LW00), at a time 

$$t_{\text{NRE}} \approx 3 \frac{1 + z}{2} \left( \frac{E_{53}}{n_6} \right)^{1/3} \text{days}.$$

Both jet and NRE can therefore yield achromatic breaks a few days after the burst. The NRE requires an external medium of a much higher density than that of a jet. This is indeed what one would expect if GRBs originated in dense star-forming regions, a scenario for which supporting evidence is accumulating (e.g., Piro et al. 2000a; Kulkarni et al. 2000).

So far, evidence of achromatic breaks has been claimed in some optical afterglows (e.g., Harrison et al. 1999; Kulkarni et al. 1999), but an unambiguous detection of this feature in the X-ray range is still missing (e.g., Kuulkers et al. 2000; Pian et al. 2001). Most authors attribute this feature to jet behavior, although this model may have some problems in accounting for the sharpness of the transition (Rhoads & Fruchter 2001). In fact, there is no a priori reason to exclude an NRE, and there is at least one case (GRB 990123) in which it has been attributed to either model (Kulkarni et al. 1999; Dai & Lu 1999). In GRB 000926, a break in the optical light curve at $t \approx 2$ days has been reported by several groups (Fynbo et al. 2000b, 2000c; Veilleux 2000a, 2000b; Halpern et al. 2000a, 2000b; Rol et al. 2000; Price et al. 2001, hereafter P01). The observed variation ($\approx 2$) of the temporal slope is much larger than the value of 0.25
expected by a spectral break (Sari et al. 1999). Indeed, a jet scenario has been proposed to explain this behavior (P01).

In this paper we report on BeppoSAX and Chandra observations of the afterglow of this burst (§ 2 and § 3). Those observations occurred around and after the break observed in the optical. We compare X-ray and optical data (§ 4), and show that they are explained by jet behavior and by a NRE in a high-density medium.

2. OBSERVATIONS, DATA ANALYSIS, AND THE X-RAY SPECTRUM

The gamma-ray burst GRB 000926 was detected by the Interplanetary Network (IPN) on \( t_0 = \) September 26.99 UT (Hurley et al. 2000a, 2000b). It was a moderately bright GRB, with a revised 25–100 keV fluence of \( 6.2 \times 10^{-6} \) erg cm\(^{-2} \), and a duration of about 25 s (Hurley et al. 2000a, 2000b). Optical observations (Dall et al. 2000; Gorosabel et al. 2000) showed an optical counterpart at a very bright level (\( R = 19.3 \)) one day after the GRB. This is the second-brightest afterglow ever observed in the optical band. This finding triggered two rapid target-of-opportunity (TOO) observations in X-rays, one with BeppoSAX, and the other with Chandra. A second Chandra observation was scheduled around \( t = t_0 + 12 \) days, to study the late time evolution of the afterglow.

The BeppoSAX (Piro, Scarsi, & Butler 1995; Boella et al. 1997) observation started on September 29.03 UT (\( t = t_0 = 2 \) days), and lasted for 12 hr. Effective exposure times were 20 ks for the Medium Energy Concentrator Spectrometer (MECS, 1.6–10 keV) and 5 ks for the Low Energy Concentrator Spectrometer (LECS, 0.1–10 keV). The analysis of the MECS image showed a previously unknown fading source in a position consistent with the optical transient, within an error of 50\( ^\circ \), which was therefore identified as the X-ray afterglow of GRB 000926 (Piro et al. 2000b, 2000c). The source was only marginally detected in the LECS. The average count rate of the source in the MECS (1.6–10 keV) was \( (3.2 \pm 0.6) \times 10^{-3} \) counts s\(^{-1} \). The spectrum is well fitted by a power law with energy index \( \alpha = (0.9 \pm 0.7) \),\(^9\) Galactic absorption \( (N_H = 2.7 \times 10^{20} \) cm\(^{-2} \), and flux \( F(1.6–10 \) keV) = \( (2.6 \pm 0.6) \times 10^{-13} \) erg cm\(^{-2} \) s\(^{-1} \). We have checked different background-subtraction methods, and have found that the corresponding systematic effect amounts to less than about 15%. This has been included in the flux error quoted above.

A Chandra (Weisskopf, O'Dell, & van Speybroeck 1996) TOO observation (hereafter C1) with the ACIS-S array began on September 29.674 UT (\( t = t_0 = 2.7 \) days), and ended on September 29.851 UT, with an exposure time of 10 ks. The X-ray afterglow was observed at a position R.A.(2000) = 17\textdegree 04'09".6, decl.(2000) = +51°47'58".6, with an uncertainty of 2\( ^\circ \), consistent with the optical position. The source count rate in the 0.3–5 keV range was \( (2.9 \pm 0.2) \times 10^{-2} \) counts s\(^{-1} \), corresponding to a flux \( F(0.2–5 \) keV) = \( (1.2 \pm 1.0) \times 10^{-13} \) erg cm\(^{-2} \) s\(^{-1} \) for the best-fit power-law spectrum. This has \( \alpha = (0.8 \pm 0.2) \), i.e., consistent with the BeppoSAX slope, and absorption \( N_H = (5 \pm 3) \times 10^{20} \) cm\(^{-2} \), consistent with that of our Galaxy. Since the BeppoSAX and Chandra spectral shapes are consistent, we have fitted them simultaneously, linking the spectral parameters (except for the normalizations). We obtain a good fit \( (\chi^2 = 25.6, \nu = 26) \) with \( \alpha = 0.85 \pm 0.15 \), a ratio of the BeppoSAX over the Chandra normalization of

\(^9\) Hereafter, errors and upper limits on fit parameters, including temporal slopes, correspond to 90% confidence level for one parameter of interest.

Fig. 1.—X-ray spectrum of the afterglow of GRB 000926, as observed by the ACIS-S array of Chandra (open squares: first observation; filled squares: second observation), and the MECS of BeppoSAX (filled circles; the LECS is not shown for clarity). The solid lines represent the best-fit power law convoluted through instrument responses. Deviations from the best fit in \( \alpha \) are plotted in the bottom panel. In the inset we show the contour plot of the photon index (\( \alpha + 1 \)) vs. \( N_H \), the intrinsic column density in the GRB rest frame, with the 99% (thick line), 90% (medium-thick line), and 68% (thin line) confidence regions.
2.3 ± 0.6, and some marginal evidence of intrinsic absorption (in addition to the absorption equal to that of our Galaxy) in the rest frame of the GRB (z = 2.06, Fynbo et al. 2000a; Castro et al. 2000), corresponding to a column density \( N_{H,GRB} = (0.4^{+0.35}_{-0.25}) \times 10^{22} \) cm\(^{-2}\). The residuals around 2 keV, i.e., the iron line region in the rest frame of the GRB (Fig. 1), are marginal, with an upper limit on an iron line of \( I < 2 \times 10^{-3} \) cm\(^{-2}\) s\(^{-1}\), corresponding to an equivalent width \( \text{EW} < 1 \) keV. For comparison, the iron line detected by Chandra in GRB 991216 has \( \text{EW} = 0.5 \) keV (Piro et al. 2000a).

The last Chandra observation (hereafter C2) started on October 10.176 UT, and ended on October 10.58 UT. The afterglow count rate had faded to \( 2.0 \pm 0.75 \times 10^{-3} \) counts s\(^{-1}\) (0.3–5.0 keV), allowing \( \sim 60 \) counts to be collected in the 33 ks exposure. With so few counts it is difficult to place good constraints on \( N_H \) and \( \alpha \) simultaneously, so we fix \( N_{H,GRB} = 0 \) (or \( 0.4 \times 10^{22} \) cm\(^{-2}\), and find \( \alpha = 0.85 \pm 0.15 \) (or \( 1.2 \pm 0.3 \)). The flux in the 0.2–5 keV range derived by the best-fit power law is equal in both cases to \( (8.3 \pm 1.1) \times 10^{-15} \) erg cm\(^{-2}\) s\(^{-1}\). An overall fit on the three data sets (see Fig. 1) gives \( \chi^2/\nu = 30.8/24 \), with spectral parameters consistent with those derived previously (see the inset in Fig. 1), and a ratio of the normalizations of C2 over C1 of \((7.7 \pm 0.85)\) and \((1.5 \pm 0.3)\), respectively. If we leave the slope of C2 unlinked in the combined fit of all data sets, we get \( \alpha_{C2} = 1.23 \pm 0.3 \). While this result is of marginal statistical significance, it is interesting to note that the difference in slope between C2 and C1 + BeppoSAX is \( \Delta \alpha = 0.4 \pm 0.3 \), i.e., consistent with the steepening of \( \frac{1}{\nu} \) expected when \( \nu \) passes into the energy window.

An intrinsic column density \( N_{H,GRB} \approx 0.4 \times 10^{22} \) cm\(^{-2}\) is marginally detected at a confidence level of \( \approx 98\% \) (see the inset in Fig. 1). We remark that, since most of the local gas is ionized by GRB photons (Boettcher et al. 1999), the real column density can be much higher. Assuming that the relation between the optical extinction \( A_V \) and \( N_H \) is similar to that in our own galaxy (e.g., Predehl & Schmitt 1995), we obtain \( A_V \approx 2 \). This value is \( \approx 2–20 \) times greater than that derived by optical measurements (P01), implying a dust-to-gas ratio much lower than that of our Galaxy. This effect has been observed in other GRBs (Galama & Wijers 2001), and it may be the result of destruction of dust by GRB radiation (Waxman & Draine 2000).

3. A VERY STEEP X-RAY DECAY

In the BeppoSAX data, the source exhibits a substantial decay, decreasing by a factor of \( 1.7 \pm 0.5 \) in 6 hr. This corresponds to a power-law decay \( F \propto (t - t_0)^{-\delta_x} \), with slope \( \delta_x \approx 4 \). This behavior is consistent with the first Chandra observation, which took place near the end of the BeppoSAX observation, and whose flux was a factor \( 2.3 \pm 0.6 \) times lower than the average BeppoSAX flux. Combining these two data sets (Fig. 2), we derive a slope \( \delta_x = 3.7^{+1.3}_{-1.6} \), in agreement with the optical slope measured after the break. The late Chandra point appears to deviate from this law, since the slope connecting C1 with C2 is \( \delta_x = 1.70 \pm 0.16 \). However, when the large error of the earlier slope is considered, the two measurements are nearly compatible (Fig. 2). A combined fit to all the X-ray data points then gives \( \delta_X = 1.89^{+0.19}_{-0.16} \), with \( F(2–10 \text{ keV}) = 1.19 \times 10^{-12} \) erg cm\(^{-2}\) s\(^{-1}\) at \( t = 1 \) day.

The X-ray decay of GRB 000926 is much steeper than that observed in typical X-ray afterglows, in which \( \delta_X \approx 1.4 \) (Piro 2001). We remark, however, that previous observations covered the evolution of the afterglow primarily at \( t - t_0 < 2 \) days. The data presented here are instead sampling the X-ray behavior at later times. It is in this domain that we expect deviations due to either a jet or an NRE.

4. JET VERSUS NRE OF A SPHERICAL FIREBALL IN A DENSE MEDIUM

The optical data (Fig. 2) are nicely fitted by the standard jet model with synchrotron emission (P01), but when X-ray data are considered, we find inconsistencies with this scenario. The relationships linking the temporal and spectral slopes (Sari et al. 1999) are \( \delta = 2\alpha + 1 \) (\( \nu < \nu_j \)) and \( \delta = 2\alpha \) (\( \nu > \nu_j \)). We find then that the X-ray temporal and spectral slopes, \( \delta_X = 1.9 \) and \( \alpha_X = 0.85 \), are consistent only with the case of a cooling frequency below the X-ray range. The slope \( p \) of the electron distribution, \( N_e \propto \gamma^{-p} \), would then be \( p = \delta = 2\alpha = 1.7 \pm 0.3 \), i.e., marginally compatible with the minimum slope needed to avoid an infinite energy content in electrons. A more relevant problem of this model is that the predicted temporal slope is significantly lower than the one measured in optical, \( \delta_0 = 2.3 \pm 0.08 \) (P01; see also Fig. 1). Furthermore, the electron slope derived from the optical data under the same scenario (\( p = 2.39 \pm 0.15 \)) is not consistent with the X-ray derivation. Finally, we note that the (admittedly marginal) evidence of a spectral steepening in
C2 argues against a jet behavior, during which $v_c$ should remain constant.

We now examine the alternative explanation of a transition to NRE of a spherical fireball. The relationships linking $\delta$ and $x$ are given in Livio & Waxman (2000). We find that the X-ray data are consistent with an NRE either in a uniform density medium (which gives $\delta = 2.17 \pm 0.45$), or in a wind ($\delta = 2.3 \pm 0.35$). The cooling frequency is now above the X-ray range, and therefore $p = 2.7 \pm 0.3$. In this case, the optical and X-ray spectral data points should lie on a single power law. We have evaluated the slope $\alpha_{oX} = -[\log (F/X) / \log (v_c/v_o)]$ of the power law connecting the flux at 1 keV, observed by Chandra ($F_X$), with the R band flux extrapolated at the time of the Chandra observation ($F_O$; see Fig. 2), and corrected for the extinction (P01). We find $\alpha_{oX} = 0.9 - 1.1$, in agreement with the slope measured in X-rays. Before the break, the evolution is indistinguishable from that of a spherical relativistic fireball, which follows a decay with $\delta = 1.3 \pm 0.2$ (ISM) or $\delta = 1.8 \pm 0.2$ (wind). The latter case is not compatible with the optical slope measured before the break (P01), and we conclude that both optical and X-ray data are consistent with a spherical expansion in a uniform medium, with the temporal break produced by a transition to NRE. From equation (2) we derive $n_{rNRE} \approx 10$. Following Freedman & Waxman (2001), we have estimated a fireball energy comparable to the observed gamma-ray isotropic energy, which is $E_{i,3} = 8 \times 10^{52} \text{ergs} (z = 2.03$ [Castro et al. 2000]), $H_0 = 75 \text{km s}^{-1} \text{Mpc}^{-1}$, $\delta_0 = \sqrt{2}$. The absorbing column density is $N_{H} \approx n_{rNRE} \approx 10^{23} \text{cm}^{-2}$, where the radius $r_{NRE} \approx 10^{16} \text{cm}$ (LW00). This is in apparent disagreement with the upper limits derived by the X-ray spectrum. This disagreement is rectified by recalling that the medium is heavily ionized by the GRB photons, and therefore its effective absorption is negligible (Boettcher et al. 1999).

5. A COLLIMATED FIREBALL IN A DENSE MEDIUM

There remains, however, a discrepancy between optical and X-ray data that is not accounted for by previous models. The X-ray decay after the break ($\delta_X = 1.70 \pm 0.16$) is significantly flatter than the optical one ($\delta_0 = 2.30 \pm 0.08$, P01). In fact, the extrapolation of the X-ray flux from the optical slope at the time of the second Chandra observation underestimates the observed flux by a factor of 2 $\pm 0.5$ (Fig. 2). This indicates the presence of a flattening taking place in between the two sets of observations, as predicted in the case of a jet expansion followed by a transition to an NRE (LW00). In this case, the lateral expansion of the jet begins when it is relativistic, and during the lateral expansion stage there is a rapid decline of the flux due to the rapid decrease of the fireball energy per unit solid angle (as this angle increases). This produces the first break in the light curve. The time at which the jet completes its sideways expansion is roughly the same time at which the flow becomes sub-relativistic. At this stage, lateral expansion is no longer important, and the rapid flux decline due to lateral expansion ceases, leading to a flattening of the light curve. This effect appears more evident in X-rays, which are not contaminated at later times by the presence of a fairly bright host galaxy (P01).

We now show that both optical and X-ray data are in agreement with this scenario. The light curve of the afterglow is composed of three subsequent power laws, with decay slopes $\delta_1$, $\delta_2$, and $\delta_3$, which we have modeled with the data empirical formula

$$F(t) = F(t_{b1}) \left[ \frac{(t/t_{b1})^{\delta_1} + (t/t_{b2})^{\delta_2}}{1 + (t/t_{b2})^{\delta_3}} \right]^{-1/a}. \quad (3)$$

The parameter $s$ describes the sharpness of the breaks. The temporal slopes are related to the power-law index of electrons by relationships that depend on the location of $v_c$, and on the density distribution of the external medium (LW00). We can exclude most of the cases as follows. The relation $s_{0, X} \approx \alpha_x$ implies that $v_c$, is either below the optical or above the X-ray range. In the first case, we would have $p = 2\alpha_X = 1.7$, which, besides being less than 2, would give temporal slopes flatter than observed. In fact, $\delta_L = (3p - 2)/4 = 0.8$, $\delta_L = p = 1.7$, and $\delta_L = 1 + 7(p - 2)/6 = 0.65$ (wind) or $\delta_L = 1 + 3(p - 2)/2 = 0.55$ (ISM). During the jet phase, $v_c = \text{const}$, while in the NRE phase, $v_c$ increases with time for a wind (decreases for ISM). In the case of a wind, $v_c$ could move above the optical range, but still give a flat slope $\delta_L = (3/2) + (p - 2)/6 = 1.15$.

Let us now examine the case of $v_c$ lying above the X-ray range. This implies $p = 2\alpha_X + 1 = 2.7$. The case of a wind is excluded because $\delta_L = 1.8$, i.e., greater than observed. For an ISM, we have $\delta_L = (3p - 1)/4 = 1.3$, $\delta_L = p = 2.7$, and $\delta_L = (9/10) + 3(p - 2)/2 = 1.95$, which appears to be consistent with the data. We have assessed this case more quantitatively by fitting equation (3), with the slopes expressed as a function of $n_i$ to the optical data (with the contribution of the host galaxy subtracted). We obtain $p = 2.57 \pm 0.3$, in nice agreement with the values derived from the X-ray spectra, $t_{s1} = 1.76 \pm 0.6$, days, $t_{s2} = 5.5 \pm 2$ days, and $s = 1.7 \pm 0.3$. Moreover, this same law (i.e., rescaling the normalization, but with the same parameters determined by the optical light curve) fits all the X-ray data points fairly well, and in particular reproduces the results of C2 (Fig. 3).

We also note that this law predicts a temporal slope of about 2.6 around 2 days, nearer to the steep decay observed in the BeppoSAX and C1 observations.

The simultaneous determination of $t_b = t_{s1}$ and $t_{NRE} = t_{s2}$ allows an unambiguous determination (i.e., not depending on estimates of $E_i$ and $n_i$) of the jet angle (LW00). In fact, $t_{NRE} = (1 + z)^{2/3}E_i/M_{i,3}n_{i,6}^{1/3}t_{b,4}^{1/4}$, which, when combined with equation (1), gives $\theta = 0.7(t_{b,4}/t_{NRE})^{1/2} = 0.4$. The total gamma-ray energy for a two-sided jet is then $E_i = 0.16E_i = 1.2 \times 10^{52} \text{ergs} \ s^{-1}$. Finally, the density $n_i = (1 + z)^{2}E_i/M_{i,3}t_{b,4}^{1/4}t_{NRE}^{-3/4} \approx 0.04$. Note that the jet angle is rather insensitive to errors in the determination of break times. Conversely, the density should be considered as an order-of-magnitude estimate, because of its strong dependence on $t_{NRE}$ and model details (LW00). Finally, we have checked the value of the density is compatible with the broadband spectrum of the GRB, following the prescriptions of Wijers & Galama (1999). Since the parameters one derives are dependent on the model adopted, we have restricted the analysis to the data before the break, when the fireball evolution is indistinguishable from the spherical case. From the radio data (D. Frail, 2000, private communication; Harrison et al. 2001) and the extrapolation of the optical-to-X-ray spectrum at lower frequencies, we derive that the synchrotron self-absorption frequency, $\nu_A$, and the frequency of the maximum flux, $\nu_m$, should be in the range between $10^{10}$ and $10^{12} \text{Hz}$, and that the flux at $\nu_m$ should be approximately a few mJy. Furthermore, as we have shown above, $v_c \gtrsim 10^{18} \text{Hz}$. The large range spanned by these
quantities gives a density spread over orders of magnitude that comfortably include the density estimate derived above.

6. CONCLUSIONS

In this paper we have shown that X-ray observations of the afterglow of GRB 000926 around and after the break observed in the optical range confirm the presence of this feature in X-rays as well. However, they are not consistent with the standard jet scenario based on synchrotron emission, requiring a more complicated model. We find that both the spectral and temporal properties of X-ray and optical data are compatible with a moderately collimated fireball ($\theta \approx 25^\circ$) expanding in a dense medium ($n \approx 4 \times 10^4$ cm$^{-3}$). This produces two breaks in the light curve. The first is due, as usual, to jet behavior. The second, at around five days, is attributed to a transition to NRE due to the high density of the external medium, and is followed by a flattening of the curve, which accounts for the late X-ray measurement, and is also supported by optical data. Optical measurements at later times should help to characterize this behavior, but to do so, it will be necessary to actually single out the afterglow from the host in the image. Current estimates of the contribution of the host galaxy from the flattening exhibited by the light curve will, in fact, cancel out any intrinsic flattening due to the afterglow. Finally, we note that we cannot exclude other possibilities, such as, for example, an event of gravitational lensing (Mao & Loeb 2001) that amplified the flux at around 12 days, or a contribution of an inverse Compton component to the late X-ray emission (Harrison et al. 2001). However, an analysis of different options goes beyond the scope of this paper.

Our results support the association of GRBs with star-forming regions. In fact, the density is consistent with that of very dense molecular clouds ($n \approx 10^4$ cm$^{-3}$). On the other hand, the density is not as high as that required to produce the iron lines observed in some X-ray afterglows (e.g., Antonelli et al. 2001; Piro et al. 2000a; and references therein), which are possibly connected with much denser ($n \approx 10^{10}$ cm$^{-3}$) progenitor ejecta. In these cases, the environment must be composed of at least two regions, since the fireball requires a medium with a density $n \lesssim 10^7$ cm$^{-3}$ to produce an afterglow lasting at least a few days. The properties of this medium, in particular the density, are not the same in all GRBs. While in this GRB we find $n \approx 4 \times 10^4$ cm$^{-3}$, in several other GRBs the density should be much lower, as indicated, for example, by the absence of breaks in the optical light curves (Kulkarni et al. 2000), or by the evidence of relativistic expansion several weeks after the GRB (Waxman, Kulkarni, & Frail 1998). Another element of diversity in GRBs appears to be the magnetic field strength. In this burst, the magnetic field density was estimated to be less than $\approx 10^{-6}$ times the equipartition value, comparable to that of GRB 971214 (Wijers & Galama 1999) and GRB 990123 (Galama et al. 1999), but 4 orders of magnitude weaker than in GRB 970508 (Wijers & Galama 1999). As suggested by Galama et al. (1999), such differences in field strength may reflect differences in energy flow from the central engine.

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