DELAYED AFTERGLOW ONSET INTERPRETED AS A BARYON-POOR VIEWING ANGLE

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ABSTRACT

We have suggested previously that baryons in gamma-ray burst fireballs come from the surrounding walls that collimate the fireball. The efficiency $\epsilon_b$ for generating blast energy can then be angle-dependent. The delayed onset of afterglow can be interpreted as being due to a baryon-poor viewing angle.

Subject headings: black hole physics — gamma rays: bursts — gamma rays: theory

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1 INTRODUCTION

Gamma-ray bursts (GRBs) are suspected to come from black holes. Nearly all GRBs produce X-ray afterglow. This is significant because, if GRBs were driven by the pure energy that can be extracted from a black hole, it is unlikely that there would be afterglow. Pairs could be produced in a variety of ways, but they would probably annihilate within $10^{11}$ cm of the central engine before making afterglow. This is not an embarrassment either for black hole models of GRBs or for models of afterglow, because baryons can be picked up after the pair fireball is launched—either from a surrounding baryonic wind that emanates from the accretion disk, from the walls of a host star, or from ambient material, such as a pre-supernova wind emitted by the star that hosts the GRB. Moreover, the possibility exists that the GRB is driven by the accretion disk surrounding the black hole and that the latter plays no active role other than to provide gravitational energy to the accreting matter. Nevertheless, the event horizon of the underlying black hole would be more convincingly revealed by failure to produce afterglow, especially now that afterglow is regarded as routine. A line of sight only after...
θ, the baryons infiltrate the fireball from the side and penetrate an angle Δ so that they flow out along the annulus θ₀ − Δ ≤ θ ≤ θ₀. Assume that the γ-rays within this annulus are isotropic at their point of emission or last scattering, in a frame that moves at Lorentz factor Γ relative to the observer. Thus, the γ-rays ultimately fill a cone of opening angle θ₀ + 1/Γ. At first, only observers in the line of sight θ₀ − Δ − 1/Γ ≤ θ ≤ θ₀ + 1/Γ see early afterglow. The Lorentz factor of the blast decreases as it sweeps up ambient matter, so that at observer time t, afterglow is seen in an enhanced annulus θ₀ − Δ − 1/Γ(1 + t/Γ) ≤ θ ≤ θ₀ + 1/Γ(1 + t/Γ) (here and throughout Q = Q/10¹⁰ in cgs units).

Given that softened GRB spectra are attributed to off-beam viewing angles, the Amati et al. relation can be best understood if (1) θ₀ ≫ 1/Γ, and (2) Δ ≥ 3/Γ (Eichler & Levinson 2004). These requirements are based on the fact that the off-beam viewing angle that is offset by δ from the γ-ray beam then receives contributions at comparable Doppler factors from a patch that is ~δ in width and in length, and is thus proportional to δ². This, being roughly proportional to (1 − β, cos δ), somewhat compensates the large decrease in E₉₉ due to the decrease in the Doppler factor 1/Γ(1 − β, cos δ). For example, the contribution to the observed fluence dF from a ring centered around the line of sight at angle δ with thickness dδ is proportional to dδ dΓ(1 − β, cos δ)², which for small δ and small 1/Γ is about 2δ dδ dΓ(1 − β, cos δ)² ∝ (1/Γ²)/δ², which is strongly viewing-angle-dependent.

In principle, an observer near the axis could see a GRB with no afterglow. How often would this occur? Observationally, it must be a small fraction of the total, as all but one GRB localized with BeppoSAX displayed X-ray afterglow observed by the NFI, which makes its observations 10¹⁰ s after the burst trigger, t = 10¹⁰ s. The expected fraction of GRBs that would display no afterglow by time t is then

\[ f(t) = \frac{1}{\theta_0 - \Delta - 1/\Gamma(t)} \int_0^{\theta_0 + 1/\Gamma(t)} \frac{d\theta}{\theta}. \]

As an example, we consider the parameter choice θ₀ = 9/Γ, Δ = 4/Γ, and Γ = (100 s) = 100. (The choice 3/Γ ≤ Δ ≤ 5/Γ has both an empirical motivation [Eichler & Levinson 2004] as well as an a priori motivation in the model of Levinson & Eichler [2003], where it is estimated that neutrons freely stream from a surface with Γ = 30, which is somewhat greater than 1/θ₀ = 10 for typical GRBs, but by less than an order of magnitude.) The fraction of observers coming hard γ-rays along baryon-poor lines of sight is ~0.25, a not insignificant fraction. If the blast decelerates as Γ ∝ t⁻¹/³, the case of a constant density ambient medium, then within 3 hr (10¹⁰ s, say), Γ = 10⁻³⁴, and even an observer exactly at the axis would detect afterglow. If Γ ∝ t⁻¹/³, the case for a wind, then after 10¹⁰ s (10⁻³⁵ s), Γ = 10⁻³⁴, and a small fraction f < 0.04 (<0.0001) fails to see afterglow. This illustrates the point that afterglow may be nearly guaranteed for an observer of a GRB after...
several hours, even if the original line of sight is baryon-poor. At a time \( t \) of only 200 s, on the other hand, still assuming the above GRB parameters and \( \Gamma(t) \propto t^{1/4} \), it follows that \( \Gamma(200 \text{ s}) \sim 80 \), and the probability for a viewer of the prompt emission of a GRB (defined here to be within 0.1 radians of the axis) to not observe its afterglow by this time (i.e., to be within 0.04 radians of the axis) would be about 0.16.

It is thus reasonable that some modest fraction of all X-ray afterglows begin, from the observer’s point of view, at \( t \geq 200 \text{ s} \). It goes without saying that the numbers here are somewhat uncertain, and the sharp zone boundaries invoked here are an oversimplification. Where we have formulated the results in terms of afterglows being seen or not seen, with no middle ground, it might actually be the case that they would be bright or dim relative to the prompt emission. Observations with Swift will allow for better measurements of afterglow onset, but the full BeppoSAX data set already allows for modest statistical analysis.

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