The Supernova Gamma-Ray Burst Connection

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Abstract. The chief distinction between ordinary supernovae and long-soft gamma-ray bursts (GRBs) is the degree of differential rotation in the inner several solar masses when a massive star dies, and GRBs are rare mainly because of the difficulty achieving the necessary high rotation rate. Models that do provide the necessary angular momentum are discussed, with emphasis on a new single star model whose rapid rotation leads to complete mixing on the main sequence and avoids red giant formation. This channel of progenitor evolution also gives a broader range of masses than previous models, and allows the copious production of bursts outside of binaries and at high redshifts. However, even the production of a bare helium core rotating nearly at break up is not, by itself, a sufficient condition to make a gamma-ray burst. Wolf-Rayet mass loss must be low, and will be low in regions of low metallicity. This suggests that bursts at high redshift (low metallicity) will, on the average, be more energetic, have more time structure, and last longer than bursts nearby. Every burst consists of three components: a polar jet (∼0.1 radian), high energy, subrelativistic mass ejection (∼1 radian), and low velocity equatorial mass that can fall back after the initial explosion. The relative proportions of these three components can give a diverse assortment of supernovae and high energy transients whose properties may vary with redshift.

INTRODUCTION

As talks summarized elsewhere in this proceedings and papers in the literature have made clear [1], most GRBs of the long-soft variety (henceforth just GRBs) are a consequence of the deaths of massive stars. Evidence supporting this comes from: 1) the location of GRBs in regions of active star formation [2]; 2) the clear presence of supernovae of Type Ic-BL ("broad-lined Ic") in conjunction with three GRBs: 980425, 030329, and 031203; 3) the presence of supernova-like bumps in most other GRBs where they might be observed [3]; and 4) the similarity in energy between the beaming-corrected GRB energy and that of a supernova.

Accepting this as a starting point, an important question must be why some massive stars die as supernovae of the ordinary variety, while others die as GRBs. The fraction that do die as GRBs is apparently very small. Taking an event rate of core-collapse supernovae visible from the earth today as ∼20 per 16 arc min squared per year [4], the integrated rate of supernovae on the sky is about 6 per second. BATSE saw about a burst a day. Correcting by a factor of 300 for beaming and another factor of three for Earth occultation and bursts that were missed for reasons other than beaming, the GRB sky rate is about 0.02 per second. That is, GRBs are a fraction of order 0.3% of all massive star deaths. This fraction could be larger if there are numerous sub-luminous events like

GRB 980425 or cosmic X-ray flashes (XRFs), and it might increase with redshift, but apparently GRBs are a rare channel of massive star death.

Another interesting question is whether GRBs and ordinary supernovae are the extrema of a continuum of events or separate classes of explosions. The existence of such diverse phenomena as XRFs, 980425, and GRBs with varying energy and supernova properties suggests a continuum. So, too, does the growing class of "hyper-energetic" or grossly asymmetric supernovae like SN 2005bf [5, 6, 7]. Add to this the fact that most broad-lined Type Ic supernovae do *not* harbor GRBs [8], and a compelling case might be made for some continuously variable parameter that dials between ordinary supernovae and energetic GRBs like 990123. Clearly, the difference is that GRBs concentrate a significant fraction of their 10^{51} - 10^{52} ergs into highly relativistic ($\Gamma > 200$) beamed ejecta while ordinary supernovae do not, but searches beyond that for a deeper physical cause take us into what is suspected, and away from what is certain.

GRB PROGENITORS

The two key quantities that determine how a massive star dies are its mass and the rotation rate of its inner few solar masses. Stars that are more massive when they die are more likely to make black holes. More massive stars also evolve more quickly and may more effectively preserve the large angular momentum they have at birth in their core [9]. Rotation is a key ingredient in any successful GRB model. If the rotational energy of a neutron star is to provide the $\sim 10^{52}$ erg inferred for some of the supernovae accompanying GRBs, it must have a rotational period ~ 1 ms. This implies a specific equatorial angular momentum, $j \approx 7 \times 10^{15}$ cm^2 s^{-1} $(P/1$ ms$)(R/10$ km$)^2$, about 20 or more times that of a typical pulsar. If a disk is to form around a black hole one needs more. At 3 M$_\odot$, the specific angular momentum of the last stable orbit is $j_{lso} = 2\sqrt{3}GM/c = 4.6 \times 10^{16}$ cm^2 s^{-1} $(M_{BH}/3M_\odot)$ for a Schwarzschild black hole, and $j_{lso} = 2/\sqrt{3}GM/c = 1.5 \times 10^{16}$ cm^2 s^{-1} $(M_{BH}/3M_\odot)$ for an extreme Kerr hole. Given that angular momentum increases monotonically with interior mass from 1.5 to 3 M$_\odot$, the necessary values for neutron star models and black hole models are qualitatively similar.

Studies of massive star evolution that include estimated magnetic torques [9] have shown that such large values of angular momentum are not easily achieved if the star spends much time as a red giant, or even if it loses its envelope early on, but has a high mass loss rate afterwords as a Wolf-Rayet (WR) star [10]. A frequently discussed scenario is a stellar merger, but the central region of a differentially rotating star that has lost its angular momentum is virtually impossible to spin up again. This limits viable models to those where the merger removes the envelope (with enough time still left for for its dispersal), produces a compact helium star that never becomes a blue or red giant itself, and still does not slow down the denser, inner regions of the star.

Several possibilities remain, however. One is that the magnetic torques used in the above study were simply too large, but then one must take care both to produce the large number of slowly rotating neutron stars that are seen, and not overproduce GRBs. Another possibility is a binary merger between two massive stars, both of which are burning helium in their centers [11]. The merger ejects both envelopes and the (now rapidly ro-

tating) residual helium star evolves to produce the burst a few hundred thousand years later, after the envelope has left the vicinity. Even then, though, the new helium star must lose a very limited amount of mass before dying, so it helps if the merger occurs late during helium burning for one or both stars.

A third possibility is that GRBs come from the merger of a black hole or neutron star with either the helium core of a massive star [12, 13] or a white dwarf [14]. In the former case, the giant star's envelope must be completely dispersed before the final merger occurs. In the white dwarf case, one would not expect such a tight correlation with star forming regions, but a fraction of GRBs could still be made this way. In both of these compact merger models, however, there is so *much* angular momentum that the total duration of the event is quite long, longer than typical GRBs. It could be that the observed burst only reflects the epoch of maximum accretion in which case both enduring activity and long precursors might be present. Or perhaps this model only makes very long GRBs.

A final possibility, and one that has received a lot of attention lately, is that GRBs result from a rare channel of single star evolution in which red giant formation is avoided altogether. The possibilities here are exciting and warrant a more lengthy discussion.

A Single Star Model

It has been recently realized [15, 16] that stars which rotate *very* rapidly on the main sequence, with equatorial speeds near 400 km s^{-1} instead of 200 - 300 km s^{-1}, may experience nearly complete mixing on the main sequence [17, 18]. In fact, rotationally-induced mixing in such stars, chiefly by Eddington-Sweet circulation, keeps the star's composition nearly homogeneous until the end of helium burning. A red giant is never formed and the star goes straight from the main sequence to being a Wolf-Rayet star. Such stars will have more rapidly rotating iron cores when they die, though still not fast enough to be GRBs if the helium star loses a lot of mass. Because the progenitors are on the very high end of the observed distribution function for O- and B-star rotation [19], GRBs will be a rare channel of star death.

This model has several beneficial features for GRBs. First, the progenitor star is a compact WR star, mostly composed of oxygen with little helium at its surface - a WO star. This agrees well with the properties of those few GRB-supernovae that have been well studied spectroscopically. Second, it is possible to produce a wider range of GRB progenitor masses. Main sequence stars as light as 10 M$_\odot$ produce helium and heavy element cores that - *modulo* the mass loss - are about as large as that of a 25 M$_\odot$ star with slow rotation (both about 9 M$_\odot$). Such big cores evolve rapidly, retain their angular momentum, and develop big iron cores when they die. They are more likely to make black holes. Below about 10 M$_\odot$, larger, possibly unphysical rotation speeds are necessary on the main sequence to cause Eddington-Sweet circulation to mix the star efficiently. On the upper end, very massive GRB progenitors can be produced from main sequence stars of more moderate mass than previously thought. For slowly rotating, solar-metallicity stars, the largest helium core that can exist when the star dies is around 15 M$_\odot$, corresponding to a main sequence star of 35 M$_\odot$. Heavier stars lose
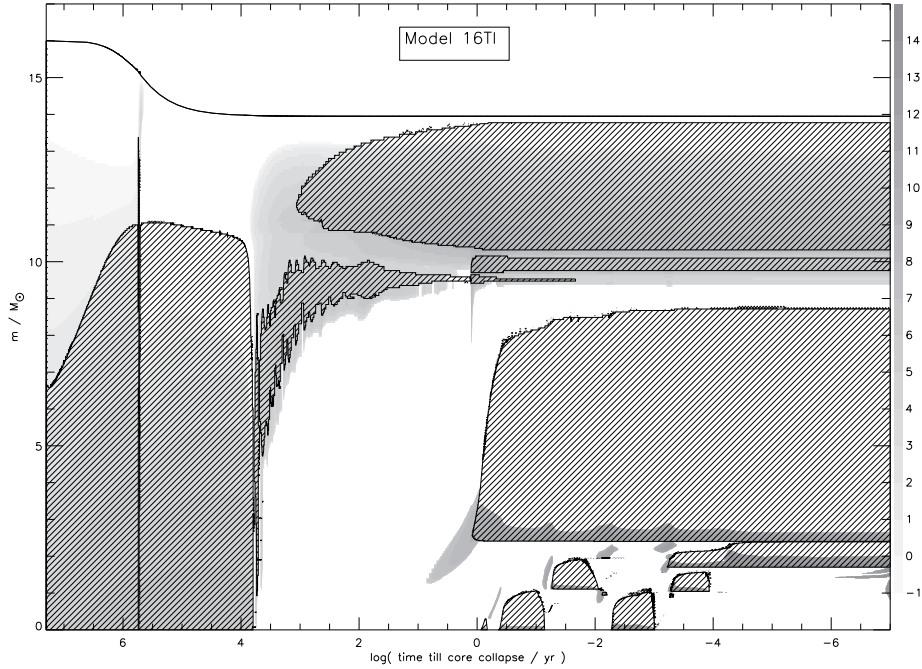
FIGURE 1. Convective history of a rapidly rotating 16 $M_\odot$ star that experiences nearly complete mixing on the main sequence and avoids red giant formation. The left axis is the interior mass, cross hatching shows regions that are convective, and gray shading indicates specific nuclear energy generation on a logarithmic scale (right gray-scale bar, in log ergs/g/s). The bottom axis is the time until death (on a logarithmic scale). This model had an initial composition of one per cent solar and an equatorial velocity half way through hydrogen burning of 380 km s^{-1}. The final mass was 14.0 $M_\odot$ and the iron core mass was 1.60 $M_\odot$. The abundances in the surface convection zone of the presupernova star were 9.5% He, 30% C, 57% O, and 2.7% Ne. The radius was 4.1×10^{10} cm.

their envelopes to winds and the resulting helium core shrinks by mass loss. But for these rapidly rotating, well-mixed stars, the upper bound on the helium core is, in principle, equal to the main sequence mass. Of course, mass loss, both on the main sequence and especially as a WR star, will still shrink the mass. As we shall see shortly however, turning the metallicity down can alleviate the mass loss of a WR star, so that GRB progenitors in low metallicity regions could have very big mass.

An upper limit to the helium core mass that comes from these rapidly rotating models is the first mass to encounter the pulsational pair instability [20], about 40 $M_\odot$ of helium and heavy elements. The evolved star experiences violent, repeated, nuclear-powered explosions when the star ignites oxygen burning. Each outburst ejects solar masses of surface material. This material surrounds the star when it finally dies (typically death happens months to years later) and prevents a GRB from getting out (though such explosions are interesting in their own right). For helium cores above about 65 $M_\odot$, the pair-instability becomes so violent that it leads to the complete disruption of the star and no GRB will be made, but above 140 $M_\odot$ a new regime is encountered where black holes are formed and GRBs of a more energetic, longer-lasting variety become possible [21]. In slowly rotating stars, without mass loss, the pulsational pair instability is first encountered for main sequence stars of $\sim$100 $M_\odot$ and black holes are made starting
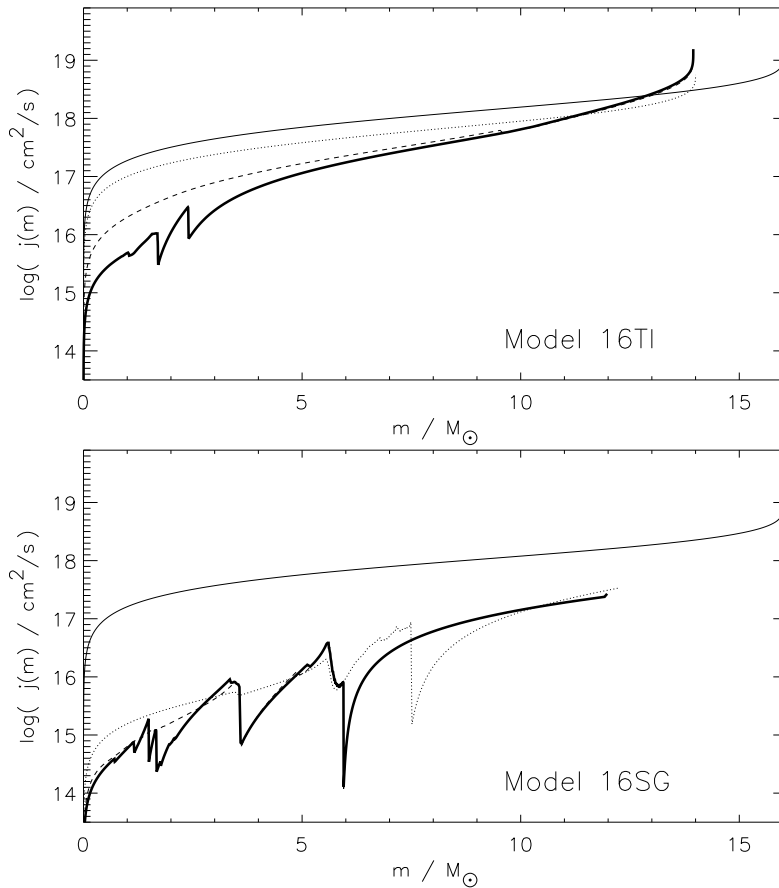
FIGURE 2. Specific angular momentum as a function of mass in two stars with initial mass 16 $M_\odot$ [15]. Both models included angular momentum transport due to rotationally induced mixing processes and magnetic torques. The angular momentum is evaluated at the zero age main sequence (top line, solid), central helium depletion (dotted line, next down), carbon depletion (dashed line), and presupernova (dark solid line). The top star had an equatorial rotation rate on the main sequence of 380 km s^{-1}, experienced complete mixing, and avoided ever making a red giant. The top star also had a Wolf-Rayet stellar mass loss rate corresponding to 1% solar metallicity. The bottom star had solar metallicity and a slower rotation rate on the main sequence, 215 km s^{-1}. The bottom star became a red supergiant, lost more mass, and produced a slowly rotating iron core that would give a 8 ms pulsar period after collapse and neutrino loss. The top star ended up with a higher mass and much greater rotation rate. This star would form a black hole accretion disk starting at 3.5 $M_\odot$. Avoiding red giant formation and reducing the mass loss greatly increases the probability of making a GRB.

at about 260 $M_\odot$, so these lower values for rapidly rotating stars are very significant changes. The numbers are currently uncertain, however, because few rapidly rotating models have been calculated and the effect of the rotation on the pair instability has not been included in a self-consistent way.

A final interesting consequence of rapid rotation and nearly homogeneous mixing, is that single stars, even at low metallicity, can end their lives as compact WR stars without the need of a binary companion to absorb the envelope. This has interesting implications for making GRBs at high redshift.

The Metallicity Dependence of GRBs

Whether the WR-star that serves as the progenitor of a GRB is made by merger or rotationally-induced mixing, it is essential that its mass loss, or more specifically, its angular momentum loss, be low. A massive WR star typically spends 0.5 to 1 million years burning helium. If, during that time, its mass loss rate is over 10^{-5} M$_\odot$ yr^{-1}, it will lose a significant fraction of its mass. Magnetic torques maintain nearly rigid rotation during helium burning, so the continued expansion of layers deep in the star to larger radius brakes the rotation of the inner core beyond what is needed later to make a GRB. Mass loss is the enemy of GRBs.

Fortunately, it has been recently determined [22] that reducing the metal content of a WR star even by a factor of a few lowers its mass loss very appreciably, approximately as $Z^{0.86}$. Once the metallicity has been reduced by a factor of 10, typical mass loss rates for 10 - 20 M$_\odot$ WR stars are $\sim 10^{-6}$ M$_\odot$ yr^{-1} and less. Losing less than a solar mass would not greatly alter the final angular momentum distribution of a massive WR star, so at metallicities $\sim 10\%$ solar and less, GRBs should be plentiful. It is important to note that the metallicity employed in the scaling here is the initial concentration of iron in the star. It does not include the carbon and oxygen at the surface of a WC or WO star that was made in the star itself during helium burning, at least not until the iron abundance becomes so low that the mass loss is negligible anyway, roughly 0.01 solar.

This does not mean that GRBs cannot happen in regions with solar metallicity, only that it is harder. Measured WR mass loss rates show a considerable spread and some merger models might also still work. The magnetic torques estimated in the models are uncertain and, for stars that are highly deformed the angular dependence of the mass loss rate is an issue. Mass loss preferentially from the poles would reduce the amount of angular momentum carried away by each gram [23].

However, the key role of mass loss and its strong metallicity dependence *does* suggest that the fraction of massive stars dying while making GRBs may be larger in regions where less nucleosynthesis has occurred. As the metallicity declines it may also be possible to make more energetic, longer lasting bursts. Higher mass and angular momentum at death increase the reservoir of material that can accrete into a black hole. It may also lead to more rapidly rotating neutron stars in the millisecond magnetar model.

The low mass loss rate also has implications for the afterglow analysis, and a lower density may be more consistent with observations [24]. One must take care, however, since the wind that is sampled in the afterglows was ejected during the post-helium burning evolution of the star, during which the mass loss rate may have varied from what is observed on the helium-burning main sequence.

THE THREE COMPONENTS OF A GRB

A GRB with an energetic supernova accompanying it will have three components: 1) a highly relativistic, $\Gamma \gtrsim 200$, central jet with an opening angle ~ 0.1 radian measured from the rotational axis; 2) a broader region of very energetic, but subrelativistic ejecta extending out to angles ~ 1 radian; and 3) slower moving ejecta in the equator. In general, region 1 is responsible for the GRB, region 2 is necessary for the supernova and the
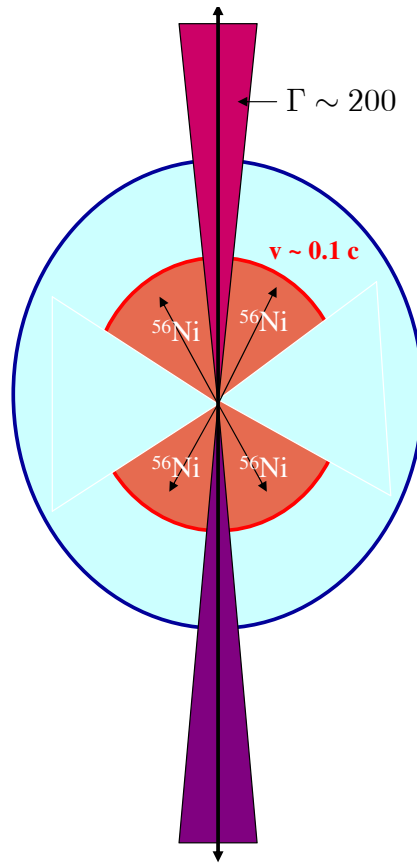
FIGURE 3. Schematic illustrating the three components of a typical GRB and its accompanying supernova. A core relativistic jet ($\sim$0.1 radian, $\Gamma \sim 200$, KE $\sim 10^{51}$ erg) is responsible for the GRB and its afterglows. A broader angle, energetic outflow (~ 1 radian, v/c $\sim$0.1, KE $\sim 10^{52}$ erg) is responsible for exploding the star and making the ^{56}Ni to power the light curve. A third component of low velocity material exists in the equatorial plane of those models in which central mass ejection is blocked by an accretion disk (e.g., collapsars). This component typically fails to achieve ejection on the first try and falls back to power a continuing explosion.

^{56}Ni to make it bright, and region 3 is naturally present in any model where outflow in the equator is blocked, e.g., by an accretion disk in the collapsar model. Region 2 probably contains most of the energy and is necessary because a narrow jet, by itself, is an ineffective way of blowing up a star or producing explosive nucleosynthesis. Region 3 may move out initially, but is largely responsible for the "fall-back" that may keep an accretion-powered source active long after the initial burst is over. One might also properly discuss a fourth region, the jet cocoon lying between regions 1 and 2, but here we count that as part of the jet.

In the collapsar model [25], the jet is produced in the near vicinity of the black hole by

neutrinos or MHD processes, while the large angle ejecta come from the disk wind. In the millisecond magnetar model, theorists have yet to talk about the two components in any detail, but one might imagine a large angle component from filling a cavity with nearly isotropic (thermal?) radiation, while simultaneously producing a narrower, electromagnetically focused outflow. Without better knowledge of the physics of how the relativistic jet is launched and the efficiency of the disk-wind, it is not possible to say what fraction of the energy goes into each of these components, but in all likelihood that fraction varies with the mass and angular momentum distribution of the presupernova star. It is also worth keeping in mind that the central engine must not only maintain a powerful jet for at least the $\sim$10 seconds it takes the jet to reach the surface of the star, but must hold the direction of that jet steady to better than 3 degrees [26]. If the jet wavers by more than that, it becomes contaminated with too many baryons on the way out to make a GRB.

If the three components can vary independently, and it is hard to see why they wouldn't, one expects a wide variety of phenomena resulting from essentially the same central engine. These could include a) ordinary GRBs [Regions 1 and 2 strongly active]; b) anisotropic broad-lined supernova without any GRB or bright afterglow [Region 1 trapped in the star, Region 2 dominant; e.g., ref. 8] c) GRBs with continuing activity after the burst [Regions 1 and 3 active]; d) XRFs and SN 1998bw [either the cocoon of an ordinary GRB seen somewhat off axis or an ordinary GRB with higher baryon loading in the jet]; and others. In this context, SN 1998bw and SN 2003dh need not be typical of all supernovae associated with GRBs or XRFs. There would be a continuum of events with the fainter GRBs and supernovae quite possibly the dominant case in a volume-limited sample.

It must be one of the observational goals of the future to gather a sufficient sample to determine if this is true. Are GRBs and core-collapse supernovae a continuum of events with a common central engine and a smoothly varying parameter - e.g., rotation - underlying them all. Or are GRBs and supernovae two discrete, different classes of high energy explosions. Personally, our underlying bias [27] is that rotation plays little role in most supernovae. These are the result of (slowly rotating) neutron star formation and neutrino transport. But "GRBs" are a diverse class of phenomena, overlapping common supernovae in observable properties. Perhaps rotation powers them all? This is a very old question, but still a critical one. Just how do massive stars die (and explode)?

GRBS AT HIGH REDSHIFT

If the properties of GRBs are sensitive to the metallicity as we have described, then one expects systematic differences in the appearance of GRBs "locally" and at high redshift (where the metallicity is presumably low). On the average, though perhaps not individually, GRBs in more metal-deficient regions will come from stars that are more massive and that have lost less angular momentum. Their disks will draw from a larger reservoir of matter and, if, as seems reasonable, the total burst of energy correlates with the total mass accreted, the GRB will last longer and have more energy. The supernova component may also be brighter if the disk wind lasts longer and carries more mass. Bigger helium stars are more tightly bound, however, and harder to explode [28], so the

supernova could experience significantly more fall-back. Continuing accretion activity would be the norm.

It is also possible, in the collapsar model, to have too much angular momentum [25, 29, 30]. Angular momentum much in excess of 10^{17} cm^2 s^{-1} will lead to a pile up in the disk at such large radii that neutrino dissipation is negligible. Unable to dissipate its binding energy, the disk becomes unstable and perhaps dominated by an outflow, accompanied by very little accretion. Such behavior has been seen recently in unpublished calculations by Weiqun Zhang and Andrew MacFadyen. Since the outflow has too little energy to explode the whole star in one try, a limit cycle may operate (though this has yet to be followed on the computer). Since angular momentum increases monotonically outwards in the equator of a GRB progenitor, material accretes efficiently until a limiting angular momentum is reached. During that time it maintains a strong jet which can escape the star and make a GRB. Eventually though, the angular momentum becomes so large that the disk ceases to be an NDAF (neutrino-dominated accretion flow) and stagnates. Matter is still falling in, however, especially from high latitudes. Mixing and shear will eventually reduce the angular momentum to the point where accretion can begin again, launch a new jet, and repeat the cycle. The characteristic time scale would be given by mixing and fall back. A few hours is reasonable [31].

This physics is possibly reflected in the observed features of GRB 050904, the most distant GRB discovered [32] and localized [33] so far (z = 6.29). This was a long, multi-peaked, bright burst that lasted well over 205 seconds [34] and had an equivalent isotropic energy of 0.66 to 3.2×10^{54} erg [35, 36] and a beaming corrected energy of 4 to 12×10^{51} erg. Repeated flaring activity was seen from the burst for 1.5 hours in the rest frame [36]. While the properties of this burst are not dramatically different from some others seen closer by, it does lie at an extreme of energy, duration and variability. It will be very interesting to see if future bursts at this redshift and higher show these same characteristics.

ACKNOWLEDGMENTS

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