Collapsars, Gamma-Ray Bursts, and Supernovae

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A diverse range of phenomena is possible when a black hole experiences very rapid accretion from a disk due to the incomplete explosion of a massive presupernova star endowed with rotation. In the most extreme case, the outgoing shock fails promptly in a rotating helium star, a black hole and an accretion disk form, and a strong gamma-ray burst (GRB) results. However, there may also be more frequently realized cases where the black hole forms after a delay of from several tens of seconds to several hours as ~0.1 to 5 $M_\odot$ falls back into the collapsed remnant following a mildly successful supernova explosion. There, the same MHD mechanisms frequently invoked to produce GRBs would also produce jets in stars already in the process of exploding. The presupernova star could be a Wolf-Rayet star or a red or blue supergiant. Depending upon its initial pressure, the collimation of the jet may also vary since "hot" jets will tend to diverge and share their energy with the rest of the star. From these situations, one expects diverse outcomes ranging from GRBs with a large range of energies and durations, to asymmetric, energetic supernovae with weak GRBs. SN 1998bw may have been the explosion of a star in which fall back produced a black hole and a less collimated jet than in the case of prompt black hole formation.

1. Introduction

In recent years, our theoretical understanding of common GRBs has moved out of the "dark ages" of the 1980's into a BATSE and Beppo-Sax inspired "rennaisance". The burst and its afterglow in various wavelengths have been successfully modeled as the interaction of a highly relativistic jet ($\gamma \gtrsim 100$) with itself (internal shocks) and with circumstellar or interstellar material - the so called "relativistic fireball model" (e.g., Piran 1999; Meszaros 1999). The origin of the jet is still widely debated, but is generally believed to involve the formation of a stellar mass (approximately 2 to 5 $M_\odot$) black hole and the rapid accretion of matter into that hole from a disk. Modes of forming the black hole vary (e.g., Fryer, Woosley, & Hartmann 1999), as do assumptions regarding the accretion rate, duration, and means of extracting disk binding energy and converting it into the relativistic motion of the jet. For accretion rates in excess of ~0.05 $M_\odot$ s^{-1} neutrino energy transport may be efficient (Popham, Woosley, & Fryer 1999). For lower accretion rates, and perhaps also for the higher ones, MHD processes - magnetic field reconnection in the disk, extraction of black hole spin energy, Alfven waves, magneto-centrifugal winds, etc. - are invoked.

As our understanding of GRBs has improved, an interesting "paradigm shift" has also been going on in the modeling of supernovae. For the last 30 years, most researchers have assumed a Type II (or Ib) supernova to be a consequence of neutrinos extracting a portion of the binding energy of a newly formed neutron star. The neutrinos then deposit a portion of their energy in a low density region just outside the neutron star and the resulting "bubble" of pairs and radiation explodes the rest of the star. There have been interesting exceptions along the way (e.g., LeBlanc & Wilson 1970; Bodenheimer &

Woosley 1983), but, for the most part, researchers have preferred their supernovae round and without magnetic fields.

Three things have happened lately to make us suspect that this is not always the way supernovae work (though, admittedly, the exceptions may be rare). First, we have observed supernovae, notably SN 1997cy and SN 1998bw, that do not fit the traditional mold (Germany et al. 1999; Galama et al. 1998), supernovae that seem to require an order of magnitude more energy than the traditional mechanism provides and which may be associated with GRBs. Second, models for GRBs have converged on a massive presupernova star - and its explosion as a "hypernova" - as one leading candidate. Finally, supernovae may have been observed as the counterparts to two or more GRBs (990425, Galama et al. 1998; 980326, Bloom et al. 1999; 970228, Reichart 1999). Rather suddenly, the supernova community and GRB community have awakened to realize just how much they have in common.

In this paper, we explore this interface between GRBs and supernovae. We find that massive stars can produce a variety of energetic explosions ranging from traditional supernovae (by far the most frequent occurrence) to energetic GRBs, and seemingly all points in between. Ordinary supernovae still come from neutron star formation in the approximately spherically symmetric explosion of a massive ($M \gtrsim 8\ M_\odot$) star with little or no fall back, but failed or weak explosions in rotating stars give hyper-accreting black holes whose jets can both explode the star in a grossly asymmetric way and produce a variety of high energy phenomena.

2. GRB Models

One leading model for a GRB involves a neutron star merging with another neutron star or with a black hole. Either way, after the merger, a black hole ends up accreting $\sim$0.01 $M_\odot$ (neutron star companion) to, at most, $\sim$0.5 $M_\odot$ (black hole companion) from a Keplerian disk. Even for this relatively simple model, assumptions and results vary widely. If the disk viscosity is high, say $\alpha \gtrsim 0.01$, the disk becomes very hot and emits its binding energy as neutrinos. Neutrino annihilation along the axis may then energize the jet (Ruffert & Janka 1999; Janka, Ruffert, & Eberl 1999; Janka et al. 1999; Rosswog et al. 1999). Since the efficiency for neutrino annihilation is small, typically $\lesssim$1%, and the viscous time scale, short ($\lesssim$100 ms), this variety of model produces relatively weak, brief jets, perhaps appropriate for the class of short, hard GRBs, but unlikely to explain long energetic events like those localized by BeppoSax. The MHD variety of this model (e.g., Meszaros 1999) assumes a much lower viscosity and thus a longer time scale for the accretion, up to tens of seconds. The merit of this sort of model is that one can assume (within a large error bar) a high efficiency for extracting energy from the disk or rotating hole. This greater energy and longer time scale are both necessary and sufficient to explain the most energetic bursts observed so far.

Another leading model, and the main subject of this paper, is the *collapsar*. A collapsar is a black hole formed by the incomplete explosion of a rapidly rotating massive star (Woosley 1993; MacFadyen & Woosley 1999, henceforth MW99). It sets up the same sorts of circumstances as the merging neutron star model for GRBs, but with a number of important distinctions: 1) the event occurs only in the most massive stars and thus tracks star formation directly; 2) a supernova is produced by every GRB because the jet not only makes a GRB, but explodes the star; 3) the amount of matter available for accretion (and thus the maximum energy available for the GRB) is one to three orders of magnitude greater than for merging compact objects; 4) the duration of the jet is set by the collapse time scale of the star, not by the disk viscous time scale; no very short bursts are possible; 5) the accretion rate is likely to be lower than for the neutrino version of merging neutron stars, but faster than some MHD versions; 6) the engine is deeply embedded in a star that the jet must penetrate in order to make the GRB; 7) the star is surrounded by an extended presupernova "wind zone" in which the mass density is proportional to r^{-2}; and 8) compared to merging neutron stars, the gravitational radiation accompanying the burst is very weak. The angular momentum one invokes in the collapsar model is also much less certain than for compact objects merging by gravitational radiation. Once the disk is set up, however, the same physics that makes jets in merging neutron star models, be it neutrinos or MHD, should work equally well for collapsars. The interaction of this jet with the rest of the star and with the stellar wind is a challenging problem in radiation-hydrodynamics, but one that is tractable.

One often sees allusions to both a "hypernova" (Paczynski 1998) model and a collapsar model. We make no distinction here. We avoid the term hypernova as applied to GRBs because one of us previously used the same word to mean a super-bright pair-instability supernova (Woosley & Weaver 1982). However, to the extent that the term hypernova is used by the GRB community, it is an observational phenomenon caused by a collapsar.

3. Supernova Fallback

The simplest way, conceptually, to form a black hole in a massive star, and thus set up the conditions for the collapsar model, is for the traditional neutrino powered explosion to fail. The iron core collapses and within a second or so has made a black hole into which the rest of the star proceeds to accrete. This may be the common case for stars above about 35 - 40 $M_\odot$(Fryer 1999), although uncertainties in convection, mass loss, rotationally induced mixing, and the explosion mechanism itself make this an uncertain number - and one that may vary with redshift and metallicity. If the star loses its hydrogen envelope along the way, and if the jet produced by the accretion maintains its energy and focus for a longer time than it takes the jet to tunnel through the star, about 5 - 10 s, a common GRB is produced (MW99). Otherwise a weaker, less collimated GRB results (helium star case; MacFadyen & Woosley 1998), or an energetic asymmetric supernova (§6).

However, there should also be a range of stellar masses for which a black hole is not made promptly, but after a "successful" shock has already been launched. The binding energies of stellar helium cores outside the collapsing iron core increases with their mass. The energy of the neutrino engine seems, if anything, to decrease with mass. Thus there is a range of masses, estimated by Fryer to be roughly 20 to 40 $M_\odot$, where a supernova occurs, but so much matter fails to achieve escape and falls back onto the neutron star that it turns into a black hole. This delayed production of a black hole is probably a more frequent occurence than prompt black hole formation.

As a representative case, consider a 25 $M_\odot$ main sequence star evolved with mass loss, rotationally induced mixing, and angular momentum transport (Heger, Woosley, & Langer 1999). This star ends its life as a red supergiant with an iron core of 1.90 $M_\odot$, a helium core of 8.06 $M_\odot$, and a low density envelope of 6.57 $M_\odot$ (total mass 14.6 $M_\odot$). The presupernova stellar radius is 8.1×10^{13} cm. The model has sufficient angular momentum in the equator ($j \sim 10^{17}$ cm^2 s^{-1}) to form an accretion disk outside the black hole.

Explosions were simulated in this star using a piston at the edge of the iron core (MacFadyen, Woosley, & Heger 1999). The motion of this piston was varied so as to produce a kinetic energy at infinity for the ejecta ranging from 0.255 $\times 10^{51}$ erg (Model 25A1) to 2.09 $\times 10^{51}$ erg (Model 25A16). The subsequent evolution was followed using

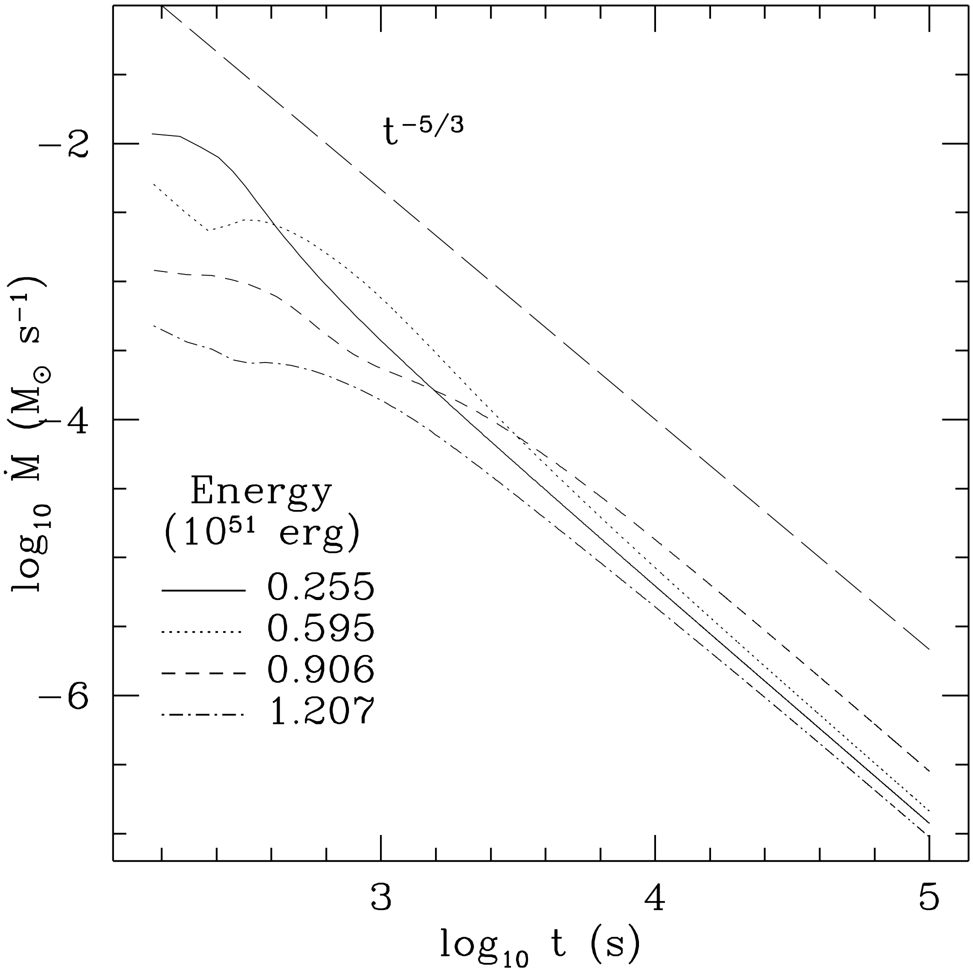

FIGURE 1. Accretion rates for fall back in four different explosions of a 25 $M_\odot$ presupernova star (see text). These five explosions gave kinetic energies at infinity for their ejecta of 0.255, 0.595, 0.906, and 1.207 $\times 10^{51}$ erg. The integrated fall back masses for these spherically symmetric calculations were 3.71, 2.85, 1.39 and 0.48 $M_\odot$ respectively. Characteristic time scales for the fallback are 100, 450, 1140, and 1060 s. Calculations were carried out using a one-dimensional version of the PROMETHEUS hydrodynamics code.

two different one-dimensional hydrodynamics codes, KEPLER (an implicit Lagrangian hydrodynamics code) and PROMETHEUS (an explicit Eulerian code). For similar assumptions regarding the launch of the shock and the inner boundary condition, the results of the two codes agreed. For energies above 1.5×10^{51} erg, all matter external to the piston was ejected, but for lower energies an increasing amount of mass fell back to the origin (Fig. 1). At late times the accretion rate followed the $t^{-5/3}$ scaling predicted by Chevalier (1989).

It is noteworthy that the accretion rate during the time most of the mass falls back, about 0.001 to 0.01 $M_\odot$ s^{-1}, is very similar to that frequently invoked in the MHD version of the merging neutron star model (§2), especially for the lower explosion energies. If jets are to form in one place, surely they should form in the other. However, for these relatively low accretion rates, the disk temperature will be too cool to emit neutrinos efficiently. Any jet that forms must be powered by MHD processes. If we make a simple *ansatz* that the jet energy, at any point in time, is an efficiency factor, ϵ, times $\dot{M}c^2$, with $\epsilon \sim 0.001 - 0.01$ (certainly modest compared to many assumptions in the literature), then the energy potentially available for making a jet in Model A01 is $\sim 10^{52} - 10^{53}$ erg. This is large compared both to the energy of the initial shock in Model 25A1 and the energy of a typical supernova.

4. Some General Considerations

Unfortunately, while a compelling case can be made, both on observational grounds (e.g., Livio 1999; Pringle 1993) and from theory (MacFadyen, Woosley, & Heger 1999) for linking the jet energy to the accretion rate, the energy alone does not define the model. One still needs to know the initial partition between internal and kinetic energy and the beaming angle. In "thermal" models, such as the neutrino version of merging neutron stars or collapsars, the initial energy is overwhelmingly in the form of radiation and pairs. In fact, the plasma starts at rest with $aT^4/\rho c^2 \sim \gamma_f \sim 100$. Expansion of the radiation converts internal energy into kinetic energy very far from the source. For Poynting flux models, on the other hand, the jet may be born relatively cold. The initial collimation of the jet may be either by pressure and density gradients, as in the collapsar of MW99, or by magnetic fields, or both. Lacking details of the jet formation process, ambiguity in the collimation angle and mass to energy ratio makes predictions difficult, but hot, poorly collimated jets will clearly have a harder time penetrating the star.

One also expects some systematic differences between cases in which the black hole forms promptly (Case A) or by fall back (Case B) that may bear on this issue of collimation. The lower accretion rate in Case B suggests a smaller disk mass in steady state (Popham et al. 1999) and the confining pressure of the medium through which the jet initially propagates will also be less in Case B, because the star has already partly exploded. In both Case A and B there will still be an inner disk that will help to collimate the initial outflow, but, depending upon how much mass falls back and its angular momentum, that disk may not extend to such large radii in Case B. All in all, one expects that the geometrical focusing of the jet at least, may not be so great in Case B, especially for thermal models. The extent of MHD collimation is, however, unknown.

Given an initially well collimated jet, one still faces a formidable computational task following its propagation out to, say, 1000 Schwarzschild radii. The jet is an inherently relativistic and can only be described accurately by a special relativistic (SR) calculation. To do less gives, at best, a qualitative description of the jet propagation while possibly generating unrealistic artifacts such as superluminal speeds (MW99). Special relativistic codes are available (e.g., Aloy et al.1999) and can be adapted to the problem, but, unfortunately, results are not yet available.

There are several SR effects worth keeping in mind though. First, a jet of radiation and matter has quite different properties, in SR, from one composed only of matter. In particular, the equivalent "dynamical" density, which must be regarded as a vector, is related to the rest mass density, n, by (Rosen et al. 1999)

$$\rho = 2n\gamma^2 \left(\frac{\gamma}{\gamma + 1} + \frac{\Gamma p}{(\Gamma - 1) n c^2} \right) \tag{4.1}$$

which clearly shows the increase of the effective ρ with γ and p. Here $\gamma = (1-(v/c)^2)^{-1/2}$, n is the rest mass density, Γ, the adiabatic index, and p, the pressure. As noted earlier, for a thermal model, p/nc^2 is initially about 100. As p turns into γ by expansion, the relativistic correction to the momentum becomes anisotropic and greatest along the jet. As a result, SR jets of radiation and matter have much more penetrating power than Newtonian jets with rest mass density, n.

Time dilation also plays an important role. In the frame of the jet, the star is crossed in a shorter time than in the lab frame. Yet perpendicular to the jet, motions remain sub-relativistic and clocks run at similar rates. Thus a SR jet loaded with radiation will diverge, in the laboratory frame, less than a similar Newtonian jet loaded with radiation. Indeed, in a Newtonian code, the sound speed and the jet speed would both be $\sim c$.

Together these effects help to explain why a jet, initially focused by the geometry of the accretion disk or by the magnetic field near the hole, but loaded with radiation, might maintain its collimation while its internal energy is converted into kinetic energy. Eventually, if the star is not too big, the jet escapes, reaches its asymptotic γ, and produces a GRB by running into circumstellar material.

However, we shall be particularly interested here in another case - jets that lose their energy before breaking out, share that energy with the star, and thus become only mildly relativistic. Our present calculations are, of necessity, carried out using a Newtonian version of PROMETHEUS, but we have attempted to capture the flavor of mildly relativistic jets as they propagate through the helium core and red giant envelope of an exploding star. To do so, we picked an inner boundary radius, 10^9 cm, which is computationally expedient (i.e., not too small), but still well within the helium core, and at about the radius where radiation and rest mass might start to become comparable (see, e.g., Fig. 26 of MW99), especially for MHD models in which the initial thermal loading of the jet is not so large. Besides the supernova structure when the jet starts to propagate, there are three key ingredients to the model, all specified at 10^9 cm: 1) the kinetic energy of the jet as a function of time, given by $\epsilon \dot{M} c^2$; 2) the opening angle of the jet, assumed to have a 10 degree half-angle, and 3) the ratio of internal pressure to kinetic energy, f_{P}. This last parameter turns out to be quite important. If the jet pressure is large compared to the stellar surroundings in which it propagates, the jet will diverge. If it is less, the jet may, under some circumstances, be hydrodynamically focused to a still smaller opening angle. For the calculations we shall consider, the pressure in the jet is dominantly due to radiation - though not by a large margin for the smaller values of f_{P}.

The principal effect of f_{P} is to increase the tendency of the jet to diverge. This divergence may, in fact have already occurred inside 10^9 cm. For a relativistic jet, the effective value of f_{P} would actually be much larger owing to the previously mentioned modification of the dynamical density and time dilation. In order to keep our jet velocities on our Newtonian grid below c however, we are compelled to study only $f_{\mathrm{P}} \lesssim 1$.

5. Some Representative Calculations

To illustrate the possible characteristics of supernovae exploded by jets, we calculated the two-dimensional evolution of Model 25A1 incorporating parameterized jets. Details of these and other similar calculations will be presented in a forthcoming paper (MacFadyen, Woosley, & Heger 1999). The spherically symmetric explosion, followed until 100 s after the launch of a weak shock in the KEPLER code, was remapped onto the Eulerian grid of a two-dimensional version of PROMETHEUS. This grid used 150 radial zones spaced logarithmically between an inner boundary at 10^9 cm and the outer boundary at 8.1×10^{13} cm. Forty angular zones concentrated near the pole were used to simulate one quadrant of the stellar volume, assuming axial and reflection symmetry across the equatorial plane. The angular resolution varied from 1.25° at the pole to 3.5° at the equator. At 100 s,

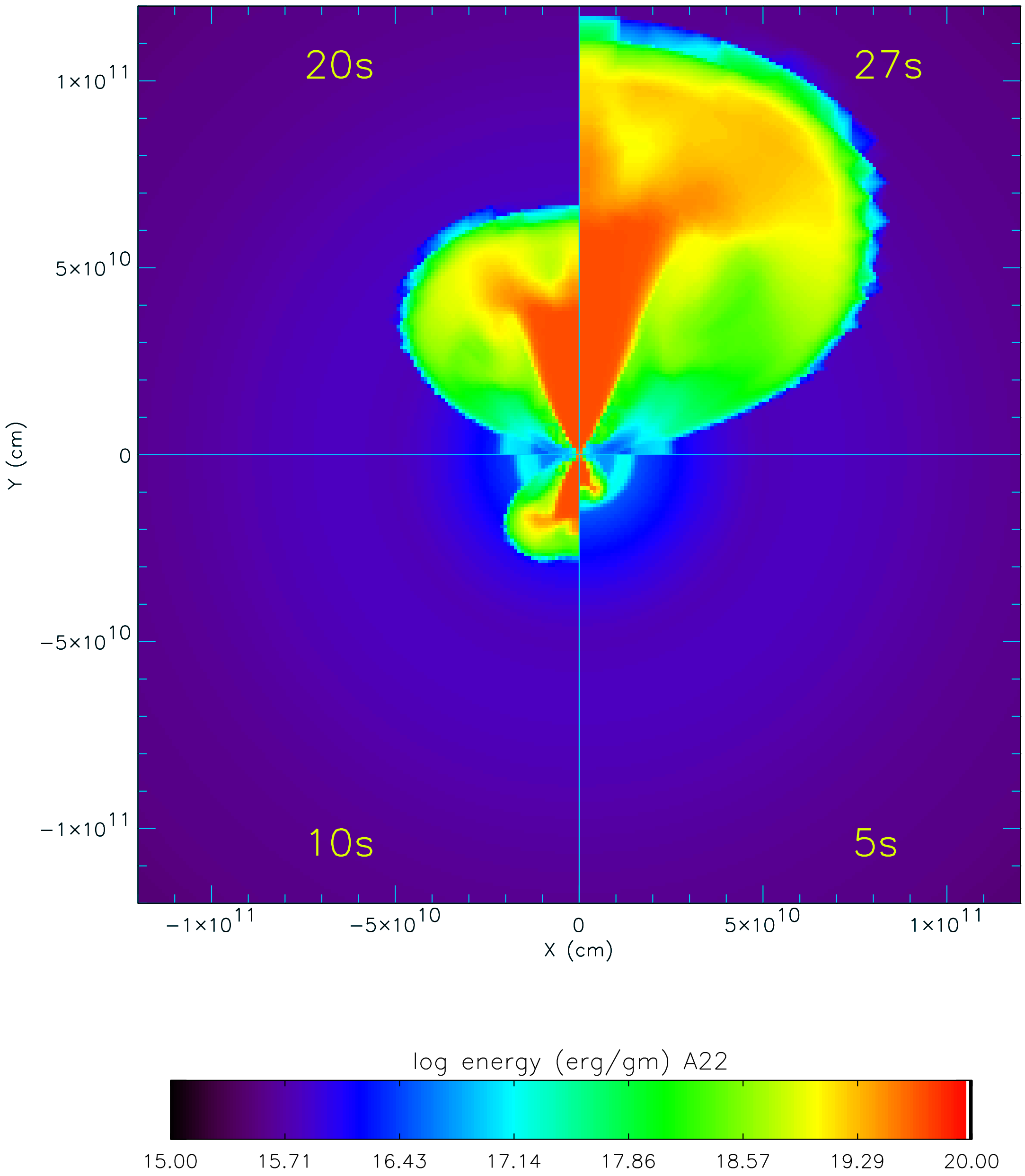

FIGURE 2. The total energy density of the jet and explosion is shown at times of 5, 10, 20 and 27 s after initiation for jet Model A22 (Table 1). The passage of the jet initiates a shock that propagates to lower latitudes, eventually exploding the entire star. The supernova shock can be seen at a radius of about 2×10^{10} cm.

the inner 1.99 $M_\odot$ of the star was removed and replaced by an open (zero radial gradient of all variables) boundary condition at 10^4 km. The 1.99 $M_\odot$ continued to contribute to the gravitational potential as a central point mass and mass accreting through the inner boundary was added to the point mass during the calculation. At this time the

TABLE 1: Explosion Characteristics at t = 400 s After Jet Initiation

Name	ϵ	f_P	Δ M ($M_\odot$)	E_{tot} (10^{51} ergs)	R($\theta > 10°$)	R($\theta > 20°$)
A33	0.001	0.001	2.76	3.38	0.075	0.037
A32	0.001	0.01	2.69	3.23	0.102	0.047
A31	0.001	0.1	2.51	3.00	0.425	0.256
A22	0.01	0.01	1.72	19.91	0.429	0.230

weak initial shock was already at 1.1×10^5 km when the jet was turned on at the inner boundary.

We gave the jet a constant velocity at this inner boundary, 10^{10} cm s^{-1}, a compromise between what the code could realistically calculate (v less than c) and the true relativistic nature of the initial jet. This velocity, the radius of the inner boundary, and the (Newtonian) kinetic energy of the jet implied a jet density, 1.9×10^3 g cm^{-3} $(\dot{M}/0.01 M_\odot \text{ s}^{-1})(\epsilon/0.01)$. This assumed that any internal energy deposited in the jet near the black hole had been decompressed by adiabatic expansion to the point where, at 10^9 cm, it was small compared to ρv^2.

We considered four cases, $\epsilon = 0.001$, $f_P = 0.001$, 0.01, and 0.1 and $\epsilon = 0.01$, $f_P = 0.01$. The results are summarized in Table 1 and Figs. 2 - 4. Here the name follows the convention "AMN" where "A" indicates the model was based upon the weakest explosion considered of a 25 $M_\odot$ (main sequence mass) supernova (0.255×10^{51} erg; Fig 1), "M" is the exponent of the efficiency factor, $\epsilon = 10^{-M}$, and "N" is the exponent of the pressure factor, $f_P = 10^{-N}$. The mass accreted, ΔM in Table 1, is smaller than the 3.71 $M_\odot$ computed without a jet (Fig. 1) for Model 25A1, because the jet impeded the accretion at high latitude and because the accretion was not quite over at after 500 seconds (Fig. 1). The total energy input by the jet was still $\epsilon \Delta M c^2$, but the number in Table 1 was reduced by the work done up to 500 s in unbinding the star and by the internal and kinetic energy which passed inside the inner boundary. The 2.55×10^{50} erg due to the initial shock has been subtracted in Table 1 so that E_{tot} reflects only the energy input by the jet.

The angular factor R($\theta > 10°$) is the ratio of the integral of the kinetic energy due to the jet outside 10 degrees polar angle (98.5% of the sky) to the total kinetic energy in the star due to the jet (see Fig. 4). These energies were computed by taking the total kinetic energy at 400 s after jet initiation in both regions and subtracting the kinetic energy of the initial supernova shock. R($\theta > 10°$) measures the extent to which the jet spread laterally and shared its energy with the rest of the star. The limiting case R=0 would correspond to a jet that shared none of its energy with the supernova outside an initial 10° polar angle. This sort of behavior is expected for "cold" jets with internal pressure small compared to the exploding helium core. The other extreme, where the jet shared its energy evenly with the entire star and produced a spherical explosion, would correspond to $R = \cos\theta = 0.985$. Our "hot" jets lie somewhere between these two limits. The quantity R($\theta > 20°$) was similarly computed for a polar angle of 20°. The isotropic limit there would be 0.940.

In all cases a very energetic asymmetric supernova resulted. Since the integrated mass of the (Newtonian) jet in our code was comparable to that of the stellar material within

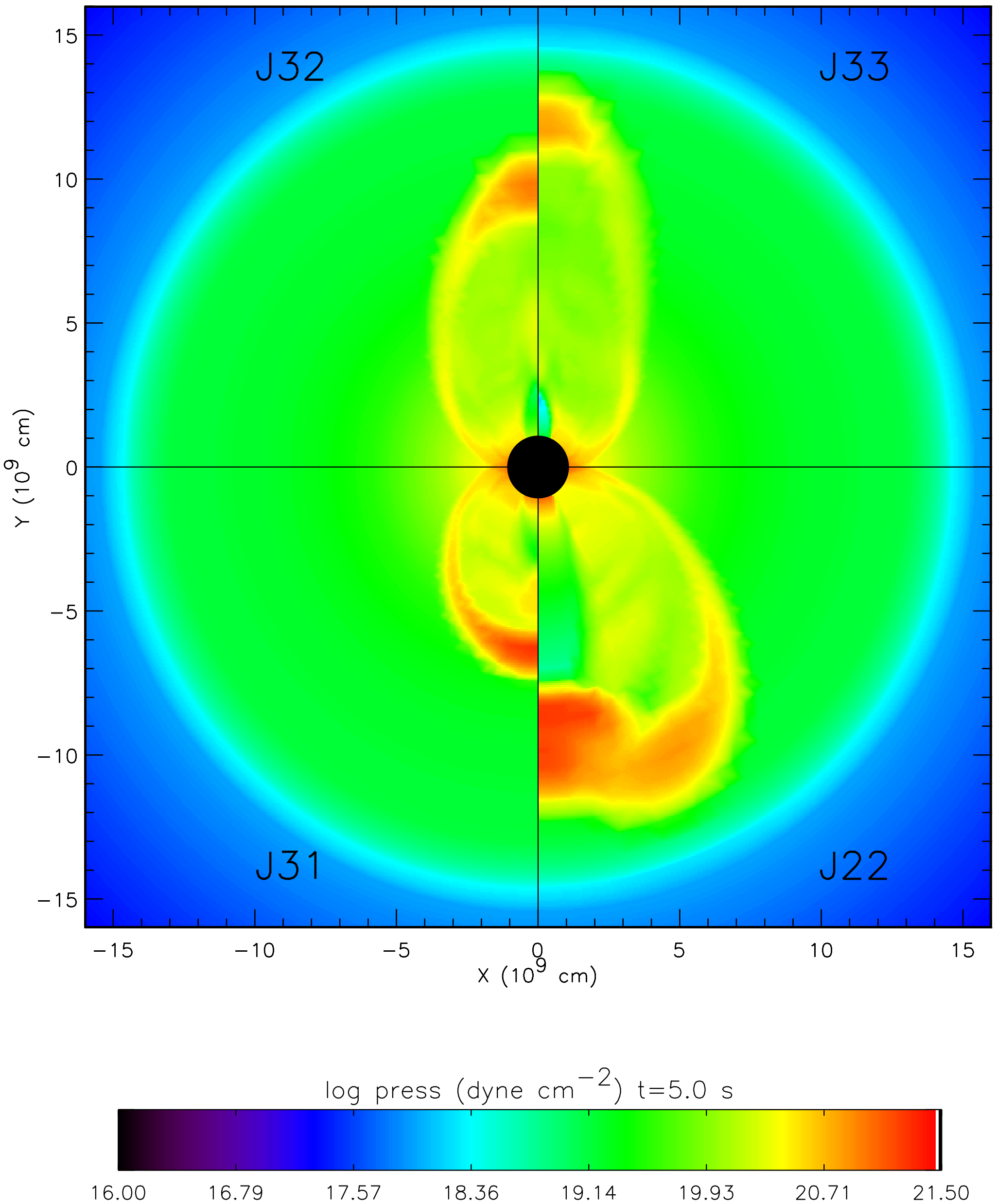

FIGURE 3. Pressure in the jet and surrounding star at 5.0 s after the initiation of the jet in four different models. Higher presure leads to greater jet divergence, more mass swept up, and slower propagation. Model A22 had a higher jet energy than the other models (Table 1).

10 degrees, the time for jet break out was approximately the stellar radius divided by the jet input speed. In reality, that would be $\sim R/c$, or for a red supergiant several thousand seconds. Since the energy of the jet engine had declined greatly by that time, due to the declining accretion rate (Fig. 1), and the jet had swept up far more than γ^{-1} of its rest mass, the jet that broke out was only mildly relativistic. Both the long time scale and

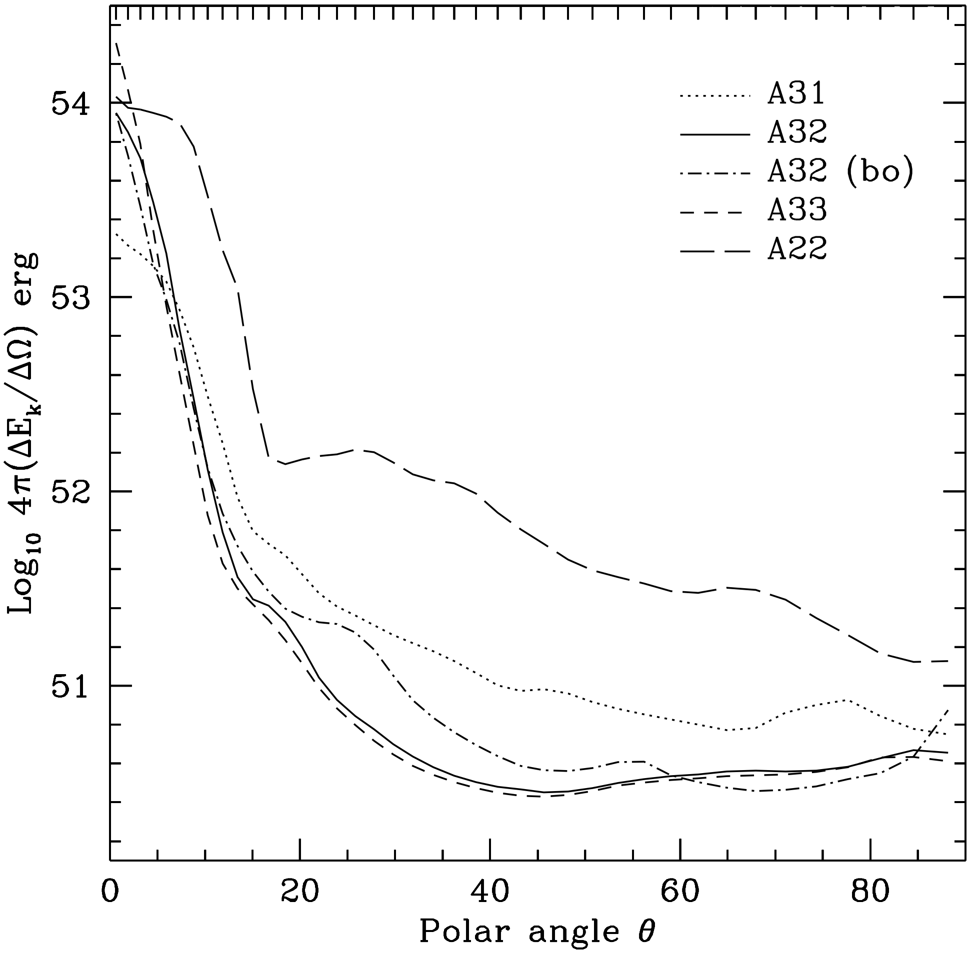

FIGURE 4. The "equivalent isotropic kinetic energy" as a function of polar angle for four models having variable energy efficiency factors and internal pressures (Table 1 and text). Model A32 is shown at two times, once at 400 s after the initiation of the jet and later, at 7716 s, as the jet penetrated the surface of the star at 8×10^{13}cm; dash-dot line. Other models are also shown for comparison at 400 s. Note that the degree of collimation is strongly dependent upon f_P. Equivalent isotropic kinetic energy is defined as the integral from the center to surface of the star of its kinetic energy in the solid angle subtended by θ and $\theta + \Delta\theta$ divided by the solid angle, $2\pi(\cos\theta - \cos(\theta + \Delta\theta))$ and multiplied by 4π. The injected energy at the base of the jet would be a flat line out to ten degrees with a value equal to $66\,\epsilon\Delta M c^2$ with ΔM in Table 1 and $66 = (1 - \cos(10°))^{-1}$. Tick marks along the top axis give the angular zoning of the two dimensional code.

the low energy input are inconsistent with what is seen in common GRBs. However, if the hydrogen envelope had been lost, a longer than typical GRB could have resulted.

Figs. 3 and 4 illustrate how the pressure balance between the jet and the star through which it propagates affected its collimation properties. The interaction at late times with the hydrogen envelope had relatively little effect on the angular energy distribution which was set chiefly by f_P and the interaction with the helium core. Model A33 had the lowest internal pressure (note that the actual value of the initial pressure depends upon the product of ϵ and $f_{\rm P}$). The final jet was collimated even more tightly than given by its initial injection. That is, a jet initially of 10 degrees half width will exit the star with a FWHM of less than two degrees, about 0.06% of the sky (though the angular resolution of the code is questionable for such small angles). Meanwhile the energy at larger angles was not much greater than that given by the initial, weak spherically symmetric explosion, $10^{50.4}$ erg. There was little sharing of the jet energy with the star and, except for the jet, the supernova energy remained low.

This is to be contrasted with Models A22 and A31 where the jet collimation was much weaker and much more energy was shared with the star. Note that though Model A22 had about 6 times the total energy of A31 owing to its larger ϵ the fraction of energy at large angles in both these models was significantly greater than in Models A32 and A33. Model A22 would be an especially powerful supernova as well as one accompanied by a jet.

6. Supernovae and GRB Diversity

Provided the necessary conditions for the collapsar model can be met - black hole formation in a massive star with sufficient angular momentum to make a disk - the discussion and results of the previous two sections suggest a wide variety of possible outcomes, including, besides ordinary GRBs:

"Smothered" and broadly beamed gamma-ray bursts; GRB 980425 - These can occur in helium stars in which the jet either fails to maintain sufficient focus (e.g., is too "hot" compared to the star through which it propagates), or loses its energy input before breaking out of the star ($\lesssim$10 s; MW99). An energetic supernova still occurs (SN 1998bw, in this case) and a weak GRB is produced, not by the jet itself, but by a strong, mildly relativistic shock from break out interacting with the stellar wind. (Woosley, Eastman, & Schmidt 1999). Because these events are so low in gamma-ray energy, many could go undetected by BATSE. Indeed these could be the most common form of GRB in the universe. Because the initial jet may be less effectively collimated in GRBs made by supernova fall back, it is tempting to associate these phenomena with delayed black hole formation and the stronger GRBs with prompt black hole formation. More study is needed.

Long gamma-ray bursts; $\tau_{\rm burst} \gtrsim 100$ *s* - Though typical "long, complex bursts" observed by BATSE last about 20 seconds, there are occasionally much longer bursts. For example, GRB950509, GRB960621, GRB961029, GRB971207, and GRB980703 all lasted over 300 s. These long durations may simply reflect the light crossing time of the region where the jet dissipates its energy (modulo γ^{-2}), especially in the "exterior shock model" for GRBs. However, if the event is due to internal shocks, the duration depends on the time the engine operates. Such long bursts would imply enduring accretion on a much longer time scale than one expects in the simplest collapsar model where the black hole forms promptly. The fallback powered models discussed in this paper could maintain a GRB for these long time scales (Fig. 1).

Very energetic supernovae - SN 1997cy - Germany et al. (1999) have called attention to this extremely bright supernova with an unusual spectrum. The supernova was Type IIn and its late-time light curve, which approximately followed the decay rate of ^{56}Co, would require $\gtrsim$2 $M_\odot$ of ^{56}Ni to explain its brightness. Perhaps this was a pair-instability supernova (Woosley & Weaver 1982; Heger, Woosley, & Waters 1999). On the other hand, circumstellar interaction could be the source of the energy and the agreement with $\tau_{1/2}(^{56}\mathrm{Co})$ merely fortuitous. This would require both a very high explosion energy and a lot of mass loss just prior to the supernova. The sort of model described in §5, especially Model A22, could provide the large energy in a massive star that would be naturally losing mass at a high rate when it died. But the radius is too large and the jet would share its energy with too great a mass to make a common GRB. Therefore we regard the detection of a short, hard GRB from the location of SN 1997cy as spurious.

Nucleosynthesis - ^{56}Ni and the r-process - An explosion of 10^{52} erg focused into 1% of the star (or 10^{53} erg into 10%) will have approximately the same shock temperature as a function of radius as an isotropic explosion of 10^{54} erg. From the simple expression $\frac{4}{3}\pi r^3 a T^4 \sim 10^{54}$ erg (Woosley & Weaver 1995), we estimate that a shock temperature in excess of 5 billion K will be reached for radii inside 4×10^9 cm. The mass inside that radius external to the black hole (assumed mass initially 2 $M_\odot$) depends on how much expansion (or collapse) the star has already experienced when the jet arrives. Provided the star has not expanded much before the jet arrives, an approximate number comes from the presupernova model, 3 $M_\odot$ times the solid angle of the explosion divided by 4 π, or $\sim$0.03 $M_\odot$. Additional ^{56}Ni is probably synthesized by the wind blowing off the accretion disk (MW99; Stone, Pringle, & Begelman 1999) and this may be the dominant source in supernovae like SN 1998bw.

The composition of the jet itself depends upon details of its acceleration that are hard to calculate. However it should originate from a region of high density and temperature (Popham, Woosley, & Fryer 1999). The high density will promote electron capture and lower Y_e. The high entropy, low Y_e, and rapid expansion rate are what is needed for the r-process (Hoffman, Woosley, & Qian 1997). The mass of the jet, $\sim 10^{-4}$ $M_\odot$ (corrected for relativity) is enough to contribute significantly to the r-process in the Galaxy even if the event rate was $\lesssim$1% that of supernovae and the jet carried only a fraction of its mass as r-process.

Soft x-ray transients from shock breakout - Focusing a jet of order 10^{52} ergs into 1 - 10% of the solid angle of a supernova results in a shock wave of extraordinary energy (Fig. 4). As it nears the surface of the star, this shock is further accelerated by the declining density gradient. MacFadyen, Woosley, & Heger (1999) estimate, for a 10^{54} erg (isotropic equivalent) shock, a break out transient of 10^{49} erg s^{-1} (times $(1 - \cos\theta_j)$, the solid angle of the jet at break out divided by 4π, where θ_j is the half opening angle of the jet at breakout) for $\sim$10 s. The color temperature at peak would be approximately 2×10^6 K (see also Matzner & McKee 1999). A 10^{53} erg shock gave a transient about half as hot and ten times longer and fainter. The impact of the mildly relativistic matter could give an enduring x-ray transient like the afterglows associated with some GRBs, even though the time scale is too long for the x-ray burst to be a common GRB itself.

Mixing in supernovae - SN 1987A - It is generally agreed (Arnett et al. 1989) that the explosion that gave rise to SN 1987A initially produced a neutron star of approximately 1.4 $M_\odot$. There may have been $\sim$0.1 $M_\odot$ of fallback onto that neutron star (Woosley 1988) and a black hole may or may not have formed. Again invoking our *ansatz* that $L_{\rm jet} = \epsilon \dot{M} c^2$, even for $\epsilon \sim 0.003$, we have a total jet energy of 6×10^{50} erg. This is about half of the total kinetic energy inferred for SN 1987A. Thus very appreciable mixing and asymmetry would be introduced by such a jet - *provided the material that fell back had sufficient angular momentum to accumulate in a disk outside the compact object.* However this would not be enough energy to make a powerful gamma-ray burst as proposed by Cen (1999).

Still to be discovered - It may be that, especially with common GRBs, we have just seen the "tip of the iceberg" of a large range of high energy phenomena powered by hyper-accreting, stellar mass black holes. We already mentioned the possibility of a large population of faint, soft bursts like GRB 980425. Other possibilities include very long GRBs below the threshold of BATSE, "orphan" x-ray afterglows from jet powered Type II supernovae, supernova remnants having toroidal structure, GRBs from the first explosions of massive stars after recombination, and more. It is an exciting time.

7. Does It All Work?

Exciting that is, if it all works as described. That a hyper-accreting black hole ($M_{\rm hole}$ = 2 to 10 $M_\odot$, accreting 10^{-1} - 10^{1} $M_\odot$ s^{-1}) gives rise to an energetic jet with dramatic observational consequences seems to us unavoidable. True the physics of jet formation is poorly understood, but the ubiquity of jets in all sorts of systems where disk accretion is going on, the success of the basic idea of AGN's as accreting massive black holes, and the identity of "microquasars" as accreting black holes all argue that this is an assumption worth exploring. That supernovae sometimes form black holes, both promptly and in a delayed manner, also seems unavoidable. Our calculatiions show that if a jet forms in a massive collapsing star, and if that jet has only a fraction of a per cent of the energy potentially available from the accretion process, that energetic supernovae and GRBs are a likely outcome.

The weakest assumption in all the models discussed here is that the requisite amount of angular momentum is present to form a disk. The best available stellar evolution models suggest it is there (Heger, Langer, & Woosley 1999), but these calculations have left out magnetic field effects that might lead to the dramatic slowing of the rotation of the helium core, especially in red supergiants (Spruit & Phinney 1998). These models also imply that neutron stars may be born rotating near break up. Whether either of these concerns will ultimately prove fatal to the model remains to be seen. Since GRBs are much rarer in the universe than supernovae, it is of course possible that the production of GRBs demands some very special circumstances, e.g., the merging of two stripped helium stars already in a late stage of evolution (Fryer, Woosley, & Hartmann 1999).

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