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A cannonball model of gamma-ray bursts: superluminal signatures

Arnon Dar[1,2] **and A. De Rújula**[1]

1. Theory Division, CERN, CH-1211 Geneva 23, Switzerland
2. Physics Department and Space Research Institute, Technion, Haifa 32000, Israel

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Abstract. Recent observations suggest that the long-duration gamma ray bursts (GRBs) and their afterglows are produced by highly relativistic jets emitted in supernova explosions. We propose that the result of the event is not just a compact object plus the ejecta: within a day, a fraction of the parent star falls back to produce a thick accretion disk. The subsequent accretion generates jets and constitutes the GRB "engine", as in the observed ejection of relativistic "cannonballs" of plasma by microquasars and active galactic nuclei. The GRB is produced as the jetted cannonballs exit the supernova shell reheated by the collision, re-emitting their own radiation and boosting the light of the shell. They decelerate by sweeping up interstellar matter, which is accelerated to cosmic-ray energies and emits synchrotron radiation: the afterglow. We emphasize here a smoking-gun signature of this model of GRBs: the superluminal motion of the afterglow, that can be searched for —the sooner the better— in the particular case of GRB 980425.

Key words: gamma rays bursts, supernovae, black holes

1. Introduction

The rapid directional localization of gamma-ray bursts (GRBs) by the satellites BeppoSAX (e.g. Costa et al. 1997), Rossi (e.g. Levine et al. 1996) and by the IPN (Inter-Planetary Network) of spacecrafts (e.g. Cline et al. 1999) led to the discovery of long-duration GRB afterglows, to determinations of their redshifts that verified their cosmological origin (Meegan et al. 1992), to the identification of their birthplaces —mainly star formation regions in normal galaxies— and to evidence of a possible association of GRBs with supernova explosions (Galama et al. 1998; Kulkarni et al. 1998a). The enormous isotropic energies inferred from the redshifts and fluences and the short-time variability have demonstrated that GRBs are produced by highly collimated emissions from gravitational stellar collapse (Shaviv and Dar 1995; Dar 1998a and references therein), but the specific progenitors and production mechanisms are unknown. In Table I we summarize some properties of the localized GRBs, for a currently favoured $\Omega = 1$ Universe with cosmological constant $\Omega_\Lambda = 0.7$, matter density $\Omega_M = 0.3$ (all in critical units), and Hubble constant $H_0 = 65$ km/(s Mpc).

The prevalent widespread belief is that GRBs are generated by synchrotron emission from fireballs or firecones produced by mergers of compact stars (Paczynski 1986, Goodman et al. 1987) or by hypernova explosions (Paczynski 1998). However, various observations suggest that most GRBs are produced in supernova events by highly collimated superluminal jets (for more details, see Dar and De Rújula 2000a).

In this paper, we outline a relativistic-cannonball model of GRBs, which, we contend, explains the main observed features of GRBs and their afterglows. We concentrate here on a major prediction of the model: the superluminal motion of the GRBs afterglow. This specific signature, as we shall see, can still be searched for —with a measure of urgency— in the very particular case of SN1998bw/GRB 980425.

2. The supernova–GRB association

There is mounting evidence for an association of supernova (SN) explosions and GRBs. The first example was GRB 980425 (Soffita et al. 1998; Kippen 1998), within whose error circle SN1998bw was soon detected optically (Galama et al. 1998) and at radio frequencies (Kulkarni et al. 1998a). The chance probability for a spatial and temporal coincidence is less than 10^{-4} (e.g. Galama et al. 1998), or much smaller if the revised BeppoSAX position (e.g. Pian, 1999) is used in the estimate. The unusual radio (Kulkarni et al. 1998a; Wieringa et al. 1999)) and optical (Galama et al. 1998; Iwamoto et al. 1998) properties of SN1998bw, which may have been blended with the afterglow of GRB 980425, support this association. The exceptionally small fluence and redshift of GRB 980425 make this event very peculiar, a fact that we discuss in detail below.

Evidence for a SN1998bw-like contribution to a GRB afterglow (Dar 1999a) was first found by Bloom et al. (1999) for GRB 980326, but the unknown redshift pre-

vented a quantitative analysis. The afterglow of GRB 970228 (located at redshift z = 0.695) appears to be overtaken by a light curve akin to that of SN1998bw (located at $z_{bw} = 0.0085$), when properly scaled by their differing redshifts (Dar 1999b). Let the energy flux density of SN1998bw be $F_{bw}[\nu, t]$. For a similar supernova located at z:

$$F[\nu, t] = \frac{1+z}{1+z_{bw}} \frac{D_L^2(z_{bw})}{D_L^2(z)} \times F_{bw}\left[\nu \frac{1+z}{1+z_{bw}}, t \frac{1+z_{bw}}{1+z}\right] A(\nu, z) , \quad (1)$$

where $A(\nu, z)$ is the extinction along the line of sight. The SN–GRB association in the case of GRB 970228 was reconfirmed by Reichart (1999) and by Galama et al. (2000). Evidence of similar associations is found for GRB 990712 (Hjorth et al. 1999; Sahu et al. 2000), GRB 980703 (Holland 2000; Dar and De Rújula 2000a) and GRB 000418: an example that we show in Fig. 1. In the case of GRB 990510, the evidence is marginal (Dar and De Rújula 2000a). For the remaining cases in Table I the data preclude a conclusion, for one or more reasons: the late afterglow is not measured; $F_{bw}[\nu']$ is not known for large $\nu' \simeq \nu\,(1+z)$; the GRB's afterglow or the host galaxy are much brighter than the SN. The case of GRB 970508, for which the afterglow is brighter than a SN contribution given by Eq. (1), is shown in Fig. 2.

All in all, it is quite possible that a good fraction of GRBs be associated with core-collapse SNe, perhaps even *all* of the most frequent, long-duration GRBs. The converse statement —that most SNe of certain types are associated with GRBs— appears at first sight to be untenable. The rate of Type Ib/Ic/II SNe has been estimated at $R_{SN} \sim 1/50\ y^{-1}$ per L_* galaxy (e.g. Van den Bergh & Tammann 1991) while the rate of GRBs (for our adopted cosmological parameters) is a mere $R_{GRB} \sim 5 \times 10^{-9}\ y^{-1}$ per L_* galaxy. Thus, very few of these SNe produce *visible* GRBs. But, if the SN-associated GRBs were beamed within an angle $\theta \sim 10^{-3}$, only a fraction $\pi\,\theta^2/4\pi \sim 2.5 \times 10^{-7}$ would be visible, making the observed rates compatible and making possible a rough one-to-one SN–GRB association (or a ten-to-one association for $\theta \sim 3 \times 10^{-3}$). Beaming within such narrow cones also solves the GRB "energy crisis" (Dar and Plaga 1999).

To proceed, we need some understanding of the generation of superluminal jets in SNe. Lacking definite theoretical guidance, we turn to observations in search for enlightment.

3. Superluminal jets

Relativistic jets seem to be emitted by all astrophysical systems wherein mass is accreted at a high rate from a disk onto a central compact object (for a recent review, see Mirabel and Rodriguez 1999a). Highly relativistic jets have been observed with high resolution in galactic superluminal sources, such as the microquasars GRS 1915+105 (Mirabel and Rodriguez 1994, 1999a,b; Rodriguez and Mirabel 1999) and GRO J165-40 (Tingay et al. 1995) where mass is accreted onto a stellar black hole, and in many active galactic nuclei (AGNs) hosting a massive black hole. These jets are not continuous streams: they consist of individual blobs of plasma (plasmoids or "cannonballs"). The firing of these cannonballs (CBs) coincides with a sudden removal of the accretion-disk material (Mirabel and Rodriguez 1999b).

As they travel, microquasar CBs expand at the speed of a relativistic plasma ($c/\sqrt{3}$ in their rest system) presumably due to the pressure of their enclosed radiation. As they become transparent and cool down, their lateral size stabilizes to a roughly constant value, presumably constrained by magnetic self-containment and/or by the ram pressure of the ambient material. Quasar CBs show no measurable expansion as they travel, sometimes for as long as Mpcs. Galactic and quasar CBs expand explosively when finally stopped by the material they traverse.

Microquasars CBs are emitted in pairs, at similar velocities, $v = \beta\,c$, and angles θ and $\sim \pi - \theta$ relative to the line of sight. Their apparent transverse velocities are $v_T^{\pm} = \beta\,c\,\sin\theta/(1 \mp \beta\,\cos\theta)$. For $\beta\,(\sin\theta + \cos\theta) > 1$ the approaching CB is superluminal: $v_T^+ > c$, a case of "relativistic aberration" (Rees 1966). For $\theta \ll 1$ and $\gamma \gg 1$:

$$v_T^+ \approx \frac{2\,\gamma^2\,\theta}{(1+\gamma^2\theta^2)}\,c , \quad (2)$$

yielding superluminal velocities $v_T \approx 2\,c/\theta$ for $\gamma^2\theta^2 \gg 1$, and $v_T \approx 2\,c\,\gamma^2\,\theta$, for $\gamma^2\theta^2 \ll 1$, provided $2\,\gamma^2\,\theta > 1$. Superluminal velocities of a few c have been observed in microquasars, and as high as 30 c in quasars (Gabudza et al. 1993).

4. The cannonball model of GRBs

The ejection of matter in a SN explosion is not fully understood. The known mechanisms for imparting the required kinetic energy to the ejecta are inefficient. Simulations of stellar collapse for parent stars rotating at a typical observed rate give rise to proto-neutron stars spinning much faster than young pulsars (Heger et al. 2000). Magnetic fields no doubt play an important role in the outwards transport of angular momentum, but current simulations (e.g. Spruit and Phinney, 1998) cannot fully cope with their effects. In the related problem of accretion disks, a freely parametrized bulk viscosity must be introduced to describe the efficient angular momentum transport, presumably due to turbulent magnetohydrodynamic effects (e.g. Longair, 1994). For all these reasons, our theoretical understanding of core-collapse SN events is still unsatisfying.

We posit that the result of a SN event is not just a compact object plus the ejecta: a fraction of the parent

star falls back onto the newly born compact object (De Rújula 1987). The free-fall time from a parent stellar radius $R_\star$ into an object of mass M_c is:

$$t_{\rm fall} = \pi \left[\frac{R_\star^3}{8\,G\,M_c}\right]^{1/2} \sim 1\ {\rm day} \left[\frac{R_\star}{10^{12}\ {\rm cm}}\right]^{3/2} \left[\frac{1.4\,M_\odot}{M_c}\right]^{1/2}. \quad (3)$$

For a parent star that rotates, this time would be longer, but for the material that falls from the polar regions. It is quite natural to suppose that the infalling material settles into an orbiting disk, or a thick torus if its mass is comparable to M_c. We assume that, as in other cases of significant accretion into a compact object (microquasars and AGNs), jets of relativistic CBs of plasma are ejected. We presume their composition to be "baryonic", as it is in the jets of SS 433, from which Ly$_\alpha$ and Fe K$_\alpha$ lines have been detected (Margon 1984), although the violence of the relativistic jetting-process may break many nuclei into their constituents.

In our admittedly sketchy model of the GRB engine, the time structure of the γ-ray signal will be essentially that of the ejections. The energies of the GRB subpulses and the "waiting times" between them are nearly proportional (e.g. van Paradijs et al. 1988). This is indicative of a process, such as discontinuous accretion, in which the "reservoir" must be replenished.

Let "jet" stand for the ensemble of CBs emitted in one direction in a SN event. If a momentum imbalance between the opposite-direction jets is responsible for the large peculiar velocities $v_{NS} \approx 450 \pm 90$ km s^{-1} (Lyne and Lorimer 1994) of neutron stars born in SNe, the jet kinetic energy must be, as we shall assume for our GRB engine, $\sim 10^{52}$ erg (e.g. Dar and Plaga 1999). For this choice the jet mass is relatively small: $M_{\rm jet} \sim 1.5\times10^{-6}\,M_{\rm NS}\,(10^3/\gamma)$, or $\sim 1.86\,M_\otimes$ for the Lorentz factor $\gamma = \mathcal{O}(10^3)$ that we independently estimate from the GRBs beaming angle, from the average fluence per pulse observed by BATSE in GRBs, and from the typical duration of these pulses.

The large peculiar velocities of pulsars may have been acquired well after their birth, in a "second" transition of the cooled and spun-down neutron star to a strange star or a quark star (Dar and De Rújula 2000b). In that case $v_{NS} \sim 100$ km s^{-1} ought to be used: the observed velocity of young pulsars, millisecond pulsars and stellar black holes in binaries and isolation (e.g. Toscano et al. 1999 and references therein). The typical jet energy would then be $\sim 10^{51}$ erg and our results would have to be accordingly scaled, but their dependence on $E_{\rm jet}$ is weak and the conclusions are unaffected.

There are other events in which a variety of GRBs could be produced by mechanisms similar to the ones we have discussed: large mass accretion episodes in binaries including a compact object, mergers of neutron stars with neutron stars or black holes, the "second transitions" just discussed, etc. In each case, the ejected cannonballs would make GRBs by hitting stellar winds or envelopes, circumstellar mass or light. We discuss only core-collapse SN explosions, as the GRBs they would produce by our mechanism, although relatively "standard", satisfactorily reproduce the general properties of the heterogeneous ensemble of GRBs.

5. The making of a GRB

The making of a GRB is illustrated in Fig. 3. In the time after core collapse $t_{\rm fall} = \mathcal{O}(1)$ day, as in Eq. (3), that it takes to "fuel and start" the GRB engine, the SN shell will have acquired a radius $R_s \sim 2.6\times10^{14}$ cm, for a typical velocity $\sim$ c/10 of the ejecta (we do not scale all results with all the ratios of actual to typical values, as we are only sketching the model). If the CBs expand with a velocity $\beta_{\rm exp}$ c in their rest system ($\beta_{\rm exp} = 1/\sqrt{3}$ for a relativistic plasma), by the time they hit the SN shell their transverse radius has grown to $\beta_{\rm exp}\,R_s/\gamma$, or $R_{CB} \sim 1.5\times10^{11}$ cm for $\beta_{exp} = 1/\sqrt{3}$ and $\gamma \sim 10^3$.

The typical number of CBs per SN event we certainly cannot predict. But the observed number of bursts in intense GRBs averages to $n_{CB} \sim 5$: the number —in our model— of well aimed and relatively energetic (i.e. observable) GRBs per SN. Let a CB have a fraction f of the total jet energy and let M_s be the mass of the SN shell. The ratio of the swept-up shell mass to the CB's energy is $M_s c^2\,(R_{CB}/R_s)^2/(4\,f\,E_{\rm jet})$, that is 6×10^{-4}/f for $M_s = 10\,M_\odot$ and $E_{\rm jet} = 10^{52}$ erg. The ensemble of CBs (for which f = 1) certainly blows a passage through the SN shell, but, for f sufficiently small, the leading CBs are significantly decelerated by the shell, opening up the possibility of CBs colliding and merging after they exit the shell, which complicates the nature and time structure of the GRB signal. The fraction of the SN shell surface that is blown up by a CB is only $5\times10^{-7}\,(\beta_{\rm exp}/0.1)^2\,(10^3/\gamma)^2$, so that it appears unlikely that the CBs are aimed precisely enough to hit the very same place: CB pile-up may be the exception, not the rule.

The collisions of the CB nuclei —whose energy is $\mathcal{O}(1)$ TeV— with those in the SN shell produce hadronic cascades. The SN shell and the CB are transparent to the neutrinos, semitransparent to the muons and opaque to the photons constituting these cascades. The CB inpact on the shell generates a very intense, narrowly collimated and very short burst of sub-TeV neutrinos. The fraction of c.m. energy that does not escape in neutrinos or muons ($\sim 1/3$) is converted into internal black-body radiation of the CB. The CBs become visible in γ-rays when the obscuring column density of the shell approaches one absorption length, $X_s(r) \sim X_\gamma \sim 10$ g cm^{-2}, resulting in a short burst of sub-TeV γ-rays from π^0 decays. As a reheated CB expands, it becomes transparent and emits its internal radiation, collimated and boosted by the CB's motion and observed in the form of MeV γ-rays: one of the pulses

that constitute a GRB. Of all these issues (Dar and De Rújula 2000a), we only discuss here the total energy in GRBs and the time duration of their pulses.

Approximately a third of the collision c.m. energy is converted in the hadronic cascades into electromagnetic radiation (via π^0 production). Energy and momentum conservation in the collision between a CB and the SN shell imply that the internal heat acquired by the CB is $E_i \sim (\beta_{exp}/6\,\gamma)\,\sqrt{2\,f\,E_{jet}\,M_s\,c^2}$. The corresponding radiation pressure makes the CB expand and cool at a rate $T_{CB} \sim 1/R_{CB} \sim 1/t$, until it becomes optically thin and releases its enclosed radiation. For an ionized CB, this takes place when $R_{CB} \simeq [3\,M_{CB}\,\sigma_T/(4\,\pi\,m_p)]^{1/2}$, where $\sigma_T \simeq 0.65 \times 10^{-24}$ cm^2 is the Thomson cross section[1].

The internal heat, reduced by expansion, is the energy the CB radiates in its rest system, which is boosted and collimated by the CB's motion. Local observers at angles θ to the CB's direction would see this energy distributed as:

$$\frac{dE}{d\Omega} \simeq \frac{\beta_{exp}^2}{\gamma^{3/2}}\left[\frac{2\,\gamma}{(1+\gamma^2\,\theta^2)}\right]^3\left[\frac{4\,\pi\,R_s^2}{3\,\sigma_T}\right]^{1/2}\frac{\sqrt{2\,m_p\,M_s}\,c^2}{24\,\pi}\,. \quad (4)$$

Remarkably, the CB's mass and energy have dropped from the above expression, except for the fact that, for the result to be correct, they must be large enough for the CB to pierce the SN shell and remain relativistic. For a most likely viewing angle $\theta \sim 1/\gamma$, and $\gamma = 10^3$, one infers from Eq. (4) an isotropic energy $E_{isot} \simeq (\beta_{exp}/0.1)^2\,6.4 \times 10^{53}$ erg. This energy —or n_{CB} times this energy in a GRB with that many pulses— are in agreement with the range of observed isotropic energies listed in Table I. The light from the SN shell is also Compton up-scattered to MeV energies, but its contribution to a GRB is subdominant relative to that of Eq. (4) (Dar and De Rújula 2000a).

The duration of a single CB-induced GRB pulse is the light crossing time of the CB when it becomes transparent to its radiation, i.e. $\sim R_{cb}/c$ in its rest frame, or

$$t \sim \left[\frac{3\,M_{CB}\,\sigma_T}{4\,\pi\,m_p}\right]^{1/2}\frac{1+\theta^2\gamma^2}{2\,\gamma\,c}\,(1+z)\,. \quad (5)$$

for the observer. For $z = 1$, a most probable $\theta \sim 1/\gamma$, and our adopted values, $E_{jet} = 10^{52}$ erg and $\gamma = 10^3$, $t \sim 2.2\ f^{1/2}$ s, comparable to the observed duration of GRB pulses. The total duration of a GRB is that of the (unpredictable) firing-sequence time of CBs into the observer's viewing cone; the duration of GRBs with only one observable pulse is given by Eq. (5).

The evidence for superluminal motion in GRBs, as we shall argue, can only be measured in their afterglow phase. The only case in which this can be done (SN1998bw/GRB 980425) is already some 850 days old: it may be dimming out of observability. Hence, we skip a more detailed discussion of the spectral properties of GRBs (Dar and De Rújula, 2000a) to concentrate on the issue of superluminal motion of the afterglow's source.

[1] Nuclei are disassembled by the CB's collision with the SN shell, and neutrons decay in $\sim$1 s of observer's time, thus the number of electrons in the CB is M_{CB}/m_p.

6. GRB afterglows

Far from their parent SNe, the CBs are slowed down by the interstellar medium (ISM) they sweep, which has been previously ionized by the forward-beamed CB radiation (travelling essentially at v = c, the CB is "catching up" with this radiation, so that the ISM has no time to recombine). As in the jets and lobes of quasars, a fraction of the swept-up ionized particles are "Fermi accelerated" to cosmic-ray energies and confined to the CB by its turbulent magnetic field, maintained by the same confined cosmic rays (Dar 1998b; Dar and Plaga 1999). The synchrotron emission from the accelerated electrons, boosted by the relativistic bulk motion of the CB, produces afterglows in all bands between radio and X-rays, collimated within an angle $\sim 1/\gamma(t)$, that widens as the ISM decelerates the CB. When the CBs finally stop, they enter a Sedov–Taylor phase, causing a temporal "break" in their afterglow.

A CB of roughly constant cross section, moving in a previously ionized ISM of roughly constant density, would lose momentum at a roughly constant rate, independent of whether the ISM constituents are re-scattered isotropically in the CB's rest frame, or their mass is added to that of the CB. The pace of CB slowdown is $d\gamma/dx = -\gamma^2/x_0$, with $x_0 = M_{CB}/(\pi\,R_{CB}^2\,n\,m_p)$ and n the number density along the CB trajectory. For $\gamma^2 \gg 1$, the relation between the length of travel dx and the (red-shifted, relativistically aberrant) time of an observer at a small angle θ is $dx = [2\,c\,\gamma^2/(1+\theta^2\,\gamma^2)]\,[dt/(1+z)]$. Inserting this into $d\gamma/dx$ and integrating, we obtain:

$$\frac{1+3\,\theta^2\gamma^2}{3\,\gamma^3} = \frac{1+3\,\theta^2\gamma_0^2}{3\,\gamma_0^3} + \frac{2\,c\,t}{(1+z)\,x_0}\,, \quad (6)$$

where γ_0 is the Lorentz factor of the CB as it exits the SN shell. The real root $\gamma = \gamma(t)$ of the cubic Eq. (6) describes the CB slowdown with observer's time.

Let the radiation emitted by a CB in its rest system (bremsstrahlung, synchrotron, Compton-boosted self-synchrotron) be isotropic and have an energy flux density $F_0(\nu_0)$. This radiation is boosted and collimated by the CB's motion, and its time-dependence is modified by the observer's time flowing $(1+z)\,(1+\gamma^2\theta^2)/(2\gamma)$ times faster than in the CB's rest system. For $\gamma \gg 1$, an observer at small θ sees an energy flux density:

$$F[\nu] \simeq \left(\frac{R_{CB}}{D_L}\right)^2\left[\frac{2\gamma}{1+\gamma^2\theta^2}\right]^3 \times F_0\left(\nu\,[1+z]\,\frac{1+\gamma^2\theta^2}{2\,\gamma}\right)\,A(\nu,z)\,, \quad (7)$$

with $\gamma = \gamma(t)$ as in Eq. (6) and $A(\nu, z)$ an eventual absorption dimming.

During the afterglow regime, the CBs emission is dominated by electron synchrotron radiation from the magnetic field in the CB. At frequencies above the plasma frequency, a CB becomes transparent to this radiation when the attenuation length due to electron free–free transitions exceeds its radius. The spectral shape is $F_0 \sim \nu_0^{-\alpha}$, with $\alpha = (p-1)/2$ and p the spectral index of the electrons. For equilibrium between Fermi acceleration and synchrotron and Compton cooling, $p \approx 3.2$ and $\alpha \approx 1.1$, while for small cooling rates, $p \approx 2.2$ and $\alpha \approx 0.6$ (Dar and De Rújula 2000c), or $p \simeq 1.2$ and $\alpha \simeq 0.1$ if Coulomb losses dominate. At very low radio frequencies self-absorption becomes important and $\alpha \approx -1/3$ (2.1) for optically thin (thick) CBs. For a detailed modelling of synchrotron radiation from quasar lobes, see, for instance, Meisenheimer et al. (1989).

Since $\gamma(t)$, as in Eq. (6), is a decreasing function of time, the afterglow described by Eq. (7) may have a very interesting behaviour. An observer may initially be outside the beaming cone: $\theta^2\gamma^2 > 1$, as we shall argue to be the case for GRB 980425, for which we estimate $\gamma_0^2\,\theta^2 \sim 100$ (other relatively dim GRBs in Table I, such as 970228 and 970508, may also be of this type). The observed afterglow would then initially rise with time. As γ decreases, the cone broadens, and at $\gamma\theta \sim 1$ the time dependence changes towards $F_\nu \propto t^{-(3+\alpha)/3} \sim t^{-1.4}$, while the ν dependence stays put at $\nu^{-\alpha}$. Such a behaviour may explain the puzzling initial rise of the optical afterglow of GRBs 970228 and 970508, as well as the second peak around $t_p \sim 3$–4×10^6 s in the unresolved radio emission from SN1998bw/GRB 980425 (Kulkarni et al. 1998a; Frail et al. 1999), if it corresponds to the GRBs afterglow.

The afterglow of GRB 970508 is shown in Fig. 2, and compared with our prediction Eqs. (6,7), for the measured index $\alpha = 1.1$. The adjusted parameters are the height and time of the afterglow's peak and $\theta = 10/\gamma_0$. The figure is for a single CB; with a few of them at chosen times and relative fluxes, it would be easy to explain the early "warning shots" at $t < 1$ day and the abrupt rise at $t = 1$ to 2 days. At $t \gg t_p$, however, they would add up to a single curve like the one shown in the figure.

As a CB is finally stopped by the ISM, it enters a Sedov–Taylor phase. The CB's radius increases as $t^{2/5}$. The Lorentz factor of electrons decreases like $t^{-6/5}$. In equipartition, the magnetic field decreases like $t^{-3/5}$. Wijers et al. (1997) have shown that these facts lead to an afterglow decline $F_\nu \sim t^{-(15\alpha-3)/5} \sim t^{-2.7}$ for $\alpha \sim 1.1$, as observed for the late-time afterglows of microquasars and of some GRBs.

7. GRB 980425: a special case

In the list of Table I, GRB 980425 stands out in two — apparently contradictory— ways: it is, by far, the closest ($z = 0.0085$, $D_L = 39$ Mpc) and it has, by far, the smallest implied spherical energy: 8.1×10^{47} erg, 4 to 6 orders of magnitude smaller than that of other GRBs. If GRB 980425 was not abnormal, Eq. (4) tells us that it must have been beamed at an angle $\theta \approx 10/\gamma_0$ relative to our line of sight. The probability of a jetted GRB to be pointing to us within an angle $\theta \leq 10/\gamma_0 \sim 10^{-2}$ is $P \sim \pi\theta^2/(4\pi) \approx 2.5 \times 10^{-5}$. For this GRB, BATSE observed a single wide peak of ~ 5 s duration and a maximum flux $(3 \pm 0.3) \times 10^{-7}$ erg cm^{-2} s^{-1} (Soffita et al. 1998). With the BATSE sensitivity of 6×10^{-2} cm^{-2} s^{-1} in the range $50 < E_\gamma < 300$ keV, such a burst can be detected up to ~ 150 Mpc. For our choice of H_0, the local luminosity density is $\sim 1.3 \times 10^{-2}\, L_*\, \mathrm{Mpc}^{-3}$ (e.g. Ellis 1997), yielding $\sim 3.7 \times 10^3$ SNe a year within 150 Mpc. Thus, the mean time to observe a SN–GRB association with $\theta > 10/\gamma_0$ is ~ 10 y, consistent with a single detection, since the launch of BATSE, of a GRB with the odd properties of 980425.

8. Is the superluminal motion of GRB 980425 observable?

As we have discussed, the peculiarities of of GRB 980425 can be understood if its source was "fired" from SN1998bw with a bulk-motion Lorentz factor $\gamma \sim 1000$, at an angle $\theta \approx 10/\gamma$ relative to our line of sight. Its transverse superluminal displacement, D_T, from the SN position can be obtained by time-integrating v_T, as in Eq. (2), using $\gamma(t)$ as in Eq. (6). The result can be reproduced, to better than 10% accuracy, by using the approximation $v_T \sim 2\gamma^2\,\theta\,c$, valid for $\gamma < 1/\theta$ (or $t > t_p$, the afterglow's peaktime):

$$D_T \simeq \frac{2\,c\,t_p}{\theta}\left[\frac{t}{t_p}\right]^{1/3}. \qquad (8)$$

At present ($t \sim 850$ d), the displacement of the GRB from the initial SN/GRB position is $D_T \sim 20\,(\gamma_0/10^3)$ pc, corresponding to an angular displacement $\Delta\alpha \sim 100\,(\gamma_0/10^3)$ mas, for $z = 0.0085$, $t_p \sim 3.5 \times 10^6$ s.

The two sources, a few tens of mas away, may still be resolved by HST. In Fig. 4 we show our prediction for the late-time V-band light curve of SN1998bw/GRB 980425. The SN curve is a fit by Sollerman et al. (2000) for energy deposition by ^{60}Co decay in an optically thin SN shell. The GRB light curve is our predicted afterglow for GRB 9980425, as given by Eqs. (6,7), and constrained to peak at the position of the second peak in the radio observations (Kulkarni et al. 1998a; Frail et al. 1999). The fitted normalization is approximately that of the mean GRB afterglow of the GRBs in Table I suppressed by the same factor as its γ-ray fluence relative to the mean γ-ray fluence in Table I. The joint system has at present (day ~ 850) an extrapolated magnitude $V \sim 26$ (Fynbo et al. 2000). It can still be resolved from its host galaxy ESO-184-G82 by HST and, perhaps, by VLT in good seeing conditions. An extrapolation of the V-band late time curve

of SNR1998bw (Sollerman et al. 2000) suggests that the present magnitude of the SN is V $\sim$ 28 , which is near the detection limit of HST and is dimming much faster than ^{60}Co-decay would imply.

In the GHz radio band, the system has been last observed in February 1999 by ATCA (Australia Telescope Compact Array) to have $\sim$ mJy flux density (Frail et al. 2000). It approached a power-law time decline with a power-law index -1.47. If a Sedov-Taylor break in the radio afterglow of GRB 980425 has not occurred yet, its spectral density may still be strong enough to determine its position with VLA and VLBI to better than mas precision. If the second peak is the GRB's afterglow, the two radio centroids should now be separated by $\sim \gamma_0/10$ mas (or by $\sim \gamma_0/20$ mas, if the first peak is the afterglow). A refined location from a reanalysis of the early ATCA observations (Kulkarni et al 1998a; Frail et al. 1999) of the initial SN and of the late afterglow may also reveal a superluminal displacement.

If the GRB afterglow has entered the late fast-decline phase seen in some GRB afterglows and in quasar and microquasar "afterglows" from jetted ejections (observed power-law index -2.7 ± 0.3), a further delay in follow-up observations can make it very difficult or impossible to detect and resolve the GRB/SNR radio image into its two predicted images.

A GRB as close as GRB 980425 (z = 0.0085) should occur only once every $\sim$ 10 years. For typical GRBs (z$\sim$ 1) there is no hope of resolving them with HST into two separate SN and GRB images. Resolving them with VLBI would also be arduous. For these reasons, we exhort interested observers to consider immediate high-resolution optical (STIS) and radio (VLA and VLBI) follow-up observations of SN1998bw and the afterglow of GRB980425.

9. Conclusions

We have argued that GRBs and their afterglows may be produced by the firing of extremely relativistic cannonballs in SN explosions. For the GRB to be observable, the CBs must be close to the line of sight, implying that their afterglows would appear to move superluminally. Only one of the located GRBs (980425) is close enough to us for this superluminal displacement to be observable with the currently available resolution. Its afterglow may by now have reached a "break" and be too dim to be seen. Or it may not. If observed, the superluminal displacement of this GRB's afterglow would be a decisive card in favour of cannonballs, as opposed to stationary fireballs.

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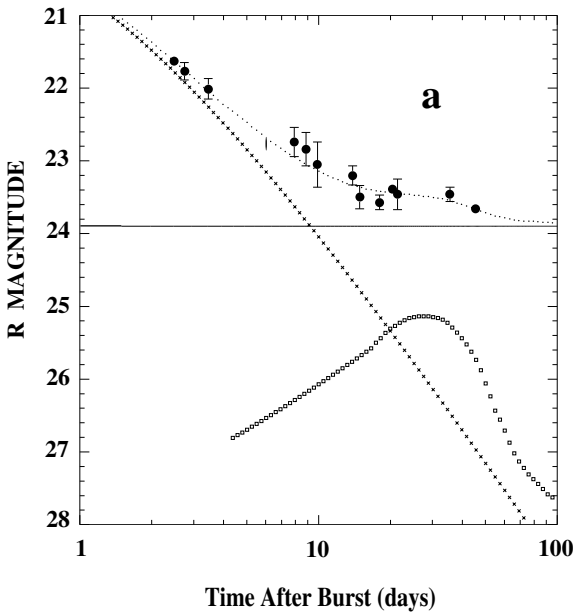
Table I - Gamma ray bursts of known redshift z

GRB	z	Ref	D_L [a]	F_γ [b]	E_γ [c]	M [d]	Ref.
970228	0.695	1	4.55	0.17	0.025	25.2	15
970508	0.835	2	5.70	0.31	0.066	25.7	16
970828	0.957	3	6.74	7.4	2.06	—	17
971214	3.418	4	32.0	1.1	3.06	25.6	18
980425	0.0085	5	0.039	0.44	8.14 E-6	14.3	19
980613	1.096	6	7.98	0.17	0.061	24.5	20
980703	0.966	7	6.82	3.7	1.05	22.8	21
990123	1.600	8	12.7	26.5	19.8	24.4	22
990510	1.619	9	12.9	2.3	1.75	*28.5*	23
990712	0.430	10	2.55	—	—	21.8	24
991208	0.706	11	4.64	10.0	1.51	> 25	25
991216	1.020	12	7.30	25.6	8.07	24.5	26
000301c	2.040	13	17.2	2.0	2.32	27.8	27
000418	1.119	14	8.18	1.3	0.49	23.9	28

Comments: *a*: Luminosity distance in Gpc (for $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$ and $H_0 = 65\,km\,s^{-1}\,Mpc^{-1}$. *b*: BATSE γ–ray fluences in units of 10^{-5} erg cm^{-2}. *c*: (Spherical) energy in units of 10^{53} ergs. *d*: R-magnitude of the host galaxy, except for GRB 990510, for which the V-magnitude is given. **References**: 1: Djorgovski et al. 1999; 2: Metzger et al. 1997; 3: Djorgovski et al. 2000; 4: Kulkarni et al. 1998b; 5: Tinney et al. 1998; 6: Djorgovski et al. 1998a; 7: Djorgovski et al. 1998b; 8: Kelson et al. 1999; 9: Vreeswijk et al. 1999a; 10: Galama et al. 1999; 11: Dodonov et al. 1999; 12: Vreeswijk et al. 1999b; 13: Feng et al. 2000; 14: Bloom et al. 2000; 15: Fruchter et al. 1999b; 16: Bloom et al. 1998a; 17: Djorgovski et al. 2000a; 18: Odewahn et al. 1999; 19: Galama et al. 1998; 20: Djorgovski et al. 2000b; 21: Bloom et al. 1998b; 22: Fruchter et al. 1999c; 23: Fruchter et al. 1999d; 24: Hjorth et al. 1999; 25: Diercks et al. 2000; 26: Djorgovski et al. 1999; 27: Fruchter et al. 2000; 28: Metzger et al. 2000.



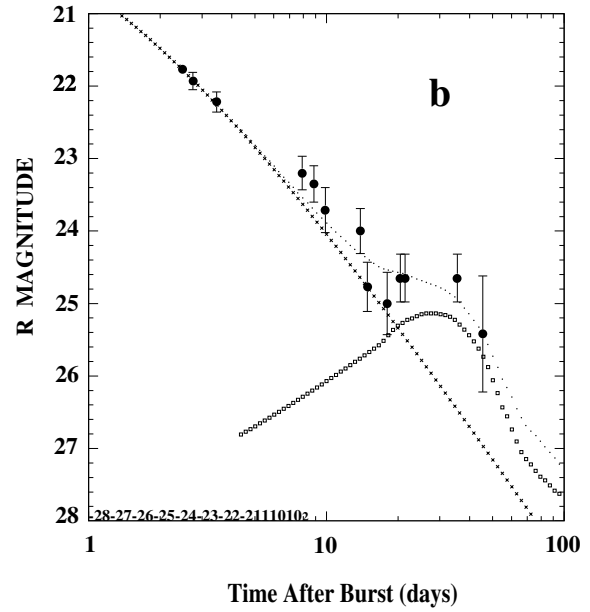


FIG. 1.— Comparisons between our predicted R-band light curve for GRB 000418 (dotted lines) and the observations as compiled by Klose et al. (2000). a) Without subtraction of the host galaxy's contribution: the straight line with R = 23.9 (Fruchter et al. 2000). b) With the host galaxy subtracted. The CB's afterglow is given by Eq.(6,7) with spectral index $\alpha = 1.9$ (Klose et al. 2000) and is indicated by crosses. The contribution from a SN1998bw-like SN placed at z=1.11854, as in Eq.(1) with Galactic extinction $A_R = 0.09$ magnitudes, is indicated by open squares. The dotted line is the sum of contributions. The SN bump is clearly discernible.

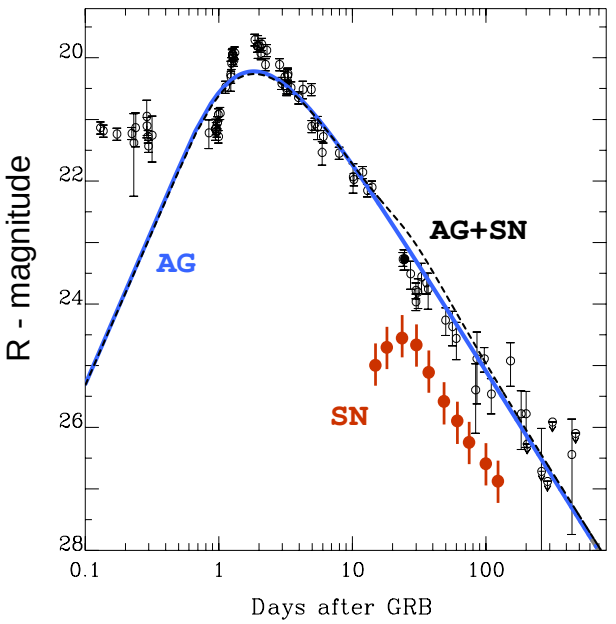


FIG. 2.— The R-band light curve of the afterglow of GRB 970508 as compiled by Fruchter et al. (1999a) with a constant (R = 25.2 magnitude) host galaxy subtracted from all the measurements. The blue "AG" curve is given by Eqs. (6,7). The contribution from a SN1998bw-like SN, placed at the GRB redshift z = 0.835, given by Eq.(1), is indicated (in red) and makes very little difference when added to the afterglow.

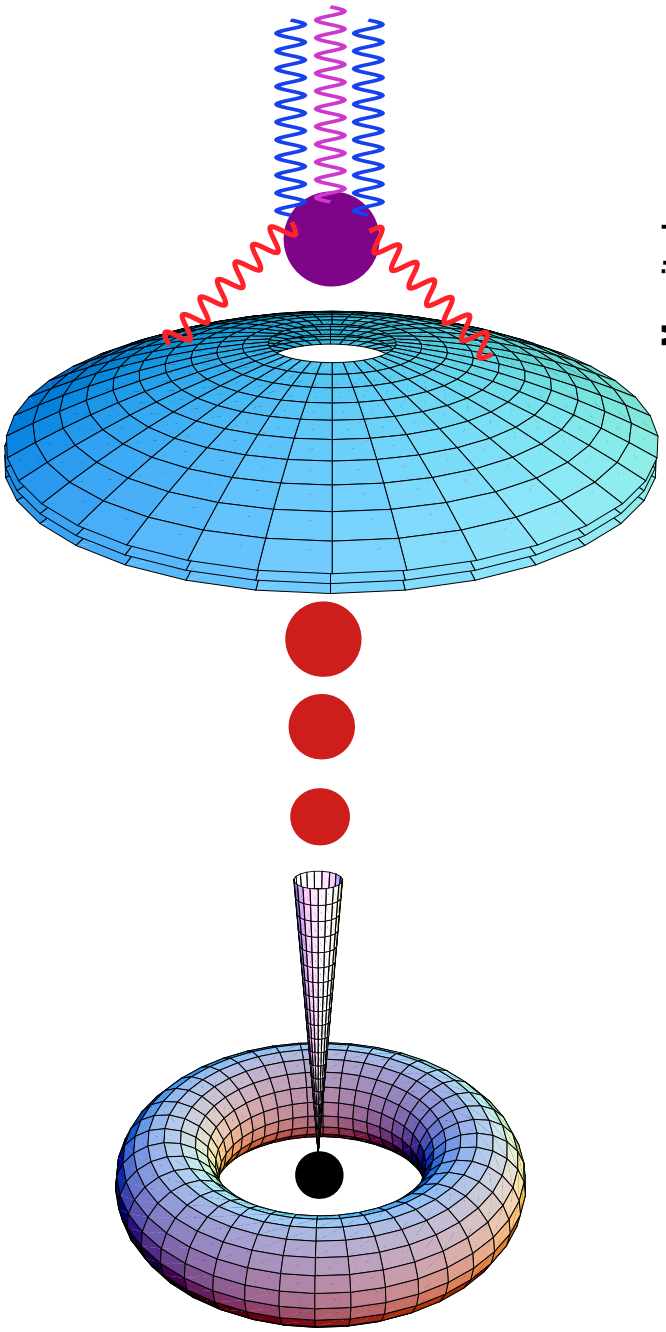


FIG. 3.— An "artist's view" (not to scale) of the CB model of GRBs and their afterglows. A core-collapse SN results in a compact object and a fast-rotating torus of non-ejected fallen-back material. Matter accreting (and not shown) into the central object produces a narrowly collimated beam of CBs, of which only some of the "northern" ones are depicted. As these CBs pierce the SN shell, they heat and reemit photons. They also scatter light from the shell. Both emissions are Lorentz-boosted and collimated by the CBs' relativistic motion.

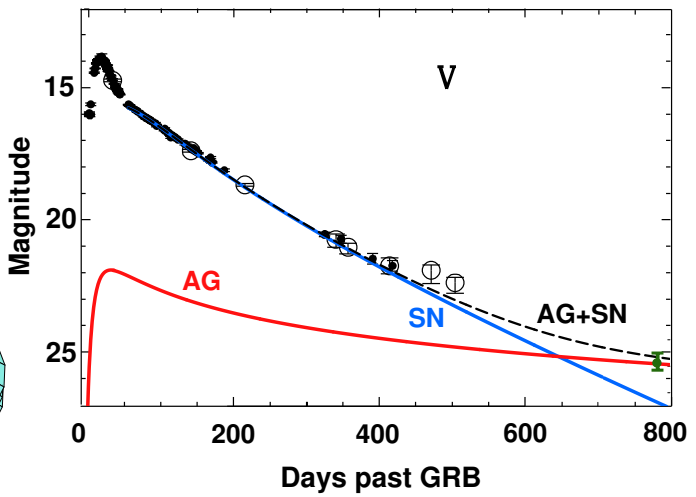


FIG. 4.— The V-band light curve of SN1998bw/GRB 980425, with the blue "SN" curve a fit to the SN by Sollerman et al. (2000). The red "AG" curve is our predicted afterglow, as given by Eqs. (6,7), fit to peak at the position of the observed second radio peak, and to reproduce the most recent observation at d = 778. The dashed curve is the total.