Energetics and Beaming of Gamma Ray Burst Triggers

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ABSTRACT

A wide range of mechanisms have been proposed to supply the energy for gamma-ray bursts (GRB) at cosmological distances. It is a common misconception that some of these, notably NS-NS mergers, cannot meet the energy requirements suggested by recent observations. We show here that GRB energies, even at the most distant redshifts detected, are compatible with current binary merger or collapse scenarios involving compact objects. This is especially so if, as expected, there is a moderate amount of beaming, since current observations constrain the energy per solid angle much more strongly and directly than the total energy. All plausible progenitors, ranging from NS-NS mergers to various hypernova-like scenarios, eventually lead to the formation of a black hole with a debris torus around it, so that the extractable energy is of the same order, \(10^{54}\) ergs, in all cases. MHD conversion of gravitational energy into kinetic and radiation energy can significantly increase the probability of observing large photon fluxes, although significant collimation may achieve the same effect with neutrino annihilation in short bursts. The lifetime of the debris torus is dictated by a variety of physical processes, such as viscous accretion and various instabilities; these mechanisms dominate at different stages in the evolution of the torus and provide for a range of gamma-ray burst lifetimes.

Subject headings: Gamma-rays: Bursts — Stars: Evolution — Cosmology: Miscellaneous — Accretion

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1. Introduction

The discovery of afterglows in the last year has moved the investigation of gamma-ray bursts (GRB) to a new plane. It not only has opened the field to new wavelengths and extended observations to longer time scales, making the identification of counterparts possible, but also provided confirmation for much of the earlier work on the fireball shock model of GRB, in which the $\gamma$-ray emission arises at radii of $10^{13} - 10^{15}$ cm (Rees & Mészáros 1992, 1994, Mészáros & Rees 1993, Paczyński & Xu 1994, Katz 1994, Sari & Piran 1995). In particular, this model led to the prediction of the quantitative nature of the signatures of afterglows, in substantial agreement with subsequent observations (Mészáros & Rees 1997a, Costa et al. 1997, Vietri 1997a, Tavani 1997, Waxman 1997; Reichart 1997, Wijers et al. 1997). More recently, significant interest was aroused by the report of an afterglow for the burst GRB971214 at a redshift $z = 3.4$, whose fluence corresponds to a $\gamma$-ray energy of $10^{53.5} (\Omega_\gamma/4\pi)$ erg (Kulkarni et al. 1998). There is also possible evidence that some fraction of the detected afterglows may arise in relatively dense gaseous environments. This is suggested, e.g. by evidence for dust in GRB970508 (Reichart 1998), the absence of an optical afterglow and presence of strong soft X-ray absorption in GRB 970828 (Groot et al. 1997, Murakami et al. 1997), the lack an an optical afterglow in the (radio-detected) afterglow of GRB980329 (Taylor et al. 1998), etc. This has led to the suggestion that “hypernova” models (Paczyński 1998, Fryer & Woosley 1998) may be responsible, since hypernovae are thought to involve the collapse of a massive star or its merger with a compact companion, both of which would occur on time scale short enough to imply a burst within the star forming region. By contrast, neutron star - neutron star (NS-NS) or neutron star - black hole (NS-BH) mergers would lead to a similar BH plus debris torus system and roughly the same total energies (a point not generally appreciated), but the mean distance traveled from birth is of order several kpc (Bloom, Sigurdsson & Pols 1998), leading to a burst presumably in a less dense environment. The fits of Wijers & Galama (1998) to the observational data on GRB 970508 and GRB 971214 in fact suggest external densities in the range of 0.04–0.4 cm$^{-1}$, which would be more typical of a tenuous interstellar medium. In any case, while it is at present unclear which, if any, of these progenitors is responsible for the bulk of GRB, or whether perhaps different progenitors represent different subclasses of GRB, there is general agreement that they all would be expected to lead to the generic fireball shock scenario mentioned above.

2. Trigger Mechanisms and Black Hole/Debris Torus Systems

The first detailed investigations of the disruption of a NS in a merger with another NS or a BH were carried out by Lattimer & Schramm (1976), and the significance of this work for GRB has only recently started to be appreciated. It has become increasingly apparent in the last few years that all plausible GRB progenitors suggested so far (e.g. NS-NS or NS-BH mergers, Helium core - black hole [He/BH] or white dwarf - black hole [WD-BH] mergers, and a wide category labeled as hypernova or collapsars including failed supernova Ib [SNe Ib], single or binary Wolf-Rayet [WR]
collapse, etc.) are expected to lead to a BH plus debris torus system. An important point is that the overall energetics from these various progenitors do not differ by more than about one order of magnitude.

Two large reservoirs of energy are available in principle: the binding energy of the orbiting debris, and the spin energy of the black hole (Mészáros & Rees, 1997b). The first can provide up to 42% of the rest mass energy of the disk, for a maximally rotating black hole, while the second can provide up to 29% of the rest mass of the black hole itself. The \( \nu \bar{\nu} \rightarrow e^+ e^- \) process (Eichler et al. 1989) can tap the thermal energy of the torus produced by viscous dissipation. For this mechanism to be efficient, the neutrinos must escape before being advected into the hole; on the other hand, the efficiency of conversion into pairs (which scales with the square of the neutrino density) is low if the neutrino production is too gradual. Typical estimates suggest a fireball of \( \lesssim 10^{51} \) erg (Ruffert et al 1997, Popham, Woosley & Fryer 1998), except perhaps in the “collapsar” or failed SN Ib case where Popham et al. (1998) estimate \( 10^{52.3} \) ergs for optimum parameters. If the fireball is collimated into a solid angle \( \Omega_j \) then of course the apparent “isotropized” energy would be larger by a factor \( (4\pi/\Omega_j) \), but unless \( \Omega_j \) is \( \lesssim 10^{-2} - 10^{-3} \) this may fail to satisfy the apparent isotropized energy of \( 10^{53.5} \) ergs implied by a redshift \( z = 3.4 \) for GRB 971214. An alternative way to tap the torus energy is through dissipation of magnetic fields generated by the differential rotation in the torus (Paczyński 1991, Narayan, Paczyński & Piran 1992, Mészáros & Rees 1997b, Katz 1997). Even before the BH forms, a NS-NS merging system might lead to winding up of the fields and dissipation in the last stages before the merger (Mészáros & Rees 1992, Vietri 1997a). The above mechanisms tap the energy available in the debris torus or disk. However, a hole formed from a coalescing compact binary is guaranteed to be rapidly spinning, and, being more massive, could contain more energy than the torus; the energy extractable in principle through MHD coupling to the rotation of the hole by the Blandford & Znajek (1977) effect could then be even larger than that contained in the orbiting debris (Mészáros & Rees 1997b, Paczyński 1998). Collectively, any such MHD outflows have been referred to as Poynting jets.

The various progenitors differ only slightly in the mass of the BH and that of the debris torus they produce, and they may differ more markedly in the amount of rotational energy contained in the BH. Strong magnetic fields, of order \( 10^{15} \) G, are needed needed to carry away the rotational or gravitational energy in a time scale of tens of seconds (Usov 1994, Thompson 1994). If the magnetic fields do not thread the BH, then a Poynting outflow can at most carry the gravitational binding energy of the torus. For a maximally rotating and for a non-rotating BH this is 0.42 and 0.06 of the torus rest mass, respectively. The torus or disk mass in a NS-NS merger is \( M_d \sim 0.1 M_\odot \) (Ruffert & Janka 1998), and for a NS-BH, a He-BH, WD-BH merger or a binary WR collapse it may be estimated at \( M_d \sim 1 M_\odot \) (Paczyński 1998, Fryer & Woosley 1998). In the HeWD-BH merger and WR collapse the mass of the disk is uncertain due to lack of calculations on continued accretion from the envelope, so \( 1 M_\odot \) is just a rough estimate. The largest energy reservoir is therefore, ‘prima facie’, associated with NS-BH, HeWD-BH or binary WR collapse, which have
larger disks and fast rotation, the maximum energy being $\sim 8 \times 10^{53} \epsilon (M_d/M_\odot)$ ergs; for the failed SNe Ib (which is a slow rotator) it is $\sim 1.2 \times 10^{53} \epsilon (M_d/M_\odot)$ ergs, and for the (fast rotating) NS-NS merger it is $\sim 0.8 \times 10^{53} \epsilon (M_d/0.1M_\odot)$ ergs, where $\epsilon$ is the efficiency in converting gravitational into MHD jet energy. Conditions for the efficient escape of a high-$\Gamma$ jet may, however, be less propitious if the “engine” is surrounded by an extensive envelope.

If the magnetic fields in the torus thread the BH, the rotational energy of the BH can be extracted via the B-Z (Blandford & Znajek 1977) mechanism (Mészáros & Rees 1997b). The extractable energy is $\epsilon f(a)M_{bh}c^2$, where $\epsilon$ is the MHD efficiency factor and $a = Jc/GM^2$ is the rotation parameter, which equals 1 for a maximally rotating black hole. $f(a) = 1 - \sqrt{\frac{3}{2}}[1 + \sqrt{1 - a^2}]$ is small unless $a$ is close to 1, where it sharply rises to its maximum value $f(1) = 0.29$, so the main requirement is a rapidly rotating black hole, $a \gtrsim 0.5$. For a maximally rotating BH, the extractable energy is therefore $0.29\epsilon M_{bh} c^2 \sim 5 \times 10^{53} \epsilon (M_{bh}/M_\odot)$ ergs. Rapid rotation is essentially guaranteed in a NS-NS merger, since the radius (especially for a soft equation of state) is close to that of a black hole and the final orbital spin period is close to the required maximal spin rotation period. Since the central BH will have a mass of about $2.5 M_\odot$ (Ruffert & Janka 1998), the NS-NS system can thus power a jet of up to $\sim 1.3 \times 10^{54} \epsilon (M_{bh}/2.5M_\odot)$ ergs. The scenarios less likely to produce a fast rotating BH are the NS-BH merger (where the rotation parameter could be limited to $a \leq M_{ns}/M_{bh}$, unless the BH is already fast-rotating) and the failed SNe Ib (where the last material to fall in would have maximum angular momentum, but the material that was initially close to the hole has less angular momentum). A maximal rotation rate may also be possible in a He-BH merger, depending on what fraction of the He core gets accreted along the rotation axis as opposed to along the equator (Fryer & Woosley 1998), and the same should apply to the binary fast-rotating WR scenario, which probably does not differ much in its final details from the He-BH merger. For a fast rotating BH of $3M_\odot$ threaded by the magnetic field, the maximal energy carried out by the jet is then $\sim 1.6 \times 10^{54} \epsilon (M_{bh}/3M_\odot)$ ergs.

Thus in the accretion powered jet case the total energetics between the various models differs at most by a factor 20, whereas in the rotationally (B-Z) powered cases they differ by at most a factor of a few, depending on the rotation parameter. For instance, even allowing for low total efficiency (say 30%), a NS-NS merger whose jet is powered by the torus binding energy would only require a modest beaming of the $\gamma$-rays by a factor $(4\pi/\Omega_j) \sim 20$, or no beaming if the jet is powered by the B-Z mechanism, to produce the equivalent of an isotropic energy of $10^{53.5}$ ergs. The beaming requirements of BH-NS and some of the other progenitor scenarios are even less constraining.

### 3. Intrinsic Time scales

A question which has remained largely unanswered so far is what determines the characteristic duration of bursts, which can extend to tens, or even hundreds, of seconds. This is of course
very long in comparison with the dynamical or orbital time scale for the “triggers” described in section 2. While bursts lasting hundreds of seconds can easily be derived from a very short, impulsive energy input, this is generally unable to account for a large fraction of bursts which show complicated light curves. This hints at the desirability for a “central engine” lasting much longer than a typical dynamical time scale. Observationally (Kouveliotou et al. 1993) the short ($\lesssim 2$ s) and long ($\gtrsim 2$ s) bursts appear to represent two distinct subclasses, and one early proposal to explain this was that accretion induced collapse (AIC) of a white dwarf (WD) into a NS plus debris might be a candidate for the long bursts, while NS-NS mergers could provide the short ones (Katz & Canel 1996). As indicated by Ruffert et al. (1997), $\nu\bar{\nu}$ annihilation will generally tend to produce short bursts $\lesssim 1$ s in NS-NS systems, requiring collimation by $10^{-1} - 10^{-2}$, while Popham, Woosley & Fryer (1998) argued that in collapsars and WD/He-BH systems longer $\nu\bar{\nu}$ bursts may be possible. Longer bursts however imply lower $e^\pm$ conversion efficiency, so the observed fluxes could then be explained only if the jets were extremely collimated, by at least $10^{-3} - 10^{-4}$. We outline here several possible mechanisms, within the context of the basic compact merger or collapse scenario leading to a BH plus debris torus, which can lead to an adequate energy release on such time scales.

If the trigger of a long-duration burst involves a black hole, then an acceptable model requires that the surrounding torus should not completely drain into the hole, or be otherwise dispersed, on too short a time scale. There have been some discussions in the literature of possible ’runaway instabilities’ in relativistic tori (Nishida et al. 1996, Abramowicz, Karas & Lanza 1997, Daigne & Mochkovitch 1997): these are analogous to the runaway Roche lobe overflow predicted, under some conditions, in binary systems. These instabilities can be virulent in a torus where the specific angular momentum is uniform throughout, but are inhibited by a spread in angular momentum. In a torus that was massive and/or thin enough to be self-gravitating, bar-mode gravitational instabilities could lead to further redistribution of angular momentum and/or to energy loss by gravitational radiation within only a few orbits. Whether a torus of given mass is dynamically unstable depends on its thickness and stratification, which in turn depends on internal viscous dissipation and neutrino cooling.

The disruption of a neutron star (or any analogous process) is almost certain to lead to a situation where violent instabilities redistribute mass and angular momentum within a few dynamical time scales (i.e. in much less than a second). A key issue for gamma ray burst models is the nature of the surviving debris after these violent processes are over: what is the maximum mass of a remnant disc/torus which is immune to very violent instabilities, and which can therefore in principle survive for long enough to power the bursts?

### 3.1. Magnetic torques and viscosity

Differential rotation may amplify magnetic fields until magnetic viscosity dominates neutrino viscosity. Moreover, the torques associated with a large scale magnetic field may also extract
energy and angular momentum by driving a relativistic outflow. If the trigger is to generate the burst energy, over a period 10–100 sec, via Poynting flux — either through a relativistic wind ‘spun off’ the torus or via the Blandford-Znajek mechanism — the required field is a few times $10^{15}$ G. A weaker field would extract inadequate power; on the other hand, if the large-scale field were even stronger, then the energy would be dumped too fast to account for the longer complex bursts.

How plausible are fields of this strength? Kluźniak and Ruderman (1998) point out that, starting with $10^{12}$ G, it only takes of order a second for simple winding to amplify the field to $10^{15}$ G; they argue further that magnetic stresses would then be strong enough for flares to break out. But amplification in a newly-formed torus could well occur more rapidly, for instance via convective instabilities, as in a newly formed neutron star (cf. Duncan & Thompson 1992, Thompson 1994). Such fields can build up on very short time scales, or order ~ few ms; however, convective overturning motions should stop after the disk has cooled by neutrino emission below a few MeV. The latter is generally estimated to be of order a few seconds (Ruffert et al, 1997). But azimuthal magnetic fields can also be generated via the Balbus-Hawley mechanism. The nonlinear evolution and/or reconnection of such fields as they become buoyant can then lead to poloidal components at least of order $\gtrsim 10^{15}$ G. Indeed, it is not obvious why the fields cannot become even higher. Note that the virial limit is $B_v \sim 10^{17}$ G.

After magnetic fields have built up to some fraction of the equipartition value with the shear motion, a magnetic viscosity develops. Assuming that $B_r B_\phi \sim B^2$, it can be characterized in the usual way by the parameter $\alpha \sim B^2/(4\pi \rho v_s^2) \sim 10^{-1} B_{15}^2 \rho_{13}^{-1} T_9^{-1}$. This viscosity continues operating also after cooling has led to the disappearance of neutrino viscosity. Assuming a value of $\alpha = 0.1$, a BH mass $3 M_\odot$ and outer disk radius equal to the Roche lobe size, Popham et al. (1998) estimate “viscous” life times of 0.1 s for NS/BH-NS, 10–20 s for a collapsar (failed SN Ib or rotating WR), and 15–150 s for WD-BH and He-BH systems (although fields of $10^{15}$ G may be more difficult to support in He-BH systems).

A magnetic field configuration capable of powering the bursts is likely to have a large scale structure. Flares and instabilities occurring on the characteristic (millisecond) dynamical time scale would cause substantial irregularity or intermittency in the overall outflow that would manifest itself in internal shocks (Rees & Mészáros , 1994). There is thus no problem in principle in accounting for sporadic large-amplitude variability, on all time scales down to a millisecond, even in the most long-lived bursts. Note also that it only takes a residual cold disk of $10^{-3} M_\odot$ to confine a field of $10^{15}$ G, which can extract energy from the black hole via the Blandford-Znajek mechanism. Even if the evolution time scale for the bulk of the debris were no more than a second, enough may remain to catalyse the extraction of enough energy from the hole to power a long-lived burst.
3.2. Double peaked bursts

There are at least two mechanisms which might lead to a delayed “second” burst (or a double humped burst). One possibility is that a merger leads to a central NS, temporarily stabilized by its fast rotation, with a disrupted debris torus around it, which produces a burst powered by the accretion energy and the magnetic fields generated by the shear motions. After the NS has radiated enough of its angular momentum, and accreted enough matter to overcome its centrifugal support, it collapses to a BH, leading to a second burst, and second cycle of energy extraction (either from the disk or from the BH via B-Z). In both cases, the time scale between bursts should be between a few to few tens of seconds.

The other possibility for a delayed second burst may arise in merging NS of very unequal masses. As the smaller one fills its Roche lobe and losses mass, the larger NS (which may also collapse to a BH) is surrounded by the gas acquired from its companion, producing a burst as above. Eventually the less massive donor comes under the critical mass for deleptonization, and this leads to an explosion (e.g. Eichler et al. 1989). Starting from a configuration with about \(0.1M_\odot\) which losses mass to its companion, Sumiyoshi et al. (1998) (see also Kluzniak & Lee 1998, Portegies Zwart 1998) find that the explosion occurs in a time scale of about 20 s. The importance of this process depends on the poorly known distribution of NS-NS binary mass ratios, and on whether the mass transfer between neutron stars of nearly equal mass can be stable.

4. Isotropic or Beamed Outflows?

*Conversion into relativistic outflow.* Even if the outflow is not narrowly beamed, the energy of a fireball would be channeled preferentially along the rotation axis. Moreover, we would expect baryon contamination to be lowest near the axis, because angular momentum flings material away from the axis, and any gravitationally-bound material with low angular momentum falls into the hole. In hypernova and SNe Ib cases without a binary companion, however, the envelope is rotating only slowly and thus would not initially have a marked centrifugal funnel; a funnel might however develop after low angular momentum matter falls into the hole along the axis on a free-fall time scale measured from the outer radius of the envelope, \(t \sim 10^4 - 10^5\) s.

The dynamics are complex. Computer simulations of compact object mergers and black hole formation can address the fate of the bulk of the matter, but there are some key questions that they cannot yet tackle. In particular, high resolution of the outer layers is needed because even a tiny mass fraction of baryons loading down the outflow severely limits the attainable Lorentz factor — for instance a Poynting flux of \(10^{52}\) ergs could not accelerate an outflow to \(\Gamma > 100\) if it had to drag more than \(\sim 10^{-4}\) solar masses of baryons with it. Further 2D numerical simulations of the merger and collapse scenarios are under way (Fryer & Woosley 1998, Eberl, Ruffert & Janka 1998, McFayden & Woosley 1998), largely using Newtonian dynamics, and the numerical difficulties
are daunting. There may well be a broad spread of Lorentz factors in the outflow — close to the rotation axis $\Gamma$ may be very high; at larger angles away from the axis, there may be an increasing degree of entrainment, with a corresponding decrease in $\Gamma$. This picture suggests, indeed, that the variety of burst phenomenology could be largely attributable to a standard type of event being viewed from different orientations. As discussed in the last section, a variety of progenitors can lead to a very similar end result, whose energetics are within one order of magnitude from each other.

Basic spherical afterglow model. Just as we can interpret supernova remnants even without fully understanding the initiating explosion, so we may hope to understand the afterglows of gamma ray bursts, despite the uncertainties recounted in the previous section. The simplest hypothesis is that the afterglow is due to a relativistic expanding blast wave. The complex time structure of some bursts suggests that the central trigger may continue for up to 100 seconds. However, at much later times all memory of the initial time structure would be lost: essentially all that matters is how much energy and momentum has been injected; the injection can be regarded as instantaneous in the context of the much longer afterglow.

The simplest spherical afterglow model has been remarkably successful at explaining the gross features of the GRB 970228, GRB970508 and other afterglows (e.g. Wijers et al. 1997). This has led to the temptation to take the assumed sphericity for granted. For instance, the lack of a break in the light curve of GRB 970508 prompted Kulkarni et al. (1998a) to infer that all afterglows are essentially isotropic, leading to their very large (isotropic) energy estimate of $10^{53.5}$ ergs in GRB 971214. The multi-wavelength data analysis has in fact advanced to the point where one can use observed light curves at different times and derive, via parametric fitting, physical parameters of the burst and environment, such as the total energy $E$, the magnetic and electron-proton coupling parameters $\epsilon_B$ and $\epsilon_e$ and the external density $n$ (Waxman 1997, Wijers & Galama 1998). However, as emphasized by Wijers & Galama, 1998, what these fits constrain is only the energy per unit solid angle $E = (E/\Omega_j)$.

Properties of a Jet Outflow. An argument for sphericity that has been invoked by observers is that, if the blast wave energy were channeled into a solid angle $\Omega_j$ then, as correctly argued by Rhoads (1997, 1998), one expects a faster decay of $\Gamma$ after it drops below $\Omega_j^{-1/2}$. A simple calculation using the usual scaling laws leads then to a steepening of the flux power law in time. The lack of such an observed afterglow downturn in the optical has been interpreted as further supporting the sphericity of the entire fireball. There are several important caveats, however. The first one is that the above argument assumes a simple, impulsive energy input (lasting $\lesssim$ than the observed $\gamma$-ray pulse duration), characterized by a single energy and bulk Lorentz factor value. Estimates for the time needed to reach the non-relativistic regime, or $\Gamma < \Omega_j^{-1/2} \lesssim$ few, could then be under a month (Vietri 1997, Huang, Dai & Lu 1998), especially if an initial radiative regime with $\Gamma \propto r^{-3}$ prevails. It is unclear whether, even when electron radiative time scales are shorter than the expansion time, such a regime applies, as it would require strong electron-proton coupling (Mészáros, Rees & Wijers 1998). Waxman, et al. (1998) have also argued on observational
grounds that the longer lasting $\Gamma \propto r^{-3/2}$ (adiabatic regime) is more appropriate. Furthermore, even the simplest reasonable departures from a top-hat approximation (e.g. having more energy emitted with lower Lorentz factors at later times, which still do not exceed the gamma-ray pulse duration) would drastically extend the afterglow lifetime in the relativistic regime, by providing a late “energy refreshment” to the blast wave on time scales comparable to the afterglow time scale (Rees & Mészáros 1998). The transition to the $\Gamma < \Omega_j^{-1/2}$ regime occurring at $\Gamma \sim$ few could then occur as late as six months to more than a year after the outburst, depending on details of the brief energy input. Even in a simple top-hat model, more detailed calculations show that the transition to the non-relativistic regime is very gradual ($\delta t/t > 2$) in the light curve. Also, even though the flux from the head-on part of the remnant decreases faster, this is more than compensated by the increased emission measure from sweeping up external matter over a larger angle, and by the fact that the extra radiation, which arises at larger angles, arrives later and re-fills the steeper light curve. The sideways expansion thus actually can slow down the flux decay (Panaitescu & Mészáros 1998), rather than making for a faster decay.

As already noted by Katz & Piran (1997), the ratio $L_\gamma/L_{\text{opt}}$ (or $L_\gamma/L_x$) can be quite different from burst to burst. The fit of Wijers & Galama for GRB 970508 indicates an afterglow (X-ray energies or softer) energy per solid angle $E_{52} = 3.7$, while at $z = 0.835$ with $h_{70} = 1$ the corresponding $\gamma$-ray $E_{52,\gamma} = 0.63$. On the other hand for GRB 971214, at $z = 3.4$, the numbers are $E_{52} = 0.68$ and $E_{52,\gamma} = 20$. The bursts themselves require ejecta with $\Gamma > 100$. The gamma-rays we receive come only from material whose motion is directed within one degree of our line of sight. They therefore provide no information about the ejecta in other directions: the outflow could be isotropic, or concentrated in a cone of angle (say) 20 degrees (provided that the line of sight lay inside the cone). At observer times of more than a week, the blast wave would be decelerated to a moderate Lorentz factor, irrespective of the initial value. The beaming and aberration effects are less extreme so we observe afterglow emission not just from material moving almost directly towards us, but from a wider range of angles.

The afterglow is thus a probe for the geometry of the ejecta — at late stages, if the outflow is beamed, we expect a spherically-symmetric assumption to be inadequate; the deviations from the predictions of such a model would then tell us about the ejection in directions away from our line of sight. It is quite possible, for instance, that there is relativistic outflow with lower $\Gamma$ (heavier loading of baryons) in other directions (e.g. Wijers, Rees & Mészáros 1997); this slower matter could even carry most of the energy (Paczyński, 1997). This hypothesis is, if anything, further reinforced by the fits of Wijers & Galama (1998) mentioned above.

Observational constraints on beaming. As discussed above, anisotropy in the burst outflow and emission affects the light curve at the time when the inverse of the bulk Lorentz factor equals the opening angle of the outflow. If the critical Lorentz factor is less than 3 or so (i.e. the opening angle exceeds 20°) such a transition might be masked by the transition from ultrarelativistic to mildly relativistic flow, so quite generically it would difficult to limit the late-time afterglow opening angle in this way if it exceeds 20°. Since some afterglows are unbroken power laws for
over 100 days (e.g. GRB 970228), if the energy input were indeed just a a simple impulsive top-hat
the opening angle of the late-time afterglow at long wavelengths is probably greater than 1/3, i.e.
\( \Omega_{\text{opt}} \gtrsim 0.4 \). However, even this still means that the energy estimates from the afterglow assuming
isotropy could be 30 times too high.

The gamma-ray beaming is much harder to constrain directly. The ratio of \( \Omega_{\gamma}/\Omega_{x} \) has been
considered by Grindlay (1998) using data from Ariel V and HEAO-A1/A2 surveys, who did not
find evidence for a significant difference between the deduced gamma-ray and X-ray rates, and
concluded that higher sensitivity surveys would be needed to provide significant constraints. More
promising for the immediate future, the ratio \( \Omega_{\gamma}/\Omega_{\text{opt}} \) can also be investigated observationally
(see also Rhoads 1997). The rate of GRB with peak fluxes above 1 ph cm\(^{-2}\) s\(^{-1}\) as determined
by BATSE is about 300/yr, i.e. 0.01/sq. deg/yr. According to Wijers et al. (1998) this flux
corresponds to a redshift of 3. If the gamma rays were much more narrowly beamed than the
optical afterglow there should be many ‘homeless’ afterglows, i.e. ones without a GRB preceding
them. The transient sky at faint magnitudes is poorly known, but there are two major efforts
under way to find supernovae down to about \( R = 23 \) (Garnavich et al. 1998, Perlmutter et al.
1998). These searches have by now covered a few tens of square degree years of exposure and
would be sensitive to afterglows of the brightness levels thus far observed. It therefore appears
that the afterglow rate is not more than a few times 0.1/sq. deg/yr. Since the magnitude limit of
these searches allows detection of optical counterparts of GRB brighter than 1 ph cm\(^{-2}\) s\(^{-1}\) it is
fair to conclude that the ratio of homeless afterglows to GRB is at most a few tens, say 20. It then
follows that \( \Omega_{\gamma} > 0.05\Omega_{\text{opt}} \), which combined with our limit to \( \Omega_{\text{opt}} \) yields \( \Omega_{\gamma} > 0.02 \). The true rate
of events that give rise to GRB is therefore at most 600 times the observed GRB rate, and the
opening angle of the ultrarelativistic, gamma-ray emitting material is no less than 5\(^{\circ}\). Combined
with the most energetic bursts, this begins to pose a problem for the neutrino annihilation type of
GRB energy source.

Obviously, the above calculation is only sketchy and should be taken as an order of magnitude
estimate at present. However, with the current knowledge of afterglows a detailed calculation of
the sensitivity of the high-redshift supernova searches to GRB afterglows is feasible, and a precise
limit can be set by such a study.

5. Conclusions and Prospects

Simple blast wave models seem able to accommodate the present data on afterglows. However we can at present only infer the energy per solid angle; as yet the constraints on the angle-integrated \( \gamma \)-ray energy are not strong. We must also remain aware of other possibilities. For instance, we may be wrong in supposing that the central object becomes dormant after the gamma-ray burst itself. It could be that the accretion-induced collapse of a white dwarf, or (for some equations of state) the merger of two neutron stars, could give rise to a rapidly-spinning, temporarily rotationally stabilized pulsar. The afterglow could then, at least in part, be due to a
pulsar’s continuing power output. It could also be that mergers of unequal mass neutron stars, or neutron stars with other compact companions, lead to the delayed formation of a black hole. Such events might also lead to repeating episodes of accretion and orbit separation, or to the eventual explosion of a neutron star which has dropped below the critical mass, all of which would provide a longer time scale, episodic energy output.

We need to be open minded, yet also not too sanguine, about the possibility of there being more subclasses of classical GRB than just short ones and long ones. For instance, GRB with no high energy pulses (NHE) appear to have a different (but still isotropic) spatial distribution than those with high energy (HE) pulses (Pendleton et al. 1996). Some caution is needed in interpreting this, since selection effects could lead to a bias against detecting HE emission in dim bursts (Norris, 1998). Then, there is the apparent coincidence of GRB 980425 with the SN Ib/Ic 1998bw (Galama et al. 1998). A simple but radical interpretation (Wang & Wheeler 1998) is that all GRB may be associated with SNe Ib/Ic and differences arise only from different viewing angles relative to a very narrow jet. The difficulties with this are that it would require extreme collimations by factors $10^{-3} - 10^{-4}$, and that the statistical association of any subgroup of GRB with SNe Ib/Ic (or any other class of objects, for that matter) is so far not significant (Kippen et al. 1998). If however the GRB 980425/1998bw association is real, as argued by Woosley, Eastman & Schmidt (1998), Iwamoto et al. (1998) and Bloom et al. (1998), then we may be in the presence of a new subclass of GRB with lower energy $E_\gamma \sim 10^{48} (\Omega_j/4\pi)$ erg, which is only rarely observable even though its comoving volume density could be substantial. In this, more likely interpretation, the great majority of the observed GRB would have the energies $E_\gamma \sim 10^{54} (\Omega_j/4\pi)$ ergs as inferred from high redshift observations.

Much progress has been made in understanding how gamma-rays can arise in fireballs produced by brief events depositing a large amount of energy in a small volume, and in deriving the generic properties of the long wavelength afterglows that follow from this (Rees 1998). There still remain a number of mysteries, especially concerning the identity of their progenitors, the nature of the triggering mechanism, the transport of the energy and the time scales involved. Nevertheless, even if we do not yet understand the intrinsic gamma-ray burst central engine, they may be the most powerful beacons for probing the high redshift ($z > 5$) universe. Even if their total energy is reduced by beaming to a “modest” $\sim 10^{52} - 10^{52.5}$ ergs in photons, they are the most extreme phenomena that we know about in high energy astrophysics. The modeling of the burst itself — the trigger, the formation of the ultrarelativistic outflow, and the radiation processes — is a formidable challenge to theorists and to computational techniques. It is, also, a formidable challenge for observers, in their quest for detecting minute details in extremely faint and distant sources. And if the class of models that we have advocated here turns out to be irrelevant, the explanation of gamma-ray bursts will surely turn out to be even more remarkable and fascinating.

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