JETS IN GRBS

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\section*{ABSTRACT}

In several GRBs afterglows, rapid temporal decay is observed which is inconsistent with spherical (isotropic) blast-wave models. In particular, GRB 980519 had the most rapidly fading of the well-documented GRB afterglows, with $t^{-2.05\pm 0.04}$ in optical as well as in X-rays. We show that such temporal decay is more consistent with the evolution of a jet after it slows down and spreads laterally, for which $t^{-p}$ decay is expected (where $p$ is the index of the electron energy distribution). Such a beaming model would relax the energy requirements on some of the more extreme GRBs by a factor of several hundreds. It is likely that a large fraction of the weak (or no) afterglow observations are also due to the common occurrence of beaming in GRBs, and that their jets have already transitioned to the spreading phase before the first afterglow observations were made. With this interpretation, a universal value of $p \approx 2.5$ is consistent with all data.

\section*{1. INTRODUCTION}

One of the most important open questions in GRBs is whether the burst emission is isotropic or strongly beamed in our direction. This question has implications on almost every aspect of the phenomenon, from the energetics of the events, to the engineering of the “inner engine” to the statistics and the luminosity function of the sources. We suggest here that GRB 980519 was a jet with an opening angle of less than 0.1 rad. We also suggests that such jets are common in most GRBs.

According to the relativistic fireball model, the emission from a spherically expanding shell and a jet would be rather similar to each other as long as we are along the jet’s axis and the Lorentz factor, $\gamma$, is large compared to the inverse of the angular width of the jet, $\theta_0$ (Piran, 1995). When $\gamma$ drops below $\theta_0^{-1}$ the jet’s material begin to spread sideways and we expect a break in the light curve of the afterglow at this stage. Since we have for spherical adiabatic evolution $\gamma(t) \approx 6(E_{52}/n_1)^{1/8}t_{\text{day}}^{-3/8}$, this break should take place at

\begin{equation}
  t_{\text{jet}} \approx 6.2(E_{52}/n_1)^{1/3}(\theta_0/0.1)^{\frac{2}{3}} \text{hr},
\end{equation}

where $E_{52}$ is the “isotropic” energy of the ejecta in units of $10^{52}$ ergs, i.e., the inferred energy assuming isotropic expansion, and $n_1$ is the surrounding ISM particle density in cm$^{-3}$. So far, with the exception of the recent GRB 990123 (Kulkarni et al., 1999), no such break was observed for afterglows extending for hundred days. More specifically, the best observed afterglows, those of GRB 970228 and GRB 970508, behave according to a single unbroken power law, as long as the observations continued (Zharkov, Sokolov, & Baryshev 1998; Fruchter et al. 1998), giving a strong indication that those sources were isotropic to a large extent.

We show here that, even without seeing a break in the lightcurve, one can identify a jet based on the powerlaw index of the optical light curve decline. Since we have a reasonable knowledge of the value of the electrons’ energy distribution index $p \approx 2.4$ we expect for high frequencies a spherical decay of $t^{-1.1-1.3}$ and a jet like decay of $t^{-2.4}$. We suggest that at least in one afterglow, GRB 980519, the observed light curve and spectra are consistent with an expanding jet and inconsistent with those expected from a spherical expansion. We suggest that in this burst the transition to spreading jet, at $\gamma \sim \theta_0^{-1}$, took place during the few hours between the GRB observations and the first detection of the afterglow. We conclude that the beaming factor in this burst is at least a few hundred. Together with the appearance of a sharp break in the light curve of the afterglow of GRB 990123, this indicates that jets are common in GRBs. In fact the rapid decline that corresponds to an expanding jet could also explain the weak or no optical afterglow seen in some of the other bursts, e.g., GRB 990217 (Piro et al. 1999; Palazzii et al. 1999).

Jets have been discussed extensively in the context of GRBs. First the similarity between some of the observed features of blazars and AGNs led to the speculation that jets appears also in GRBs (Paczynski 1993; Dermer & Chiang 1998). Second, the regions emitting the GRB as well as the afterglow must be moving relativistically. The emitted radiation is strongly beamed and we can observe only a region with an opening angle $1/\gamma$ off the line of sight. Emission outside of this very narrow cone is not observed. This have lead to numerous speculations on the existence of jets and to attempts to search for observational signature of jets both during the GRB phase (Mao and Yi 1994) and in the context of the afterglow (Rhoads, 1997a,b; 1998; Mészáros et al., 1998; Panaitescu & Mészáros 1998). Finally, GRBs appear naturally in the context of several leading scenarios for the “inner engine”. (Mochkovitch et al., 1993; Davies et al., 1994; Katz, 1997, Mészáros & Rees, 1997, Nakamura, 1997).

\section*{2. JET EVOLUTION}

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\footnote{The following numerical factors are different from those given by Rhoads (1998) and Panaitescu, & Mészáros (1998). We explain these differences in section 2.}
The simple fireball model [and the Blandford-McKee (1977) solution] assumes a spherical expansion. However, even if the relativistic ejecta is beamed then as long as the Lorentz factor $\gamma$ of the relativistic motion satisfies $\gamma > \theta^{-1}$, the hydrodynamics of the jet won’t be influenced by the fact that it has a finite angular size (Piran, 1995). The matter doesn’t have enough time (in its own rest frame) to expand sideways. This situation changes drastically when $\gamma \approx \theta^{-1}$ when the sideways expansion becomes significant. A full solution of the evolution of a jet at this stage requires 2D relativistic hydro simulations. However, one can obtain a reasonable idea on what goes on using simple analytical estimates.

Rhoads (1997a,b;1998) considered the evolution of a relativistic jet that is expanding sideways at the local speed of sound, $c_s$ so that $\theta \sim \theta_0 + c_s \text{proper}/ct \sim \theta_0 + \gamma^{-1}/\sqrt{3}$. In this case the hydrodynamic transition takes place at $\gamma \sim \theta^{-1}/\sqrt{3}$. However, as the rest mass of the shocked material is negligible compared with its internal energy, the expansion can be ultra relativistic with a Lorentz factor comparable to the thermal Lorentz factor. This would lead to $\theta \sim \theta_0 + c_s \text{proper}/ct \sim \theta_0 + \gamma^{-1}$ and to a transition when $\gamma \sim \theta_0^{-1}$. The sideways expansion leads, for an adiabatic evolution, to an exponential slowing down as $\gamma \propto \exp[-r/\theta \text{j et}]$, where $l_{\text{jet}} \equiv [E_{\text{jet}}/(4\pi/3)nB^2c^2]^{1/3}$ is the Sedov length in which a spherical expanding shell with energy $E_{\text{jet}}$ acquire mass whose rest mass energy equals to its own energy ($n$ is the ISM density). $E_{\text{jet}}$ is the actual energy in the jet. Thus, $r$ is practically a constant during the spreading phase. Therefore, the observer time, which is related to the radius and the Lorentz factor as $t \propto r/\gamma^2$ satisfies simply $t \propto r^{-2}$.

Our estimate for the break time (Equation [1]) is the simplest one. It is based just on spherical adiabatic expansion. It differs by a factor of 20 in time (corresponding to a factor of $\sim 3$ in the opening angle $\theta_0$) from the expression given by Rhoads (1998). The discrepancy arises from several factors: (i) As discussed above, we assume that the jet expands sideways at the speed of light while Rhoads (1998) assumes that jet expands at the sound speed $c/\sqrt{3}$. (ii) Rhoads (1998) uses $t \approx R/2\gamma^2 c$. This expression is valid for a point source moving along the line of sight with a constant velocity. We use $t \approx R/4\gamma^2 c$ reflecting the deceleration of the source and its finite angular size (Sari, 1997, 1998; Waxman 1997, Panaitescu and Mészáros 1998). (iii) We use the simple adiabatic energy condition: $E = \gamma m c^2$, where $m$ is the rest mass of the shocked ISM, while Rhoads (1998) uses $E = 2\gamma^2 m c^2$. A third possibility is to use the more exact numerical factor derived from the Blandford-McKee (1976) solution: $E = 12\gamma^2 m c^2/17$. (iv) We estimated the time in the local frame as $R/\gamma c$. Rhoads noted that the Lorentz factor was higher earlier and hence the effective proper time is shorter by a factor of 2.5 allowing for less spreading. However, far from the shock, the matter moves with a considerably lower Lorentz factor allowing it to spread more easily.

Panaitescu & Mészáros (1998) consider similar hydrodynamics as Rhoads (1998) but notice that once $\gamma \sim 1/\theta_0$ the observer is able to see the edge of the jet. They find two transitions, the first one when $\gamma \sim 1/\theta_0$ at around our break time estimate and the second one around Rhoads’. However, there would be only one transition if the time between the two breaks turns out to be very short. A reliable estimate of the numerical factor clearly requires full 2D simulations. It might also be, as suggested by Rhoads (1998b), that the transition takes place over a relatively long time and that most observations, that are conducted in a finite time interval, will show only part of the asymptotic break.

We consider now synchrotron emission from a powerlaw distribution of accelerated electrons produced by shocks in an expanding jet. The instantaneous spectrum is given by the four broken power laws discussed in Sari, Piran & Narayan (1998). However, the time dependence of the break frequency and the overall normalization depend strongly on the hydrodynamic evolution. Therefore, the lightcurve from a jet differs strongly from the light curve of a spherical evolution. Surprisingly, it is possible to obtain general expressions, appropriate to both spherical and jet evolution (by spherical we mean any system with $\gamma > \theta^{-1}$ and by a jet a system with $\gamma \leq \theta^{-1}$). We write these generalized expressions and specialize to jet and sphere only at the very end. We begin with the typical frequency $\nu_m$, at the observer frame:

$$\nu_m = \frac{eB}{m_e c} \gamma^2 \propto \gamma^4 \begin{cases} t^{-3/2} & \text{spherical,} \\ t^{-2} & \text{jet.} \end{cases}$$

(2)

The cooling frequency, the synchrotron frequency of electrons that cool on the dynamical time of the system, is given by

$$\nu_c = \frac{36\pi^2 c^3 m_e e}{\gamma B^2 t^2} \propto \gamma^{-4} t^{-2} \begin{cases} t^{-1/2} & \text{spherical,} \\ \text{const.} & \text{jet.} \end{cases}$$

(3)

The peak flux is obtained at the lowest of the two frequencies $\nu_m$ and $\nu_c$. Let $N_e$ be the total number of electrons radiating towards the observer, i.e., those located in a cone of opening angle $\gamma^{-1}$. $N_e$ is different from $\sigma_T m_e c^2 \pi R^2 t^2/6\pi$, which is the total number of radiating electrons, including those that are not radiating towards the observer. $N_e$ can be approximated by $N_e = \pi \gamma^{-2} R^2 n/3$. The total energy per unit time per unit frequency emitted by these electrons, $\sigma_T m_e c^2 N_e \gamma / 6\pi$, is distributed over an area of $\pi \gamma^{-2} d^2$ at a distance $d$ from the source. The observed peak flux density is therefore

$$F_{\nu,\text{max}} = \frac{2\sigma_T m_e c^2 R^3 n B_e^2}{\pi e} \propto R^3 \gamma^2 \begin{cases} \text{const.} & \text{spherical,} \\ \nu^{-1} & \text{jet.} \end{cases}$$

(4)

It seems to hold quite generally at late times (except perhaps the first few hours, see Sari & Piran, 1999) that $\nu_c \gg \nu_m$. The electrons responsible for low energy emission are therefore those with $\nu_c$. In this case, the self absorption frequency can be estimated as

$$\nu_a \propto R^{3/5} \gamma^{2/5} \begin{cases} \text{const.} & \nu^{-1/5} \text{spherical,} \\ \nu^{-1} & \text{jet.} \end{cases}$$

(5)

We now turn to calculate the light curves for several frequency ranges. The flux at low frequencies, which is self absorbed, evolves as

$$F_{\nu < \nu_a} \propto R^2 \begin{cases} \nu^{1/2} & \text{spherical,} \\ \text{const.} & \text{jet.} \end{cases}$$

(6)

The flux at frequencies that are above the self absorption frequency but below the typical frequency $\nu_m$ evolve as

$$F_{\nu_a < \nu < \nu_m} \propto R^3 \gamma^{2/3} \begin{cases} \nu^{1/2} & \text{spherical,} \\ \nu^{-1/3} & \text{jet.} \end{cases}$$

(7)

We therefore expect that the low frequencies ($\nu < \nu_m$) flux would rise like $t^{1/2}$ as long as the evolution is spherical. Then,
once $\gamma$ drops below $\theta_0^{-1}$ and the jet begins to spread, the flux at frequencies above the self absorption would decrease as $r^{-1/3}$. At lower frequencies which are in the self absorbed regime the flux will be a constant until the self absorption frequency is reached.

These predictions are different from those derived by Rhoads, who considered the case when $\nu_m < \nu_c$ where he found that the flux rises linearly with time. However, based on GRB 970508, it seems that this regime of $\nu_m < \nu_c$ is relevant only for very late times, about a hundred days after the burst.

At high frequencies two light curves are possible, depending whether the radiating electrons are cooling ($\nu > \nu_c$) or not ($\nu < \nu_c$). The slope itself also depends on the electron power low distribution index $p$. Below the cooling frequency we obtain

$$F_{\nu_m < \nu_c} \propto F_{\nu_m} \left(\frac{\nu}{\nu_m}\right)^{(p-1)/2} \propto R^3 \gamma^{-2p} \propto \left(\frac{\nu}{\nu_c}\right)^{p/2}$$

Above the cooling frequency we have

$$F_{\nu_c < \nu < \nu_m} \propto \left(\frac{\nu}{\nu_c}\right)^{-\nu_m - (p-1)/2} \propto \left(\frac{\nu}{\nu_m}\right)^{(p-1)/2}$$

Note that for a spreading jet, the light curve decay index (but not the spectrum) is independent of whether $\nu > \nu_c$ or $\nu < \nu_c$. This is due to the fact that $\nu_c$ is constant in time in the case of a spreading jet. Since $p$ determines both the light curve and spectrum, a parameter free relation between the temporal decay index $\alpha$ and the spectral index $\beta$ can be given. For a spherical expansion we have:

$$\alpha = \begin{cases} \frac{3\beta}{2}, & \nu < \nu_c, \\ \frac{3\beta}{2} - 1/2, & \nu > \nu_c. \end{cases}$$

While for an expanding jet we have:

$$\alpha = \begin{cases} 2\beta + 1, & \nu < \nu_c, \\ 2\beta, & \nu > \nu_c. \end{cases}$$

These results are summarized in Table 1.

3. OBSERVATIONS

3.1. GRB 980519

GRB 980519 was one of the brightest of the bursts detected in the BeppoSAX WFC (Muller et al. 1998; in ‘t Zand et al. 1999), second only to the recent GRB 990123 (Feroci et al. 1998). The BATSE measured fluence above 25 keV was $(2.54 \pm 0.41) \times 10^{-5}$ ergs cm$^{-2}$, which places it among the top 12% of BATSE bursts (Connaughton 1998). An X-ray observation with the BeppoSAX Narrow Field Instruments detected an afterglow (Nicastro et al. 1998). GRB 980519 had the most rapid fading of the well-documented GRB afterglows, consistent with $r^{-2.05 \pm 0.04}$ in $BVR$ (Halpern et al. 1999). The power-law decay index of the X-ray afterglow, $\alpha_\gamma = 2.07 \pm 0.11$ as reported by Owens et al. (1998), is consistent with the optical. The X-ray temporal decay of GRB 980519 is the fastest of the seven afterglows that were well measured by BeppoSAX (Owens et al. 1998). The optical spectrum alone is well fitted by a power law of the form $\nu^{-1.2 \pm 0.25}$, while the optical and X-ray spectra together are adequately fitted by a single power law $\nu^{-1.05 \pm 0.10}$.

The relation between the spectral slope and the temporal decay is inconsistent with the simple spherical fireball model that predicts that the time decay light curve index, $\alpha$, and the spectral shape power law index, $\beta$, are related according to equation (10). This inconsistency is independent of the value of $p$. These observations are consistent with each other if we assume an expanding jet phase for which equation (1) is applicable.

It is difficult to determine the exact value of $p$ from these observations. However, we note that they are consistent with a value of $p \sim 2.4$ that arises in other bursts. This will fit the optical power law decay if the electrons are not cooling i.e., $\nu_c$ is above the optical band. It will also fit the optical spectral index which has large uncertainty. The optical to X-rays slope is intermediate between the value obtained for slow cooling ($\sim -0.8$) and that obtained for fast cooling ($\sim -1.25$). This indicates that the cooling frequency is between the optical and X-rays.

The fact that this transition took place less than 8.5 hours after the burst shows that the opening angle of this jet was rather small: $\theta < 0.1$, leading to a beaming factor of 300 or larger! We note that the two strongest GRBs detected by the BeppoSAX WFC are inferred to have a large beaming factor. This may indicate that a significant fraction of the spread in luminosities is given by the beaming effect.

3.2. GRB 990123

GRB 990123 was a remarkable burst with a very high GRB fluence and with a prompt optical and X-ray emission. We interpret this emission as resulting from the early forward shock (X-ray) and from the early reverse shock (optical). The reverse shock has also produced the early radio flare (Sari and Piran 1999). The forward shock emission is directly related to the latter optical and X-ray emission, while the reverse shock emission decayed like $r^{-2}$, and disappeared quickly. The late optical afterglow showed a power law decay with $r^{-1.1 \pm 0.03}$. This behavior continued from the first late observation (about 3.5 hours after the burst) until about 2.04 $\pm 0.46$ days after the burst. Then the optical emission began to decline faster (Kulkarni et al. 1999). The simplest explanation is that we have observed the transition from a spherical like phase to an expanding jet phase. The transition took place at $2 \pm 2$ days, corresponding to $\theta_0 \sim 0.1$. This implies a beaming factor of about 100 reducing the energy of the burst to $3 \times 10^{52}$ ergs. This is the first, and by now the only, burst in which such a break was detected. The decay before the break is well measured and fits an electron distribution with $p \approx 2.5$.

3.3. GRB 980326

GRB 980326 was another burst with a rapid decline. Groot et al. (1998) derived a temporal decay slope of $\alpha = 2.1 \pm 0.13$ and a spectral slope of $\beta = 0.66 \pm 0.7$ in the optical band. Such rapid temporal decay suggests a jet like evolution. As Groot et al. (1998) note, the large uncertainty in the spectral index allows in this case also a spherical expansion interpretation (with somewhat unusual values $p = 4.2$ or $p = 5.2$). However, this measured temporal decay was dependent upon a report of a host galaxy detection at $R = 25.5 \pm 0.5$, which was included as a constant term. The detection of a host has since been determined to be spurious; better data show no constant component to a limiting magnitude of $R = 27.3$ (Bloom & Kulkarni 1998). When the previously assumed constant component is removed, the overall light curve is concave, in disagreement with a jet
interpretation. If the last detection is interpreted as a different phenomenon (Kulkarni, 1999) then the remaining points show a rapid decline - in agreement with a jet.

3.4. GRB 970228 and GRB 970508

In both GRB970228 and GRB970508 there was no observed break in the light curve as long as the afterglow could be observed. GRB970228 was observed by HST six months later, at which point it was still following a power-law decay as $t^{-1.14±0.05}$ (Fruchter et al. 1998). GRB970508 was observed for 9 months to decline as $t^{-1.23±0.04}$ (Zharikov et al., 1998), at which point became as faint as its host galaxy. This set a limit on the beaming in these events of $\theta_0 ≥ 1$. The beaming factor is therefore less than an order of magnitude.

### Table 1

| spectral index $\beta$, $F_\nu \propto \nu^{-\beta}$ | light curve index $\alpha$, $F_\nu \propto t^{-\alpha}$ |
|-------------------------------------------------|----------------------------------|
| $\nu < \nu_c$ $(p-1)/2 \equiv 0.7$ | $\alpha = 3(p-1)/4 \equiv 1.05$ for jet $p < 2.4$ |
| $\nu > \nu_c$ $p/2 \equiv 1.2$ | $\alpha = 3\beta/2$ for sphere $\alpha = 2\beta + 1$ |

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