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, a 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 be 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 (1993a): the inner core of a massive, rapidly rotating star collapses into a $\sim 10 M_\odot$ Kerr black hole with $\sim 5 \times 10^{54}$ erg 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 (1977) 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: gamma-rays: bursts – stars: binaries: close – stars: neutron – stars: supernovae

1. Introduction

The recent detection of the afterglows following some gamma-ray bursts (GRB) detected by BeppoSAX opens up a new era in the studies of GRBs. Many afterglows were
Fig. 1.— The absolute visual light curves are shown schematically for various eruptive variables. These include one case of a dwarf nova (U Gem, cf. Fig. 5.23 of Sterken & Jaschek 1996), two cases of a nova (V 1500 Cyg and DQ Her, cf. Fig. 40 of Hoffmeister et al. 1985), two cases of a supernova (SN 1993J, Richmond et al. 1994; SN 1994D, Richmond et al. 1995), and one case of a hypernova, i.e. the optical afterglow 970508 (Sokolov et al. 1997).

detected in X-rays (e.g. Costa et al. 1997), but so far only two were detected optically (970228: van Paradijs et al. 1997; 970508: Bond 1997), and just one in 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,b).

An afterglow is created by a collision between GRB ejecta and ambient medium, be it circum-stellar, interstellar, or intergalactic, and it is a natural consequence of any relativistic fireball model (Rees & Mészáros 1992, Paczyński & Rhoads 1993, Wijers et al. 1997a, Waxman 1997a,b, 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 Fig. 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 Wijers (1997). With the
large range of absolute magnitudes covered by the light curves an error of \( \sim 1 \) magnitude
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. I
shall use this term to describe the full GRB/afterglow event. Assuming spherical emission
its total energy was \( \sim 10^{52} \) erg (Waxman 1997b), more than any known supernova. The
terms like ‘failed supernova’ (Woosley 1993a) or ‘mini-supernova’ (Blinnikov & Postnov
(1997) seem inappropriate for so energetic explosions. Note, that hypernova ejecta are
relativistic (Goodman 1997, Frail et al. 1997), making it more violent than any other
variable represented in Fig. 1.

The purpose of this paper 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
micro-quasar (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 half a dozen of non-detections. 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 (Groot et al. 1997, van Paradijs 1997).
Therefore, the absence of this optical afterglow has to be taken seriously. In the following
sub-sections 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 HST image taken on September 4, 1997, shows the extended object
unchanged, and the point source fading according to the \( t^{-1} \) law, at a fixed position
(Fruchter 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 the 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 just a coincidence, though not a very unlikely one. Future observations of this very faint $\sim 25$th mag extended object may provide some clues. Its spectrum may show if this is indeed a galaxy at a moderate redshift, and is it undergoing a 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 for which the redshift has been measured: $z = 0.835$ in absorption (Metzger et al. 1997a) and in emission (Metzger et al. 1997b). The [OII] 372.8 nm emission line indicates a normal interstellar medium rather than AGN. We also know that it is not resolved by the HST (Fruchter, Bergeron & Pian 1997), i.e. the emission line region has to be very compact. Therefore, a 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 is 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 Jenkins (1997): extinction by dust. The case has been made stronger by Murakami’s (1997) report that the ASCA X-ray spectrum is well fitted by a power law with a low energy absorption indicating 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 $\sim (1 + z)^3$, as 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 (Groot et al. 1997, van Paradijs 1997). 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.

Note that gas column density as measured by Murakami (1997) points to a positional coincidence between the burst and dense interstellar medium. So, we have another case for a relation between GRBs and star forming regions, and against GRBs and merging neutron stars. Admittedly, the case is weak. If the GRB is at a very large redshift then the absorption of soft X-rays may be due to a galaxy which just happened to be along the line of sight, but is unrelated to the burst.

### 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 co-moving volume and co-moving time. The combined BATSE & 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 ‘roll-over’ caused by the cosmological redshift (Dermer 1992, Mao & Paczyński 1992, Piran 1992). According to Wijers (1997) the following numbers follow from the ‘no evolution’ scenario: the energy per GRB is $\sim 4 \times 10^{51}$ erg, the energy generation rate is $\sim 10^{53}$ erg Gpc$^{-3}$ yr$^{-1}$, and the GRB rate per L$^*$ galaxy is $\sim 4 \times 10^{-6}$ 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 $z = 0$ (Lilly 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 et al. (1997). The increase in the
comoving GRB rate with the cosmological distance compensates various redshift effects responsible for the ‘roll-over’ 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 to the no evolution model. According to Wijers (1997) the energy per burst in this ‘evolutionary’ scenario increases to $\sim 10^{53}$ erg, the rate of energy generation per galaxy is reduced by approximately one 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 $z \approx 1$, then the distance scale to the bursts increase 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 to ordinary supernovae.

4. A micro-quasar

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 (Paczyński 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 as about ten binary stars are known to have black hole components of $\sim 10 \, M_\odot$ (cf. Tanaka & Shibazaki 1996, p. 615). 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:

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

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

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

It is not clear how a superstrong field is generated, even though it has become popular in theoretical papers over the last few years Paczyński 1991, Duncan & Thompson 1992,
The following is a possible scenario. A rapidly rotating massive star, just prior to its core collapse, has a convective shell (Woosley 1997). According to Balbus (1997) 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 which generate strong and rapidly variable gamma-ray emission (cf. Ulrich et al. 1997, and references therein). It is thought that the underlying ‘central engine’ is a supermassive black hole with a disk/torus of matter which 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, as 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 gamma-ray burst 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 ∼ 5 hour orbit.

5. Discussion

A few different terms have been introduced in this paper in reference to the objects which may be responsible for gamma-ray bursts.
The term hypernova is proposed to name the phenomenon which is obviously explosive, and which 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 ‘mini-supernova’ (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 term ‘clean’ fireball is often used to describe the popular model. It is ‘clean’ by design, to maximize the efficiency of conversion of the kinetic energy into gamma-ray emission. The rationale behind this design is the perceived energy problem: how to obtain the ~ $10^{51}$ erg in gamma-rays out of merging neutron stars? The energy problem may be even more acute if the new ‘evolutionary’ distance scale turns out to be correct (Wijers et al. 1997). The concept of a ‘dirty’ fireball is more natural, as any explosive event is likely to create ejecta with a large range of specific kinetic energies or, in the case of a relativistic explosion, a large range of Lorentz factors. A fear of energy scale was never useful in astrophysics, as demonstrated by the history of supernovae and quasars. There is nothing in the laws of physics that would forbid explosions with $10^{55}$ erg, or even more. For those who are free of energy fobia a ‘dirty’ fireball appears more natural than a ‘clean’ one.

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 Ginga experiment detected a number of X-ray precursors to gamma-ray bursts. In particular, the spectrum of X-ray precursor to GRB 900126 was well fitted with a $k T \approx 2$ keV black body (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 was the distance. Recently, the presence of occasional X-ray precursors was reported by Sazonov et al. (1997).

The concept of a ‘microquasar’ (Paczyński 1993, Woosley 1993b, Hartmann & Woosley 1995, Woosley 1995) is introduced as a specific example of a scenario in which a massive, rapidly rotating star may generate over $10^{54}$ erg in kinetic energy of its ejecta upon the end of its nuclear evolution. While the geometry of the object, a stellar mass Kerr black hole with a massive torus rotating around it, is identical to the ‘failed supernova’ scenario of Woosley (1993a), the term ‘failed’ does not seem appropriate for an event vastly more energetic than any supernova. As the neutrino driven explosion does not appear to be feasible (Jaroszyński 1996, Janka & Ruffert 1996, Vietri 1996, Ruffert et al. 1997, Mészáros & Rees 1997, and references therein), a magnetically driven event, analogous to the Blandford & Znajek (1977) quasar model is the next obvious candidate. This 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 proven or disproven 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’, or whatever process following the formation of a hot neutron star, there is no generally accepted physical process which would be efficient enough to make this happen. The theoretical problem with the SN II explosions persists in spite of 2 or 3 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 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, $\sim 10^8 - 10^9$ years, 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 (Jenkins 1997). Gradual emergence of the fireball out of the circum-stellar 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 relativistic 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.
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 proven or disproven 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, 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 1997) 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 as the afterglows are more common in X-rays than in optical domain.

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