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TOWARD A MODEL FOR THE PROGENITORS OF GAMMA-RAY BURSTS[1]

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ABSTRACT

We consider models for gamma-ray bursts in which a collimated jet expands either into a homogeneous medium or into a stellar wind environment, and we calculate the expected afterglow temporal behavior. We show that (1) following a break and a faster decay afterglows should exhibit a flattening, which may be detectable in both the radio and optical bands, and (2) only observations at times much shorter than a day can clearly distinguish between a fireball interacting with a homogeneous medium and one interacting with a stellar wind. Using our results, we demonstrate that constraints can be placed on progenitor models. In particular, existing data imply that while some long-duration bursts may be produced by collapses of massive stars, it is almost certain that not all long-duration bursts are produced by such progenitors.

Subject headings: gamma rays: bursts — stars: mass loss — supernovae: general

1. INTRODUCTION

During the past 3 years, the understanding of gamma-ray bursts (GRBs) has literally been revolutionized. The discovery by *BeppoSAX* of X-ray afterglows (e.g., Costa et al. 1997) followed by the discovery of optical transients (e.g., van Paradijs et al. 1997) led eventually to a full confirmation of the cosmological nature of (at least a subclass of) GRBs. The latter has been achieved both by direct redshift measurements (e.g., Metzger et al. 1997) and by imaging of the host galaxies (e.g., Sahu et al. 1997).

Since GRBs involve the generation of huge amounts of energy during very short time intervals, most GRB models involve compact or collapsed objects (e.g., Paczyński 1986; Eichler et al. 1989; Fryer, Woosley, & Hartmann 1999; and see Mészáros 1999 for a review). In spite of impressive successes of expanding relativistic "fireball" models (e.g., Paczyński & Rhoads 1993; Katz 1994; Mészáros & Rees 1997; Vietri 1997; Waxman 1997a; Sari, Piran, & Narayan 1998), the precise nature of GRB progenitors remains unknown.

In recent years, it has become clear that, as in supernovae, GRB progenitors may in fact span a rather heterogeneous class. At least two broad groups are evident from plotting spectral hardness versus burst duration (e.g., Katz & Canel 1996; Kouveliotou et al. 1996; Fishman 2000). One group consists of relatively hard and short (mean duration of ~ 0.2 s) bursts while the other of softer and longer (mean duration of ~ 20 s) bursts. All the afterglows and optical transients discovered so far followed bursts belonging to the second group.

On the basis of the burst durations and the estimated burst frequencies, it is generally speculated (e.g., Fryer et al. 1999) that the short-duration bursts are the results of mergers, mostly of neutron star–neutron star (NS-NS) and black hole–neutron star (BH-NS) pairs, while the long-duration bursts are mostly the results of collapses of massive stars. The latter scenario received some support from the tentative identification of GRB 980425 with the Type Ic supernova SN 1998bw (Galama et al. 1998; Kulkarni et al. 1998; Iwamoto et al. 1998) and from a tentative detection of a supernova underlying GRB 980326 (Bloom et al. 1999).

In the present work, we attempt to take the identification of GRB progenitors one step further, by examining in some detail the behavior of GRB afterglows. In particular, we investigate expected (and observed) breaks in the power-law decline of afterglows and their potential relation to jets and to interaction with a preoutburst stellar wind environment. The general framework and calculations are presented in § 2, and a discussion and conclusions follow.

2. JETS AND WINDS

An examination of the temporal decay of the afterglows of GRBs reveals the following three trends:

1. In a few afterglows (like GRB 970228 and GRB 970508), the decay broadly followed a single, unbroken power law, behaving like $t^{-1.14\pm0.05}$ and $t^{-1.23\pm0.04}$ for the above two, respectively (e.g., Fruchter et al. 1999a; Zharikov, Sokolov, & Baryshev 1998; although see Reichart 1999; Galama et al. 2000).
2. In some GRBs (like GRB 990123 and GRB 990510), the optical afterglow decayed like one power law initially and then began to decline faster. For example, GRB 990123 behaved like $t^{-1.1\pm0.03}$ from 3.5 hr after the burst until about 2 days after the burst, when it started a steeper decline (Kulkarni et al. 1999; Fruchter et al. 1999b). Similarly, GRB 990510 behaved like $t^{-0.76\pm0.01}$ at early times ($t \ll 1$ day) and $t^{-2.40\pm0.02}$ at late times (Stanek et al. 1999).
3. In two GRBs (GRB 980519 and GRB 980326), the afterglow was observed to fade very rapidly, like $t^{-2.05\pm0.04}$ and $t^{-2.1\pm0.13}$, respectively (e.g., Halpern et al. 1999; Groot et al. 1998).

Two types of potential explanations have been suggested for the break in (or very fast decline of) the light curve. In one explanation, the fireball is initially *a highly collimated jet*, with the break occurring when the Lorentz factor Γ becomes smaller than $1/\theta$, where θ is the jet opening angle (e.g., Rhoads 1999; Panaitescu & Mészáros 1999; Sari, Piran, & Halpern 1999; Dar 1998; Harrison et al. 1999; Stanek et al. 1999). In the second model, it has been suggested that the steep decline (e.g., of GRB 980519) was

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caused by the interaction of *a spherical burst* with a preburst Wolf-Rayet star wind (e.g., Chevalier & Li 1999, 2000; Mészáros, Rees, & Wijers 1998; Frail et al. 2000a).

Let us first examine these two suggestions and their potential relation to progenitor models. The first point to note is that collimation and acceleration of jets (in the context of MHD extraction of energy, as opposed to neutrinos) is generally thought to occur by an accretion disk that is threaded by a large-scale vertical magnetic field (e.g., Blandford 1993; Spruit 1996; Livio 1999; although purely hydrodynamical disk models have also been considered, e.g., MacFadyen & Woosley 1999). This model has received some additional recent support from very high resolution VLBI observations of the M87 jet (Junor, Biretta, & Livio 1999), which show the collimation process occurring on scales of 30–100 Schwarzschild radii from the putative central black hole, with the jet exhibiting limb brightening in the radio. Generally, good collimation requires a relatively large ratio, $R_d/R_{\rm CO} \gg 1$ (where R_d is the disk outer radius and $R_{\rm CO}$ is the radius of the central compact object). Optimal collimation is obtained when the Alfvén surface is at a distance of the order of the disk radius. For a vertical field strength at the surface of the disk that behaves approximately as $B_z \sim (r^2/R_{\rm CO}^2 + 1)^{-1/2}$, the jet opening angle is given approximately by $\theta \sim (R_{\rm CO}/R_d)^{1/2}$. The condition for good collimation is naturally satisfied in the case of a collapsing massive star but not in the coalescence of NS-NS or BH-NS binaries (where $R_d/R_{\rm CO} \sim 1$). Hence, while highly collimated jets may be expected from massive star collapses (in which case high collimation is also *needed* for the jet to be able to escape the collapsing mantle), collimation is probably at best moderate from NS-NS and BH-NS mergers. We should note that while it is sometimes argued that the very high initial bulk Loretz factors required for prompt gamma-ray emission suggest that *energy* is extracted directly from the black hole (e.g., by the Blandford-Znajek 1977 mechanism) the magnetized accretion disk is still usually assumed to be responsible for the *collimation.*

Second, it is virtually *impossible* to avoid the existence of a stellar wind environment in massive star GRB progenitor models. The wind mass-loss rates from Wolf-Rayet stars are approximately of order $\dot{M} \sim 6.3 \times 10^{-6}(M_{\rm WR}/10\ M_\odot)^{2.5}$ $M_\odot$ yr^{-1} (e.g., Hamann & Koesterke 1998), and they do not depend very significantly on metallicity (e.g., Willis 1991; Leitherer 1991; in addition, most GRBs with afterglows so far are at redshifts $z \lesssim 1$, so the change in the cosmic metallicity is not dramatic).

The above two points indicate immediately the following consequences:

1. Since *all* the observed afterglows belong to the long-duration group of GRBs, *if* some afterglows do not show any clear signs of either highly collimated jets or interaction with a wind (e.g., in terms of breaks, fast declines, or radio evolution), then the group of long-duration GRBs almost certainly do not *all* result from collapses of massive stars.

2. Since GRBs resulting from collapses of massive stars lead *both* to highly collimated jets (at least sometimes) and to a stellar wind environment (always), it is important to examine the development of a jet interacting with a wind.

Based on the above two points, we reexamine now the behavior expected from collimated jets.

2.1. *Jet Transition to Subrelativistic Expansion*

We first consider jets expanding into a homogeneous medium. The discussion is generalized in § 2.2 to jets expanding into a wind.

As long as the jet Lorentz factor Γ is larger than the inverse of the jet's opening angle θ, it behaves as if it were a conical section of a spherical fireball. At this stage, the Lorentz factor as a function of jet radius is given by the Blandford-McKee (1976) solution, $\Gamma = (17E_i/16\pi n m_p c^2)^{1/2} r^{-3/2}$, where n is the number density ahead of the shock and E_i is the energy the fireball would have carried if it were spherically symmetric; i.e., the jet energy is $E = \theta^2 E_i/2$ (for a double-sided jet). Once Γ drops below θ^{-1}, the jet expands sideways, and its behavior deviates from the spherically symmetric case. We define t_θ as the time, as measured by a distant observer, at which $\Gamma = 1/\theta$. Using the Blandford-McKee solution, and the relation $t = r/4\Gamma^2 c$ between observer time and jet radius (Waxman 1997b), we find

$$\theta \approx \left(\frac{17}{1024\pi}\frac{E_i}{n m_p c^5}\right)^{-1/8} t_\theta^{3/8} = 0.12\left(\frac{E_{i,53}}{n_0}\right)^{-1/8} t_{\theta,\rm day}^{3/8}\ , \quad (1)$$

where $E_i = 10^{53} E_{i,53}$ ergs and $n = 1 n_0$ cm^{-3}.

After a transition stage, in which the jet expands sideways, the flow approaches spherical symmetry and can again be described by a simple self-similar solution. The transition takes place over a time $t_s \approx r_\theta/c$, where r_θ is the jet radius at time t_θ. Thus,

$$t_s \approx r_\theta/c = 270\left(\frac{E_{i,53}}{n_0}\right)^{1/4} t_{\theta,\rm day}^{1/4}\ \text{day}\ . \quad (2)$$

It is straightforward to show that after the transition the flow becomes subrelativistic (e.g., Waxman, Kulkarni, & Frail 1998). At time t_θ the energy associated with the mass enclosed within a sphere of radius equal to the jet radius r_θ, $M_\theta \equiv 4\pi n m_p r_\theta^3/3$, is similar to the jet total energy, $E/M_\theta c^2 = 6/17$. Thus, after spherical symmetry is approached the flow is described by the Sedov–von Neumann–Taylor solutions.

The fireball radius during the subrelativistic expansion is given by the Sedov–von Neumann–Taylor relation $r = \xi(Et^2/nm_p)^{1/5}$, where $\xi \approx 1$ depends on the gas adiabatic index. We define the time $t_{\rm SNT}$ as the time at which $\dot{r}_{\rm SNT}/c = 1$. For $\xi = 1$ we have

$$t_{\rm SNT} = 67\left(\frac{E_{i,53}}{n_0}\right)^{1/4} t_{\theta,\rm day}^{1/4}\ \text{day}\ . \quad (3)$$

The transition from a jet to a Sedov–von Neumann–Taylor behavior should occur during the period $t_{\rm SNT} \lesssim t \lesssim t_s$, with noticeable deviations from the collimated jet behavior starting at $t \sim t_{\rm SNT}$.

After the transition, the power is dominated by synchrotron emission from a subrelativistic fireball (e.g., Frail, Waxman, & Kulkarni 2000b). Assuming that a fraction ξ_e (ξ_B) of the thermal energy behind the shock is carried by electrons (magnetic field) and that the electrons are accelerated to a power-law energy distribution, $dn_e/d\gamma_e \propto \gamma_e^{-p}$ with $p = 2$, the flux at frequencies above

$$\nu_* \approx 1\left(\frac{1+z}{2}\right)^{-1}\left(\frac{\xi_e}{0.3}\right)^2\left(\frac{\xi_B}{0.3}\right)^{1/2} n_0^{1/2}\ \text{GHz} \quad (4)$$

is given by (see, e.g., Appendix of Frail et al. 2000b)

$$f_\nu \approx 1\left(\frac{1+z}{2}\right)^{-1/2}\left(\frac{\xi_e}{0.3}\right)\left(\frac{\xi_B}{0.3}\right)^{3/4} n_0^{3/4} E_{51}\, d_{28}^{-2} \nu_{\rm GHz}^{-1/2} \times \left(\frac{t}{t_{\rm SNT}}\right)^{-9/10} \text{ mJy} . \tag{5}$$

Here $d_L = (1+z)^{1/2} 10^{28} d_{28}$ cm and ν_* is the synchrotron peak frequency at $t = t_{\rm SNT}$. Equation (5) is valid for frequencies where emission is dominated by electrons with the cooling time larger than the expansion time. At higher frequencies, above

$$\nu_c \approx 10^{13} \frac{2}{1+z}\left(\frac{\xi_B}{0.3}\right)^{-3/2} n_0^{-5/6} E_{51}^{-2/3}\left(\frac{t}{t_{\rm SNT}}\right)^{-1/5} \text{ Hz} , \tag{6}$$

the spectrum steepens to $f_\nu \propto \nu^{-1}$.

Equations (4)–(6) imply that at $t \sim t_{\rm SNT}$ radio emission at the 1 mJy level is expected. While the optical flux at this stage is of the order of 1 μJy, and thus not easy to detect, it is not altogether undetectable.

2.2. *Jet-Wind Interaction*

Let us now consider a fireball jet expanding into a wind, where the ambient medium density is $\rho = \dot{M}/4\pi v_w r^2$ (where v_w is the wind speed). During the stage in which $\Gamma > 1/\theta$, we may obtain an approximate description of the dynamics by using the r-dependent number density $n(r) = Ar^{-2}$ in the Blandford-McKee relation for $\Gamma(r, E, n)$. Using this relation, and $t = r/4\Gamma^2 c$, we find that the density (ahead of the shock) at observed time t is

$$n \approx \frac{4\pi}{17} cA^2 (E_i m_p t)^{-1} = 0.4\left(\frac{\dot{M}_{-5}}{v_{w,3}}\right)^2 E_{i,53}^{-1} t_{\rm day}^{-1} \text{ cm}^{-3} , \tag{7}$$

where $\dot{M} = 10^{-5} \dot{M}_{-5}\, M_\odot$ yr^{-1} and $v_w = 10^3 v_{w,3}$ km s^{-1}. The relation between the jet opening angle and the time at which a deviation from spherical behavior is observed, equation (1), may be generalized to the wind case by replacing n (in eq. [1]) with $n(t)$ given by equation (7), to give

$$\theta \approx 0.11\left(\frac{E_{i,53}}{\dot{M}_{-5}/v_{w,3}}\right)^{-1/4} t_{\theta,\rm day}^{1/4} . \tag{8}$$

Similarly, for the wind case $t_{\rm SNT}$ is given by

$$t_{\rm SNT} = 69\left(\frac{E_{i,53}}{\dot{M}_{-5}/v_{w,3}}\right)^{1/2} t_{\theta,\rm day}^{1/2} \text{ day} . \tag{9}$$

During the time at which the jet expands sideways, it appears to a distant observer as if it were expanding into a medium of uniform density. This is due to the fact that during the time r_θ/c, over which sideways expansion takes place, the jet radius does not increase significantly beyond r_θ. Hence, the density ahead of the shock can be approximated as being constant.

The temporal behavior of the afterglow flux at frequencies above the synchrotron peak is summarized for the different cases in Table 1, for a power-law energy distribution of the electrons with $p = 2 + \epsilon$.

3. DISCUSSION AND CONCLUSIONS

During the past year, there has been a growing consensus that at least some of the observed GRBs involve collimated jets. At the same time, the observationally inferred association of some GRBs with collapses of massive stars naturally implies that in some cases the GRBs interact with an existing preoutburst wind.

In the present work, we have first examined the behavior of the afterglow in the case of a collimated jet, including an interaction with a preexisting wind. Our results can be summarized as follows:

1. We showed that while a break (followed by a steeper decline) in the power-law decline is expected at $t \sim t_\theta$, when the Lorentz factor decreases below the inverse of the jet opening angle, a *flattening* in the light curve is expected at $t \sim t_{\rm SNT}$, when the flow approaches spherical symmetry. This new effect is expected to occur about 6 months after the burst (for $z \gtrsim 1$; see eqs. [3] and [9]). The temporal behavior of afterglow flux at different stages of the jet evolution is summarized in Table 1. We should also note that, contrary to a frequently quoted statement, for a power-law energy distribution of the electrons with $p \approx 2$ (as observations indicate, e.g., Frontera et al. 2000) the transition from a relativistic to a nonrelativistic expansion of a *spherical* fireball is *not* marked by a pronounced break in the decline (for $p = 2$ the transition is only from $t^{-0.75}$ to $t^{-0.9}$ for frequencies where photons are emitted by electrons cooling on timescales longer than the expansion time, while no transition is expected at a higher frequency; see Table 1).

2. While a measurement of the break time t_θ alone does not allow for a direct determination of the jet opening angle θ, due to the dependence on the unknown ratio of fireball energy to surrounding gas density (see eqs. [1] and [8]), a measurement of *both* t_θ and the flattening time $t_{\rm SNT}$ allows a determination of this ratio and therefore allows for a direct determination of the jet opening angle θ (see eqs. [3] and [9]).

3. The afterglow flux after flattening, i.e., once spherical symmetry is approached, is given by equations (4)–(6) for the case of expansion into a uniform density. Radio emission at the 1 mJy level and optical emission at the 1 μJy level are expected at this stage.

4. On a timescale of days, the wind density is similar to typical ISM densities (see eq. [7] and Chevalier & Li 2000), and therefore an interaction with a wind would give results

TABLE 1

THE TEMPORAL DECAY INDEX α OF AFTERGLOW FLUX, $f \propto t^{-\alpha}$, FOR AN ENERGY DISTRIBUTION OF THE ELECTRONS $dn_e/d\gamma_e \propto \gamma_e^{-(2+\epsilon)}$

	SPHERICAL FIREBALL		COLLIMATED JET		
CASE	Relativistic Expansion	Nonrelativistic Expansion	Before Sideways Expansion	During Sideways Expansion (before Spherical Symmetry)	After Spherical Symmetry
Uniform density......	$\frac{3}{4}[1] + \frac{3}{4}\epsilon$	$\frac{9}{10}[1] + \frac{3}{2}\epsilon$	$\frac{3}{4}[1] + \frac{3}{4}\epsilon$	$2[2] + \epsilon$	$\frac{9}{10}[1] + \frac{3}{2}\epsilon$
Wind ($n \sim r^{-2}$).......	$\frac{5}{4}[1] + \frac{3}{4}\epsilon$	$\frac{3}{2}[1] + \frac{7}{6}\epsilon$	$\frac{5}{4}[1] + \frac{3}{4}\epsilon$	$2[2] + \epsilon$	$\frac{3}{2}[1] + \frac{7}{6}\epsilon$

NOTE.—Values in brackets are for frequencies higher than the cooling frequency.

that are not too different from the case of a uniform density. As a consequence, steepening of the afterglow flux decline on a day timescale implies a similar jet opening angle for the wind and ISM cases (see eqs. [1] and [8]), a similar flattening time (see eqs. [3] and [9]), and hence similar fluxes (~ 1 mJy in the radio and ~ 1 μJy in the optical) at the onset of flattening.

5. The temporal decay indices for fast-cooling electrons are similar in the wind interaction and uniform density cases (see Table 1). Consequently, differences may be detected by looking at slow-cooling electrons, i.e., radio observations, as pointed out also in Chevalier & Li (1999). On a timescale of days, the synchrotron peak frequency is higher than radio frequencies, and the radio flux is expected to rise as $t^{1/2}$ in the case of spherical expansion into a uniform density, while it is expected to be constant for expansion into a wind (during the sideways expansion of a jet, the radio flux is expected to decrease as $t^{-1/3}$ for both uniform density and wind cases). However, although radio observations may provide a clearer discrimination between wind and uniform density models, the interpretation of radio data may be complicated due to the effects of scintillation (e.g., Frail et al. 2000a).

6. Points 4 and 5 above imply that it would be difficult to discriminate between the wind interaction and uniform cases through late-time observations. The two cases do give significantly different results, though, at $t \ll 1$ day, when the densities are substantially different. Very early observations are therefore strongly favored.

7. Our results show that the case of an interaction with a wind is *not* characterized by a significantly faster decline than the uniform density case. Rather, to obtain a faster decline in the wind (noncollimated) case, one must assume a steeper electron index. Observations of a faster decline are therefore generally not indicative of an interaction with a wind.

Examining the data on some GRBs in the light of the results presented above, we note the following:

1. It does *not* appear that GRB 970228 and GRB 970508 involved highly collimated jets (since a steep, t^{-2}, decline has not been observed on a timescale of tens of days). Indeed, it is shown in Frail et al. (2000b) that the GRB 970508 radio data imply a wide-angle, $\theta \approx 0.5$, jet expanding into a uniform, $n \sim 1$ cm^{-3}, density.[4] Within the uncertainties, it is difficult to completely rule out an interaction with a wind for GRB 970228 (e.g., Chevalier & Li 2000), although that appears unlikely. Thus, while it is not altogether impossible that GRB 970228 was produced by a supernova (as suggested by Reichart 1999 and Galama et al. 2000 on the basis of the temporal properties and late spectral energy distribution), no sign of a supernova (similar to SN 1998bw) was found to underlie GRB 970508 (Fruchter 2000).

2. GRB 990123 and GRB 990510 may have had collimated jets. The relatively flat early decline in GRB 990510, however, argues against interaction with a wind in this case or suggests that the density in (at least some part of) the wind drops less steeply than $n \sim r^{-2}$. Furthermore, there is no significant evidence for a Type Ic supernova underlying the GRBs (Fruchter et al. 1999a). It would be very interesting to search for the expected flattening in these two GRBs. Note that a nondetection of the expected flattening sets, for a given break time t_θ, an upper limit to the jet opening angle (cf. eqs. [1] and [3]). However, since for $t_\theta \sim$ 1 day and $\theta \sim 0.1$ the flattening is expected to occur on a timescale of months, the present nondetection of flattening over a ~ 10 day timescale does not provide a strong upper limit on θ.

3. GRB 980519 and GRB 980326 may have involved collimated jets. For this interpretation to be correct, however, the jet had to expand sideways rather quickly. An underlying supernova has been tentatively identified in the case of GRB 980326 (Bloom et al. 1999). We should note that if the rapid sideways expansion interpretation is correct then the jet should also get to the nonrelativistic stage relatively early. Thus, flattening of the light curve is expected in this case, too.

Returning now to the question of the progenitors, we note the following. It has been argued that in all cases in which an afterglow has been unambiguously detected the GRBs occurred *inside* galaxies, suggesting that these GRBs are not the result of NS-NS mergers (e.g., discussion in Paczyński 1998; Livio et al. 1998). This conclusion was based on the large asymmetric kicks introduced in the latter systems by supernova explosions. However, a detailed calculation showed that only $\sim 15\%$ of the GRBs are expected to be found *outside* dwarf galaxy hosts (Bloom, Sigurdsson, & Pols 1999). Thus, one might conclude that at least some of the observed GRBs (with afterglows) could be the result of mergers of compact objects. The fact that GRB 970228 and GRB 970508 showed neither a *clear* signature of a highly collimated jet, nor of an interaction with a wind, could be taken as supporting evidence for this picture. As we explained in § 2, NS-NS and BH-NS mergers are not expected to produce highly collimated jets or interactions with a wind. Nevertheless, it remains true that NS-NS and BH-NS mergers are generally expected to produce short-duration bursts (and they may provide the only model capable of producing extremely short [<1 s] bursts). In particular, even with the introduction of a reasonable disk viscosity, it is difficult to see how the duration of the bursts could be extended much beyond ~ 10 s (where most of the *BeppoSAX* sources are found). Hence, we tentatively conclude that most of the long, relatively soft, GRBs with afterglows observed so far probably do not represent NS-NS (or BH-NS) mergers. Assuming this conclusion to be correct, we may still be left with (at least) two main classes of progenitors for the (relatively) long-duration, softer bursts: (1) collapses of massive stars and (2) BH–helium star mergers. The mergers of BHs with white dwarfs, while capable (in principle) of producing long-duration bursts, appear to be too infrequent (e.g., Fryer et al. 1999) to account for the observed bursts.

Neutron stars kicked by supernova explosions into their binary companion's envelope and transformed there into black holes (e.g., Bethe & Brown 1998; but see Armitage & Livio 2000) have many similarities with collapses of massive stars and therefore will not be considered separately.

Our results suggest strongly that not all the long-duration GRBs originate in the collapses of massive stars

[4] A model for the GRB 970508 afterglow, where a spherical fireball expands into a wind, has been proposed by Chevalier & Li (2000). However, Frail et al. (2000b) have shown that this model is not consistent with the data.

since there exist cases where no evidence was found for either collimated jets or interactions with a wind. This prompts us to examine some of the aspects of models of the type of BH–helium star mergers.

In a BH–helium star merger, the helium core is dissipated to form a massive disk (of radius $R_d \sim 10^9$–10^{10} cm, comparable to the core radius) around a spinning BH (e.g., Fryer & Woosley 1998). Hence, there is no problem for this model (again, in principle) to form collimated jets ($R_d/R_{\rm CO} \gg 1$; see § 2). We should note, though, that in the same way that not all the Galactic BH X-ray binaries produce highly collimated jets (see reviews of the properties by Chen, Shrader, & Livio 1997; Mirabel & Rodriguez 1998), it can (perhaps) be expected that not all the GRBs will involve highly collimated jets. Since in the common envelope phase that precedes the merger matter may be ejected preferentially in the orbital plane (e.g., Rasio & Livio 1996; Sandquist et al. 1998), a significant interaction of the jet with the matter ejected from the giant star's envelope may be avoided.

A comparison of the possible models with the discussion in points 1–3 above therefore suggests the following (clearly at this stage very tentative) scenarios for progenitors:

1. GRBs like GRB 980519 and GRB 980326 are produced by collapses of massive stars, of the type that result in supernova explosions.
2. GRBs like GRB 990123 and GRB 990510 may be produced by BH–He star mergers.
3. GRBs like GRB 9760228 and GRB 970508 may be produced either by BH–He mergers that did not manage to collimate jets or by a scenario presently considered unlikely (like mergers of two compact objects).

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