

Gamma-Ray Bursts: The Central Engine

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Abstract. A variety of arguments suggest that the most common form of gamma-ray bursts (GRBs), those longer than a few seconds, involve the formation of black holes in supernova-like events. Two kinds of “collapsar” models are discussed, those in which the black hole forms promptly - a second or so after iron core collapse - and those in which formation occurs later, following “fallback” over a period of minutes to hours. In most cases, extraction of energy from a rapidly accreting disk (and a rapidly rotating black hole) is achieved by magnetohydrodynamical processes, although neutrino-powered models remain viable in cases where the accretion rate is $\gtrsim 0.05 M_{\odot} \text{ s}^{-1}$. GRBs are but one observable phenomenon accompanying black hole birth and other possibilities are discussed, some of which (long, faint GRBs and soft x-ray transients) may await discovery. Since they all involve black holes of similar mass accreting one to several M_{\odot} , collapsars have a nearly standard total energy, around 10^{52} erg, but both the fraction of that energy ejected as highly relativistic matter and the distribution of that energy with angle can be highly variable. An explanation is presented why inferred GRB luminosity might correlate inversely with time scales and arguments are given against the production of ordinary GRBs by supergiant stars.

GENERAL GRB MODEL REQUIREMENTS

Given the locations afforded by x-ray and optical afterglows, redshifts have now been determined for approximately 10 GRBs so that we have at least a small sampling of GRB energies [5]. They are by no means standard candles. Even discounting the unusual case of GRB 980425 (8×10^{47} erg), energies range from about 5×10^{51} erg (GRB 980613) to 2×10^{54} erg (GRB 990123). In addition, GRB time profiles and spectra are very diverse and separate into at least two classes - the “short-hard” bursts (with average duration 0.3 s) and the “long-soft” bursts (average duration 20 s). The first challenge any model builder must confront is deciding just which GRBs, and which features, he or she is attempting to model since it is increasingly doubtful that all GRBs are to be explained in the same way. Moreover, in all of today’s models, the gamma-rays observed from a cosmological

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GRB are produced far from the site where the energy is initially liberated - presumably conveyed there by relativistic outflow or jets. How much of what we see in GRB reflects the central engine and how much the environment where the outflow dissipates its energy? So our first step is to define the problem we are attempting to address.

Even after the dramatic progress of the last two years, few definitive statements can be made about GRBs without provoking controversy. Still, in 1999, most people feel that the following are facets of a common GRB that the central engine must provide:

- 1) Highly relativistic outflow - $\Gamma \gtrsim 100$, possibly highly collimated.
- 2) An event rate that, at the BATSE threshold and in the BATSE energy range, is about 1/day. Beaming, of course, raises this number appreciably.
- 3) Total energy in relativistic ejecta $\sim 10^{53} - 10^{54} \epsilon_\gamma^{-1} f_\Omega$ erg where ϵ_γ is the efficiency for turning relativistic outflow into gamma-rays ($\sim 10\%$?), and f_Ω is the fraction of the sky into which that part of the flow having sufficiently high Γ ($\gtrsim 100$) is collimated ($\sim 1\%$?). For reasonable values of these parameters, the total energy required for a common GRB is 10^{52} erg. Fainter GRBs can result from the same 10^{52} erg event if the efficiency for producing relativistic matter is reduced (e.g., GRB 980425); brighter ones if the collimation is tighter.
- 4) A duration of relativistic flow in our direction no longer than the duration of the GRB. This constraint is highly restrictive for the short (0.3 s) bursts and may imply multiple models. For GRB models produced by internal shocks, the flow may additionally need to last *as long as* the GRB (*modulo* the relativistic time dilation). This makes a natural time scale ~ 10 s attractive.
- 5) In the case of long bursts, association with star forming regions in galaxies and, in perhaps three cases, with supernovae of Type I.

The near coincidence of 10^{52} erg with the energy released in the gravitational collapse of a stellar mass object to a neutron star (or, equivalently, the accretion disk of a black hole), has long suggested a link between GRBs and neutron star or black hole formation, a connection championed by Paczynski before cosmological models became fashionable. Viable models separate into three categories (Table 1), where ϵ_{MHD} is the unknown efficiency for magnetohydrodynamical processes to convert either gravitational accretion energy at the last stable orbit ($\sim 0.1 \dot{M} c^2$) or neutron star rotational energy into relativistic outflow. Those using black hole accretion [6,7,14,9] typically employ 1 - 10% for ϵ_{MHD} ; pulsar advocates [16,17] need approximately 100%.

The collapsar model is incapable of producing relativistic jets of total duration less than a few seconds (hence short hard bursts are difficult - impossible unless the beam orientation wanders). Merging neutron stars and black holes, on the other

TABLE 1. Gravitational collapse models for GRBs

Model	Energy Source	Mass Reservoir	Possible Energy	Jet From	^{56}Ni /SN	Beaming
n*+n*,BH	BH accretion	0.01 - 0.5 M_{\odot}	10^{50} $10^{53}\epsilon_{\text{MHD}}$	$\nu\bar{\nu}$ MHD	No	$\sim 10\%?$
collapsar	BH accretion	1 - 5 M_{\odot}	10^{52} $10^{54}\epsilon_{\text{MHD}}$	$\nu\bar{\nu}$ MHD	Yes	0.1% - 10%
pulsar	n* rotation		$10^{52}\epsilon_{\text{MHD}}$	MHD	?	$\sim 1\%?$

hand, can produce short bursts if the disk viscosity is high (i.e., $\alpha \sim 0.1$), but cannot, with the same disk viscosity, produce long bursts. Merging neutron stars also lack the massive disks that help to focus the outflow in collapsars and it may be more difficult for them to emit highly collimated jets. Hence their “equivalent isotropic energies” may be smaller (unless MHD collimation dominates). It seems more natural to associate the merging compact objects with short hard bursts, but this conjecture presently lacks any observational basis. Hopefully future observations, with e.g. HETE-2, will clarify whether short bursts are associated with host galaxies in the same way as the long ones.

The pulsar based models have not been studied nearly as extensively as either the collapsar or merging compact objects, perhaps because the MHD phenomena they rely on are difficult to simulate numerically. The magnetic fields and rotation rates invoked for the pulsar models, though large ($P \sim \text{ms}$; $B \sim 10^{15}$ gauss), are not much greater than employed for the disk in MHD collapsar models. However, it is not at all clear how such models would make the large mass of ^{56}Ni inferred for SN 1998bw or the highly collimated flow required to explain energetic events like GRB 990123. Also, the bare pulsar version of the model [16] ignores the effects of neutrino-powered winds and the supernova-based version [17] ignores the collapse of the massive star that would continue, at least at some angles, during the few seconds it takes the pulsar to acquire its large field. A complete calculation of the implosion of the iron core of a massive star, including the coupled effects of rotation, magnetic fields, and neutrinos has not been done, but could be in the next decade.

COLLAPSARS - TYPE 1

We thus consider here a model that can, in principle, satisfy the five constraints above, at least for long bursts, and has the added virtue of being calculable, with a few assumptions, on current computers. A *collapsar* is a massive star whose iron

core has collapsed to a black hole that is continuing to accrete at a very high rate. The matter that it accretes, that is the helium and heavy elements outside the iron core, is further assumed to have sufficient angular momentum ($j \sim 10^{16} - 10^{17} \text{ cm}^2 \text{ s}^{-1}$) to form a centrifugally supported disk outside the last stable orbit. The black hole is either born with, or rapidly acquires a large Kerr parameter. It may also be possible to create a situation quite similar to a collapsar in the merger of the helium core of a massive star with a black hole or neutron star [4].

What follows has been discussed in the literature [7,8,1]. The black hole accretes matter along its rotational axis until the polar density declines appreciably. Accretion is impeded in the equatorial plane by rotation. The accretion rate through the disk is insensitive to the disk viscosity because a steady state is rapidly set up in which matter falls into the hole at a rate balancing what is provided by stellar collapse at the outer boundary. The mass of the accretion disk is inversely proportional to the disk viscosity and accretion rates $0.01 - 0.1 M_{\odot} \text{ s}$ are typical during the first 20 s as the black hole grows from about $3 M_{\odot}$ to about 4 or $5 M_{\odot}$. The accretion rate may be highly time variable down to intervals as short as 50 ms [7], and an appreciable fraction of the matter passing through the disk is ejected as a powerful “wind” that itself carries up to a few $\times 10^{51}$ erg and a solar mass [7,15]. Given the high temperature in the disk, this disk wind will, after some recombination, probably be mostly ^{56}Ni . This may be the origin of the light curve of SN 1998bw and other supernovae associated with GRBs.

Disk accretion also provides an energy source for jets. In the simplest, but perhaps least efficient version of the collapsar model, energy is transported from the very hot ($\sim 5 \text{ MeV}$) inner disk to the rotational axis by neutrinos. Neutrinos arise from the capture of electron-positron pairs on nucleons in the disk and deposit a small fraction of their energy, $\sim 1\%$, along the axis where the geometry is favorable for neutrino annihilation. The efficiency factor for neutrino energy transport is a sensitive function of the accretion rate, black hole mass and Kerr parameter, and the disk viscosity [13]. Only in cases where the accretion rate exceeds about $0.05 M_{\odot} \text{ s}^{-1}$ for black hole masses $3 - 5 M_{\odot}$ and disk viscosities, $\alpha \sim 0.1$, will neutrino transport be significant. Using the actual accretion rate, Kerr parameter, hole mass as a function of time, and $\alpha \sim 0.1$, MacFadyen finds for a helium core of $14 M_{\odot}$, a total energy available for jet formation up to $\sim 10^{52}$ erg. The typical time scale for the duration of the jet, and a lower bound for the duration of the GRB, is ~ 10 s, the dynamical time scale for the helium core.

In addition to any neutrino energy transport, one has the possibility of magnetohydrodynamical processes which could, in principle, efficiently convert a large fraction of the binding energy at the last stable orbit, up to $42\% \dot{M}c^2$, into jet energy. Adopting a more conservative value, $\epsilon_{\text{MHD}} \sim 1\%$ [8], one still obtains $10^{52} - 10^{53}$ erg available for jet formation. Dumping this much energy into the natural funnel-shaped channel that develops when a rotating star collapses gives rise to a hydrodynamically collimated jet focused into $\sim 1\%$ of the sky [7,8,1]. Magnetic collimation though uncertain, could, in principle, increase the collimation factor still further.

Thus jets of equivalent isotropic energy 10^{54} , and possibly 10^{55} erg (if, e.g., $\epsilon_{\text{MHD}} \sim 0.1$) seem feasible in this model. The event rate of collapsars is also adequate [3].

The collapsar model also makes several “predictions” some of which have already been confirmed (these same predictions were inherent in the original 1993 model [18]. First, the GRB should originate from massive stars, in fact the *most* massive stars, and be associated with star forming regions. In fact, given the need for large helium core mass, collapsars may be favored not only by rapid star formation, but also by low metallicity. This reduces the loss of both mass and of angular momentum. Pre-explosive mass loss also provides a natural explanation for the surrounding medium needed to make the GRB afterglows and makes a prediction that the density decline as r^{-2} . The GRB duration, ~ 10 s, corresponds to the collapse time scale of the helium core. The explosion is expected to be highly collimated, though just how collimated was not realized until 1998 [7]. The jet blows up the star in which it is made so one expects some kind of supernova. Since the presence of a massive hydrogen envelope prohibits making a strong GRB, the supernova must be of Type I (a possible exception would be an extreme Type IIb supernova, one that had lost all but a trace of hydrogen in its surface). That the explosion might also produce a lot of ^{56}Ni from a disk powered wind was not appreciated until [7]. Without the ^{56}Ni , the supernova would have been very dim, which is why I originally referred to the collapsar model as a “failed supernova”.

It also seems natural that both the variable accretion rate [7] and the hydrodynamical interaction of the jet with the star which it penetrates may introduce temporal structure into the burst. Implications for GRB diversity are discussed in §4.

COLLAPSARS - TYPE 2

It is also possible to produce a collapsar in a delayed fashion by fallback in an otherwise successful supernova [8]. A spherically symmetric explosion is launched in the usual way by neutron star formation and neutrino energy transport, but the supernova shock has inadequate strength to explode the whole star. Over a period of minutes to hours a variable amount of mass, ~ 0.1 to $5 M_{\odot}$, falls back into the collapsed remnant, often turning it into a black hole [19] and establishing an accretion disk. The accretion rate, ~ 0.001 to $0.01 M_{\odot} \text{ s}^{-1}$, is inadequate to produce a jet mediated by neutrino annihilation [13], but MHD processes may still function with the same efficiency as in the Type 1 collapsar (or merging neutron stars, for that matter). Then the total energy depends not on the accretion rate, but the total mass that reimplodes. For $1 M_{\odot}$ and $\epsilon_{\text{MHD}} = 1\%$, this is still 10^{52} erg.

A key difference is the time scale, now typically 10 - 100 times longer. Thus the most likely outcome of a Type 2 collapsar in a star that has lost its hydrogen envelope is a less luminous, but longer lasting GRB. Indeed, there exist GRBs that have lasted hundreds of seconds and there may be a class of longer, fainter GRBs

awaiting detection. Since black holes may be more frequently produced by fall back than by failure of the central engine [2], these sorts of events might even be more common than ordinary GRBs.

Both kinds of collapsars can also occur in stars that have *not* lost their envelopes. Stars with lower metallicity have less radiative mass loss so that solitary stars (or widely detached binaries) might also end their lives with both a rapidly rotating massive helium and a hydrogen envelope. Because the motion of the jet head through the star is sub-relativistic [1] and because fall back only maintains a high accretion rate for 100 - 1000 s, highly relativistic jets will not escape red supergiants with radii $\gtrsim 10^{13}$ cm. What happens in more compact blue supergiants is less certain. Generally speaking, the largest fall back masses will characterize the weakest supernova explosions and also have the shortest fall back time scales. With a jet head speed of 10^{10} cm s⁻¹, it would have taken 300 s, for example, to cross the blue progenitor of SN 1987A. The fall back mass in 87A is believed to have been $\lesssim 0.1 M_{\odot}$, probably inadequate to turn the neutron star into a black hole and certainly too little to make a powerful GRB, but perhaps enough to make a jet anyway - or at least cause some mixing. Larger mass helium cores (87A was $6 M_{\odot}$) might have more fall back though, definitely making black holes and more energetic jets. Whether the jet can still have a large Lorentz factor remains to be calculated.

Even if they do not make GRBs, collapsar powered jets in blue and red supergiant stars may still lead to very energetic, asymmetric supernova explosions, possibly accompanied by large ⁵⁶Ni production and luminous soft x-ray transients due to shock breakout [8]. These transients may have luminosity up to $\sim 10^{49}$ erg s⁻¹ times the fraction of the sky to which high energy material is ejected (typically 0.01) and color temperatures of 2×10^6 K.

GRB DIVERSITY

As previously noted, the inferred total energy in gamma-rays for those GRBs whose distances have been determined is quite diverse. One appealing aspect of the collapsar model is that its outcome is sufficiently variable to explain this diversity. The observed burst intensity is sensitive not only to the jet's total energy, but also to the fraction of that energy in the observer's direction that has Lorentz factor Γ above some critical value (~ 100). Most collapsars accrete about the same mass, 1 - $3 M_{\odot}$, before accretion is truncated by the explosion of the star. For an efficiency factor of 1%, this implies a total jet (and disk wind) energy of $\sim \text{few} \times 10^{52}$ erg. However, depending on the initial collimation of the jet, its internal energy (or equivalently the ratio of its pressure to its kinetic energy flux), and its duration, very different outcomes can result. A poorly collimated jet, or one that loses its energy source before breaking through the surface of the star may only eject a little mildly relativistic matter and make, e.g., GRB 980425. A focused, low entropy jet that lasts ~ 10 s after it has broken free of its stellar cocoon might make GRB

990123.

Duration can be affected by such things as the presupernova mass and angular momentum distribution. Internal energy depends on details of the jet acceleration. Neutrino powered jets, for example, have much higher internal energies than some MHD jets and may be harder to focus. Hydrodynamical focusing of the jet also depends on the density distribution in the inner disk, which in turn depends on disk viscosity and accretion rate. And of course the efficiency factor need not always be 1%, e.g., for neutrino-powered models and MHD models.

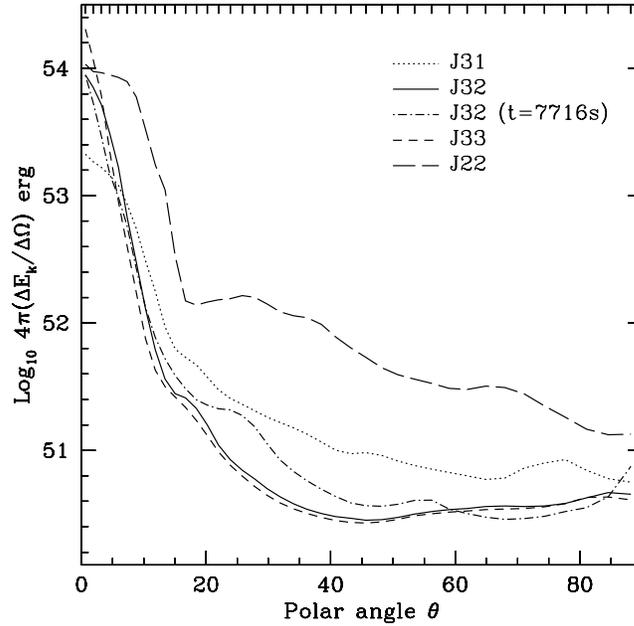


FIGURE 1. Equivalent isotropic energy as a function of angle for several models.

Calculations [8,1] illustrate this. Fig. 1 shows the “equivalent isotropic kinetic energy” as a function of polar angle for three models having the same total jet energy, 3×10^{51} erg, at the base. All models except the dot-dash line for J22 are shown 400 s after the initiation of the jet, well after it has broken out of the helium core. The three models differ only in the ratio of internal energy to kinetic energy given to the jet at its base. Yet, even for a constant viewing angle, $\theta = 0$, the inferred isotropic energies vary by an order of magnitude. Larger variations are possible if one goes to other values of viewing angle - *not* because the GRB is being viewed “from the side”, but because the material coming at the observer has both less energy and a lower Lorentz factor. Thus it is also possible that GRB 980425 was a more typical GRB viewed off axis [10], but not in the sense of a single highly relativistic beam which emitted a few photons in our direction. Instead we saw emission from matter coming towards us with a lower Γ .

Fig. 2 is not the result of any current calculation, but just a sketch to illustrate

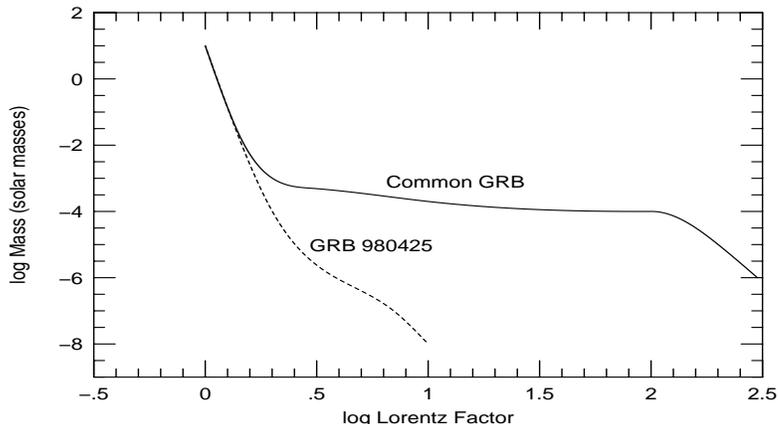


FIGURE 2. Mass ejected vs. Lorentz factor for two hypothetical models.

what calculations may ultimately show. (See, for comparison, Fig. 4 of [1], a first pass at one collapsar model using a code with the necessary relativistic hydrodynamics. Unfortunately this calculation has not yet been run long enough to show the final distribution of Lorentz factors). There is a large concentration of mass, $\sim 10 M_{\odot}$, moving at sub-relativistic speeds. This is the supernova produced by the jet passing through the star. Though the speed is “slow”, most of the energy may be concentrated here if the jet did not last long enough or stay focused enough to become highly relativistic (dotted line). Then there is a relativistic ‘tail’ to the ejecta. Even though it is a small fraction of the mass, this tail could, in some cases, namely the common GRBs, contain most of the energy in the explosion.

Table 2 indicates some of the diverse outcomes that might arise. Here R_{15} is an approximate radius in units of 10^{15} cm where the material might give up its energy. A typical Wolf-Rayet mass loss rate has been assumed for those cases where external shocks are clearly important (x-ray afterglows and GRB 980425). Supernovae also typically have a photospheric radius of 10^{15} cm. $\Omega/4\pi$ is the fraction of the sky into which the mass is beamed. The fractions sum to over 100% because the supernova is not beamed.

TIME VARIABILITY, LAG TIME, AND LUMINOSITY

At this meeting we also heard of two fascinating results with important implications for the use of GRBs as calibrated “standard candles” for cosmology.

TABLE 2. Relativistic mass ejected in two artificial models

Γ	M/M _⊙	E(erg)	$\Omega/4\pi$	R ₁₅ (10 ¹⁵ cm)	Comment
Common GRB					
100	10 ⁻⁴	10 ⁵²	< 1%	< 3	GRB
10	10 ⁻⁴	5 × 10 ⁵¹	10%	3	X-ray tail
1	10	5 × 10 ⁵¹	100%	1	SN Ib/c
GRB 980425					
7	10 ⁻⁷	10 ⁴⁸	10%	0.01	GRB 980425
2	10 ⁻⁵	10 ⁵⁰	20%	10	X-ray, radio afterglow
1	10	10 ⁵²	100%	1	SN 1998bw

Ramirez-Ruiz and Fenimore (Paper T-04) discussed a correlation between “variability” and luminosity. The more rapidly variable the light curve, the higher the absolute luminosity. Norris, Marani, & Bonnell [11] also showed data to support a high degree of (anti-)correlation between absolute luminosity and the “time lag”, the delay time between the arrival of hard and soft-subpulses. The shorter the lag, the brighter the burst.

Both these effects may be understood as an outcome of Fig. 1. The bursts for which we infer the highest luminosities are those that are observed straight down the axis of the jet, $\theta = 0$. This is also the angle at which we see the largest Lorentz factors. Slightly away from $\theta = 0$, both the equivalent isotropic energy and Γ drop precipitously.

For larger Lorentz factors, the burst will be produced closer to the source. Ref. [12] gives a thinning radius where the GRB becomes optically thin to Thomson scattering that is proportional to $\Gamma^{-1/2}$. The distance where internal shocks form from two shells having Lorentz factors Γ_1 and Γ_2 is $\Gamma_1\Gamma_2c\Delta t$. For smaller radii and larger Γ , time scales will thus be contracted. That is larger Γ may imply more time structure on shorter scales and perhaps reduced lag times as well. Then variability and time lags would be related to the equivalent isotropic energy because both are functions of the viewing angle.

GRB 980425 is an exception since its GRB was produced by a external shock interaction between mildly relativistic matter and the presupernova mass loss.

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