CAN FIREBALL MODELS EXPLAIN GAMMA-RAY BURSTS?

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ABSTRACT

The observed afterglows of gamma-ray bursts (GRBs), in particular the afterglow of GRB 970228 after 6 months, seem to rule out, as the origin of GRBs, relativistic fireballs driven by the mergers or accretion-induced collapse of compact stellar objects in galaxies. GRBs can be produced by superluminal jets from such events.

Subject headings: gamma rays: bursts — radiation mechanisms: nonthermal

1. INTRODUCTION

The isotropy of gamma-ray bursts (GRBs) in the sky and their brightness distribution have provided the first strong indication that they are at cosmological distances (e.g., Meegan et al. 1992; Fishman & Meegan 1995). The recent discovery of an extended faint optical source coincident with the optical transient of GRB 970228 (Groot et al. 1997; van Paradijs et al. 1997; Sahu et al. 1997) and, in particular, the detection of absorption- and emission-line systems at redshift \( z = 0.835 \) (Metzger et al. 1997a, 1997b) in the spectrum of the optical counterpart of GRB 970508, which may arise from a host galaxy (e.g., Pedersen et al. 1998), have provided further evidence that GRBs take place in distant galaxies. The peak luminosity of GRB 970508 in the 0.04–2.0 MeV range exceeded \( 10^{51} \Delta \Omega \) ergs s\(^{-1}\) (assuming \( \Omega_c \approx 0.2, \Lambda = 0, \) and \( H_0 \approx 70 \) km Mpc\(^{-1}\) s\(^{-1}\)) at redshift \( z = 0.835 \), where \( \Delta \Omega \) is the solid angle into which the emitted radiation was beamed. Such \( \gamma \)-ray luminosities and their short time variability strongly suggest that GRBs are produced by the mergers and/or accretion-induced collapse (AIC) of compact stellar objects (Blinnikov et al. 1984; Paczynski 1986; Goodman, Dar, & Nussinov 1987). The nonthermal spectrum of the \( \gamma \)-rays and energy considerations strongly suggest that their emission is by highly relativistic outflows with bulk Lorentz factors of \( \gamma = 1/(1 - \beta^2)^{1/2} \gg 100 \). Consequently, relativistic fireballs (Paczynski 1986; Goodman 1986) and relativistic jets (e.g., Shaviv & Dar 1995; Dar 1997a, 1997b) were proposed as the producers of the observed radiation by self-interactions within the flow (e.g., Paczynski & Xu 1994; Rees & Mészáros 1994) or by interactions with external matter (e.g., Rees & Mészáros 1992; Mészáros & Rees 1993) or with external radiation (e.g., Shemi 1994; Shaviv & Dar 1995, 1997).

Following the discovery of the afterglow of GRB 970228, various authors have concluded that it supports the fireball model of GRBs (e.g., Wijers, Rees, & Mészáros 1997; Sahu et al. 1997). However, here we show that the combined observations of GRBs and their afterglows, in particular the afterglow of GRB 970228 after 6 months (Fruchter et al. 1997, 1998), rule out spherical fireball models (e.g., Mészáros & Rees 1997). But the ejecta from the merger/AIC of compact stellar objects may consist of highly relativistic fragments that are beamed into a small solid angle. Jetting the ejecta in GRBs can solve the problems of the relativistic fireball models and explain the general properties of GRBs and their afterglows.

2. FAILURES OF SIMPLE FIREBALLS

2.1. Energy Crises

The spherical blast-wave models assume (e.g., Mészáros & Rees 1997; Wijers et al. 1997) that the ultrarelativistic spherical shell, which expands with a Lorentz factor of \( \gamma = 1/(1 - \beta^2)^{1/2} \), drives a collisionless (magnetic) shock into the surrounding interstellar medium (ISM). They also assume that the collisionless shock that propagates in the ISM with a Lorentz factor of \( \gamma_c = \sqrt{2}\gamma \) accelerates it and heats it up to a temperature \( T \propto \gamma_m c^2 \) (in its rest frame). Energy-momentum conservation in the ultrarelativistic limit, which reads \( d[M + nm_c(4\pi/3)r^3\gamma'] \approx 0 \) with \( i = 2 \), then implies that the bulk Lorentz factor of the decelerating debris (mass \( M \)) and swept-up ISM (ambient density \( n \)) decreases for large \( r \) like \( \gamma \propto r^{-1} \). In fact, the assumption that a highly relativistic, collisionless shock heats up the ISM to a temperature \( T_r \approx \gamma_m c^2 \) in its rest frame has never been substantiated by self-consistent microscopic calculations nor by direct observations of radiation from decelerating superluminal jets. For \( T_r < m_c c^2 \) (or fast cooling), one has \( i = 1 \) and \( \gamma \approx r^{-3} \). It is further assumed that superthermal electrons, with a power-law spectrum, \( d\nu/dE_c \sim E_c^{-p} \) and \( p \approx 2.5 \), in the rest frame of the shocked ISM emit synchrotron radiation, with a power-law spectrum \( I_{\nu} = \nu^{p} \frac{d\nu}{dn\nu} \sim \nu^{-(p-\frac{3}{2})} \), from an assumed equipartition internal magnetic field. Photons that are emitted with a frequency \( \nu' \) in the rest frame of the shocked material and at an angle \( \theta' \) relative to its bulk motion are viewed in the lab frame at a frequency \( \nu \) and an angle \( \theta \) that satisfy \( \nu = \gamma (1 + \beta \cos \theta') \nu' \) and \( \tan \theta = \sin \theta'/\gamma (\beta + \cos \theta') \), respectively. Consequently, for \( \gamma \gg 1 \), photons that are emitted isotropically in the rest frame of the shocked material, have, in the lab frame, an angular and spectral distribution

\[
\frac{dI_{\nu}}{d\cos \theta} \approx \frac{4\nu^3}{(1 + \gamma^2 \theta^2)^3} I_{\nu'}(\nu, \gamma \nu, \theta') \approx \frac{4\nu^3}{(1 + \gamma^2 \theta^2)^3} I_{\nu'}(\nu, \theta') \sim \nu^{p-\frac{3}{2}},
\]

Thus, a distant observer sees essentially only photons emitted in his direction from radius vectors \( r \) with angles \( \theta = \theta' = 1/\gamma \) relative to his line of sight (LOS) to the explosion center (\( r = 0 \)). If the photons are emitted uniformly from a thin shell behind the shock, then they reach the observer at a time

\[
t \approx \frac{r}{2\alpha c |\gamma(r)|^2} + \frac{\nu^2}{2c},
\]
where \( \alpha_s = 2 (6/i + 1) = 14 \) and 8 for \( i = 1 \) and 2, respectively. Photons that are emitted from the shock front at \( \theta = 0 \) reach the observer at a time

\[
t = r/(2\alpha_s c \gamma^2).
\]

Neglecting redshift effects, the differential luminosity seen by the observer at time \( t \) is obtained by integrating equation (1) over \( r \) and \( \theta \), which satisfy equation (2). Because the angular delay dominates equation (2), the emissivity is weighted in the integration by \( 2\pi \sin \theta \) and the integrand peaks at \( \theta^2 = 1/(6 - i + p) \gamma^2 \). Substituting that into equation (2), we find that for \( i = 2 \), most of the high-frequency photons that arrive at time \( t \) come from a ring around the LOS whose distance \( r \) and Lorentz factor \( \gamma(r) \) satisfy equation (3) with \( \alpha_s \approx 3.6 \) and \( r = 0.77r_{\text{max}} \). While for \( i = 1 \), we find \( \alpha_s \approx 4.9 \) and \( r \approx 0.84r_{\text{max}} \). Very similar results were obtained by Panaitescu & Mészáros (1998) from exact numerical integrations.

The relativistic expansion lasts until \( \gamma(r) \approx 2 \), i.e., \( t \approx r/(8\alpha_s c) \). Since the energy of the swept-up material is \( \approx (4\pi/3) r^3 \gamma^2 m_p c^2 \), the explosion energy must satisfy

\[
E \geq 2.7 \times 10^{54} n(\alpha_s/1+z)^4 i^2 z^2 \text{ ergs,} \tag{4}
\]

where \( n \) is the mean density of the swept-up ISM in units of \( \text{cm}^{-3} \), \( t_z \) is the observer time in years, and \( z \) is the redshift of the host galaxy where the explosion took place. (The factor \( i^2 = 4 \) for a thick/adiabatic shell follows from the assumption that the proton and electron temperatures are both \( \approx T_\gamma c \).) The shape, colors, angular size (0") and magnitude (\( V = 25.7 \pm 0.15 \)) of the host nebula of GRB 970228 that were measured by the Hubble Space Telescope at \( t_z \approx 0.52 \) (Fruchter et al. 1997, 1998) suggest that it is a galaxy with a redshift \( z \approx 1 \). For \( z = 1 \), a standard ISM density \( n \approx 1 \text{ cm}^{-3} \), and \( \alpha_s \approx 4 \), equation (4) yields \( E \geq 3 \times 10^{54} \) ergs. Such a kinetic energy, however, is larger by orders of magnitude than the maximal plausible kinetic energy release in the merger of neutron stars (NSs) and of neutron stars and black holes (BHs), or in the AIC of white dwarfs (WDs) and NSs. This is true for the following reason: a large fraction of the total binding energy release in such events (\( \sim M_p c^2 \approx 1.8 \times 10^{54} \text{ ergs} \)) is radiated in gravitational waves and neutrinos. Typically, in core-collapse supernova explosions, the kinetic energy of the debris is about \( \approx 1\% \) of the total gravitational binding energy release. The NS merger/AIC is not expected to convert a larger fraction of the gravitational binding energy release into the kinetic energy of a spherical explosion. First, a large fraction of the binding energy is radiated away by the gravitational waves’ emission, which is relatively unimportant in Type II supernova explosions. Second, the neutrino deposition of energy and momentum in the ejecta is less efficient in NS mergers, because it lasts for only milliseconds and because neutrino trapping and the gravitational redshift of neutrino energy are stronger than in core-collapse supernovae. This is confirmed by detailed numerical calculations of spherical explosions driven by neutrinos in NS mergers (e.g., Janka & Ruffert 1996; Ruffert et al. 1997).

2.2. Absence of Simple Scaling

Relativistic blast-wave models predict that GRB afterglows are scaled by powers of their basic parameters: total energy \( E \), initial Lorentz factor \( \Gamma \), surrounding gas density \( n \), and distance \( D \). However, GRBs 960720, 970111, 970228, 970402, 970508, 970616, 970828, 971214, 971227, and 980109 exhibited unscaled behavior and very different spectral properties. For instance, GRB 970111 and GRB 970228 had \( \gamma \)-ray fluences \( \sim 25 \) times larger than GRB 970228, but their afterglows were not detected in X-rays, in the optical band, and in the radio band (e.g., Groot et al. 1998). The upper bound on the optical peak response of GRB 970228 was \( \sim 10^5 \) and \( \sim 10^3 \) smaller than that of GRB 970228 and GRB 970508, respectively (Groot et al. 1998). GRB 970508 was 6 times weaker in \( \gamma \)-rays than GRB 970228 (Kouveliotou et al. 1997) but 6 times brighter in the optical band (e.g., Pedersen et al. 1998 and references therein). Such spectral variability is observed in the afterglows of gamma-ray flares from extragalactic relativistic jets of blazars and also in flares from Galactic relativistic jets of microquasars (Galactic superluminal sources) such as GRS 1915+105 (Mirabel & Rodríguez 1994) and GRO J1655−40 (Tingay et al. 1995).

2.3. A Conical Rescue?

Conical fireballs with an opening angle \( \theta_0 \ll 1 \) reduce the GRB energy inferred from the observed energy in \( \gamma \)-rays and X-rays by a factor of \( \sim \theta_0^2/4 \). It can solve the energy crisis. Moreover, viewing effects, perhaps, can explain some of the diversity of GRB afterglows. However, neither spherical fireballs nor conical fireballs, nor the ejection of a single relativistic plasma sphere (Chiang & Dermer 1997), can explain the short time variability of multipeaked GRBs.

2.4. Short Time Variability

It was suggested that collisions between narrow shells moving with different bulk Lorentz factors can explain the light curves of multipeaked GRBs. First, a variable central engine must be fine-tuned in order to arrange for shells to collide only after a distance where the produced \( \gamma \)-rays are not reabsorbed, which is larger by many orders of magnitude than the size of the central engine (Shaviv 1996). Second, even with the fine-tuning of the central engine, the transverse size of the emitting area whose radiation is beamed toward the observer, \( r_\theta \sim r/\Gamma \), where \( \Gamma = \gamma(0) \), implies variability on timescales (e.g., Shaviv 1996; Fenimore, Madras, & Nayakshin 1996)

\[
\Delta t \sim r_\theta^2/2c \approx r_\theta^2 c \Gamma^3 \sim T_{\text{GRB}}, \tag{5}
\]

i.e., comparable to the total duration of the GRB. This is in conflict with the observed multipeak structure and short time variability of GRBs (e.g., Fishman & Meegan 1995). Local instabilities in spherical and conical shells are not efficient enough in producing high-intensity pulses (Shaviv 1996).

2.5. Extended GeV Emission

The Lorentz factor of a relativistically expanding shell, which sweeps up ambient matter, decreases quickly as its energy is shared by the swept-up matter. It cannot explain the emission of multi-GeV \( \gamma \)-rays, which is extended over hours (in the observer frame) with an energy fluence similar to that in the keV/MeV GRBs, as observed in GRB 910503 (Dingus et al. 1994) and in GRB 940217 (Hurley 1994). Note, in particular, that inverse Compton scattering of GRB photons or external photons by the decelerating debris is not efficient enough in producing the observed intensity of the extended emission of GeV photons. Also, it cannot explain the MeV \( \gamma \)-ray emission that extends over 2 days, which would perhaps
be the case if the cluster of four GRBs (Meegan et al. 1996; Connaughton et al. 1998) were a single GRB.

3. GRBs FROM ACCRETION JETS

Highly collimated relativistic jets seem to be emitted by all astrophysical systems where mass is accreted at a high rate from a disk onto a central black hole. They are observed in Galactic superluminal sources, like the microquasars GRS 1915+105 (Mirabel & Rodríguez 1994) and GRO J1655−40 (Tingay et al. 1995), and in many extragalactic blazars where mass is accreted onto, respectively, stellar and supermassive BHs. The ejection consists of episodes of the emission of highly relativistic fragments into a narrow cone along the axis of the accretion disk. Beamed emission of relativistic fragments (initially a conical shell?) with much larger Lorentz factors may take place at the merger/AIC death of close binary systems (initially a conical shell?) with much larger Lorentz factors (Dar 1997a, 1997b). Jetting the ejecta in the containing compact stellar objects. Such jets, which are pointing in our direction, can produce the cosmological GRBs and their afterglows (Dar 1997a, 1997b). Jetting the ejecta in the merger/AIC of compact stellar objects can solve the energy crisis of GRBs by reducing the total energy release in GRBs by a factor of $\Delta \Omega / 4\pi$, where $\Delta \Omega$ is the solid angle into which the ejection is beamed. In fact, beaming angles $\Delta \Omega \sim 10^{-2}$ are required in order to match the observed GRB rate (e.g., Fishman & Meegan 1995) and the current best estimates of the NS-NS merger rate in the universe (e.g., Lipunov, Postnov, & Prokhorov 1997). Such angles are typical of superluminal jets from blazars. The estimated rate of AIC of WDs and NSs is much higher, $\sim 1 \text{ s}^{-1}$ in the universe compared with $\sim 1 \text{ minute}^{-1}$ for NS-NS mergers. If GRBs are produced by the AIC of WDs and NSs (e.g., Goodman et al. 1987; Dar et al. 1992), then $\Delta \Omega \sim 10^{-4}$. Note that the ejection of a single, highly relativistic plasma sphere (Chiang & Dermer 1997) cannot produce the observed multipeaked GRBs and requires an enormous production rate to compensate for the very small beaming angle.

The Fe $\alpha$ and Mg $\alpha$ absorption lines and O $\alpha$ emission lines at redshift $z = 0.853$ in the afterglow of GRB 970508 seem to indicate that GRBs are produced in dense stellar regions (e.g., starburst regions). The boosting of stellar light by superluminal jets from merger/AIC dense stellar regions with typical photon column densities $N_\gamma = N_{\text{col}} \times 10^{21} \text{ cm}^{-2}$ has been proposed by Shaviv & Dar (1995, 1997) as the origin of multipeaked GRBs. Beaming and boosting of starlight by relativistic jet fragments can explain quite naturally the fluence, the typical energy, the duration distribution, the light curves, the spectral evolution, and the afterglows of GRBs. Due to space limitation, here we only demonstrate that it solves the main difficulties of the fireball models (and the difficulties of the original Shaviv-Dar 1997 model that were pointed out by Dermer (1997):)

1. Stellar photons with energy $\epsilon = \epsilon_\gamma \text{ eV}$ are boosted by the jet to a typical energy

$$E_\gamma \approx \frac{\Gamma^3 \epsilon_\gamma}{(1 + z)} \text{ MeV.} \quad (6)$$

2. After initial expansion, the jet fragments may reach a constant total cross section $S = S_{32} \times 10^{52} \text{ cm}^2$ because of magnetic confinement. Because of energy-momentum conservation, a jet with an initial kinetic energy $E_j$ and a bulk-motion Lorentz factor $\Gamma$ decelerates by the swept-up ionized interstellar matter according to $\gamma = \Gamma^2 (1 + r / R_0)$, or $r = R_0 / (\gamma^2 / R_0 - 1)$.

where $r$ is its propagation distance in the interstellar medium and $R_0 = E_j / m_n c^2 \Gamma^3$ is the typical distance that the jet fragments propagate before significant deceleration and decline of $\gamma$-ray production. If, typically, $E_j = E_{52} \times 10^{52} \text{ ergs}$, $\Gamma = \Gamma_1 \times 10^3$, and $n = n_1 \times 10^2 \text{ cm}^{-3}$ for starburst regions, then $R_0 \approx 0.67 (E_{52} n_1 \Gamma_1) \times 10^9 \text{ cm}$. The typical duration of GRBs produced by jet boosting of starlight is given by

$$T_{\text{GRB}} \approx \frac{R_0}{c \Gamma^2} = 30 R_0 \Gamma_1^{-2} \text{ s,} \quad (7)$$

where $R_0 = R_{18} \times 10^{18} \text{ cm}$. The duration of a pulse produced by a jet fragment with a transverse dimension $R_f \ll R_0 / T$ when it passes near a luminous star is given by

$$T_f \approx \frac{R_f}{c \Gamma} \sim E^{-1/2}. \quad (8)$$

3. GRBs FROM ACCRETION JETS

The bimodality of the duration distribution of GRBs (e.g., Fishman & Meegan 1995) may have a simple statistical origin (Shaviv 1995).

4. The electrons in the ejecta and the swept-up interstellar matter whose total mass increases like $M \sim 1 / \Gamma$ are accelerated by the jet to a power-law spectrum $I_{\gamma} = \nu^{p / 2} \text{ cm}^{-2} \text{ s}^{-1}$, with intensity proportional to their magnetic energy density. For an observer within the beaming cone, this synchrotron emission is Lorentz-boosted and collimated according to equation (1); i.e., it is amplified by a factor of $\gamma \sim \gamma_{\text{typ}}^{(p-1)/2}$. Thus, an observer within the beaming cone sees a synchrotron afterglow with intensity $I_{\gamma} \sim \gamma_{\text{typ}}^{(p-1)/2} / \gamma^2 \sim \nu^{p / 2} \text{ cm}^{-2} \text{ s}^{-1}$ (where $p = 2.5 \pm 0.5$, $I_{\gamma} \sim \nu^{(p-1)/2} \gamma_{\text{typ}}^{(p-1)/2} \sim \nu^{0.75 \pm 0.25} (t + t_0)^{-1.25 \pm 0.08}$), the initial expansion of the ejecta, the changes in opacity within the jet and along the trajectory of the emitted radiation, and the viewing angle effects due to the change in the beaming angle can produce complex time and wavelength dependences of the afterglow in the initial phase. Moreover, the absorption of optical photons, UV photons, and X-rays by the interstellar gas and dust around the burst location depends strongly on energy. Gas column densities $N_\gamma \geq 10^{22} \text{ cm}^{-2}$, which are also required by
the detection of GeV emission from bright GRBs (see below), can explain why some GRB afterglows that were detected in X-rays were not detected in the optical band also. If this explanation for the suppression of optical afterglows of GRBs is correct, then X-ray afterglows of GRBs that are not accompanied by optical afterglows must show harder X-ray spectra than those of GRBs with optical afterglows. Such GRBs must also be accompanied by strong emission of high-energy photons and neutrinos (Dar 1997a, 1997b).

Inhomogeneous ISM and jet instabilities can modify the late-time behavior of the afterglows. For instance, if the jet is deflected by a stellar or interstellar magnetic field, the afterglow may disappear suddenly from the field of view (collisions and the deflection of jets on scales 10–100 pc were observed in active galactic nuclei; Mantovani et al. 1997).

5. The high column density of gas in star-forming regions, $N_H = N_{23} \times 10^{23} \text{ cm}^{-2}$, with $N_{23} \geq 1$, provides an efficient target for hadronic production of high-energy photons via $pp \rightarrow \pi^0X$ followed by the prompt $\pi^0 \rightarrow 2\gamma$ decay. A power-law proton spectrum produces a power-law photon spectrum with the same power index and efficiency (see, e.g., Dar 1997b) $\sigma_{pN_{th}}$, where $g = 10^{-1} \times g_1 = 0.195 \exp [-3.84(p-2)+1.22(p-2)^2]$ and $\sigma_{p} \approx 3 \times 10^{-26} \text{ cm}^2$ is the $pp$ inelastic cross section. Consequently, GRBs in star-forming regions emit a power-law spectrum of high-energy photons with a total fluence

$$F(>100 \text{ MeV}) \approx E_{52} g N_{23} \frac{3}{D_{28}^2 \Delta \Omega_2} \left(1+\frac{3}{2}\right) 10^{-6} \text{ ergs cm}^{-2}, \quad (12)$$

comparable to the GRB fluence in MeV $\gamma$-rays. It explains the detection of GeV photons by the EGRET instrument on board the Compton Gamma Ray Observatory (CGRO) from a handful of bright bursts (see, e.g., Dingus 1995). Given the EGRET sensitivity and limited field of view, the detection rate implies that high-energy emission may accompany most GRBs.

Significant hadronic production of $\gamma$-rays with energy $\sim 18$ GeV, as observed in GRB 940217, requires $N_{th} > 10^{22} \text{ cm}^{-2}$ and incident proton energies $\sim 10^{-3} \times 18$ GeV, i.e., $\gamma > 115$. Consequently, for $n = n_\gamma \times 10^3 \text{ cm}^{-3}$, the effective duration of emission of 18 GeV photons is

$$t \approx \frac{R_\gamma}{6c^2} \approx \frac{E_{52} n_\gamma}{n_\gamma S_{32}} 2.5 \times 10^3 \text{ s}, \quad (13)$$

which is consistent with the EGRET/CGRO observations (Hurley 1994).

4. CONCLUSIONS

The observed properties of GRBs and their afterglows seem to rule out, as the origin of GRBs, relativistic fireballs powered by mergers/AIC of compact stellar objects within galaxies. In spite of their flexibility and multitude of free parameters, the fireball models appear unable to explain simultaneously the total energy of GRBs, their enormous diversity, their short timescale variability, their spectral evolution, the delayed emission of MeV and GeV $\gamma$-rays in some GRBs, and the spectral versatility of GRB afterglows. However, if the mergers/AIC of compact stellar objects eject highly relativistic shell fragments into a small solid angle, most of the problems of the spherical fireball models can be avoided, and the general observed properties of GRBs and their afterglows can be explained. If GRBs are produced by highly relativistic jets that are pointing in our direction, they should show superluminal motions with speeds $v \leq c \Gamma$. Such superluminal motions may be detected in long-term (years) VLBI observations of radio afterglows of GRBs (see, e.g., Taylor et al. 1997).

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