Gamma-Ray Bursts and Jet-Powered Supernovae

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Abstract. The last five years have seen growing challenges to the traditional paradigm of a core collapse supernova powered by the neutrino emission of a young proto-neutron star. Chief among these challenges are gamma-ray bursts (GRBs) and the supernovae that seem to accompany them. Here we review some recent - and not so recent - models for GRBs and supernovae in which strong magnetic fields, rotation, or accretion into a black hole play a role. The conditions for these energetic explosions are special and, at this point, there is no compelling reason to invoke them in the general case. That is, 99\% of supernovae may still operate in the traditional fashion.

1 Introduction

The demise of spherically symmetric models for supernovae can be traced to 1987. Though we certainly already understood that stars (and pulsars) rotated and had magnetic fields and that this might affect the explosion \cite{22}, that neutrino powered convection had to be included in any realistic model \cite{49}, and that instabilities would be encountered as the shock moved out \cite{3}, it was the clear evidence for mixing on a large scale in SN 1987A \cite{4} that drove us inexorably to multi-dimensional models. The migration was facilitated by developments in computer hardware and software that made multi-dimensional calculations practical. Still hope remained that, globally, things would still be pretty spherically symmetric. In particular, the shock wave coming out from the neutron star, though bounding regions that bubbled and mixed, was roughly spherical.

Events of similar significance happened in 1997, when it became clear that GRBs are located at cosmological distances \cite{10,44}, and again in 1998 when a supernova, SN 1998bw, was discovered in conjunction with a GRB. The supernova had very peculiar properties and, if modeled in one dimension (surely a gross approximation), had a kinetic energy in excess of $10^{52}$ erg \cite{19}. Even more dramatic was the discovery that a significant fraction of that energy was contained in relativistic ejecta \cite{21}.

During the next four years evidence accumulated both for supernovae associated with GRBs \cite{3,36} and for unusually energetic supernovae (see talk by Nomoto). The term “hypernovae” \cite{30} was often used to describe these exceptional explosions, and has lately come to denote almost any unusual supernova with inferred high energy (along the line of sight) or broad lines. Here we will
avoid the term, which is not associated with any particular model, and speak of the specific *mechanisms* that might be responsible for exploding stars with great energy, gross asymmetry, and/or relativistic mass ejection. Obviously energy and asymmetry are not independent. A grossly asymmetric explosion may appear anomalously energetic - in terms of broad lines for example - along one line of sight and not another.

In this regard, GRBs themselves may be an extreme case of a continuous distribution of events ranging from nearly spherical supernovae with kinetic energies of order $10^{51}$ erg, to events like GRB 990123 with an inferred equivalent isotropic energy of over $10^{54}$ erg. But is it energy or asymmetry? Recent analysis of the afterglows of GRBs [11] has shown that the total energies in GRBs are really remarkably clustered around $10^{51}$ erg, even for 990123, and that their exceptional brilliance is a consequence of having focused some appreciable fraction of that energy into a narrow, relativistic jet ($\Gamma \sim 200$) moving in our direction. Other observations have also shown the association of GRBs with star forming regions inside galaxies [8]. Taken together, a picture is emerging that at least some massive stars die while producing relativistic jets.

2 Jet-Powered Supernovae (JetSN) and Pulsar-Powered Supernovae

2.1 Rotation

All modern models for GRBs and JetSN invoke rapid rotation, either of a neutron star or of a disk around a black hole. For typical equations of state, a neutron star with radius 10 km and period $\sim 5$ ms has $\sim 10^{51}$ erg of rotational kinetic energy, and this is an upper bound on the final period that is needed, especially since most of the action occurs when the radius is 30 km, not 10 km.

The evolution of massive stars including the transport of angular momentum by magnetic [14] and non-magnetic processes [15] has been considered until core collapse in various papers by Heger, Woosley, Spruit, and Langer. To summarize, common red supergiants, the progenitors of most supernovae, end up producing neutron stars with rotation rates near break up when magnetic fields are omitted, and around 10 ms when current estimates of magnetic torques [39] are included. The 10 ms value accounts for angular momentum loss due to neutrinos flowing out of the neutron star, but does not include possible braking by a neutrino-powered magnetic stellar wind or by the propeller mechanism operating in conjunction with fallback [15].

For GRB progenitors, a bare helium core is more appropriate. A helium star born (e.g., from a merger) with equatorial rotation 10% of Keplerian and low metallicity can retain enough angular momentum to form a centrifugally supported disk around a central (Kerr) black hole of $\sim 3 \, M_\odot$ provided that magnetic fields are left out of the calculation [14,15]. However, when an approximate treatment of angular momentum transport by magnetic fields is included [39] along with mass loss, the resulting rotation become too low to form centrifugally supported disks in the inner part of the core [10].
Admittedly our knowledge of magnetic torques inside evolved massive stars is still uncertain, but these results suggest that: a) magnetic field torques during the pre-supernova evolution are an important consideration, and b) within uncertainties, all current models may be allowed, but may require special circumstances. This may be why GRBs only occur in about 1% of supernovae (based on estimates of GRB beaming and the supernova rate in the universe).

Since nature is continuous, however, we may also expect many supernovae in which rotation plays an important role (i.e., the inferred pulsar rotation rate is faster than 5 ms), but no GRB is produced.

### 2.2 Pulsar-powered supernovae

Shortly after pulsars were discovered and their rapid rotation rates inferred, it was suggested that they might power supernovae \[29\]. If energies of \(>10^{50}\) erg must be rapidly dissipated by means other than neutrinos or gravity waves, it is unavoidable that a pulsar will influence supernova dynamics, leading, for example, to additional mixing. However, pulsars as the cause of common supernova explosions encounters at least two objections. First, the accretion rate shortly after neutron star formation is \(\sim 0.1\) to \(1\) \(M_\odot\) s\(^{-1}\). The Alfven radius for this accretion rate is then

\[
r_A = 1.3 \times 10^4 \text{ cm } \mu_{30}^{4/7} \dot{M}_{32}^{-2/7}
\]

with \(\mu_{30}\) the magnetic moment in G cm\(^{-3}\) (\(10^{30}\) is approximately the value for B \(\sim 10^{12}\) G) and \(\dot{M}_{32}\), the accretion rate in units \(10^{32}\) g s\(^{-1}\). For the Alfven radius to be greater than the neutron star radius, \(\sim 10\) km, with an accretion rate of \(0.3\) \(M_\odot\) s\(^{-1}\) the magnetic moment must exceed \(5 \times 10^{33}\) and the B field must exceed \(5 \times 10^{15}\) G. When the explosion is developing, the protoneutron star radius is actually more like \(30\) km and the necessary magnetic moment about 10 times greater. This implies, baring ultrastrong magnetic fields, that no pulsar will be able to function during the critical epoch when the accretion rate is high and the probability of black hole formation large.

Second is the issue of \(^{56}\)Ni nucleosynthesis. A shock like the one produced in neutrino powered explosions will raise a significant quantity of material to temperatures greater than \(5 \times 10^8\) K and thus make iron group elements \[52\]. To do so the shock must receive its energy in a time short compared with that needed to cross the region where the nickel is made, about 4000 km. This is, at most, a few tenths of a second. If a pulsar does not deposit at least \(10^{51}\) erg in this brief interval, very little nickel will be made to power the light curve. Such short braking times again require very large magnetic fields and rotation rates. While it may be that the occasional neutron star is born with these extreme properties (see below), we do not think it happens in most supernovae.

### 2.3 MHD jets and explosions

Another supernova model with us for over 30 years invokes powerful bi-polar outflows energized by magnetic wind up and instabilities in a differentially ro-
A massive Wolf-Rayet star being exploded by the passage of relativistic jets along its axes [54]. The jet was initiated at 2000 km in a Wolf-Rayet star with radius 700,000 km and had a Lorentz factor of 10 for the first 10 seconds which slowly declined to 2 at 1000 s. The energy input was $5 \times 10^{50}$ erg s$^{-1}$ (per jet) for 10 s declining to $10^{47}$ erg s$^{-1}$ at 1000 s. The initial ratio of internal energy to kinetic energy in the jet was 20 and the opening angle, 20 degrees (which was quickly reduced by hydrodynamical focusing). The picture shows radial velocity 80 s after the initiation of the jet.

Fig. 1. A massive Wolf-Rayet star being exploded by the passage of relativistic jets along its axes [54]. The jet was initiated at 2000 km in a Wolf-Rayet star with radius 700,000 km and had a Lorentz factor of 10 for the first 10 seconds which slowly declined to 2 at 1000 s. The energy input was $5 \times 10^{50}$ erg s$^{-1}$ (per jet) for 10 s declining to $10^{47}$ erg s$^{-1}$ at 1000 s. The initial ratio of internal energy to kinetic energy in the jet was 20 and the opening angle, 20 degrees (which was quickly reduced by hydrodynamical focusing). The picture shows radial velocity 80 s after the initiation of the jet.

Generically these outflows are referred to as LeBlanc-Wilson jets. Their creation again requires very large magnetic fields and rotation rates, once regarded as unrealistic. Interest in this variety of model has been rekindled however [47,48,3], both by the observation of jets in GRBs and by promising models for soft gamma-ray repeaters and anomalous x-ray pulsars that invoke magnetic fields up to $10^{15}$ G [1,42].

Granted that such neutron stars exist and may be born rotating rapidly, a robust supernova model does not necessarily follow. A jet is not a particularly efficient way to explode a star. Even one introduced with a significant opening
angle is rapidly collimated by its passage through the star \[33\] and collides with only a small fraction of the mass (Fig. 1). Lateral shocks move around the star, but a lot of the matter falls back, enough that it may be difficult to preserve the neutron star. The jet may also produce very little \[56\] Ni, not enough to explain the light curves of Type Ib and Ic supernovae. The velocities of the resulting supernova will be highly asymmetric with very high values along the axis. This will give great variation in the properties of ordinary supernovae seen at different angles. Such variations are not seen.

This is not to say that a model for supernovae in which rotation and magnetic fields play a major role is ruled out. The magnetic torque on a spinning protoneutron star, \( \tau = \frac{dL}{dt} \) with \( L \) the angular momentum, is approximately \( B_r B_\phi R^3 \), suggesting that an angular momentum of \( I \omega \sim 10^{48} \left( \frac{I}{10^{45}} \right) \left( \frac{\omega}{10^3} \right) \) ergs could be braked in a few seconds if the wound up poloidal field, \( B_\phi \), and radial field, \( B_r \), exceeded \( 10^{15} \) gauss. This would lead to the rapid dissipation of \( \sim 10^{51} \) ergs, possibly by Alfvén waves \( \sim r^2 (\delta B)^2 v_A \) with \( v_A \sim 10^{10} \) cm s\(^{-1}\), the Alfvén speed), long wavelength electromagnetic waves \[33\], or magnetic reconnection. Larger rotation rates and stronger fields could provide greater energies. Neutrino energy deposition and the overturn it causes might aid in producing the necessary \( B_r \). Further work is needed here, especially on the idea that neutrino energy deposition and MHD models for supernovae are not exclusive.

3 Models with Black Holes

Models for supernovae in which a large part of the energy comes from an accreting black hole are newcomers to the scene, motivated chiefly by a need to explain GRBs. However, it is recognized that these same models may have broader applicability and, in less extreme versions or in stars that still retain their hydrogen envelope, might power supernovae. Such supernovae would probably retain unusual properties such as gross asymmetry or high energy.

3.1 Supranovae

It has been suggested by Vietri & Stella \[45,46\] and others that GRBs might result from the delayed implosion of rapidly rotating neutron stars to black holes. The neutron star forms in a traditional (neutrino-powered) supernova, but is “supramassive” in the sense that without rotation, it would collapse, but with rapid rotation, collapse is delayed until angular momentum is lost. The momentum can be lost by gravitational radiation and by magnetic field torques. Vietri and Stella assume that the usual pulsar formula holds and, for a field of \( 10^{12} \) gauss, a delay of order years (depending on the field and mass) is expected, but other parameters might give a shorter delay. When the centrifugal support becomes sufficiently weak, the star experiences a period of runaway deformation and gravitational radiation before collapsing into a black hole. It is assumed that \( \sim 0.1M_\odot \) is left behind in a disk which accretes and powers the burst explosion.
As a GRB model, the supranova has several advantages. It, as well as the collapsar model discussed later, predicts an association of GRBs with massive stars and supernovae. Moreover it produces a large amount of material enriched in heavy elements located sufficiently far from the GRB as not to obscure it. The irradiation of this material by the burst or afterglow can produce x-ray emission lines as have been reported in several bursts \cite{31,32,35}. However, the supranova model also has some difficulties \cite{26}. It may also take fine tuning to produce a GRB days to years after the neutron star is born. Shapiro \cite{38} has shown that neutron stars requiring differential rotation for their support will collapse in only a few minutes. The requirement of rigid rotation reduces the range of masses that can be supported by rotation to, at most, \(~20\%\) above the non-rotating limit \cite{33,37}.

3.2 Collapsars

Basic collapsars

Generically, a collapsar is a rotating massive star whose central core collapses to a black hole surrounded by an accretion disk \cite{50,23}. Accretion of at least a solar mass through this disk produces outflows that are further collimated by passage through the stellar mantle. These flows attain high Lorentz factor as they emerge from the stellar surface and, after traversing many stellar radii, produce a GRB and its afterglows by internal and external shocks. The passage of the jet through the star also gives a very asymmetric supernova of order \(10^{51}\) erg \cite{53}.

There are three ways to make a collapsar and each is likely to have different observational characteristics.

- A standard (Type I) collapsar is one where the black hole forms promptly in a helium core of approximately 15 to 40 M\(_\odot\). There never is a successful outgoing shock after the iron core first collapses. A massive, hot proto-neutron star briefly forms and radiates neutrinos, but the neutrino flux is inadequate to halt the accretion. Such an occurrence seems likely in helium cores of mass over \(~15\) M\(_\odot\) because of their large binding energy \cite{52} and the rapid accretion that characterizes the first second after core collapse \cite{12}.

- A variation on this theme is the “Type II collapsar” wherein the black hole forms after some delay - typically a minute to an hour, owing to the fallback of material that initially moves outwards, but fails to achieve escape velocity \cite{25}. Such an occurrence is again favored by massive helium cores. Unfortunately the long time scale associated with the fallback may be, on the average, too long for typical long, soft bursts. Their accretion disks are also not hot enough to be neutrino dominated and this may affect the accretion efficiency \cite{28} and therefore the energy available to make jets.

- A third variety of collapsar occurs for extremely massive metal-deficient stars that probably existed only in the early universe \cite{1,13}. For non-rotating stars with helium core masses above 133 M\(_\odot\) (main sequence mass 260 M\(_\odot\)), it is known that a black hole forms after the pair instability is encountered \cite{17}. It is widely suspected that such massive stars existed in abundance in the first
generation after the Big Bang at red shifts \( \sim 5 - 20 \). For rotating stars the mass limit for black hole formation will be raised. The black hole that forms here, about 100 M\(_{\odot}\), is more massive, than the several M\(_{\odot}\) characteristic of Type I and II collapsars, but the accretion rate is also much higher, \( \sim 10 \) M\(_{\odot}\) s\(^{-1}\), and the energy released may also be much greater. The time scale is also much longer.

For both Type I and II collapsars it is also essential that the star loses its hydrogen envelope before death. No jet can penetrate the envelope in less than the light crossing time, typically 100 s for a blue supergiant and 1000 s for a red one. After running into \( 1/\Gamma \) of its rest mass, a ballistic jet loses its energy.

Because of space limitations, we will not review details of the collapsar model here, but refer the reader to the published literature especially [23, 53, 54]. We will emphasize however two recent developments of great interest: nucleosynthesis in collapsar disks and the prediction by the collapsar model of other forms of high energy transients, especially cosmological x-ray flashes and events like GRB 980425/SN 1998bw.

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**56Ni production and the r-process** Lacking a hydrogen envelope, the supernova that accompanies a GRB made by a collapsar will be Type Ib or Ic with an optical luminosity given entirely by the yield of 56Ni. In Type I collapsars however, the material that would have become 56Ni falls into the black hole. The jet itself subtends a small solid angle and carries a small, albeit very energetic mass. It cannot propagate outwards until the mass flux inwards at the pole has declined, i.e., the density has gone down. This makes it hard for the jet itself to synthesize much 56Ni. How then is the supernova visible?

It is believed that the 56Ni in collapsars is made not by the jet, but by the disk wind. In the parlance of Narayan et al., it could be that at late times (after \( \sim 10 \) s), a neutrino-dominated accretion disk (NDAF) switches to a convection dominated accretion disk (CDAF) with a large fraction of the mass flow being ejected. MacFadyen and Woosley even found considerable mass outflow from NDAFs. We postulate that a certain fraction of the accreting matter - composed initially of nucleons or iron group elements - is ejected at high velocity (\( \sim 0.1 \) c) by the accretion disk.

But will the material be 56Ni? Nucleosynthesis in collapsar disks has been explored recently by Pruet and colleagues at LLNL [33]. They find that the composition flowing out from the disk and in the jet is very sensitive to both the accretion rate and assumed viscosity of the disk. For an “\( \alpha \)-disk” with \( \alpha \approx 0.1 \) or less and accretion rates 0.1 M\(_{\odot}\) s\(^{-1}\) and more the composition will not be 56Ni, but more neutron-rich isotopes of iron, or even r-process nuclei. For accretion rates around 0.01 M\(_{\odot}\) s\(^{-1}\) the composition will be proton-rich (\( Y_e \approx 0.51 \)), though still dominated by 56Ni. Interestingly typical accretion rates for Type I collapsars are \( \sim 0.05 \) M\(_{\odot}\) s\(^{-1}\) (less at later times) and 56Ni synthesis is possible. For Type II collapsars the accretion rate is lower and the disk is proton-rich. Lower values of \( \alpha \) shift the nucleosynthesis to low \( Y_e \) and for \( \alpha = 0.01 \) or less, Type I collapsar disks make no 56Ni.
X-ray flashes and supernovae The collapsar model was originally intended as an explanation for GRBs but time, additional calculations, and observations suggest it has broader implications. These essentially hinge on the answer to the question “If a GRB from a collapsar is only seen by observers in about 0.3% of the sky, what do other observers see?” Clearly these will be the most common events. Additionally, one may inquire what happens when a collapsar occurs in a star still having a hydrogen envelope [25], if the parameters are such that high Lorentz factor is not achieved, or the jet engine turns off before the jet emerges from the star [24].

In the equatorial plane of a collapsar - the common case - probably little more is seen than an extraordinary supernova. In fact the supernova may not even appear exceptionally energetic because the high velocities are all along the rotational axis (Fig. 1). Off axis though, in a collapsar that made a GRB, one will see x-ray flashes made by the explosion of the jet cocoon as it breaks out of the star [34,54]. The cocoon contains about $10^{50} - 10^{51}$ erg [53] and has Lorentz factor $\Gamma \sim 5 - 10$ (Fig. 2). By way of an external shock with the pre-explosive wind of the stellar progenitor, this material can produce a bright transient visible out to $\sim 30$ degrees from each axis. Even though it has lower energy per solid angle than the GRB jet (which is concentrated within about 5 degrees), relativistic beaming compensates to make the observable fluence comparable. That is, the

![Fig. 2. The break out of a relativistic jet and its cocoon 22 seconds after the jet’s initiation in the star [54].](image)

Fig. 2. The break out of a relativistic jet and its cocoon 22 seconds after the jet’s initiation in the star [54].
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GRB beams its emission to $1/\Gamma \sim 0.005$ radians $= 1/4$ degree while the x-ray flash (XRF) is beamed to perhaps 10 degrees. The duration of such events depends on the Lorentz factor and the pre-explosive mass loss, but could be from tens of seconds to minutes.

These properties mesh well with the recently discovered class of cosmological XRFs [18, 20] which share many of the properties of long-duration GRBs (duration, frequency of occurrence, isotropy on the sky, non-thermal spectrum, non-recurring), but have no hard emission above about 10 keV. If our speculations are correct, every (long-soft) GRB should have an underlying XRF that may even be visible as a precursor to the GRB. We also predict supernovae in association with XRFs and these might be looked for [10].

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