On the Variability of Gamma-Ray Burst Afterglows — A Possibility of a Transition to Nonrelativistic Motion

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Variability on time scales $\delta t < t$ is observed in many gamma-ray burst afterglows. It is well known that there should be no such variability if the afterglow is emitted by external shock, which is produced by the interaction of ultrarelativistic ejecta with the ambient interstellar medium, within the framework of simple models. The corresponding constraints were established by Ioka et al. (2005) and in some cases are inconsistent with observations. On the other hand, if the motion is not relativistic, then the fast variability of the afterglow can be explained much more easily.

In this connection we discuss various estimates of the time of the transition to subrelativistic motion in GRB source. We point out that this transition should occur on an observed time scale of $\sim 10$ days. In the case of a higher density of the ambient interstellar medium $\sim 10^{-3} \text{ cm}^{-3}$ or dense stellar wind with $M \sim 10^{-5} - 10^{-4} \text{ M}_\odot/\text{year}$ the transition to a subrelativistic motion can occur on a time scale of $\sim 1$ day. These densities may well be expected in star-forming regions and around massive Wolf-Rayet stars.

Keywords: gamma-ray bursts — afterglows — variability

INTRODUCTION

According to current models of gamma-ray bursts (GRBs), ultrarelativistic motion of the jet pointing toward the observer takes place in their sources (see reviews by Mészáros, 2002; Zhang and Mészáros, 2003; Piran, 2003). Their afterglows in X-ray, optical, and radio bands are explained by the radiation that emerges at the front of the external shock produced by jet interaction with the ambient interstellar medium surrounding the source. In this case, a variable light curve cannot emerge from a homogeneous spherical emitting shell, that moves inside a cone with the opening angle $\theta > \gamma^{-1}$, where $\gamma$ — the Lorentz factor of the jet. For the remote observer, the variability time scale should be $\delta t \sim t$.

However, the variability of optical afterglows at time scales $\delta t < t$ is observed in many cases. The best-known is GRB 030329 whose afterglow was studied in great detail due to its exceptional brightness (Burenin et al., 2003; Urata et al., 2004; Lipkin et al., 2004). Similar variability was also observed in other cases where detailed measurements of the light curve were obtained: GRB 021004 (see e.g., Holland et al., 2003; Bersier et al., 2003; de Ugarte Postigo et al., 2003; Bersier et al., 2003; de Ugarte Postigo et al., 2003; 050408 (de Ugarte Postigo et al., 2007), 060526 (Dai et al., 2007; Khamitov et al., 2007) and others.

Various explanations for the variability of GRB afterglows were discussed in detail by Ioka et al. (2003), who also established constraints on the afterglow variability time scales and amplitudes for various models. They are all based on the assumption of ultrarelativistic motion of the jet. In some observed afterglows, the constraints obtained in simple models of the jet are violated (Ioka et al., 2003; Khamitov et al., 2007).

However, the motion may well become moderately relativistic on the observed time scales in case of higher density of the ambient medium or in presence of a dense stellar wind. For example, Dai & Li (1999) discussed this possibility for the afterglow of GRB 990123 and showed that the transition to a nonrelativistic motion on a time scale of about 2.5 days occurs if the density of the surrounding medium is $\sim 10^6 \text{ cm}^{-3}$. In this paper, the sideways expansion of the jet once the condition $\gamma < \theta^{-1}$ is satisfied (Rhoads, 1997; 1999; Sari et al., 1999) was not taken into account. Because of this expansion, the jet collects more material on its way and slows down faster.

In this note, we discuss various estimates of the time of the transition to subrelativistic motion and show that it may well be $\sim 1$ day.

WHEN DOES THE ULTRARELATIVISTIC MOTION END?

The most simple estimate of the time of the transition to nonrelativistic motion, $t_{NR}$, taking into account the sideways expansion of the jet, was obtained
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by Waxman et al. (1998):

\[ t_{NR} \approx 27 \left( \frac{E_{52}}{n_1} \right)^{1/3} \theta_{0.1}^{2/3} \text{ days}, \]  

(1)

where \( E_{52} \) is the “isotropic” energy of the shell in units of \( 10^{52} \text{ ergs/cm}^2 \), \( n_1 \) is the particle number density in the medium surrounding the source in units of \( \text{cm}^{-3} \), and \( \theta_{0.1} = \theta/0.1 \) — is the jet opening angle.

This estimate was obtained using the dependency \( \gamma(t) \) for adiabatic shell and assuming that the motion after the onset of jet sideways expansion approaches a spherically symmetric one and take place according to the same adiabatic solutions. In order of magnitude, it agrees well with the other estimates that can be obtained from a more comprehensive analysis of the jet dynamics. For example, if the jet begins to expand at \( \gamma = \theta^{-1} \), then, given that after that the gamma factor depends on the observed time as \( \gamma \propto t^{-1/2} \) (Rhoads 1999), we will obtain:

\[ t_{NR} = t_j \theta^{-2}, \]  

(2)

where \( t_j \) is the time of the beginning of jet sideways expansion. If we take the expression for \( t_j \) from Sari et al. (1999), then \( t_{NR} \approx 26 \text{ days} \) with the same parameter dependency as above.

Rhoads (1999) assumed that the jet in its rest frame expands with the speed of sound \( c_s = c/\sqrt{3} \), not with the speed of light. Accordingly, the jet expansion begins later, at \( \gamma \approx (3\sqrt{2}/\theta)^{-1} \). Using the \( \gamma(t) \) dependency from this work and applying the same inference as above, we obtain \( t_{NR} = 25 \text{ days} \) for the same parameters. Panaitescu and Mészáros (1999) assumed that the jet also expands with the speed of sound. They pointed out that, when \( \theta > 0.1 \), the shell ceases to be ultrarelativistic even before the onset of the sideways expansion. In this work, \( t_{NR} \) was estimated explicitly. Rewriting it with our parameters, we obtain \( t_{NR} = 6.1 \text{ days} \), with the same parameter dependency as in (1).

If we take into account that initially the motion of the shell may not be adiabatic and it can lose a substantial part of its energy through radiation, then the estimate of \( t_{NR} \) can decrease significantly. For synchrotron radiation, the motion should be radiative if much of the energy that the material gains at the shock front goes into the accelerated electrons and the electrons cool down rapidly compared to the dynamical time. The latter always holds at the beginning of shell motion. The expression for the energy, to be used to calculate the subsequent adiabatic motion if the evolution was initially radiative is given by Sari et al. (1998). Substituting this energy into (1) yields:

\[ t_{NR,r} \approx 7.6 \epsilon_B^{-1/5} \epsilon_e^{-1/5} E_{52}^{-1/15} n_1^{-4/15} \gamma_2^{-4/15} \theta_{0.1}^{2/3} \text{ days}, \]  

(3)

where \( \epsilon_B \) and \( \epsilon_e \) are the energy density fractions of the magnetic field and accelerated electrons behind the shock, \( \gamma_2 = \gamma_0/100 \) is the initial gamma factor of the ejecta. This estimate should be used if it is assumed that \( \epsilon_e \sim 1 \), i.e., the electrons are accelerated effectively at the shock front.

The estimate of \( t_{NR} \) for a stellar wind with a density proportional to \( r^{-2} \) can be taken from Livio and Waxman (2000). Rewriting it with our typical parameters, we will obtain:

\[ t_{NR,w} \approx 5.7 E_{52} (M_5/v_3)^{-1} \theta_{0.1}^{2/3} \text{ days}, \]  

(4)

where \( M_5 \) is the mass loss rate of the star in units of \( 10^{-5} \text{ M}_\odot \text{ year}^{-1} \) and \( v_3 \) is the wind velocity in units of \( 10^3 \text{ km s}^{-1} \). If the electrons are accelerated effectively and the evolution is initially radiative, then this estimate should be much smaller, just as in the above case of a constant-density medium.

DISCUSSION

From these estimates we see, that the observed transition time to nonrelativistic motion is \( \sim 10 \text{ days} \) even for the commonly accepted typical parameters. A higher density of the ambient medium \( n \sim 10^4 \text{ cm}^{-3} \) for an adiabatic shock, or \( n \sim 10^2 \text{ cm}^{-3} \), if the electrons at the shock front are accelerated effectively and the shell is initially radiative, or a stellar wind with \( M \sim 10^{-5} – 10^{-4} \text{ M}_\odot \text{ year}^{-1} \) is required for \( t_{NR} \sim 1 \text{ day} \).

A higher density of the interstellar medium is actually may well be expected near GRB sources, since at least a large fraction of them are related to supernova explosions at the end of the evolution of massive stars and occur in regions of enhanced star formation (see, e.g., the review by Woosley and Bloom, 2006, and references therein). In addition, massive stars at the end of their evolution intensively lose their outer layers and should be surrounded by dense stellar winds (e.g., Crowther, 2007). In some cases, the presence of a wind around GRB sources is confirmed observationally. For example, high-resolution spectroscopy of the GRB 021004 afterglow shows that its progenitor was a massive Wolf-Rayet star surrounded by a wind with a mass loss rate of \( \sim 10^{-4} \text{ M}_\odot \text{ year}^{-1} \) and an expansion velocity up to \( 3000 \text{ km s}^{-1} \) (Mirabal et al. 2003; Lazzati et al. 2006).

If the motion is no longer ultrarelativistic, then the fast variability of the afterglow on a time scale \( \delta t \ll t \) can be explained, for example, by the presence of density inhomogeneities. In fact, the presence of these inhomogeneities can also be expected. For example, the stellar winds around Wolf-Rayet stars are known to be highly inhomogeneous and to have a clumpy structure (Hamann and Koesterk, 1998; Crowther, 2007). In addition, the cooling time in the observed optical part of
the spectrum should be short. This holds for the synchrotron spectrum at late evolutionary phases of the shock (e.g., Sari et al. 1998).

Thus, the transition to subrelativistic motion on the observed time scale of $\sim 1$ day is actually quite possible and, in this case, the fast variability of GRB afterglows can be easily explained. Of course, the fast variability of GRB afterglows can also be explained under special assumptions in the case of an ultrarelativistic jet (Ioka et al. 2005). However, the transition to a nonrelativistic motion should at least be considered as one of the possible explanations of this fast variability. This requires a higher density interstellar medium or dense stellar wind, which are expected in star forming regions and around massive Wolf-Rayet stars.

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