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GAMMA-RAY BURSTS FROM STELLAR MASS ACCRETION DISKS AROUND BLACK HOLES[1]

S. E. WOOSLEY
University of California Observatories/Lick Observatory, Board of Studies in Astronomy and Astrophysics, University of California, Santa Cruz, Santa Cruz, CA 95064; and General Studies Group, Physics Department, Lawrence Livermore National Laboratory
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ABSTRACT

A cosmological model for gamma-ray bursts is explored in which the radiation is produced as a broadly beamed pair fireball along the rotation axis of an accreting black hole. The black hole may be a consequence of neutron star merger or neutron star–black hole merger, but for long complex bursts, it is more likely to come from the collapse of a single Wolf-Rayet star endowed with rotation ("failed" Type Ib supernova). The disk is geometrically thick and typically has a mass inside 100 km of several tenths of a solar mass. In the failed supernova case, the disk is fed for a longer period of time by the collapsing star. At its inner edge the disk is thick to its own neutrino emission and evolves on an viscous time scale of several seconds. In a region roughly 30 km across, interior to the accretion disk and along its axis of rotation, a pair fireball is generated by neutrino annihilation and electron-neutrino scattering which deposit approximately 10^{50} ergs s^{-1}. Electron scattering is more important in those cases where the baryonic contamination is high and the time scale for expansion increased. Extensive baryonic mass loss also occurs from the disk, and this may pose problems for production of a hard burst. Gamma-ray burst or not, this sort of event should occur in nature and should have an observable counterpart.

Subject headings: accretion, accretion disks — black hole physics — gamma rays: bursts — stars: evolution — supernovae: general

1. INTRODUCTION

Recent developments in the observational study of gamma-ray bursts (Meegan et al. 1992) have highlighted the fact that we are far from understanding these events. Controversy and speculation abound as to whether they originate locally, in an extended Galactic halo of tens of parsecs, or at cosmological distances (Harding 1991; Higdon & Lingenfelter 1990; Lingenfelter & Higdon 1992; Paczyński 1990a, 1991a, b; Mao & Paczyński 1992; Woosley 1992a). It may well be that the final solution will involve both Galactic and extra-Galactic components as the arguments on both sides are compelling (see Woosley 1992b for a Galactic halo model). Here an extra-Galactic model is explored.

Such models require $\sim 10^{51}$ ergs more or less, in gamma-radiation (Mao & Paczyński 1992), more for long enduring bright bursts, less if the bursts are beamed. The only phenomenon known to release such energy in the requisite short time scale is gravitational collapse to a neutron star or a black hole, and most cosmological models have that as their basis. However, the solution cannot be as simple as spherically symmetric collapse (Meszaros & Rees 1992; Woosley & Baron 1992; Woosley 1992a). Leaving aside for the time being solutions involving magnetic fields (e.g., Narayan, Paczyński, & Piran 1992), the only mechanism that has been proposed for getting gravitational energy out in a short enough time scale and in the form of gamma-rays is neutrino transport. Yet the same neutrino luminosity will drive a baryonic wind that contains the gamma-radiation until it is degraded to low luminosity and energy (Shemi & Piran 1990; Woosley & Baron 1992). Models based upon the accretion-induced collapse of a white dwarf, for example (Dar et al. 1992), do not work.

A possible resolution to this dilemma is to break the radial symmetry and have the neutrinos deposit their energy in a region where the baryon density is low. Meszaros & Rees (1992), for example, have proposed that two neutron stars may be heated by mutual tidal interaction in the merging process to the point where they both become strong neutrino emitters. The neutrinos from the two stars then meet in the middle, annihilate to some extent producing pairs, and the pairs expand in a broadly focused "jet." As discussed in the next section, there may be problems with this specific model, but the idea of making the pairs in a high-entropy region and allowing them to expand along the axis is a good one. It is an important aspect of the model proposed here as well.

One basic problem with such models is that the time scale for coalescence by gravitational radiation is too short, a few milliseconds. One is thus led to consider situations in which cylindrical symmetry prevails, that is, an accretion disk (Paczyński 1991b; Narayan et al. 1992) where an uncertain viscous time scale can be substituted for a better-known, but too short, time scale for gravitational radiation.

We follow here the logical outcome of a massive accretion disk formed around a black hole, emphasizing some of the important physics. We also discuss a type of event that probably happens much more frequently than neutron star mergers and seems better suited to the production of a gamma-ray burst—a "failed" supervova of Type Ib.

2. SETTING UP THE INITIAL CONDITIONS

2.1. *Neutron Star Mergers*

This topic has been covered recently by Meszaros & Rees (1992) and Bilsden & Cutler (1992). A key physical variable is the amount of viscous tidal heating. The heating rates given by Meszaros & Rees and Bilsden & Cutler are very similar, but the latter work considers only the energy released as the stars

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approach their tidal radius (several R_*) while the former gets a much larger energy by integrating all the way to contact (P. Meszaros 1992, private communication). The larger energy is adequate in principal to power a gamma-ray burst, but then the duration of the gamma-ray burst, governed by the gravitational radiation time scale, is too short ($0.03r_6^4$ ms). Perhaps the most interesting emission happens after the neutron stars have already merged (Narayan et al. 1992). The total of two neutron star masses, 2.8 $M_\odot$, is probably beyond the black hole mass limit, but some of the neutron star material will be left behind in a disk of about 0.1 $M_\odot$. However, once the two neutron stars have merged, but before a black hole is formed, the composite object must experience a Kelvin-Helmholtz evolution of approximately 1 s. During that time a few times 10^{53} ergs of neutrinos will be emitted. This emission will drive a mass loss of about 0.01 $M_\odot$ (Woosley 1992a) which will need to be overcome by any pair fireball created in later evolution.

2.2. *Black Hole–Neutron Star Mergers*

The merger of a neutron star with a black hole was first studied in detail by Lattimer & Schramm (1974, 1976). The neutron star will not be disrupted unless the black hole is less than a critical mass around 5–10 $M_\odot$. Even for a black hole of this size one expects that a large amount of the neutron star will enter the horizon before being dispersed into a disk. Thus we expect a black hole of 3–5 $M_\odot$ surrounded by the shredded remnant of a neutron star, perhaps $\sim$0.1 $M_\odot$. The disruption process will also lead to a large amount of mass loss (Lattimer & Schramm 1974, 1976). Pieces of the neutron star of less than $\sim$0.1 $M_\odot$ are explosively unstable and can only be contained by the gravitational field of the black hole. Viscous transport will move matter out to where the gravitational field is weaker. Dissipation will also lead to neutrino emission and neutrino-driven mass loss. Again, a surrounding cloud of baryons of 0.01 $M_\odot$ or more seems a reasonable expectation.

2.3. *Failed Supernovae—Type Ib*

The leading model for a Type Ib supernova is iron core collapse in a massive star that has lost its hydrogen envelope (e.g., Wheeler & Levreault 1985; Filippenko & Sargent 1986; Woosley, Langer, & Weaver 1992). Such Wolf-Rayet stars may have variable masses depending upon the uncertain mass loss they have experienced, which in turn depends upon their location in a binary system or, in the case of single stars, their metallicity. Those stars that make the supernovae probably have masses at the time they collapse of 3–6 $M_\odot$ (Ensman & Woosley 1988). However, larger stars should also experience core collapse. All stars heavier than about 35–40 $M_\odot$ are thought to lose their envelopes before dying (Chiosi & Maeder 1986). On the average, these larger stars have bigger iron cores which make them more difficult to explode (Wilson et al. 1986). The fate of stars that do *not* explode is of interest here.

A typical case might be a 10–15 $M_\odot$ helium star with a radius of 3×10^{10} cm. A star of 30 $M_\odot$ on the main sequence evolved without mass loss would have a helium core of this size. Larger stars that continued to lose mass after exposing their helium core might also converge on this configuration, depending again on metallicity and the mass-loss rate chosen (Woosley et al. 1992). The iron core in such a star would be between 1.5 and 2.3 $M_\odot$, depending upon how convection and critical reaction rates are treated (Weaver & Woosley 1992). As the core collapses, mass begins to accrete from the mantle. If neutrino energy deposition is unable to turn the accretion around, a situation all too common in the computer codes of those attempting to model supernova explosions, the hot protoneutron star grows. Typically the accretion rate is $\sim$0.5 $M_\odot$ s^{-1} (Woosley & Weaver 1980; Bodenheimer & Woosley 1983; Cooperstein, Bethe, & Brown 1984; more specifically the accretion rate is $\dot{M} = [8\pi/3]Ht^{-1}$ with H a characteristic of the stellar mantle, about 10^{32} g). In a few seconds the core has lost enough neutrinos and grown to sufficient mass that it collapses to a black hole. Material from the mantle and helium core continue to accrete at a rate that declines slowly with time, roughly as t^{-1}. What happens beyond this point depends on the uncertain distribution of angular momentum in the star.

Bodenheimer & Woosley (1983) have shown that for certain assumptions regarding angular momentum and pressure at the "inner boundary," a supernovae explosion may still result, powered by rotation and nuclear burning. Even in that case, though, a solar mass or so of material still accretes onto the black hole over a few seconds. If no explosion occurs, perhaps owing to a deficiency of angular momentum or less resistance from the inner boundary (parameterized in the Bodenheimer & Woosley calculation), most of the stellar mass would accrete.

The disk forms on a free-fall time scale, $446/\rho^{1/2} \sim 1$ s for the stellar mantle, but will continue to be fed as the rest of the star comes in. The polar regions, unhindered by rotation, will collapse first on a dynamic time scale ($\sim$5 s), while the equatorial regions evolve on a viscous time scale that is longer. The characteristic "butterfly" shape of the thick accretion disk forms (Bodenheimer & Woosley 1983). The radius at which the disk forms in the equator is given by the angular momentum in the material that collapses. The angular momentum distribution within Wolf-Rayet stars is, of course, unknown. Even the surface rotation speed is debated, although there is one candidate thought to be rotating at near-breakup (Schmutz 1991). A much less extreme assumption would be that centrifugal force is $\sim$1% of gravity, then $j \sim (0.01GMr)^{1/2} \sim 10^{16}$–$10^{17}$ ergs s. For angular momenta in this range, the disk forms at about 100 km. A few seconds after core collapse, one might have a disk containing approximately 0.5 $M_\odot$ at a radius of 100 km surrounding a black hole of mass 3 $M_\odot$. Both the disk and black hole continue to grow at a few tenths $M_\odot$ s^{-1}.

Such occurrences may be common. The Type Ib supernova rate is about one per century in our Galaxy (van den Bergh & Tammann 1991), and failed explosions could occur at a comparable rate. Certainly one event per 1000 yr is not unreasonable and would violate no observational constraints. This is at least 100 times the event rate of the neutron star mergers described above. It may be that collapse to a black hole could produce some interesting emission even in a star that had not lost its hydrogen envelope, but the large radii for such stars, 10^{12} cm for blue supergiants to several times 10^{13} cm for red supergiants, suggests that even should the pairs form a jet and escape, the characteristic time scale for the burst would be too long. Still, such events should not be without observational consequences.

3. THE ACCRETION PROCESS AND PAIR FORMATION

From these diverse starting points we reach a similar configuration—a black hole of several $M_\odot$ surrounded by an accretion disk of from 0.1 to 1 $M_\odot$. More total mass is available from the "failed" supernova, but it will not all reside in the inner disk at any one time. For a radius of 100 km, the surface density of the disk would be in the range 10^{18}–10^{19} g cm^{-2}, and since the black hole gravitational field keeps the disk from being more than 100 km thick, the average density in the disk will initially be 10^{11}–10^{12} g cm^{-3}, more in the equatorial plane. Compressional heating in the failed supernova case and tidal disruption in the merging neutron star case will heat the material so that its composition is neutrons and protons. The most important emission will come from between $3R_s$, the last stable orbit beyond which the mateiral plunges into the black hole, and $10R_s$, beyond which the gravitational potential is much less. That is, we are interested in what happens between 30 and 100 km.

After its formation, the disk evolves under the action of viscous stress so that angular momentum is continually transferred outward while matter in the inner region migrates inward. This happens on a diffusion time scale, $\tau_\nu \sim r^2/\nu$, where ν is the viscosity (Pringle 1981). In a variety of models for accretion disks, turbulent viscosity is thought to be responsible for both mass and angular momentum transport as well as for viscous dissipation. Using a self-consistent mixing length model or a linear normal mode analysis (Lin & Papaloizou 1980; Ruden, Papaloizou, & Lin 1988), one finds $\nu \sim 10^{-2}c_s^2/\Omega$ where c_s, the sound speed in the disk, is $\sim 10^9$ cm s^{-1}. For an angular velocity near Keplerian at 30 km, $\Omega \sim 3000$, and $\tau_\nu \sim$ 3 s. Longer time scales are appropriate to the material farther out in the failed supernova model. Thus a total duration of tens of seconds, as observed in gamma-ray bursts, seems appropriate. A magnetic field could also be accommodated in the same prescription (Shakura & Sunyaev 1973), but is neglected here. Clearly our estimate of the viscosity is very uncertain, but would be approximately correct for a convective disk (Lin & Papaloizou 1980).

The accretion rate will be given by the mass in the disk divided by this characteristic time scale, or a few tenths $M_\odot$ s^{-1}. This and other considerations discussed below suggest that systems with only 0.1 $M_\odot$ or less to accrete will probably not provide long complex gamma-ray bursts, so for now we focus attention on the "failed" Type Ib supernova. The energy dissipated in the accretion to $3R_s$ will be approximately $\frac{1}{2}\dot{M}Q$ where Q is the specific energy of the last stable orbit (Shakura & Sunyaev 1973), $\frac{1}{6}c^2$. For an accretion rate of a few tenths $M_\odot$ s^{-1}, this implies a luminosity of about 5–10 $\times 10^{52}$ ergs s^{-1} radiated as neutrinos of all flavors. At its inner edge, where most of the energy is dissipated, the accretion disk is optically thick to neutrinos and has an area of $\sim 2\pi rh$, or for $h \sim r \sim 30$ km, $A = 5 \times 10^{13}$ cm^2. The neutrinos will be thermal with $(\frac{7}{8})A\sigma T^4 \approx 2 \times 10^{52}$ ergs s^{-1} per flavor, which implies $T_\nu \sim 5$ MeV. These temperatures, luminosities, and dimensions are all typical of protoneutron stars in Type II supernovae during the first seconds of the explosion (Wilson et al. 1986; Bethe 1990).

3.1. *Energy Deposition Along the Rotational Axis*

These neutrinos, along with the heat developed from viscous dissipation, will drive abundant mass loss from the disk. Viscous dissipation of angular momentum will also lead to material moving toward the axis of rotation, but in general the lowest density should be along the axis of rotation just above and below the black hole (or $3R_s$). In the entire region interior to the disk, neutrinos will meet and annihilate (Goodman, Dar, & Nussinov 1987). The cross section for this process is $\sigma = KG_F^2\langle\epsilon_\nu^2\rangle$ with $G_F^2 = 5.29 \times 10^{-44}$ MeV^{-2} cm^2 and $K = 0.20$ and 0.10 for e-flavored and μ- and τ-flavored neutrinos, respectively. The instantaneous density of neutrinos in the region interior to the accretion disk is $\sim L/A\epsilon_\nu c$ or 5×10^{32} cm^{-3} with l and ϵ_ν the luminosity and mean energy for each flavor of neutrino. The mean-squared energy is about 250 MeV^2. Thus along a path length of 30 km the optical depth for electron neutrinos is ~ 0.003. For μ- and τ-neutrinos, K is smaller, but the mean neutrino energy, larger. We expect comparable deposition from each flavor (see also Goodman et al. 1987).

Thus for a total neutrino luminosity of 5×10^{52} ergs s^{-1}, roughly 10^{50} ergs s^{-1} will be deposited in the regions interior to the accretion disk and along the rotation axis. It is noteworthy that this deposition scales quadratically with the neutrino luminosity. Returning to cases other than the collapsed massive star, the mass of the accretion disk is only 0.1 $M_\odot$. This can provide a total energy of $\sim 0.1Mc^2 = 2 \times 10^{52}$ ergs. If that energy is to be delivered over a period of 20 s to explain a long complex burst of that duration, then the neutrino luminosity would be 10^{51} ergs s^{-1}, 50–100 times less than the case discussed above. This would lead to several thousand times less energy being converted to pairs, and unless the event were highly beamed (in which case there would need to be many more sources), it would not be visible. Such cases might give rise to bright brief transients of less than 1 s, though. They have the advantage of less baryonic material shrouding the explosion and could have more rapid rise times.

3.2. *Burst Energetics and the Potential Importance of Electron Scattering*

Suppose, as the above estimates indicate, neutrino emission is capable of depositing 10^{50} ergs s^{-1} inside the accretion column. The pair plasma created will expand, but not faster than light. Thus at any time the energy density in pairs will be greater than $10^{50}(d/c)/d^3 \sim 10^{26}$ ergs cm^{-3}, which corresponds to a pair and radiation temperature of 1 MeV. Here d is the dimension of the region, about 30 km. The actual expansion rate will depend upon how much baryonic matter is present in the radiation (Paczyński 1990b). If the time scale can be increased by a factor of 10, and interesting instability occurs.

The energy density within the region of interest is that of radiation and pairs, aT^4, and for a region of arbitrary size, $l \ll d$, within that region the total energy is proportional to l^3T^4. The optical depth for neutrino electron scattering within that region (averaged over an assumed equal distribution of μ-, τ-, and e-flavors) is $9 \times 10^{-13}\epsilon_{\rm MeV}\,T_{\rm MeV}^4\,l$ (Woosley & Weaver 1992), and the fraction of the disk luminosity intercepted by this region is $\sim(l/d)^2$. Note that the optical depth here contains only one power of ϵ since it is to be used with the luminosity, not the flux. This simple formula shows that heating and internal energy content both scale in the same way with l and T, implying a time constant for energy increase, 1 ms $(R/30\ {\rm km})^2$ L_{53}^{-1} $(10\ {\rm MeV}/\epsilon_\nu)$, that is independent of both. In the space of a few ms, the temperature in the region will run away.

The runaway will stop when either the region becomes optically thick to neutrinos or emission of neutrinos by pair annihilation balances absorption. Both of these imply $kT \sim 10$ MeV. Complete development of the instability would thus give an energy density roughly 10^4 times larger than derived above and would convert the neutrino emission with high efficiency into beamed kinetic energy and radiation. Unfortunately the time scale derived above, $d/c \sim 10^{-4}$ s, falls short by more than an order of magnitude of the requisite time for this runaway to develop, so unless the fireball dimensions can be greatly increased, the instability seems only to function if the jet is nonrelativistic, that is, contains so much baryonic matter that is expands at $\sim 0.1\epsilon$ instead of c. An energy density of 10^{28} ergs cm^{-3} in radiation, pairs, and nonrelativistic baryons limited to a velocity of 0.1c, for example, would correspond to a pair temperature of about 3 MeV, a baryon density of 10^9 g cm^{-3}, and a mass-loss rate of about 0.05 $M_\odot$ s^{-1}. No hard radiation would emerge directly from pair recombination (see below), but the energy would now all be located in the kinetic energy of the ions, a few times 10^{50} ergs s^{-1}. One would have to invoke additional features of the model (shocks?) to somehow convert this streaming motion back into hard radiation.

4. THE GAMMA-RAY BURST AND BARYON CONTAMINATION

Paczyński (1990b) has discussed the physics of grossly super-Eddington pair-dominated winds. For an energy deposition of 10^{50} ergs s^{-1}, a gamma-ray burst is possible from a pair fireball if the rate of baryonic mass loss (ρAc) is less than 10^{-6} $M_\odot$ s^{-1}. At first glance, this seems an intolerably restrictive value. Neutrino luminosities of 10^{53} ergs s^{-1} would drive mass losses of ~ 0.01 $M_\odot$ even from the gravitational potential of a neutron star (Woosley & Baron 1992; Woosley 1992a; Duncan, Shapiro, & Wasserman 1986). A baryon concentration this great would adiabatically degrade the radiation after the pairs annihilated until there was no gamma-ray burst. However, the inward mass flow from the disk will be inhibited by the pressure of the pair gas created inside. At a temperature of 1 MeV, the pressure is 10^{26} dyn cm^{-2}. Mass loss from the disk gives a ram pressure of about $10^{26}(\dot{M}/0.01\ M_\odot\ \mathrm{s}^{-1})(v/10^9\ \mathrm{cm\ s}^{-1})(10^{13}\ \mathrm{cm}^2/A)$ dyn cm^{-2}. Instead of impinging mass flow, one may have a region of near-constant temperature and pressure which merges smoothly with the "atmosphere" of the neutron star. After a brief transient as the jet forms, what baryons are present in the pairs will be there from diffusion, which is very inefficient. But then the interface may be unstable. Which of these two solutions the star finds—pair-dominated plasma standing off the baryonic wind, or wind impinging and mixing with the pairs—is critical. It determines whether the model succeeds in generating a gamma-ray burst, and it will require much more careful study.

If a relativistically expanding bubble of radiation and pairs is produced (henceforth "the jet"), one still has to contend with the overlying matter. Presumably the jet does not lift this material off the star, but merely shoves it to the side. In any case the pressure within the pair bubble greatly exceeds that of the overlying matter in the collapsing star, and the total energy is much larger than the gravitational binding. An analogous picture might be a supernova at the edge of a molecular cloud (Tenorio-Tagle, Bodenheimer, & Yorke 1985). The region along the polar axis is also evacuated in the failed supernova case after about 5–10 s (Bodenheimer & Woosley 1983). The jet is probably not a very highly collimated one. Focusing will depend upon the curvature of the accretion disk just above the equator and the location of the sonic radius. Based on the pictures of Bodenheimer & Woosley, a solid angle of roughly 10% seems reasonable, but their calculation has inadequate resolution to give a reliable value.

5. CONCLUSIONS

Gamma-ray bursts may be produced at cosmic distances by the collapse of "failed" supernovae, especially the collapse to a black hole of a Wolf-Rayet star. Shorter and/or less energetic bursts are possible from merging neutron stars, merging white dwarfs, and black holes merging with neutron stars. The burst is generated as neutrino emission from a massive accretion disk produces a relativistically expanding bubble of radiation and pairs along the rotational axis. Burst luminosities would be roughly 10^{50} ergs s^{-1} beamed into about 10% of the sky. The duration of the burst would be given by the hydrodynamic time scale for the entire star to collapse or the viscous evolution time for that portion of the disk where most of the mass resides, whichever is greater. The former is of order 1 minute. In its simplest manifestation, the luminosity would peak early on, corresponding to the maximum in accretion rate, and decline monotonically with time. The hardness of the emission would also decline in step with the luminosity. Bursts of this sort are seen, but so are many other more complicated light curves. At the latest time, the emission would shift into the X-ray as the baryonic component of the jet became an important contaminant. Because long complex bursts are only produced by "failed" supernovae in massive stars, they should be associated with star-forming regions in the galaxies in which they occur. They would not happen in elliptical galaxies.

The burst commences as the pair jet breaks through overlying baryonic matter. The rise time could be very fast, presumably less than the radius of the star divided by c, or a fraction of a second. Fine time structure could exist in the burst owing to irregularities in the accretion rate, the characteristic time scale there being the rotation period, about 1 ms. Longer scale time variation could occur if the orientation of the jet wandered so that the observer was sometimes along the axis and sometimes off axis, or if baryonic mass loss from the disk occasionally contaminated the fireball. Since the hard radiation is a consequence of relativistic beaming (Paczyński 1986; Fenimore, Epstein, & Ho 1992), lower flux from a burst observed off-axis would also correspond to a softer spectrum. Variation could also occur if the jet was modulated by the surrounding baryonic matter.

A potential problem with models of this sort is the extent to which a baryonic wind blown off the surface of the accretion disk by the neutrino emission is able to penetrate into the jet. The jet may resist this penetration, but detailed calculations are needed to see which wins. Other potential problems loom. The origin of very hard radiation ($E_\gamma \gg 1$ MeV) seen in many bursts (Matz et al. 1985; Matz 1986) is not clear. The temperature we estimate for the pair fireball here is ~ 1 MeV; the origin of nonthermal emission above 10 MeV is particularly difficult to explain and would require the consideration of nonthermal processes (magnetic field windup and dissipation in the disk? energy transport by Alfvén waves?). These models, in their simplest manifestation, would also produce no detectable optical flash, no "cyclotron line features," and no early X-ray precursors.

On the other hand, the model has the appeal of something that is likely to happen with regularity in nature. If the signature of a 5 $M_\odot$ black hole accreting stellar masses of material in a minute is not a gamma-ray burst, what is it? And what does all this imply for the production of supernovae in situations where they might not otherwise occur? Bodenheimer & Woosley (1983) asked the question which still has not been properly addressed: "What *is* the observational signature of a 'failed' supernova?"

Indeed, the term "failed" supernova has been repeatedly used in quotes throughout this paper because one can hardly call an event which yields more power than any other phenomenon in the modern universe a failure. In neutrinos, one expects $\sim 10^{54}$ ergs, as much as three supernovae. In kinetic energy 10^{51} ergs may be developed if the jet is rich in baryons. If it is not, then these are the brightest gamma-ray sources in the universe by a very wide margin.

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