The Central Engines of Gamma-Ray Bursts

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Abstract.
Leading models for the “central engine” of long, soft gamma-ray bursts (GRBs) are briefly reviewed with emphasis on the collapsar model. Growing evidence supports the hypothesis that GRBs are a supernova-like phenomenon occurring in star forming regions, differing from ordinary supernovae in that a large fraction of their energy is concentrated in highly relativistic jets. The possible progenitors and physics of such explosions are discussed and the important role of the interaction of the emerging relativistic jet with the collapsing star is emphasized. This interaction may be responsible for most of the time structure seen in long, soft GRBs. What we have called “GRBs” may actually be a diverse set of phenomena with a key parameter being the angle at which the burst is observed. GRB 980425/SN 1988bw and the recently discovered hard x-ray flashes may be examples of this diversity.

INTRODUCTION

Recent years have seen a welcome decline in estimates of the energy that must be provided by the central engine of GRBs - from almost $10^{54}$ erg to $\sim 10^{52}$ erg (including the supernova that accompanies the GRB). While retaining their title as the brightest explosions in the modern universe, current estimates of kinetic and neutrino energies have demoted GRBs to merely comparable to supernovae. This decrease has come about mostly because the beaming long indicated by the theoretical models has been verified experimentally.

While the energy requirements on the model have become less problematic, other demands have arisen. The successful model must not only deliver a few times $10^{51}$ erg in highly relativistic ejecta, it must collimate those ejecta into a narrow outflow with typical width 0.1 radian. Adherents of the internal shock model further need the Lorentz factor to vary rapidly so that the efficiency for making gamma-rays is not small. Diverse light curves should have a natural explanation and the events must occur in star forming regions. At least occasionally, GRBs should give be accompanied by Type I supernova, by which we mean a supernova, without hydrogen, powered at peak light by the decay of radioactive $^{56}$Ni and $^{56}$Co.

One model that shows promise in satisfying these constraints is the collapsar model. Collapsars occur naturally in star forming regions, make bright Type I supernovae, offer a natural mechanism for narrow jet collimation, and can explain the diverse light curves of long GRBs. They may also explain why GRBs have a nearly constant total energy. The model also has its difficulties. The large requisite angular momenta are difficult to achieve when current estimates of magnetic torques and mass loss rates are included and the model also offers no clear route to making short hard GRBs. However, unlike other models, the collapsar model makes many testable predictions.

These predictions (and postdictions) include: a) association of GRBs with massive stars and star formation; b) an increasing fraction of GRBs at low metallicity (high redshift); c) collimation of the outflow into a narrow jet with typical opening angle 0.1 radian; d) an asymmetric Type I supernova accompanying every GRB; e) an event rate of about 1% that of ordinary supernovae (we only see a few tenths of a percent of these as GRBs); f) a distribution of circum-source matter consistent with the wind of a Wolf-Rayet star at the end of its life; g) possible large production of $^{56}$Ni by the disk of the accreting black hole; h) continuing energetic outflows for a long time after the GRB; i) diverse phenomena seen at different polar angles; and j) a jet whose temporal structure (and hence a GRB whose light curve) is relatively insensitive to the central engine, but set by the interaction of the jet with the overlying star.

Not all of these predictions are unique to the collapsar model. Any model that produces the same relativistic outflow in the middle of a massive helium star will give similar results. In the end, details like the duration of the event, the $^{56}$Ni production, and other specific properties of the supernova will help to distinguish the operation of
BASIC COLLAPSARS

Generically a collapsar is a rotating massive star, devoid of hydrogen envelope, whose central regions collapse to a black hole surrounded by an accretion disk [49, 22]. 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 respectively.

There are actually several 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. For iron cores near 1.9 solar masses, as can occur in massive metal-deficient stars [50], and soft equations of state, eventual collapse to a black hole is assured. For most other equations of state, collapse to a black hole is also certain if the iron core accretes an additional half-solar mass or so without launching an outgoing shock. Such an occurrence seems very likely in helium cores of high mass because of the rapid accretion that characterizes the first second after core collapse [12]. Such high mass helium cores are more frequently realized in systems with low metallicity because low metallicity inhibits mass loss. The mass threshold for forming a black hole promptly is not known with certainty, but based upon two dimensional models with crude neutrino physics is thought to be around 10 solar masses of helium. A lower limit is the 6 solar mass helium core of SN 1987A (a main sequence star of $\sim 20 M_\odot$) which certainly did not form a black hole promptly [8] because we saw the neutrino signal continue for $\sim 10$ s.

• 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 [23]. The time scale for such an event is set by the interval between the first outgoing shock and the GRB event. Such an occurrence is again favored by massive helium cores and might have occurred in SN 1987A [7]. The binding energy rises rapidly above main sequence masses of 25 $M_\odot$ in metal-poor stars [50]. Delayed black hole formation of this sort seems unavoidable above some threshold mass that is probably smaller than that required for Type I collapsars. There is nucleosynthetic evidence in low metallicity stars in our own Galaxy for a progenitor population where most of the iron failed to escape the star [10].

Type II collapsars should be common events, probably more frequent than Type I. They are also capable of producing powerful jets that might make gamma-ray bursts. Unfortunately their time scale may be, on the average, too long for the typical long, soft bursts. If the GRB-producing jet is launched within the first 100 s or so of the initial supernova shock, it still emerges from the star before the supernova shock has gotten to the surface, i.e., when the star is still dense enough to provide collimation. Their accretion disks are also not hot enough to be neutrino dominated and this may affect the accretion efficiency [27].

• A third variety of collapsar occurs for extremely massive metal-deficient stars (above $\sim 300 M_\odot$) that may have existed in the early universe [1, 14]. For non-rotating stars with helium core masses above 137 $M_\odot$ (main sequence mass 280 $M_\odot$), it is known that a black hole forms after the pair instability is encountered [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 in the lab frame for this accretion is of order 20 s or so, not so different from GRBs. However, one must dilute both the spectrum and the time scale according to the red shift. The spectrum even in the lab frame is unknown, but if it were similar to nearby GRBs, one might expect long, hard x-ray flashes rather than classical GRBs.

For 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 which is 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.
PROGENITORS

As Heger & Woosley show elsewhere in these proceedings, a bare 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 black hole of $\sim 3\,M_\odot$. Without magnetic fields, the angular momentum is sufficient to form a Kerr black hole and support most of the star in an accretion disk. 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. Even though our knowledge of magnetic torques inside evolved massive stars is still quite uncertain, this is a concern for the collapsar model.

The mass loss rate of Wolf-Rayet stars (WR-stars) during helium burning (i.e., most of their lifetime) is observed to be large, but has an uncertain dependence on the metallicity. A value of $\sim 10^{-5}\,M_\odot\,\text{yr}^{-1}$ should be typical for collapsar progenitors (Heger & Woosley, this volume) implying a number density (of helium nuclei) outside the star $\sim 10^3 r_1 G^{-2} \text{cm}^{-3}$, large compared with what is inferred from afterglows [28]. This wind is clumpy and has an uncertain angular distribution. Perhaps the polar region has a lower mass loss.

Because the mass loss carries away both mass and angular momentum, it is detrimental to collapsar production. To the extent that mass loss is suppressed in such stars by low metallicity, one may expect the fraction of stars that become GRBs to increase with redshift. Lower mass loss rates for red supergiant stars with low metallicity also raises the maximum mass of helium core that can result from the evolution of single stars. For solar metallicity this number is about $12\,M_\odot$ [50]. For 1/4 solar metallicity, the number is already considerably higher.

No observations constrain the mass loss rate of WR-stars during the post-helium burning phases (100 - 1000 years), nor have the necessary stability analyses been carried out to see if such stars are stable. The loss rate could be quite high (or conceivably, even lower if these stages are stable). Unlike supergiants, the surface of a WR-star remains in sonic communication with the central core up to the last few minutes of core collapse. Strong acoustic waves from pulsationally unstable oxygen and silicon burning stages could, in principle, expel large quantities of material out to $\sim 10^{15}\text{cm}$ (the escape speed times the duration of oxygen burning). Alternatively, it is known that helium cores between about 40 and 65 $M_\odot$ encounter the pulsational pair instability [17]. Up to several solar masses can be ejected with supernova-like energies from days to years prior to the collapse of the core to a black hole. These are probably too massive to be common GRBs, but could occur occasionally, especially at low metallicity.

COLLAPSARS - A STANDARD BOMB?

Frail et al. [11] have suggested that GRBs are a standard bomb in the sense that, within an order of magnitude, they all have the same total kinetic energy, $\sim 3 \times 10^{51}\text{erg}$. This can be understood in the collapsar model as an approximate constancy of the total accreted mass and black hole mass. Collapsars of Type I have an accretion rate of $\sim 0.1 \, M_\odot\,\text{s}^{-1}$ for about 20 $s$ into a black hole initially of about 3 $M_\odot$. Slower accretion rates can continue for a longer time, but the total energy in all cases is limited by the fact that the jet explodes the star shutting off its own accretion. The gravitational binding energy outside the iron core of a 15 $M_\odot$ helium star is $\sim 2 \times 10^{51}\text{erg}$ (contributing in part to the difficulty of exploding these stars by ordinary means). Some of this falls into the black hole, but the jet needs to deposit at least $10^{51}\text{erg}$ in the star simply to unbind it and shut off the accretion. Much more energetic jets will not be produced because the mass in the disk is limited and the explosion shuts off the flow.

THE JET-STAR INTERACTION

The propagation of relativistic jets through the massive, partially collapsed progenitors of collapsars has been considered in refs. [2, 51] and the reader is referred to those papers for extensive discussions (see also Zhang, Woosley, & MacFadyen, this volume). Regardless of the initial Lorentz factor and opening angle, after a few seconds the jet inside the star is characterized by two shocks, one at the leading “head” moving subrelativistically, and another deeper in where the initial outflow runs into material piled up behind the leading shock. Some of the material it runs into has also slowed due to interaction with the jet walls. Only the initial outflow deep within the star remembers the properties of the central engine. In calculations this outflow is taken either to be born highly relativistic ($\Gamma \sim 100$) or to have such large internal energy that it becomes highly relativistic before going very far.

Between the two shocks is material with moderate Lorentz factor ($\Gamma \sim 10$) and large internal energy per baryon, roughly $10\,m_p c^2$. It is this material that, after exiting the star, makes most of the prompt burst. The large Lorentz factors that characterize GRBs ($\sim 100$) are developed outside the star as expansion converts internal energy back into highly relativistic motion. That is conversion of internal energy in the moving frame gives $\Gamma \sim 10$ which translates into $\Gamma \sim 200$ in the laboratory.
frame. Considerable lateral expansion of the jet also occurs after exiting the star. This is also true of the mildly relativistic cocoon of matter surrounding the exiting jet (see also [25]).

**GRB Light Curves**

Within this context, all short time scale variability of the central engine itself is washed out by the first shock. Variations of energy input where the jet is born, do not manifest themselves in the GRB light curve.

Still, GRB light curves are known to be diverse and complex. Where does the time structure originate? We believe that it comes from the jet-star interaction. Mixture of nearly stationary matter into the jet by the (relativistic) Kelvin-Helmholtz instability can load the jet with baryons and slow it down. A particularly large wavelength instability can even temporarily block the flow giving bursts that seem to turn on and off multiple times.

Modulating the jet in this fashion has two effects. First, it can give rise to complex light curves even for a constant power input at the base. Second, it can provide the variable Lorentz factor necessary for the internal shock model.

**Luminosity-Variability-Angle Correlations**

The angle with which the jet emerges increases with time as the star is blown aside. An observer situated at a relatively large angle may not even see the GRB until it has been operating at smaller polar angles for some time. If the jet power or its efficiency for conversion to gamma-rays declines with time, it will appear less luminous. Variations of energy input where the jet is born, do not manifest themselves in the GRB light curve.

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**SUPERNOVAE**

One of the earliest predictions of the collapsar model was that each GRB should be accompanied by a supernova-like display. The idea that a black hole formation in a rotating helium star would make a supernova of some sort was discussed by Bodenheimer & Woosley [6]. Woosley [49] extended the idea to GRB production. In what many regard as a gross understatement, these early models were characterized as “failed supernovae” because the usual mechanism for producing an outgoing shock and a successful explosion (neutron star formation and neutrino emission) was assumed to be inoperable. Calculations showing that the passage of a relativistic jet through the star not only leads to collimation of the jet, but explosion of the star were carried out by MacFadyen, Woosley, & Heger [22, 23] and Khokhlov et al. [20]. The kinetic energy energy available to the explosion is approximately the work the jet does prior to breaking out of the star [51]. For a jet power of $\sim 5 \times 10^{50}$ erg s$^{-1}$ (both jets) and a traversal time 5 - 10 s, this gives $\sim 3 \times 10^{51}$ erg, comparable to but somewhat greater than the kinetic energy of an ordinary supernova. For a typical 10 s GRB this gives jet energies - after break out - also of about $3 \times 10^{51}$ erg per jet, similar to what is inferred from afterglows and a kinetic energy conversion of 20%. Of course the supernova is initially grossly asymmetric and one might infer a much more energetic explosion viewing the supernova along the jet axis.

Lacking a hydrogen envelope, the supernova will be Type Ib or Ic with an optical luminosity given entirely by the yield of $^{56}$Ni. It is not generally appreciated how poorly determined this yield is in most GRB models. In ordinary (spherically symmetric) supernovae the iron-group yield (mostly $^{56}$Ni) is set by the amount of ejected material that experiences explosion temperatures in excess of $5 \times 10^{9}$ K. This in turn is given by the strength of the explosion and the density structure at the edge of the collapsing iron core. In Type I collapsars however, the material that would have become $^{56}$Ni falls into the black hole. In Type II collapsars some $^{56}$Ni is ejected, but not as much as in an explosion that left a neutron star. Depending on the fallback mass, most of the $^{56}$Ni reimplodes. 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 $^{56}$Ni. How then is the supernova visible?

We think that the $^{56}$Ni may be made not by the jet, but by the disk wind ([22, 27] and MacFadyen, this volume). 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 be-
ing ejected. On the other hand, MacFadyen and Woosley found considerable mass outflow even 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 (∼0.1 c) by the accretion disk. If the energy of the burst is given by the amount of material accreted and the outflow fraction is constant, the brightness of the supernova could correlate with the energy of the GRB. This simple relation is could be complicated by uncertain efficiency factors for converting disk energy into jet energy and mass loss from the disk. If the accretion rate is very high and the disk viscosity quite low, the density in the disk may be so high that electron capture must be considered.

In any case, it is quite possible to get a highly variable amount of $^{56}$Ni, and therefore a variable luminosity for the peak of the supernova. SN 1998bw may not be a standard candle. Observationally, besides SN 1998bw, evidence for supernova-like light curves, color, and time history has been found in at least three GRBs: GRB 011211 [5]; GRB 980326 [4], and GRB 970228 [34, 15]. What we would all like to see is the spectrum of a putative supernova accompanying a cosmologically distant GRB.

**ALTERNATE MODELS**

**Merging Neutron Stars**

The principal alternative model to the collapsar remains the merging neutron star pair or neutron star - black hole pair discussed elsewhere in this proceedings. These have the admirable properties of being associated with events that are known to occur in nature and have sufficient angular momentum to form an accretion disk around the black hole after the merger. An energy of $3 \times 10^{51}$ erg in relativistic ejecta is more challenging for these models than some others, but easily within reach of those employing magnetohydrodynamics (MHD) to extract black hole rotational energy or disk binding energy. However, even though a few of these might happen in star-forming regions, the vast majority are expected to occur outside [13]. It may also be difficult for merging neutron stars to collimate their outflows within 0.1 radians, at least in those versions where neutrino transport produces the jet. Given the difficulty the collapsar model has in making short hard bursts, we continue to associate compact mergers with this subclass [13].

Other popular models for the long, soft GRBs associated with massive star death involve either the delayed production of a black hole or the prompt production of a very magnetic, rapidly rotating neutron star.

It has been suggested by Vietri & Stella [41, 42] and others that GRBs may result from the delayed implosion of rapidly rotating neutron stars to black holes. The neutron star is “supramassive” in the sense that without rotation, it would collapse, but with 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 radiation formula holds and, for a field of $10^{12}$ gauss, a delay of order years (depending on the field radius and mass) is expected. 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 ∼0.1 $M_\odot$ is left behind in a disk which accretes and powers the burst in a manner analogous to the merging neutron star model.

The model has several advantages. It, as well as the collapsar model that it in some ways resembles, 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 [30, 31, 33].

However, the supranova model also has some difficulties (see also [24]). First, it may take fine tuning to produce a GRB days to years after the neutron star is born. Shapiro [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 [38, 37]. Small changes in the angular momentum and mass cause large variations in the delay between the supernova and GRB. This is because the pulsar radiation formula employed depends on $\omega^{-4}$ and the critical angular momentum where collapse ensues depends on the excess mass above the non-rotating limit. That the combination would have been just right in a (randomly selected) event like GRB 011211 [33] to give a delay of a few days is highly constraining.

Second, the supernova had best happen years and not days before the GRB (in conflict with Reeves et al). Supernovae are optically thick to gamma-rays until well after their optical peak, that is, at least a month even for Type I. Nor can any relativistic jet penetrate an object whose light crossing time is well in excess of the duration of the central engine (∼$10^{12}$ cm). Supranovae that are younger might make lines, but they don’t make GRBs. Third, the very success of the collapsar model in producing a collimated jet with opening angle near 5 degrees must be held in its favor. This collimation, as well as the time structure in the GRB light curve require a high
pressure stellar mantle to be present when the black hole launches its jet [51]. Finally, the timing of supernovae seen in conjunction with GRBs demands a simultaneous explosion. The optical maximum of a Type I supernova of any subclass occurs a few weeks after explosion. This time modulated by the redshift is consistent with SN 1998bw/GRB 980425 and with supernovae seen in the tails of the optical afterglows of several other GRBs.

The collapsar gets around these restrictions by producing a jet that exits the star while the central engine is still on and making a supernova nearly simultaneously. Lines might be energized by a continuation of the same jet at late times (see “Post-Burst Phenomenology”). In the event that it proves necessary to eject appreciable matter just prior to the GRB, one may want to consider pulsationally driven mass loss (see “Progenitors”).

“Magnetar Model”

Another model, championed most recently by Wheeler et al [43], is the “super-magnetar” model (see also [40]). As usual, the iron core of a massive star collapses to a neutron star. For whatever reasons, unusually high angular momentum perhaps, the neutron star acquires at birth an extremely powerful magnetic field, $10^{15} - 10^{17}$ gauss. If the neutron star additionally rotates with a period of a ms or so, up to $10^{52}$ erg in rotational energy can be extracted on a GRB time scale by a variation of the pulsar mechanism. This model has the attractive features of being associated with massive stars, making a supernova as well as a GRB, and utilizing an object, the magnetar, that is implicated in other phenomena - soft gamma-ray repeaters and anomalous x-ray pulsars. It has the unattractive feature of invoking the magnetar fully formed in the middle of a star in the process of collapsing without consideration of the effects of neutrinos or rapid accretion. The star does not have time to develop a deformed geometry or disk that might help to collimate jets. To break the symmetry, Wheeler et al invoke the operation of a prior LeBlanc-Wilson [21] jet to “weaken” the confinement of the radiation bubble along the rotational axis. Numerical models to give substance to this scenario are needed (though see [44]).

GRBS - A UNIFIED MODEL

According to the “Unified Model” for active galactic nuclei (e.g., [3], one sees a variety of phenomena depending upon the angle at which the source is viewed. These range from tremendously luminous blazars, thought to be jets seen on axis, to narrow line radio galaxies and Type 2 Seyferts thought to be similar sources seen edge on. Given that an accreting black hole and relativistic jet may be involved in both, it is natural to seek analogies with GRBs.

In the equatorial plane of a collapsar, probably little more is seen than an extraordinary supernova that, were it close enough to observe, would be an exceptionally bright radio source. Roughly 1% of all supernovae might be of this variety - perhaps a larger fraction at high redshift. Given that we have seen $\sim 1000$ relatively nearby supernovae, it would not be surprising to find a few in the cataloged sample. They would be of Type Ib/c and perhaps extraordinarily energetic. SN 1998bw could be a prototype, but without the high velocities that come from observing the event at high latitude. There are indications that a few of these may have been seen. Besides SN 1998bw there are SN 1997ef and 1997ey [26], and perhaps SN 2002ap. These supernovae, all of Type I, are characterized by a large inferred kinetic energy (at least for the equivalent isotropic explosion) and a variable, but occasionally large mass of $^{56}$Ni. Very high velocity intermediate mass elements were also seen in SN 1998bw [29]. Completing the connection from the other end, there are also an increasing number of GRBs which show evidence for supernova-like activity in the tail of their optical afterglow, most recently in GRB 011211 [5]. Perhaps the most interesting phenomena are those at intermediate angles. The models clearly show, and nature generally demands that the edges of jets are not discontinuous surfaces. Moving off axis, one expects and calculates a smooth decline in the Lorentz factor and energy of relativistic ejecta. These low energy wings with moderate Lorentz factor come about in three ways [51]. First, the jet that breaks out still has a lot of internal energy. Expansion of this material in the comoving frame leads to a broadening of the jet. Some of the material is even decelerated by expansion pushing back towards the origin. As a result a small amount of material with low energy ends up moving with intermediate Lorentz factors - say 10 - 30 and at angles up to several times that of the main GRB-producing jet. Second, as the star explodes from around the jet, the emerging beam opens up. At late times the outflow continues (see “Post-burst Phenomenology”), but with decreased power. Third, the jet is surrounded by a hot mildly relativistic cocoon. This material has low energy, but can expand to large angles. As a consequence of the spreading of the jet, a large region of the sky, much larger than that which sees the main GRB, will see a hard transient with less power, lower Lorentz factor, and perhaps coming from an external shock instead of internal ones.

We have speculated for some time now [47, 48, 45, 46] that these ordinary bursts seen off axis might appear as hard x-ray transients of one sort or another. We have identified them with GRB 980425 and with the class of
hard x-ray flashes reported by Heise et al. [18]. We do not say that these are ordinary high $\Gamma$ jets seen just beyond a sharp edge [19]. The events are made by matter moving towards us.

In the particular case of GRB 980425, it is important to know if the optical afterglow of a normal GRB that was not directed at us would have had an observable effect on the supernova light curve. After all, the optical afterglow nearly so beamed as the GRB and might be visible at lower latitude. However, Granot et al. [16] show that the afterglow would be invisible at the time the supernova was studied provided that the polar angle to our line of sight is greater than about 3 or 4 times that of the main GRB. This does raise the interesting possibility though that some future event might show the supernova and afterglow more nearly balanced in a “soft” relatively faint GRB.

**POST-BURST PHENOMENOLOGY**

After the main burst is over, accretion continues at a decaying rate. The lateral shock launched by the jet starts at the pole and wraps around the star, but does not reach into the origin at the equator (one may envision an angle-dependent “mass cut”). Consequently, some reservoir remains to be accreted at late time. This accretion occurs at a rate given by the viscosity of the residual disk and the free fall time of material farther out not ejected in the supernova. MacFadyen, Woosley, & Heger [23] and Chevalier [9] estimate the accretion rate from fall back to be $\sim 3 \times 10^{-6} \frac{e_{01}}{t_4} \frac{\epsilon_{5/3}}{M_\odot} \text{ s}^{-1}$. Here $t_4$ is the elapsed time since core collapse in units of $10^4$ s. Given the slow rate, the disk that forms is not neutrino dominated and there may be considerable high velocity flow from its surface (MacFadyen, this volume; [22, 27]). The outflow will still be jet-like in nature since the equatorial plane is blocked by the disk and its energy will be $\sim 5 \times 10^{46} \frac{t_4^{5/3}}{e_{01}} \epsilon_{5/3} \text{ erg} \text{ s}^{-1}$ where $e_{01}$ is the efficiency for converting rest mass into measured in percent. This is comparable to the energy in x-ray afterglows and might be important for producing the emission lines reported in some bursts [32, 24] and for providing an extended tail of hard emission in the GRB itself.

As a consequence of this continuing outflow, the polar regions of the supernova made by the GRB remain evacuated and the photosphere of the object resembles an ellipse seen along its major axis but with conical sections removed along the axis. An observer can see deeper into the explosion than they could have without the operation of the jet’s “afterburner”.

**CONCLUSIONS**

The collapsar model is able to explain many of the observed characteristics of GRBs. Here we have explored some of its predictions (enumerated in the “Introduction”). Probably the greatest challenges facing the model today are not the large energy associated with GRBs, or even the relativistic collimated flow. They are an understanding of how the necessary angular momentum comes about in the precollapse star - presumably by the special circumstances that make GRBs rare compared with supernovae - and of how accretion energy in the disk is transformed into jets. The former is a problem we share with competing models for GRBs like the supranova and millisecond magnetar models; the latter is also a long standing obstacle in understanding AGNs. There is hope that numerical simulation might address both in a few years.

We have described a “unified theory of GRBs” in which diverse phenomena are expected depending upon the angle at which a standard model for the explosion is viewed. In this theory the Lorentz factor and the energy of relativistic ejecta vary both with polar angle and with time. This paradigm is similar to the unified theory of AGNs. Some of the phenomena it predicts, like hard x-ray flashes are just now being discovered. Others like the long duration gamma-ray transients expected from Type II and III collapsars may await discovery.

In the collapsar model, the light curves of GRBs reflect more the interaction of the jet with the star as it emerges than time variability of the central engine itself. We have mentioned how correlations in break times, luminosity, and opening angle might come about and discussed some of the special properties of the accompanying supernova.

In the near future we hope to carry out the next steps in realistic collapsar simulation - special relativistic studies (in three dimensions) of jet propagation inside the star and longer time scale calculations of the supernova it produces.

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