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GRB 990123 REVISITED: FURTHER EVIDENCE OF A REVERSE SHOCK

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ABSTRACT

Recently, we presented a new theoretical analysis of the reverse shock emission. We use this analysis here to revisit the early afterglow of GRB 990123. The first mechanism that was suggested as the source of the optical flash observed in GRB 990123 was the reverse shock. However, it was shown later that other processes can generate this flash as well. We find new and compelling evidence that the optical flash and the following radio flare of GRB 990123 did resulted from a reverse shock. This suggests that a significant fraction of the energy of the relativistic ejecta must have been carried by baryons. It also suggests that the external medium is an interstellar medium and that in this burst the reverse shock emission dominates at early time over other possible processes. We use the early optical emission to constrain the physical parameters of the original ejecta and the microscopic parameters in the emitting reverse-shocked region.

Subject headings: gamma rays: bursts — hydrodynamics — shock waves

1. INTRODUCTION

The ninth magnitude optical flash of GRB 990123 was one of the most exciting discoveries associated with gamma-ray bursts (GRBs). This was followed by a detection of a strong unusual radio flare from the same source (Kulkarni et al. 1999; Galama et al. 1999). Such a strong prompt optical emission was predicted, just a few months earlier, to arise from the reverse shock during the early afterglow (Sari & Piran 1999a). Later this interpretation was questioned and other models for prompt optical emission were proposed (e.g., Beloborodov 2002). We return to this issue here.

In the fireball model for GRBs, the afterglow results from a blast wave that propagates into the circumburst medium (see Piran 1999 for a review). This blast wave originates from the energy dissipation of the relativistic ejecta to the circumburst medium. The early afterglow is produced during this dissipation and thus can be used to study the nature of the ejecta. In the case that the ejecta is baryonic, a reverse shock is produced during this dissipation. This reverse shock is predicted to produce a strong optical flash and radio flare (Sari & Piran 1999b, 1999c).

Recently, we presented a new theoretical analysis of the reverse shock emission (Nakar & Piran 2004, hereafter NP04). This analysis includes a new test of reverse shock emission and diagnostic tools for the physical parameters of the original ejecta. Here we use these new tools to reinvestigate the early afterglow of GRB 990123. Numerous authors analyzed the early afterglow of GRB 990123 in the past (Sari & Piran 1999b; Mészáros & Rees 1999; Kulkarni et al. 1999; Galama et al. 1999; Kobayashi & Sari 2000; Kobayashi 2000; Wang et al. 2000; Panaitescu & Kumar 2001; Fan et al. 2002; Soderberg & Ramirez-Ruiz 2002; Zhang et al. 2003). These works show that the optical flash and the radio flare may result from a reverse shock emission, and they use the optical light curve to find different parameters of the burst (finding a range of different values). The advantage of our analysis over previous ones is that we apply the new results and tools presented in NP04. First, we use the new results of the behavior of the radio emission in the generic case of a reverse shock emission. This behavior enables us to test if the emission is indeed resulting from a reverse shock and to find the self-absorption frequency at the time of the optical flash. Furthermore, we use the exact equations in the mildly relativistic regime (while previous works used approximations that are not valid in this regime). Finally, we extract the initial conditions of the ejecta (width and initial Lorentz factor) from the optical light curve alone, without using the poorly known microscopic parameters and without using the prompt emission duration.

For completeness, we begin (§ 2) with a short summary of the theoretical model of the reverse shock emission presented in NP04. We summarize, in § 3, the early afterglow observations of GRB 990123. The analysis of the optical light curve and the resulting constraints on the physical parameters of the relativistic wind is presented in § 4. In § 5, we test whether the observations fit with a reverse shock emission. The results, their implications to GRB modeling, and future prospects are summarized in § 6.

2. THE REVERSE SHOCK EMISSION—THEORY

We begin with a brief summary of the main results of NP04. These results give the theoretical predictions of the optical and the radio emission of a baryonic reverse shock in a constant interstellar medium (ISM) environment. The physical parameters that determine the emission of the reverse shock are (1) the (isotropic equivalent) energy E, the width Δ, and the initial Lorentz factor Γ_o of the ejected wind; (2) the circumburst density, n; (3) the microscopic parameters, namely, the energy equipartition parameters ϵ_e and ϵ_B that describe the ratio of the electrons and magnetic field energy to the total internal energy, and p, the power-law index of the electrons' energy distribution.

The strength of the reverse shock is determined by the dimensionless parameter ξ (Sari & Piran 1995):

$$\xi \equiv l^{1/2}\Delta^{-1/2}\Gamma_o^{-4/3}, \qquad (1)$$

where $l \equiv [3E/(4\pi n m_p c^2)]^{1/3}$ ($m_p c^2$ is the proton rest-mass energy). According to this definition,

$$\Gamma_o = 188\xi^{-3/4}\Delta_{12}^{-3/8}(E_{52}/n)^{1/8}. \qquad (2)$$

Throughout the Letter, we denote by Q_x the value of the quantity

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Q in units of 10^x (cgs). The peak of the optical emission is observed at

$$t_0 = \frac{\Delta}{c}(1 + 0.7\xi^{3/2})(1 + z), \qquad (3)$$

when the reverse shock finishes crossing the ejecta; c is the speed of light, and z is the redshift. The structure of the optical and the radio reverse shock light curves depends on the relative values of the three reverse shock break frequencies at t_0: ν_a^r, the self-absorption frequency, ν_m^r, the synchrotron frequency, and ν_c^r, the cooling frequency. In principle, numerous patterns are possible. However, over a wide range of the parameter space (and as we show below, particularly for GRB 990123) these frequencies satisfy $\nu_{\rm radio} < \nu_m^r(t_0) < \nu_a^r(t_0) < \nu_{\rm opt} < \nu_c^r(t_0)$, where $\nu_{\rm radio}$ and $\nu_{\rm opt}$ are the observed radio and optical frequencies, respectively. We consider this frequency sequence as the *generic case*. In this case, the peak optical flux is

$$F_0^r = 0.1\ \mathrm{mJy}(1 + z)^{-(4+p)/8}1.5^{2.5-p}\left[\frac{3(p-2)}{p-1}\right]^{p-1} \times \epsilon_{e-1}^{p-1}\epsilon_{B-2}^{(p+1)/4}n^{(p+2)/8}E_{52}^{1+p/8}t_{0,2}^{-3p/8}D_{28}^{-2}A_{F,0}^r(\xi), \qquad (4)$$

where D is the proper distance. The function $A_{F,0}^r(\xi)$ is approximated in the range of $0.1 < \xi < 2.5$ by

$$A_{F,0}^r(\xi) \approx 180\xi^{0.65}(6 \times 10^{-4}\xi^{-2.6})^{(p-1)/2}. \qquad (5)$$

The values of $A_{F,0}^r(\xi)$ out of this range can be found in NP04.

The flux before t_0 depends strongly on ξ, and thus the rising slope, α_1, can be used to determine ξ using (in the generic case)

$$\alpha_1 \approx 1.2\left[0.5 + \frac{p}{2}(\xi - 0.07\xi^2)\right]. \qquad (6)$$

The reserve shock decay index is, however, a constant, $\alpha_2 \approx -2$, and its main use is to identify the reverse shock emission.

In contrast to the optical emission, the radio continues to rise at $t > t_0$, and it peaks at a later time, t_*, when $\nu_{\rm radio} = \nu_a^r$. Over a wide range of ξ-values (when the shock is not ultra-relativistic), $\nu_{\rm radio} < \nu_m^r(t_0) < \nu_a^r(t_0) \approx 10^{12}$–$10^{13}$ Hz. In this case, the radio emission is expected to rise first as $\sim t^{0.5}$ until $\nu_{\rm radio} = \nu_m^r$ and then as $\sim t^{1.25}$ until t_*. At $t > t_*$, it is expected to decay, similarly to the optical emission, as $\sim t^{-2}$. This behavior provides a second and independent test for the reverse shock emission:

$$\frac{F_*}{F_0}\left(\frac{t_*}{t_0}\right)^{(p-1)/2+1.3} = \left(\frac{\nu_{\rm opt}}{\nu_{\rm radio}}\right)^{(p-1)/2} \sim 1000, \qquad (7)$$

where this value can be larger or smaller by a factor of ~ 3 (for a given p) owing to uncertainty in the hydrodynamics (see Kobayashi & Sari 2000). It provides also an independent measurement of $\nu_a^r(t_0)$:

$$\nu_a^r(t_0) \approx \frac{t_*}{t_0}\nu_{\rm radio}. \qquad (8)$$

Detailed radio observations at $t < t_*$ that identify the break during the rising phase, when $\nu_m^r = \nu_{\rm radio}$, would enable the determination of $\nu_m^r(t_0)$ as well.

3. OBSERVATIONS

At $z = 1.6$, GRB 990123 is one of the brightest GRBs observed so far. Almost all of the energy is emitted in two very energetic hard pulses that last together $\sim$25 s. A much softer and less energetic emission (<120 keV) is observed $\sim$20 s before and up to $\sim$50 s after this main event. The total isotropic equivalent energy emitted in γ-rays during the burst is $\sim 10^{54}$ ergs. The timing of the main γ-ray event differs between different detectors. While BATSE triggered on the first soft emission, $\sim$20 s before the main event, *BeppoSAX* triggered 18 s later than BATSE on the beginning of the main event.

GRB 990123 is also the only burst where optical emission was observed during the prompt emission (Akerlof et al. 1999). The first detection of 11.7 mag is recorded $\sim$7 s after the *BeppoSAX* trigger. The optical emission peaks at the second snapshot that took place $\sim$32 s after the *BeppoSAX* trigger with 8.9 mag ($\approx$0.8 Jy)! After the peak, a fast decay is observed with a power-law slope of ≈ -2, which becomes shallower at later times.

The early radio observations of GRB 990123 show also an unusual flare (Kulkarni et al. 1999). The first observation after 0.25 days shows a 8.46 GHz intensity of $62 \pm 32\ \mu$Jy. The flux in this band rises to a peak flux of $260 \pm 32\ \mu$Jy after 1.25 days and then declines rapidly. Observations at other wavelengths from this epoch ($\sim$1 day; Galama et al. 1999) show a flux of $118 \pm 40\ \mu$Jy at 4.88 GHz and upper limits of several hundreds of microjanskys at 15, 86, and 222 GHz.

4. CONSTRAINING THE BURST PARAMETERS

Already in 1999, Fenimore et al. (1999) pointed out that the initial decay index of the optical flash, $\alpha_2 \approx -2$, agrees with the predictions of a reverse shock emission (Sari & Piran 1999a, 1999b, 1999c). At later times, the decay becomes more moderate, as expected from the forward shock contribution. Motivated by this observation, we first use the optical observations to constrain the physical parameters of the burst assuming that the flash arises from a reverse shock emission. Later, we carry the additional tests of reverse shock emission, described in NP04.

When modeling the early afterglow, it is important to find the time when the main part of the relativistic ejecta is emitted from the source. It is not necessarily the trigger time. In GRB 990123, the radiated energy, and therefore most likely the energy ejected from the source, is clearly dominated by the main two pulses. Kobayashi et al. (1997; see also Nakar & Piran 2002) have shown that in internal shocks the observed time of the γ-ray pulses reflects the emission time of the wind from the source. Therefore, we estimate that the main part of the relativistic wind is beginning to be ejected by the source at the time that the first dominant pulse starts rising—the *BeppoSAX* trigger time (18 s after the BATSE trigger). This is the point where we set the observer clock to $t = 0$. According to this setting, the duration of the burst is $\sim$25 s and the peak of the optical emission is observed at $t = 32$ s.

The observations of the optical flash of GRB 990123 include only one data point before the peak. Since there are two observations after the peak that show similar decay ($t = 57$ s and $t = 142$ s), $\alpha_2 \approx -2$, a broken power-law fit is possible only if the peak is between the first and the second observations.

Thus, we have only lower limits to $F_0 > 0.8$ Jy and $\alpha_1 > 2$ and an upper limit to $t_0 < 32$ s, and s can take any value.[3] As we have only a lower limit on α_1, equation (6) yields only a lower limit on ξ (we use $p = 2.3$ throughout):

$$\xi \gtrsim 1. \tag{9}$$

Equations (3) and (2) result in the upper limits

$$\Delta \lesssim 2.5 \times 10^{11}\ \mathrm{cm}, \tag{10}$$

$$\Gamma_o \lesssim 600 \left(\frac{E_{54}}{n}\right)^{1/8}. \tag{11}$$

It is reassuring to find that the width of the shell obtained for $\xi \approx 1$ divided by the speed of light is similar to the duration of the GRB (~10 s in the burst's frame).

Next we use equation (4) to constrain ϵ_e, ϵ_B, and n. We consider the total energy emitted in γ-rays, $\sim 10^{54}$ ergs, as a reasonable estimate of the remaining energy in the ejecta, E. Therefore, we do not attempt to estimate it from the optical flash observations. Instead we express the dependence of the resulting constraints on the value of E. Taking $\xi > 1$ and requiring $F_0 > 0.8$ Jy leads, using equation (4), to

$$\epsilon_{e-1}^{p-1}\epsilon_{B-2}^{(p+1)/4} n^{(p+2)/8} \gtrsim 15 E_{54}^{-(1+p/8)}. \tag{12}$$

Another constraint follows the requirement that $\nu_{\rm opt} < \nu_c^r(t_0)$ (otherwise the optical light curve would not show the generic behavior of $\alpha_2 \approx 2$):[4]

$$n\epsilon_{B-2}^{3/2} \lesssim 20 E_{54}^{-1/2}. \tag{13}$$

These two constraints (together with $\epsilon_e + \epsilon_B < 1$) result in the following limits:

$$\epsilon_e \gtrsim 0.1 E_{54}^{-0.75}, \tag{14}$$

$$5 \times 10^{-3} E_{54}^{-1.6} n^{-2/3} \lesssim \epsilon_B \lesssim 0.1 E_{54}^{-1/3} n^{-2/3}, \tag{15}$$

$$n \gtrsim 5 \times 10^{-3} E_{54}^{-2.4}\ \mathrm{cm}^{-3}. \tag{16}$$

5. WAS THE OPTICAL FLASH A RESULT OF REVERSE SHOCK EMISSION?

The optical flash passes the first test of a reverse shock emission: $\alpha_2 \approx -2$ (Fenimore et al. 1999; Sari & Piran 1999a, 1999b, 1999c). NP04 have shown that in the generic case ($\nu_{\rm radio} < \nu_m^r < \nu_a^r < \nu_{\rm opt} < \nu_c$ at t_0) the reverse shock emission results also in a tight relation between the radio and the optical emission, equation (7). For the observed frequencies of GRB 990123 ($\nu_{\rm opt} = 5 \times 10^{14}$ Hz and $\nu_{\rm radio} = 8.6$ GHz) and $p = 2.3$,

$$\left(\frac{\nu_{\rm opt}}{\nu_{\rm radio}}\right)^{(p-1)/2} = 1300. \tag{17}$$

The observations of GRB 990123 show a remarkable agreement with this prediction (taking the times and the fluxes of the flash and the flare as the times and the fluxes of the peak observation: $t_0 = 32$ s, $F_0 = 0.8$ Jy, $t_* = 1.25$ days, and $F_* = 260$ μJy):

$$\frac{F_*}{F_0}\left(\frac{t_*}{t_0}\right)^{(p-1)/2+1.3} \approx 800\text{–}4000, \tag{18}$$

where the result includes the uncertainty in the hydrodynamics (see eq. [7]). If the above test is passed, then the self-absorption frequency at t_0, $\nu_a^r(t_0)$, can be estimated from the ratio between t_* and t_0:

$$\nu_a^r(t_0) \approx \frac{t_*}{t_0}\nu_{\rm radio} = 3 \times 10^{13}\ \mathrm{Hz}. \tag{19}$$

This frequency is determined by the physical conditions at t_0. As a consistency check, we compare this result to the possible values of $\nu_a^r(t_0)$ obtained by the limits on ϵ_e, ϵ_B, and n. We consider the case of $\xi = 1$ and $p = 2.3$, for which

$$\nu_a^r(t_0) = 6 \times 10^{12}\ \mathrm{Hz}[(1+z)^{-(p+6)/8}\epsilon_{e,-1}^{p-1}\epsilon_{B,-2}^{(p+2)/4} \times (nE_{54})^{(p+6)/8} t_{0,2}^{-(3p+10)/8}]^{2/(p+4)}. \tag{20}$$

Within the parameter space of ϵ_e, ϵ_B, and n that satisfies equations (12) and (13) and taking $E_{54} = 1$, we obtain $1.5 \times 10^{13}\ \mathrm{Hz} < \nu_a^r(t_0) < 3.5 \times 10^{13} n^{1/6}$ Hz! Although the dependence of this range on the value of E is not trivial, it is weak, and the value $\nu_a^r(t_0) = 3 \times 10^{13}$ Hz is consistent with the allowed range for any reasonable value of E, $0.5 < E_{54} < 10$. This constraint on the value of $\nu_a^r(t_0)$ is independent of the value found in equation (19). Once more, the agreement between the two estimates is remarkable.

Finally, we note that although radio observations from $t < t_*$ can theoretically be used to further constrain the conditions at t_0, the large errors of the single radio observation from this epoch is insufficient to do so.

6. CONCLUSIONS

We have analyzed the early afterglow of GRB 990123 according to the theoretical predictions of the reverse shock emission presented in NP04. We find that GRB 990123 shows the clear signature of a reverse shock emission in two independent and robust tests. Apart from these two tests, we carry a consistency check between the radio emission and our analysis of the optical emission, which is passed successfully. This consistency check gives us further confidence both in the analysis and in the fact that the optical flash and the radio flare of GRB 990123 are a generic case of a reverse shock emission.

The consistency with the "generic" reverse shock model further suggests, but does not prove of course, that the optical flash of GRB 990123 did not arise from another mechanism such as

[3] Since there is only a single observation before the peak, the rising phase may also be very irregular, with no power-law behavior. In this case, the hydrodynamical profile of the relativistic ejecta is highly irregular. However, having no detailed observations of this phase, we use here the simplest light curve that fits the observations—a broken power law. Note that the tests, which show that the emission is a reverse shock emission, are independent of the shape of the rising light curve and can be carried also if it is irregular.

[4] The requirement that $\nu_{\rm radio} < \nu_m^r(t_0) < \nu_{\rm opt}$ is satisfied for any reasonable value of the parameters and therefore cannot be used as a constraint. The values of $\nu_m^r(t_0)$ and $\nu_c^r(t_0)$ can be found in NP04.

a pair-loaded forward shock (Beloborodov 2002; Thompson & Madau 2000; Mészáros et al. 2001). In turn, this indicates that the ejecta of GRB 990123 had (at least at this stage) a significant baryonic component, as otherwise a reverse shock is not expected. Finally, it also suggests that the external density profile of GRB 990123 was similar to an ISM and not a wind, since in the latter, $\nu_c < \nu_{\rm opt}$ is expected (Chevalier & Li 2000).

Our analysis of the optical emission shows that the reverse shock was mildly relativistic and that the initial Lorentz factor is less than $600(E_{54}/n)^{1/8}$. We find that the width of the initial shell is similar to the duration of the burst or smaller. We constrain also the equipartition parameters and find that $\epsilon_e \gtrsim 0.1E_{54}^{-0.75}$, while $5 \times 10^{-3}E_{54}^{-1.6}n^{-2/3} \lesssim \epsilon_B \lesssim 0.1E_{54}^{-1/3}n^{-2/3}$. The external density is limited by $n \gtrsim 5 \times 10^{-3}E_{54}^{-2.4}$ cm^{-3}.

The determination of the initial conditions of GRB 990123 and the constraints of the microscopic parameters and the external density are very limited owing to the sparse optical and radio observations. *Swift* and its follow-up observations will hopefully provide during the next few years detailed light curves. These would enable a more detailed analysis and a much better determination of the parameters of the burst's relativistic outflow.

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