ARE GAMMA-RAY BURSTS IN STAR-FORMING REGIONS?

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ABSTRACT

The optical afterglow of the gamma-ray burst GRB 970508 ($z = 0.835$) was a few hundred times more luminous than any supernova. Therefore, the name “hypernova” is proposed for the whole GRB/afterglow event.

There is tentative evidence that the GRBs 970228, 970508, and 970828 were close to star-forming regions. If this case is strengthened with future afterglows, then the popular model in which GRBs are caused by merging neutron stars will have to be abandoned, and a model linking GRBs to cataclysmic deaths of massive stars will be favored. The presence of X-ray precursors, first detected with Ginga, is easier to understand within a framework of a “dirty” rather than a “clean” fireball. A very energetic explosion of a massive star is likely to create a dirty fireball rather than a clean one.

A specific speculative example of such an explosion is proposed: a microquasar. Its geometrical structure is similar to the “failed supernova” of Woosley: the inner core of a massive, rapidly rotating star collapses into a $\sim 10 M_\odot$ Kerr black hole with $\sim 5 \times 10^{54}$ ergs of rotational energy, while the outer core forms a massive disk/torus. A superstrong $\sim 10^{15}$ G magnetic field is needed to make the object operate as a microquasar similar to the Blandford & Znajek model. Such events must be vary rare, $10^4$–$10^5$ times less common than ordinary supernovae, if they are to account for the observed GRBs.

Subject headings: binaries: close — gamma rays: bursts — stars: neutron — supernovae: general

1. INTRODUCTION

The recent detection of the afterglows following some gamma-ray bursts (GRBs) detected by BeppoSAX opens up a new era in the studies of GRBs. Many afterglows were detected in X-rays (see, e.g., Costa et al. 1997), but so far only two were detected optically (970228, van Paradijs et al. 1997; 970508, Bond et al. 1997) and just one in the radio domain (970508, Frail et al. 1997). A major breakthrough was the determination of the absorption- and emission-line redshift $z = 0.835$ for 970508 (Metzger et al. 1997a, 1997b).

An afterglow is created by a collision between GRB ejecta and an ambient medium, be it circumstellar, interstellar, or intergalactic, and it is a natural consequence of any relativistic fireball model (Rees & Meszaros 1992; Paczyński & Rhoads 1993; Wijers, Rees, & Meszaros 1997b; Waxman 1997a, 1997b; Sari 1997; Vietri 1997; and many references therein). A very impressive confirmation of the relativistic expansion was provided by the change in the scintillation pattern of the 970508 radio emission, as detected by Frail et al. (1997) and predicted by Goodman (1997).

The observed optical emission of 970508 is compared in Figure 1 with that of other cataclysmic variables: dwarf novae, novae, and supernovae. I adopted $z = 0.835$ as the redshift of 970508, and the corresponding $K$-correction following R. A. M. J. Wijers (1997, private communication). With the large range of absolute magnitudes covered by the light curves, an error of $\sim 1$ mag would be of little importance. The optical afterglow 970508 was a few hundred times more luminous than the brightest supernova. A few months after the peak it still remains more luminous than any supernova. Therefore, it seems appropriate to call it a hypernova.

The purpose of this Letter is to present evidence that the observed GRBs are related to star-forming regions, and therefore they are not caused by merging neutron stars. A speculative possibility of the underlying mechanism for the explosion is outlined: a microquasar (Paczyński 1993). This is a stellar equivalent of the Blandford & Znajek (1977) quasar model, powered by a rapid extraction of rotational energy of a $\sim 10 M_\odot$ Kerr black hole with a superstrong $\sim 10^{15}$ G magnetic field.

2. BURST LOCATIONS

There are only two optical afterglows known and a half-dozen nondetections. In most cases the negative result may be explained by unfavorable circumstances: a large errors box, a bright moon, or an inadequate search. But there was one burst, 970828, for which the error box was small, the moon was dark, and many deep optical searches placed stringent upper limits on any optical variable, a factor $\sim 300$ below the expectations based on a simple scaling of the 970228 and 970508 events (van Paradijs 1998). Therefore, the absence of this optical afterglow has to be taken seriously. In the following subsections, all three events are briefly discussed.

2.1. GRB 970228

The optical afterglow (van Paradijs et al. 1997; Sahu et al. 1997) has a fuzzy object next to it. A recent Hubble Space Telescope (HST) image taken on 1997 September 4 shows the extended object unchanged, and the point source fading according to the $t^{-1}$ law, at a fixed position (Pian et al. 1997). It is likely that the “fuzz” is a dwarf galaxy at a redshift $z \sim 1$. In any case, it is not a giant galaxy.

Note that by the time a binary neutron star merges, it has moved many kiloparsecs away from its place of origin, because it had acquired a large velocity as a consequence of two consecutive supernovae explosions, even if those explosions were spherically symmetric (Tutukov & Yungelson 1994). With velocities of a few hundred km s$^{-1}$, such binaries escape from dwarf galaxies. Therefore, if the GRB 970228 was caused by a merger of two neutron stars, or a neutron star and a stellar mass black hole, its location near the edge of a dwarf galaxy would be a coincidence. Future observations of this very faint $\sim 25$th magnitude extended object may provide some clues. Its spectrum may show whether this is indeed a galaxy at a mod-
erate redshift and whether it is undergoing vigorous star formation.

The optical afterglow 970228 makes a weak case against the merging neutron star scenario, and it is neutral with respect to an association between the GRB and a star-forming region.

2.2. GRB 970508

This is the only afterglow with known redshift: \( z = 0.835 \) in absorption (Metzger et al. 1997a) and in emission (Metzger et al. 1997b). The [O ii] 372.8 nm emission line indicates a normal interstellar medium rather than an active galactic nucleus (AGN). It is not resolved by the HST (Fruchter, Bergeron, & Pian 1997), i.e., the emission-line region is very compact. Therefore, the probability that the positions of the optical afterglow and the line emission region coincide by chance is small. It is reasonable to assume that the two are related, and that \( z = 0.835 \) is the GRB’s redshift and not just a lower limit.

The compactness of the emission-line object makes it a good candidate for a star-forming region, and the GRB seems to be associated with it. This makes it a weak case against a merging neutron star scenario.

2.3. GRB 970828

The simplest way to account for the absence of an optical afterglow has been proposed by E. B. Jenkins (1997, private communication): extinction by dust. The case became stronger following Murakami’s (1998) report that the ASCA X-ray spectrum is well fitted by a power law with a low-energy absorption indicating a hydrogen column density of \( 4 \times 10^{21} \) cm\(^{-2} \). The object is at a high galactic latitude, so the absorption is likely to be close to the source. If this burst is at a cosmological distance, then the column density is increased by \( \sim (1 + z)^3 \), since the spectral turnover is at energy \((1 + z)\) times higher than observed. Also, the observations made in the \( R \) band correspond to a wavelength \((1 + z)\) times shorter at the source, with the correspondingly larger interstellar extinction. Combining all these effects and adopting a standard dust-to-gas ratio may easily provide enough extinction to explain the absence of detectable optical afterglow (van Paradijs 1998). If this is the correct explanation, then GRB 970828 had to be close to a high-density interstellar medium, i.e., close to a star-forming region.

3. THE BURST RATE

In the simplest cosmological scenario for GRB distribution, commonly accepted till the end of 1996, it was customary to adopt no evolution: the GRB rate was assumed to be constant per comoving volume and comoving time. The combined BATSE and PVO distribution of burst intensities has the “Euclidean” slope of \(-1.5\) at the bright end and a slope of \(-0.8\) at the faint end (Fenimore 1993), with the “rollover” caused by the cosmological redshift (Dermers 1992; Mao & Paczynski 1992; Piran 1992). According to R. A. M. J. Wijers (1997, private communication), the following numbers follow from the “no evolution” scenario: the energy per GRB is \( \sim 4 \times 10^{51} \) ergs, the energy generation rate is \( \sim 10^{51} \) ergs Gpc\(^{-3}\) yr\(^{-1}\), and the GRB rate per L\(^*\) galaxy is \( \sim 10^{-1} \) yr\(^{-1}\).

All these numbers were obtained assuming isotropic GRB emission. If the emission is beamed, then the energy per burst is reduced, the burst rate is increased by the same factor, but the GRB energy generation rate per Gpc\(^3\) remains unchanged at a value \( \sim 5 \times 10^4 \) times lower than the rate at which supernovae generate kinetic energy in their explosions.

Recently, the massive star formation rate was found to be \( \sim 10 \) times higher at \( z \approx 1 \) than it is at \( z = 0 \) (Li et al. 1996; Madau et al. 1996). If the GRB rate follows the massive star formation rate (Totani 1997), then the consequences are dramatic, as emphasized by Sahu et al. (1997) and by Wijers, Bloom, & Bagla (1997a). The increase in the comoving GRB rate with the cosmological distance compensates various redshift effects responsible for the rollover in the counts, and extends the range of distances over which the “Euclidean” slope of the counts holds. As a result, the distance scale to the bursts is increased compared with the “no evolution” model. According to R. A. M. J. Wijers (1997, private communication), the energy per burst in this “evolutionary” scenario increases to \( \sim 10^{53} \) ergs, the rate of energy generation per galaxy is reduced by approximately 1 order of magnitude, and the GRB rate is reduced as well. This makes the “evolutionary” GRBs more powerful and less common than the “no evolution” bursts used to be. If the star formation rate increases beyond the redshift \( z = 1 \), then the distance scale to the bursts increases even more, making them even more energetic and even less common.

It is too early to decide which of the several cosmological distance scales is correct, but with a few dozen GRB/afterglow redshifts the choice will be clear. In any case, GRBs are very rare compared with ordinary supernovae.

4. A MICROQUASAR

If GRBs are associated with star-forming regions, and if hypernovae are somehow related to supernovae, i.e., they are violent ends of massive star evolution, then a microquasar scenario (Paczynski 1993) is a plausible explanation.

At the end of its nuclear evolution, the inner iron core of a very massive star collapses into a few solar mass black hole. We know this is a real process since about 10 binary stars are
known to have black hole components of $\sim 10 M_\odot$ (cf. Tanaka & Shibazaki 1996). If the star is spinning rapidly, then its angular momentum prevents all matter from going down the drain, and a rotating, very dense torus forms around the rapidly spinning Kerr black hole (Woosley 1993a). The largest energy reservoir, which may in principle be accessed with a super-strong magnetic field (cf. Blandford & Znajek 1977), is the rotational energy of the black hole:

$$E_{\text{rot, max}} \approx 5 \times 10^{54} \text{ ergs} \left( \frac{M_{\text{BH}}}{10 M_\odot} \right).$$

(1)

The maximum rate of energy extraction by the field was estimated by Macdonald et al. (1986, eq. [4.50]) to be

$$L_{B,\text{max}} \approx 10^{51} \text{ ergs s}^{-1} \left( \frac{B}{10^{15} \text{ G}} \right)^2 \left( \frac{M_{\text{BH}}}{10 M_\odot} \right)^2.$$  

(2)

It is not clear how a superstrong field is generated, even though it has become popular in theoretical papers over the last few years (Paczynski 1991, 1993, Duncan & Thompson 1992, Narayan, Paczynski, & Piran 1992, Usov 1992, Woosley 1993a, 1993b, 1995, Hartmann & Woosley 1995, Vietri 1996, Mészáros & Rees 1997, and many others). The following is a possible scenario. A rapidly rotating massive star, just prior to its core collapse, has a convective shell (S. E. Woosley 1997, private communication). According to S. Balbus (1997, private communication), a large-scale magnetic field may be generated in the shell, and it may reach equipartition with the convective kinetic energy density. Following the collapse, the polar caps of the shell end up in the black hole, while the equatorial belt becomes part of the torus. At least two different field topologies may emerge. In one case the magnetic field lines link the torus to the black hole, while in the other case the field connection is severed. In both cases the collapse increases the field strength while the magnetic flux is conserved, and a substantial radial component leads to a rapid field increase driven by differential rotation. If there is no magnetic link between the torus and the black hole, then the magnetic field helps to release gravitational energy associated with the torus accretion. If a magnetic link is preserved, then a much larger rotational energy of the black hole can be extracted by the Blandford & Znajek (1977) mechanism, creating a microquasar.

It is well established that AGNs/blazars have relativistic jets that generate strong and rapidly variable gamma-ray emission (cf. Ulrich, Maraschi, & Urry 1997 and references therein). It is thought that the underlying “central engine” is a supermassive black hole with a disk/torus of matter that provides accretion energy or the magnetic field confinement. While theorists argue about the specific mechanism in which blazars produce the observed gamma-ray emission, the emission is there. The formation of a similar structure on a stellar mass scale, a Kerr black hole with a massive disk/torus, is not speculative at all, since it is a natural end product of massive star evolution. The presence of a superstrong magnetic field, and the ability of the system to generate a GRB, is just a speculation at this time. However, the observed properties of blazars make this speculation plausible.

A pre-microquasar must be a member of a short-period massive binary in order to be rapidly rotating prior to core collapse. Single stars lose most of their angular momentum when they evolve to a red giant phase. A member of a binary retains rapid rotation thanks to the tidal interaction with the companion star. The examples of such systems are the short-period Wolf-Rayet binaries and, in particular, Cyg X-3, with its $\sim 5$ hr orbit.

5. Discussion

A few different terms have been introduced in this Letter in reference to the objects that may be responsible for GRBs.

The term hypernova is proposed to name the phenomenon that is obviously explosive and that is much more luminous and energetic than any supernova. Considering the energetics of the GRB/afterglow phenomenon, a term “hypernova” seems more reasonable than “failed supernova” (Woosley 1993a) or “minisupernova” (Blinnikov & Postnov 1997). It is likely that optical afterglows unrelated to any GRBs will be detected in future massive variability searches (Rhoads 1997); the term hypernova will be more appropriate for such optical events than the “afterglow.”

The concept of a “microquasar” (Paczynski 1993; Woosley 1993b, 1995; Hartmann & Woosley 1995) is introduced as a specific example of a scenario in which a massive, rapidly rotating star may generate over $10^{54}$ ergs in kinetic energy of its ejecta upon the end of its nuclear evolution. This might be a magnetically driven event that is analogous to the Blandford & Znajek (1977) quasar model. It may work if a superstrong $\sim 10^{15}$ G magnetic field is available to rapidly extract the spin energy of the Kerr black hole and to use it to power a relativistic explosion.

It is not likely that the concept of a GRB as a microquasar powered by the Blandford & Znajek (1977) mechanism can be proved or disproved on purely theoretical grounds. It is useful to realize that while we have plenty of sound evidence that Type II supernovae explode as a result of some “bounce” following the formation of a hot neutron star, there is no generally accepted physical process that would be efficient enough to make this happen. The theoretical problem with the bounce persists in spite of two or three decades of intense effort by a large number researchers. The problem is vastly worse with the GRBs as they are $10^4$–$10^5$ times less common than supernovae. This may imply that a very special set of circumstances is necessary to generate the suitably energetic explosion.

While a purely theoretical approach is difficult, some inferences can be made without a quantitative model. The death of a massive star cannot be more than a few million years away from its birth time, and therefore it explodes within its star-forming region, or very close to it. This makes it distinct from a popular merging neutron star model: a merger follows orbital evolution driven by gravitational radiation, long after the binary had formed. During this time, $\sim 10^3$–$10^4$ yr, the system travels tens of kiloparsecs, having acquired a high velocity during the two supernovae explosions (Tutukov & Yungelson 1994).

The star-forming site for the GRBs in the microquasar scenario implies that on many occasions the optical afterglow may be heavily obscured by the dust commonly present in such regions (E. B. Jenkins 1997, private communication). Gradual emergence of the fireball out of the circumstellar dust shell may affect the early afterglow, possibly accounting for the early rise in the 970508 optical light curve.

In the microquasar scenario, the energy is released in a region full of debris of the collapsing star. Only a small fraction of all energy is likely to end up in the most relativistic ejecta, which are responsible for gamma-ray emission following the standard fireball scenario. The bulk of kinetic energy is likely to be associated with the much more massive and less relativ-
istic ejecta. In other words, a microquasar is likely to create a dirty fireball. This has an important consequence for the afterglow. In a clean fireball model, the energy that powers the afterglow is the residual kinetic energy of what is left of the original GRB shell. In a dirty fireball, when the fastest leading shell is decelerated by the ambient medium, the slower moving ejecta gradually catch up and provide a long-lasting energy supply to the afterglow, much larger than the one related to the GRB shell. Therefore, the afterglow may persist for much longer than predicted by the standard, clean fireball model.

Any dirty fireball model is likely to generate more or less thermal emission from the optically thick, relatively slow ejecta, at the very beginning of the explosion. It is interesting that the *Ginga* experiment detected a number of X-ray precursors to gamma-ray bursts (Murakami et al. 1991). The observed intensity corresponded to the source radius of $\sim 0.6 \, \text{km} \times (d/1 \, \text{kpc}) \approx 6 \times 10^{10} \, \text{cm} \times (d/1 \, \text{Gpc})$, where $d$ is the distance. Recently, the presence of occasional X-ray precursors was reported by Sazonov et al. (1998).

I have presented a weak case for a relation between GRBs and star-forming regions, based on the existing observations of the 970228, 970508, and 970828 bursts and their afterglows. The case will be proved or disproved when we shall have a few dozen afterglows. If it is established that the bursts are found in or near star-forming regions, then the merging neutron star scenario will have to be abandoned, and some supernova-like event, e.g., a violent death of a massive star, will become a likely explanation for the origin of GRBs. The microquasar scenario is a possible candidate for such an event.

The recent observations of X-ray spectra (Murakami 1998) offer yet another important promise for the future. With high enough spectral resolution, it will be possible to measure the redshift of the X-ray source, or a lower limit to the redshift, even if no optical afterglow is detected. This is important, since the afterglows are more common in X-rays than in the optical domain.

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REFERENCES

Blandford, R. D., & Znajek, R. L. 1977, MNRAS, 179, 433
Blinnikov, S. I., & Postnov, K. A. 1997, preprint (astro-ph/9709172)
Bond, H. E., et al. 1997, IAU Circ. 6654
Costa, E., et al. 1997, Nature, 387, 783
Dermer, C. D. 1992, Phys. Rev. Lett., 68, 1799
Duncan, R. C., & Thompson, C. 1992, ApJ, 392, L9
Fenimore, E. E., et al. 1993, Nature, 366, 40
Frail, D. A., Kulkarni, S. R., Nicoastro, L., Feroci, M., & Taylor, G. B. 1997, Nature, 389, 261
Fruchter, A., Bergeron, L., & Pian, E. 1997, IAU Circ. 6674
Goodman, J. 1997, NewA, 2, 449
Hartmann, D. H., & Woosley, S. E. 1995, Adv. Space Res., 15(5), 143
Hoffmeister, C., Richter, G., & Wenzel, W. 1985, Variable Stars (Berlin: Springer)
Lilly, S. J., et al. 1996, ApJ, 460, L1
Macdonald, D. A., Thorne, K. S., Price, R. H., & Zhang, X.-H. 1986, in Black Holes, the Membrane Paradigm, ed. K. S. Thorne, R. H. Price, & D. A. Macdonald (New Haven: Yale Univ. Press)
Madau, P., et al. 1996, MNRAS, 283, 1388
Mao, S., & Paczyński, B. 1992, ApJL, 388, L45
Mészáros, P., & Rees, M. J. 1997, ApJ, 482, L29
Metzger, M. R., et al. 1997a, Nature, 387, 878
———. 1997b, IAU Circ. 6676
Murakami, T. 1998, in Proc. Fourth Huntsville Symp. on Gamma-Ray Bursts, ed. C. A. Meegan, R. Preece, & T. M. Koshut, in press
MacDonald, P. R., Paczyński, B., & Piran, T. 1992, ApJ, 395, L83
Paczyński, B. 1991, A&A, 41, 257
———. 1993, in Ann. NY Acad. Sci., 688, Proc. Relative Atrophysics and Particle Physics, ed. C. W. Ackerlof & M. A. Srednicki, 321
Paczyński, B., & Rhoads, J. E. 1993, ApJ, 418, L5
Pian, E., et al. 1997, ApJ, 492, L103
Piran, T. 1992, ApJ, 389, L45
Rees, M. J., & Mészáros, P. 1992, MNRAS, 258, 41P
Rhoads, J. E. 1997, ApJ, 487, L1
Richmond, M. W., et al. 1994, AJ, 107, 1022
———. 1995, AJ, 109, 2121
Sahu, K. C., et al. 1998, IAU Circ. 6674
Sari, R. 1997, preprint (astro-ph/9706078)
Sazonov, S. Y., et al. 1998, A&AS in press (astro-ph/9708156)
Sokolov, V. V., et al. 1997, preprint (astro-ph/9709093)
Sterken, C., & Jaschek, C. 1996, Light Curves of Variable Stars. A Pictorial Atlas (Cambridge: Cambridge Univ. Press)
Tanaka, Y., & Shibazaki, N. 1996, ARA&A, 34, 607
Totani, T. 1997, ApJ, 486, 71
Tutukov, A. V., & Yungelson, L. R. 1994, MNRAS, 268, 871
Ulrich, M.-H., Maraschi, L., & Urry, C. M. 1997, ARA&A, 35, 445
Usos, V. V. 1992, Nature, 357, 472
van Paradijs, J. 1998, in Proc. Fourth Huntsville Symp. on Gamma-Ray Bursts, ed. C. A. Meegan, R. Preece, & T. M. Koshut, in press
van Paradijs, J., et al. 1997, Nature, 386, 686
Vietri, M. 1996, ApJ, 471, L91
———. 1997, ApJ, 488, L105
Waxman, E. 1997a, ApJ, 485, L5
———. 1997b, ApJ, 489, L33
Wijers, R. A. M. J., Bloom, J. S., & Bagla, J. S. 1997a, preprint (astro-ph/9708183)
Wijers, R. A. M. P., Rees, M., & Mészáros, P. 1997b, preprint (astro-ph/9704153)
Woosley, S. E. 1993a, ApJ, 405, 273
———. 1993b, in AIP Conf. Proc. 280, Proc. Second Compton Observatory Science Workshop, ed. M. Friedlander, N. Gehrels, & D. Macomb (New York: AIP), 995
———. 1995, in Ann. NY Acad. Sci., 759, Proc. 17th Texas Symp. on Relativistic Astrophysics and Cosmology, ed. H. Böhringer, G. E. Morfill, & J. E. Trümper, 446