A Possible Explanation for the Radio “Flare” in the Early Afterglow of GRB990123

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Received _______________; accepted _______________
ABSTRACT

We suggest that the deceleration of the relativistic shock by a denser part of the interstellar medium off line-of-sight produced the observed radio “flare” in the early afterglow of GRB990123. We find that this scenario is consistent with observations if the particle number density of this denser part of the medium is between $\sim 200$ and $\sim 2 \times 10^4$ cm$^{-3}$. Because of the premature deceleration of part of the shock, the later stage of the afterglow should decay modestly faster than the powerlaw expected from an isotropic shock propagation.

Subject headings: gamma rays: bursts — cosmology: miscellaneous
1. Introduction

GRB990123 had some remarkable characteristics that drew intense interest from astrophysicists. Its source appears to be at a cosmological redshift $z \geq 1.61$ (Kelson et al. 1999). Assuming isotropic emission this leads to a huge energy release: $\gtrsim 3 \times 10^{54}$ ergs in $\gamma$-rays alone (Kulkarni et al. 1999a). Prompt optical follow-ups saw a very bright (magnitude 9) early afterglow optical flash (Akerlof et al. 1999). Since the $\gamma$-ray burst (GRB) itself, its afterglow has been monitored almost constantly in X-rays, the optical band and radio.

Radio observations of GRB990123 have been particularly puzzling. As expected from afterglow models, initial measurements (six hours after the burst) obtained only upper limits (Frail et al. 1999a). One day later, however, new observations showed a 8-$\sigma$ detection at 8.46 GHz of $260\pm32\mu$Jy (Frail et al. 1999b). On the other hand, observations at 4.88 GHz made during a period overlapping with the 8.46 GHz detection, yielded only upper limits (Galama et al. 1999). Finally, three to five days after the burst the afterglow radio output was again consistent with zero (Kulkarni et al. 1999b). Figure 1 summarizes the detection and upper limits. The radio emission is rather peculiar, as it does not conform to the gradual rise-and-decay time profile with a timescale of $\mathcal{O}(10)$ days which is expected from the standard GRB afterglow model and which was rather successfully confirmed by the radio afterglow observations of GRB970508 (Waxman, Kulkarni and Frail 1998).

Several possibility have been raised to explain this one-time radio “flare”. Kulkarni et al. (1999b) have suggested that the flare is an interstellar scattering and scintillation event. Alternatively, it might be part of the early afterglow from the external reverse shock, if self-absorption of the radio emission suppressed the radio flux during the first day as well as during the second day but only at the 4.88 GHz band (Sari and Piran 1999).

Here we investigate a third possibility (Shi and Gyuk 1999), that the radio “flare”
might be due to the relativistic shock ploughing into a dense part (a cloud, or ejecta, for example) of the interstellar medium (ISM) off line-of-sight (LOS). This off LOS portion of the shock was therefore decelerated more efficiently than the rest (including that along LOS), and in turn gave rise to the premature emission of radio which also faded away relatively rapidly. We envision a geometry as in Figure 2. We will refer generally to this denser part of ISM off the LOS as a “cloud”.

In the standard GRB afterglow model, the afterglow is generated by synchrotron radiation in the external shock of the GRB event as the shock gradually decelerates in a homogeneous ISM (with density \( n \sim 1 \text{ cm}^{-3} \)). The frequency of the synchrotron radiation depends strongly on the Lorentz factor, \( \gamma_e \), of the electrons in the shock, which in turn scales with the Lorentz factor, \( \gamma \), of the shock. Therefore, the afterglow starts at shorter wavelengths, in X-rays, and progressively moves to longer wavelengths, as the shock gradually slows down in the ISM. After \( \mathcal{O}(10) \) days, the afterglow peaks in the radio band. A similar progression is envisioned to occur in the portion of the shock that encounters the off-LOS cloud, except over a much shorter timescale. However, because the afterglow radiation is beamed to an opening angle \( \sim 1/\gamma \) we can only see the off-LOS cloud shock if it is within \( \sim 1/\gamma \) of the LOS. Thus relativistic beaming alone may prevent short wavelength (optical etc.) “flares” originating from the off-LOS cloud from being detectable.

If the size of the cloud is comparable to the distance of the cloud to the GRB source, we can crudely approximate the deceleration of the relativistic shock in the cloud as if the shock were decelerating in an homogeneous ISM of enhanced particle density \( (n \gg 1 \text{ cm}^{-3}) \) and with spherical symmetry. This approximation should hold sufficiently well for the later epoch of the deceleration, which is relevant to radio emission. In so doing, we employ the scaling relations in the standard afterglow model.
The Lorentz factor of the relativistic shock scales as

\[
\gamma \approx \begin{cases} 
6 E_{52}^{1/7} n_1^{-1/7} \gamma_{100}^{-1/7} t_{\text{day}}^{-3/7} [(1 + z)/2.6]^{3/7}, & \text{for radiative shocks;} \\
7 E_{52}^{1/8} n_1^{-1/8} t_{\text{day}}^{-3/8} [(1 + z)/2.6]^{3/8}, & \text{for adiabatic shocks.}
\end{cases}
\]  

This is from energy and momentum conservation considerations (see e.g., Piran 1998). In equation (1), \( E_{52} \) is the initial energy of the shock in units of \( 10^{52} \) erg, assuming a \( 4\pi \) expansion angle; \( n_1 \) is the particle number density of the medium in cm\(^{-3}\); \( \gamma_{100} \) is the initial Lorentz factor of the shock in units of 100; \( t_{\text{day}} \) is the time elapsed since the GRB in days, as seen by the observer; and \( z \) is the redshift of the GRB. In the radiative regime, the particles in the shock convert their kinetic energy into radiation rather efficiently. In the adiabatic regime, the radiation loss is negligible.

For the external shock in a GRB, the transition from the radiative regime to the adiabatic regime occurs at a time (Piran 1998)

\[
t_{r\rightarrow a} \sim 0.002 E_{52}^{4/5} n_1^{3/5} (\epsilon_e/0.6)^{7/5} (\epsilon_B/0.01)^{7/5} [(1 + z)/2.6]^{12/5} \gamma_{100}^{-4/5} \text{ day},
\]

where \( \epsilon_e \) is the fraction of thermal energy of the shock that resides in the random motion of electrons, and \( \epsilon_B \) is the ratio of the magnetic field energy to the thermal energy density of the shock (\( \sim 4\gamma^2 n_1 m_p c^2 \) where \( m_p \) is the proton mass and \( c \) the speed of light). Canonical values are \( \epsilon_e \sim 0.6 \) and \( \epsilon_B \sim 0.01 \), obtained by fitting the standard afterglow model to the observed afterglow of GRB970508 (Wijers and Galama 1998; Granot, Piran and Sari 1998). Before \( t_{r\rightarrow a} \) the cooling time is shorter than the dynamic timescale, and the shock is radiative.

For an energetic GRB event such as GRB990123 where \( E_{52} \sim 10^3 \), and a cloud much denser than the average ISM (\( n_1 \gg 1 \)), the transition occurs much later than a day. We therefore assume a radiative shock in our treatment.

There are three synchrotron emission frequencies that are crucial: \( \nu_m \), the peak synchrotron radiation frequency if electrons in the shock are slow-cooling; \( \nu_c \), the peak
synchrotron radiation frequency if electrons are fast-cooling; and \( \nu_a \), the self-absorption frequency of the synchrotron radiation below which the radiation is absorbed by electrons in the shocks. Depending on the ratio of these key frequencies, the synchrotron radiation from the external shock can have very different spectral shapes.

In the standard afterglow picture, the shock-heated electrons develop a power law number density distribution \( N(\gamma_e) \propto \gamma_e^{-p} \) where \( \gamma_e \geq \gamma_{e,min} \) is the Lorentz factor of electrons. The minimum Lorentz factor cut-off is

\[
\gamma_{e,min} \approx \frac{p - 2 m_p c \epsilon_e \gamma}{p - 1} \approx 2.2 \times 10^3 \left( \epsilon_e/0.6 \right) E_{52}^{1/7} n_1^{-1/7} \gamma_{100}^{-1/7} t_{day}^{-3/7} [(1 + z)/2.6]^{3/7},
\]

where \( m_p \) and \( m_e \) are proton and electron masses respectively (Piran 1998). The power law index \( p \) is found to be \( \sim 2.5 \) by fitting the observed GRB spectra and that of the afterglows.

If electrons are slow-cooling, their peak synchrotron emission will be in the observer’s frame at a frequency

\[
\nu_m = \frac{\gamma_e^2 c}{1 + z} \frac{eB}{2\pi m_e c} \approx 7 \times 10^{12} \left( \epsilon_B/0.01 \right)^{1/2} \left( \epsilon_e/0.6 \right)^2 E_{52}^{4/7} n_1^{-1/14} \gamma_{100}^{-4/7} t_{day}^{-12/7} [(1 + z)/2.6]^{-5/7} \text{Hz},
\]

where \( e \) is the electron charge and \( B \) is the magnetic field.

If, however, the shocked electrons cool quickly, they will mostly radiate from a cooled state, whose Lorentz factor is

\[
\gamma_{e,c} \approx \frac{3 m_e c}{4\sigma_T(B^2/8\pi) \gamma t} \approx 7 \times 10^4 \left( \epsilon_B/0.01 \right)^{-1} E_{52}^{-3/7} n_1^{-1/7} \gamma_{100}^{3/7} t_{day}^{2/7} [(1 + z)/2.6]^{-2/7}
\]

where \( \sigma_T = 8\pi e^4 / 3m_e^2 c^4 = 6.65 \times 10^{-25} \text{cm}^2 \) is the Thompson scattering cross section (Piran 1998). The emitting frequency in the observer’s frame is

\[
\nu_c = \frac{\gamma_{e,c}^2 c}{1 + z} \frac{eB}{2\pi m_e c} \approx 5 \times 10^{15} \left( \epsilon_B/0.01 \right)^{-1.5} E_{52}^{-4/7} n_1^{-13/14} \gamma_{100}^{4/7} t_{day}^{-2/7} [(1 + z)/2.6]^{-5/7} \text{Hz}.
\]

To find the self-absorption frequency \( \nu_a \), we follow Granot et al. (1999) and Wijers and Galama (1999) to calculate at what frequency the optical depth becomes unity. A crude
estimate of the optical depth $\tau$ is $\tau \sim \alpha'_\nu R / \gamma$, where $\alpha'_\nu$ is the absorption coefficient at a frequency $\nu'$, and $R / \gamma$ is the thickness of the shock, all in the local rest frame. However, we cannot directly adopt the formula for $\nu_a$ in Granot et al. (1999), or Wijers and Galama (1999), because both have assumed a slow electron cooling regime in an adiabatic shock. In our problem, the electrons are fast-cooling, and the shock is radiative. We therefore substitute the electron Lorentz factor $\gamma_{e,c}$ (fast-cooling regime) for $\gamma_{e,min}$ (slow-cooling regime), and likewise substitute the shock Lorentz factor $\gamma$ in radiative shocks for that in adiabatic shocks. The resultant self-absorption frequency is then

$$\nu_a \sim 10^8 (\epsilon_B / 0.01)^{6/5} E_{52}^{4/5} n_1^{4/5} t_{\text{day}}^{-4/5} [(1 + z)/2.6]^{-1/5} \text{Hz.} \quad (7)$$

We have implicitly assumed $\nu_a \ll \nu_c$ since for rapid cooling most of the electrons will be at Lorentz factor $\gamma_{e,c}$. For these electrons, absorption at frequencies $\gg \nu_c$ falls off rapidly. If we further assume that the time-integrated absorption from newly injected electrons in transition to their final cooled state is small, we will always have $\nu_a \ll \nu_c$.

Therefore, with $E_{52} \sim 10^3$, $n_1 \gg 1$ and $t_{\text{day}} \sim 1$, and canonical values of $\epsilon_B$, $\epsilon_e$ and $\gamma_{100}$, there is a hierarchy in frequencies: $\nu_a \ll \nu_c < \nu_m$. The peak flux of the synchrotron radiation seen by an observer is at $\nu_c$ (Piran 1998):

$$F_\nu(\nu_c) = F_{\nu,\text{max}} \approx 1.8 \times 10^3 \mathcal{F}(\epsilon_B/0.01)^{1/2} E_{52}^{8/7} n_1^{5/14} \gamma_{100}^{-8/7} t_{\text{day}}^{-3/7} [(1 + z)/2.6]^{10/7} d_{28}^{-2} \mu \text{Jy}, \quad (8)$$

where $\mathcal{F} < 1$ is a geometric factor to account for the fact that the emission is from off LOS so we only see an edge of the radiation cone, and $d_{28}$ is the luminosity distance in the units of $10^{28}$ cm. Fluxes at other frequencies are (Piran 1998)

$$F_{\nu u} \approx \begin{cases} (\nu/\nu_a)^2 F_\nu(\nu_a) & \text{if } \nu < \nu_a; \\ (\nu/\nu_c)^{1/3} F_\nu(\nu_c) & \text{if } \nu_a < \nu < \nu_c; \\ (\nu/\nu_c)^{-1/2} F_\nu(\nu_c) & \text{if } \nu_c < \nu < \nu_m; \\ (\nu/\nu_m)^{-p/2} F_\nu(\nu_m) & \text{if } \nu > \nu_m. \end{cases} \quad (9)$$
The spectrum and its evolution is schematically plotted in Figure 3.

We require $\nu_c, \nu_a > 8.46$ GHz at the time of $t_{\text{day}} \sim 1$ so that a non-detection of radio signal at 4.88 GHz is compatible with a simultaneous detection at 8.46 GHz. This condition is satisfied if $n_1 \lesssim 2 \times 10^4$. Assuming at a redshift $z \approx 1.61$, the luminosity distance to GRB990123 is $d_{28} \sim 4$ (its order of magnitude is insensitive to different choices of cosmology). The peak flux is then $F_{\nu,\text{max}} \sim 3 \times 10^5 \mathcal{F} n_1^{5/14} \mu\text{Jy}$ when adopting for other parameters values mentioned above. Scaling down to 8.46 GHz, we find $F_{\nu}(8.46 \text{ GHz}) \sim F_{\nu,\text{max}}(8.46 \text{ GHz}/\nu_c)^2 \sim 3 \times 10^{-3} \mathcal{F} n_1^{31/14} \mu\text{Jy}$.[1] To yield a 260 $\mu$Jy detection would therefore require $n_1 \gtrsim 200$. Because at this part of the spectrum $F_\nu \propto \nu^2$, a flux of 260±32 $\mu$Jy at 8.46 GHz implies a flux of 86 $\mu$Jy at 4.88 GHz, consistent with the 3$\sigma$ limit of 130 $\mu$Jy measured at this frequency (Galama et al. 1999). Given $200 \lesssim n_1 \lesssim 2 \times 10^4$, the Lorentz factor of the prematurely decelerated portion of the shock at $t_{\text{day}} \sim 1$ is of order $\mathcal{O}(1)$.

The non-detection of radio emission six hours after the burst may be due to strong absorption (i.e., $\nu_a$ too large), or it may simply be that the shock hadn’t yet encountered the cloud. While three days later, this portion of the shock has become very weak, and its emission is further absorbed by the main shock that propagates along LOS. It should be kept in mind that a factor of several below the level of the detected emission might render the emission undetectable.

Assuming that the dimension of the cloud is comparable to the size of the fireball $\sim 4\gamma^2 t$ at $t_{\text{day}} \sim 1$, we find a mass for the cloud to be $\sim 10^{-5}$ to $10^{-3} M_\odot$. We speculate that it may be ejecta from the GRB site.

The main portion of the relativistic shock along LOS is not affected by the cloud

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[1] We have assumed $\nu_a \sim \nu_c$, which will be the case for $n_1 \gtrsim 200$. 

off LOS. It generates the main afterglow as expected from the standard GRB afterglow model. The temporal decay of this afterglow in a given frequency band follows a powerlaw $t^{-1.1}$ (Vietri 1997; Waxman 1997; Sari, Piran and Narayan 1998). But as its radiation cone become wider (opening angle $\theta \sim 1/\gamma$), the viewing area of an observer is larger. Eventually the area will engulf the portion of the shock that was prematurely decelerated and terminated. The temporal decay of the main afterglow should then be faster than $t^{-1.1}$. The transition to a faster decay law is not unique: for example, if the relativistic shock is a narrow jet, the temporal decay of its afterglow steepens when its opening angle $\theta < 1/\gamma$. Depending on the details of the model it may either steepen by an additional $t^{-3/4}$ power (Mészáros & Rees 1999), or steepen to $t^{-p}$ (Kulkarni et al. 1999). The rate of afterglow decay due to an off-LOS hole in a spherical shock should be more modest than that due to a jet and indeed in this scenario, we should expect the afterglow decay will eventually approaches its initial shallower decay profile, as the influence of the geometric defect becomes increasingly less significant.

In summary, we show that the radio “flare” observed in the early afterglow of GRB990123 may be due to a relativistic shock encountering a denser part of the ISM, (with a density between $\sim 200$ and $\sim 2 \times 10^4 \text{ cm}^{-3}$) off line-of-sight. A transition from a $t^{-1.1}$ decay to a modestly faster temporal decay is expected in the later stage of the afterglow. This scenario also implies that the relativistic shock that generates the afterglow is unlikely to be beamed by more than a factor of a few.

We thank George Fuller, Bob Gould and Art Wolfe for discussions. XS acknowledges support from NSF grant PHY98-00980 at UCSD. GG wishes to thank the Department of Energy for partial support under grant DEFG0390ER40546 and Research Corporation.
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Fig. 1.— Radio observations at 8.46 GHz (the solid lines, upper limits are $2\sigma$, Kulkarni et al. 1999b) and 4.88 GHz (the dashed lines, $3\sigma$ upper limits, Galama et al. 1999).
Fig. 2.— A possible geometry near the site of GRB990123.
Fig. 3.— A schematic plot of the afterglow spectrum from the off line-of-site deceleration in the cloud.