Stellar Rotation
Proceedings IAU Symposium No. 215, © 2003 IAU
André Maeder & Philippe Eenens, eds.

Supernovae, Gamma-Ray Bursts and Stellar Rotation

S.E. Woosley

Department of Astronomy and Astrophysics, UCSC, Santa Cruz CA 95064, USA

A. Heger

Department of Astronomy and Astrophysics, Enrico Fermi Institute, The University of Chicago, 5640 S. Ellis Avenue, Chicago IL 60637, USA

Abstract. One of the most dramatic possible consequences of stellar rotation is its influence on stellar death, particularly of massive stars. If the angular momentum of the iron core when it collapses is such as to produce a neutron star with a period of 5 ms or less, rotation will have important consequences for the supernova explosion mechanism. Still shorter periods, corresponding to a neutron star rotating at break up, are required for the progenitors of gamma-ray bursts (GRBs). Current stellar models, while providing an excess of angular momentum to pulsars, still fall short of what is needed to make GRBs. The possibility of slowing young neutron stars in ordinary supernovae by a combination of neutrino-powered winds and the propeller mechanism is discussed. The fall back of slowly moving ejecta during the first day of the supernova may be critical. GRBs, on the other hand, probably require stellar mergers for their production and perhaps less efficient mass loss and magnetic torques than estimated thus far.

1. Introduction

For seventy years scientists have debated the physics behind the explosion of massive stars as supernovae (Baade & Zwicky 1934; Colgate & White 1966) and the possible role of rotation in these events (Hoyle 1946; Fowler & Hoyle 1964; LeBlanc & Wilson 1970; Ostriker & Gunn 1971). During the last five years, the discovery of supernovae showing evidence for gross asymmetry and anomalously large energy (e.g. Kawabata et al. 2002) coupled with a growing realization that GRBs require rapidly rotating massive stars for their progenitors, has rekindled interest in this historic controversy.

Here we briefly review (§2) the currently favored models for GRBs. The starting point for each is a rapidly rotating, massive ($M \gtrsim 10\,M_\odot$) Wolf-Rayet star (WR-star) whose central iron core has become unstable. The amount of angular momentum required for the material just outside the core ($j \gtrsim 10^{16}$ cm^2 s^{-1}) is far in excess of what is observed in young pulsars and also greater than what is predicted by current stellar models (Heger, Woosley, & Spruit 2003; see also Heger et al. this volume). In fact, the models predict angular momenta in presupernova stars in between what is needed for GRBs and pulsars - too slow

https://doi.org/10.1017/S0074180900196275 Published online by Cambridge University Press

for the former, too fast for the latter (§3). We are thus led to consider scenarios in which excess angular momentum exists in a small fraction of WR-stars near death, as well as mechanisms for *removing* angular momentum from neutron stars produced by ordinary supernovae (§4). Given that current estimates of gravitational radiation by the $r-$mode instability are orders of magnitude too small, a promising possibility is braking the rotation of young neutron stars by the "propeller mechanism". This happens when a strongly magnetic neutron star is spun down by interacting with slow moving matter that fails to achieve ejection in the supernova. As this material falls back on the spinning neutron star, it is spun up and ejected, carrying with it excess angular momentum.

We conclude with some speculations (§5) on how the diverse needs for slowly rotating pulsars and rapidly rotating GRB progenitors might be achieved.

2. Models for Gamma-Ray Bursts

Recent developments in the study of GRBs have been reviewed by Meszaros (2002) and we will only mention a few relevant to the present discussion. It is now acknowledged that the most common variety of GRBs, the so called "long-soft" bursts, originate at cosmological distances with an average redshift of about 1.3 (there may be observational bias in this number and the true average could be greater). Each burst is beamed to a small fraction of the sky with a typical opening angle of $\sim$5 degrees; thus for every burst we see, there are approximately 300 that we do not see. Correcting for this beaming and making a reasonable estimate for the efficiency of producing gamma-rays, the kinetic energy of the GRB producing jets is $\sim 3\times10^{51}$ erg (Frail et al 2001). Approximately two dozen events cluster within an order of magnitude of this this value. It is interesting that this is close to the kinetic energy of a typical supernova (1×10^{51} erg), but, on the other hand, ordinary supernovae do not collimate their ejecta into jets and do not concentrate a large fraction of their energy into highly relativistic motion. It is estimated, on the basis of variability arguments and self-opacity considerations, that the Lorentz factor in these jets is typically in excess of $\Gamma \sim 300$, making them by far the most rapidly moving bulk matter in the universe. The event rate in the observable universe for GRBs, both those beamed at us and away, is about 1000 per day.

Observations of GRB afterglows, where they have been seen, show the bursts come from star-forming regions in distant galaxies. There have also been reports of approximately five Type I supernovae coincident in location and onset with GRBs. The most striking and well observed of these was SN 1998bw, in coincidence with GRB 980425. This supernova, a Type Ic, had very unusual properties including anomalously high velocities, high energy, asymmetry, and evidence for relativistic motion (inferred from its radio afterglow).

Taken together, the evidence suggests that at least this common subclass of GRBs is produced by the death of massive stars. The energies involved are similar to supernovae, but somehow a large fraction of the energy has been channeled into relativistic, bi-polar outflows. We see a burst only when we look directly down the axis of these outflows. Finally, since the bursts typically last $\sim$20 s, the star producing the GRB cannot be a giant star (neither blue nor red) because a jet lasting 20 s or less would lose its energy before escaping from

https://doi.org/10.1017/S0074180900196275 Published online by Cambridge University Press

the star. It would also be unrealistic for a jet that lasted much longer, say the ~1000 seconds required for light to cross a red supergiant, to die abruptly 10 - 20 s after escaping. The progenitor has apparently lost its envelope.

Within this context several models have been proposed. Each involves the death of a WR-star initiated by iron-core collapse, and in each, the parent star is exploded by jets that then travel very far outside the stellar surface before making the actual GRB. As we shall see, each model, also invokes rapid rotation of the parent star.

2.1. Supranovae

Vietri & Stella (1998, 1999) have suggested that GRBs 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. With rapid rotation, however, collapse is delayed until angular momentum is lost by gravitational radiation and magnetic field torques. Vietri and Stella assume that the usual pulsar formula holds and, for a field of 10^{12} G, a delay of order years (depending on the field 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 $\sim 0.1\,M_\odot$ is left behind in a disk which accretes and powers the burst explosion.

As a GRB model, the supranova has several advantages. It predicts an association of GRBs with massive stars and supernovae - as do all the models discussed here. 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 (e.g. Piro et al. 1999, 2000). However, the supranova model also has some difficulties. It may also take fine tuning to produce a GRB days to years after the neutron star is born. Shapiro (2000) 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. The angular momentum required is essentially that of a neutron star born rotating at break up.

2.2. Millisecond Magnetars

Another model, championed most recently by Wheeler et al. (2000, 2002), is the "super-magnetar" model (see also Usov 1992). As usual, the iron core of a massive star collapses to a neutron star, but for whatever reasons, unusually high angular momentum perhaps, the neutron star acquires, at birth, an extremely powerful magnetic field, 10^{15} - 10^{17} G. If the neutron star additionally rotates with a period of ~ 1 ms, 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

https://doi.org/10.1017/S0074180900196275 Published online by Cambridge University Press

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 (1970) jet to "weaken" the confinement of the radiation bubble along the rotational axis. Numerical models to give substance to this scenario are needed (see also Wheeler, Meier, & Wilson 2002).

2.3. Collapsars

This is currently the leading model for GRBs, in part because of the detailed calculations that have been done to support the scenario. A collapsar is a rotating massive star whose central core collapses to a black hole surrounded by an accretion disk (Woosley 1993; MacFadyen & Woosley 1999). 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.

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

- A standard (Type I) collapsar (MacFadyen & Woosley 1999) 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 $\sim 10\,M_\odot$ because of their large binding energy and the rapid accretion that characterizes the first second after core collapse.

- 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 (MacFadyen Woosley, & Heger 2001). Such an occurrence is again favored by massive helium cores. Unfortunately the long time scale associated with the fall back 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 (Narayan, Piran, & Kumar 2001) and therefore the energy available to make jets.

- A third variety of collapsar occurs for extremely massive metal-deficient stars (above $\sim$300 $M_\odot$) that probably existed only in the early universe (Fryer, Woosley & Heger 2001). 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. 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

https://doi.org/10.1017/S0074180900196275 Published online by Cambridge University Press

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.

Of these possibilities, the collapsar Type I is currently favored and most frequently discussed, in part because of its shorter characteristic time scale.

3. GRB Progenitors

Using the same formalism and code as discussed by Heger et al. (these proceedings), a 15 $M_\odot$ *helium* core has been evolved from the onset of central helium burning until iron core collapse. Estimates of the dominant magnetic and non-magnetic modes of angular momentum transport were included. The assumed mass loss rate was taken from Wellstein & Langer (1999) reduced by 3 to account for clumping (Hamann & Koesterke 1998). We take a metallicity of 10% solar and further decrease the mass loss by the square root of this number. Altogether the mass loss rate was

$$\log\left(\frac{\dot{M}}{M_\odot\ yr^{-1}}\right) = -10.95 + 1.5\log\left(\frac{L}{L_\odot}\right). \quad (1)$$

This is equal to 1.7×10^{-5} $M_\odot$ yr^{-1} when the star dies, a value some might regard as low for an 8.6 $M_\odot$ WR-star but at least an order of magnitude greater than inferred for SN 2002ap (Berger, Kulkarni & Chevalier 2002) and SN 1998bw (Li & Chevalier 1999), two well studied massive Type Ic supernovae. The initial model was assumed to be rigidly rotating with a surface angular speed corresponding to a fraction of break up (typically 10% or 30%). A sampling of results is given in Table 1 and in the figures. For other models and more extensive discussion see Heger, Woosley & Spruit (2003).

The first three columns in Table 1 define the initial model and physics employed (magnetic torques, amount of rotation expressed in terms of a percentage of Keplerian at the surface, and mass loss by winds). Next is the period a pulsar would have if it formed in this star, then the non-dimensional spin parameter, a, a black hole would acquire, if all the angular momentum below the mass coordinate indicated were to go into the black hole of that mass (formal values in excess of 1 are shown in brackets solely to give a measure for the angular momentum available in the model). In the last column we show the mass ranges in which the equatorial mass could form a centrifugally supported accretion disk around a central compact object. The dashed lines in Fig. 2 indicate the specific angular momentum needed for a rotationally supported disk at the last stable orbit of a Schwarzschild or extreme Kerr (a = 1) black hole.

As the figures and table show, mass loss and magnetic torques are detrimental to any GRB model that invokes hyper-critical rotation of the collapsed remnant. This is true even for initial rotation rates unlikely to be achieved in single stars (e.g. 30% critical at the surface). Most of the angular momentum is lost during helium burning and very little in the advanced burning stages.

https://doi.org/10.1017/S0074180900196275 Published online by Cambridge University Press

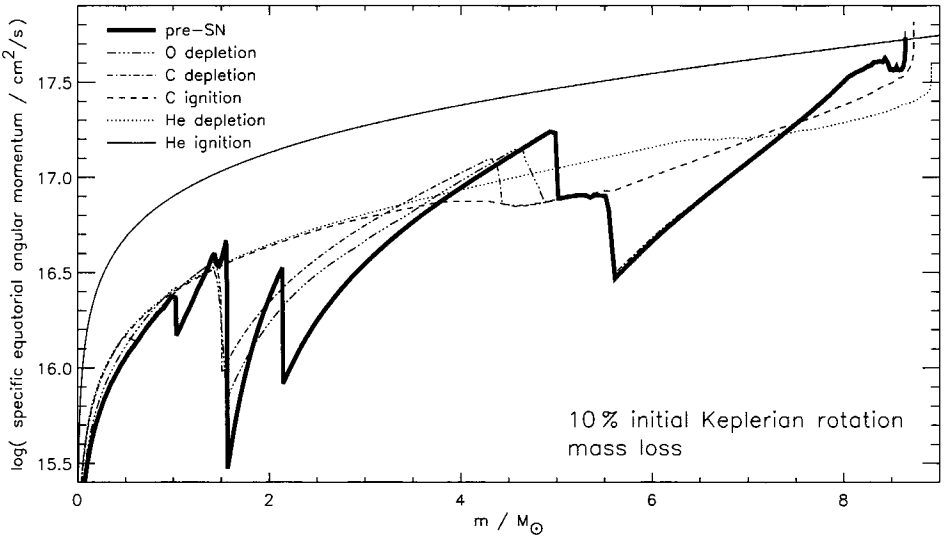

Figure 1. Angular momentum in the equatorial plane as a function of the interior mass coordinate, m, at different evolutionary stages for a 15 $M_\odot$ helium star. Mass loss was included, but no magnetic torques. The specific angular momentum is shown during different evolutionary stages and for the presupernova star. The peak-like structure in $j(m)$ at late times is indicative of rigidly rotating convective shells. This model has adequate rotation at death to produce a collapsar (line 2; Table 1).

TABLE 1

B	% K	$\dot{M}$	P(ms)	a(2)	a(2.5)	a(3)	a(4)	Mass range for making disk
–	10	–	0.09	(2.5)	(3.4)	(3.8)	(3.7)	0 – 15
–	10	yes	0.23	(1.1)	0.90	0.98	(1.2)	0 – 2.5, 2.7 – 8.6
–	30	–	0.06	(4.1)	(4.8)	(5.6)	(5.9)	0 – 15
–	30	yes	0.18	(1.7)	(1.3)	(1.3)	(1.7)	0 – 8.4
yes	10	–	0.45	0.58	0.76	0.80	0.88	2.4 – 2.8, 5.7 – 15
yes	10	yes	3.4	0.08	0.09	0.11	0.10	8.5 – 8.8
yes	30	–	0.26	(1.2)	(1.4)	(1.4)	(1.5)	0 – 15
yes	30	yes	1.9	0.16	0.14	0.16	0.17	7.4 – 8.8

4. Slowing the Rotation Rate of Young Neutron Stars

While the rotation rates in Fig. 2 and Table 1 are too slow for GRB progenitors, they are much too fast for ordinary pulsars. This remains true even for the more moderate rotation rates coming from red supergiant progenitors and discussed by Heger et al. (this volume). A young neutron star can be braked by neutrino emission, by gravitational radiation, and by electromagnetic torques. The first two have the virtue of carrying away angular momentum and energy in a form that, at least for now, is invisible. In principle, core collapse could occur in the

https://doi.org/10.1017/S0074180900196275 Published online by Cambridge University Press

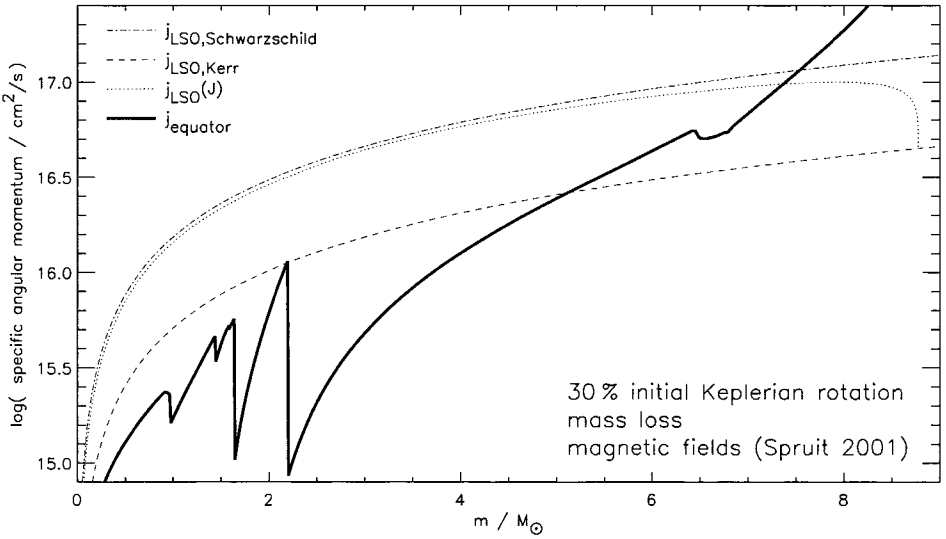

Figure 2. Same as Fig. 1, but with an initial rotation rate of 30 % Keplerian rotation and angular momentum transport by magnetic fields according to Spruit (2002) included. Dashed lines show the necessary angular momentum to give a rotationally supported disk for a Schwarzschild black hole (upper curve) or a Kerr Black hole (lower curve). Only the outermost layers of the core satisfy either condition and the model is not a viable collapsar progenitor (bottom line, Table 1). However, less mass loss or less efficient magnetic torques could change this conclusion.

presence of rotation so large as to be dynamically important, or even to make a collapsar, but the excess angular momentum could be radiated away before any measurements of the pulsar period become possible.

Neutrinos carry away angular momentum because their last interaction occurs at the surface of the neutron star where the specific angular momentum is high. The ratio of angular momentum to effective mass (E/c^2) is greater than the average for the neutron star and neutrino loss results in the loss of specific angular momentum in the remaining star. Unfortunately, such losses are limited by the small fraction of the neutron star's mass emitted as neutrinos (~20%). Calculations by Janka (2002, private communication) show that the maximum lengthening of the period is 30%.

For some time it was thought that gravitational radiation induced by the "r-mode instability" would rapidly brake young neutron stars. However, Arras et al (2003) have recently found that the r-mode waves saturate at amplitudes far lower than obtained in previous numerical calculations (Lindblom, Tohline & Vallisneri 2001) that assumed an unrealistically large driving force. Much less gravitational radiation occurs and the braking time for a rapidly rotating neutron star becomes millennia rather than hours. Arras et al. calculate that

$$\tau_{\text{spin down}} = 2000 \text{ yr } (\frac{\alpha_e}{0.1})^{-1} (\frac{335 \text{ Hz}}{\nu})^{11}, \tag{2}$$

https://doi.org/10.1017/S0074180900196275 Published online by Cambridge University Press

with α_e, the maximum amplitude of the instability (for which Arras et al estimate 0.1 as an upper bound). A 3 ms pulsar will thus take about 2000 years to substantially brake. Kaspi & Helfand (2002), on the other hand, note several slowly rotating young pulsars, in particular J1811-1925 in G11.2-0.3 with P_{init} = 62 ms and age 2000 years. It seems that pulsars are either born rotating slowly - because their parent stars rotated slowly - or else have been braked by electromagnetic torques. In the later case, the excess energy should either appear as radiation or contribute to the kinetic energy of the explosion.

In this regard the estimated rotation rates calculated for presupernova cores by Heger et al. elsewhere in these proceedings lie in an interesting range, too slow to be the sole source of the supernova's energy, yet too fast for ordinary pulsars. Such calculations are admittedly very uncertain, but, taken at face value, raise an interesting question. Could pulsars frequently be born rotating with 5 to 10 ms periods, yet be slowed to values 30 to 100 ms, say, during their first year? One possibility is the pulsar mechanism itself, but we would like to consider here two others - magnetic stellar winds and the propeller mechanism.

4.1. Neutrino-Powered Magnetic Stellar Winds

During the first 10 s of its life a neutron star emits about 20% of its mass as neutrinos. This powerful flux of neutrinos passing through the proto-neutron star atmosphere drives mass loss and the neutron star loses $\sim 0.01 M_\odot$ (Duncan, Shapiro & Wasserman 1986; Qian & Woosley 1996; Thompson, Burrows & Meyer 2001). Should magnetic fields enforce corotation on this wind out to a radius of 10 stellar radii, appreciable angular momentum could be lost from a 1.4 $M_\odot$ neutron star (since $j \sim r^2\omega$). The issue is thus one of magnetic field strength and its radial variation.

For a neutron star of mass M and radius, R_6, in units of 10 km, the mass loss rate is approximately (more accurate expressions are given by Qian & Woosley)

$$\dot{M} \approx 10^{-3}\ \mathrm{M_\odot\ s^{-1}} \left(\frac{\mathrm{L_{\nu,tot}}}{10^{53}\ \mathrm{erg\ s}}\right)^{5/3} \mathrm{R_6}^{5/3} \left(\frac{1.4\ \mathrm{M_\odot}}{\mathrm{M}}\right)^2. \quad (3)$$

The field will cause corotation of this wind out to a radius (Mestel & Spruit 1987) where

$$\rho\ (v_{\mathrm{wind}}^2 + \omega^2 r^2) \approx \frac{B^2}{4\pi}. \quad (4)$$

Calculations that include the effect of rotation on the neutrino-powered wind have yet to be done, but one can estimate the radial density variation from the one-dimensional models of Qian & Woosley. For a mass loss rate of 10^{-2} $M_\odot$ s^{-1} they find a density and radial speed at 100 km of 10^8 g cm^{-1} and 1000 km s^{-1} respectively. At this time, the proto-neutron star radius is 30 km and these conditions persist for $\sim$ 1 s. Later, they find, for a mass loss rate of 10^{-5} $M_\odot$ s^{-1} and a radius of 10 km, a density at 100 km of $\sim 10^5$ g cm^{-3} and velocity 2000 km s^{-1}. This lasts $\sim$ 10 s. Unless ω is quite low, v_{wind} is not critical. For $\omega \sim 1000$ rad s^{-1} the field required to hold 10^8 g cm^{-3} in corotation at 100 km is $\sim 3 \times 10^{14}$ G; for 10^5 g cm^{-3} it is 10^{13} G.

To appreciably brake such a rapidly rotating neutron star, assuming $B \sim r^{-2}$, thus requires ordered surface fields of $\sim 10^{15}$ - 10^{16} G. Similar conclusions

https://doi.org/10.1017/S0074180900196275 Published online by Cambridge University Press

have been reached independently by Todd Thompson (2003). Such fields are characteristic of magnetars, but probably not of ordinary neutron stars. On the other hand if the rotation rate were already slow, $\omega \sim 100$ rad s^{-1} ($P \sim 60$ ms), even a moderate field of 10^{14} G could have an appreciable effect. It should also be kept in mind that the field strength of a neutron star when it is 1 - 10 s old could be very different than thousands of years later when most measurements have been made.

4.2. Fallback and the Propeller Mechanism

After the first 1000 s, the rate of accretion from fall back is given (MacFadyen, Woosley & Heger 2001) by

$$\dot{M} \approx 10^{-7}\, t_5^{-5/3}\, \mathrm{M}_\odot\, \mathrm{s}^{-1}, \tag{5}$$

with the time in units of 10^5 s. For the mass loss rate in units of 10^{26} g s^{-1}, we obtain

$$\dot{M}_{26} \approx 2\, t_5^{-5/3}\, \mathrm{g\ s}^{-1}. \tag{6}$$

For a dipole field with magnetic moment $\mu_{30} = B_{12} {R_6}^3$, with B_{12} the surface field in units of 10^{12} G, the infalling matter will be halted by the field at the Alfven radius (Alpar 2001),

$$r_\mathrm{A} = 6.8\, \mu_{30}^{4/7}\, \dot{M}_{26}^{-2/7}\ \mathrm{km}. \tag{7}$$

At that radius matter can be rotationally ejected, provided the angular velocity there corresponding to co-rotation exceeds the Keplerian orbital speed. The ejected matter carries away angular momentum and brakes the neutron star. This is the propeller mechanism (Illarionov & Sunyaev 1975; Chevalier 1989; Lin, Bodenheimer & Woosley 1991; Alpar 2001).

Obviously r_A must exceed the neutron star radius (10 km here) if the field is to have any effect. The above equations thus require a strong field, $B > 10^{12}$ G, and accretion rates characteristic of times at least one day. Additionally there is a critical accretion rate, for a a given field strength and rotation rate, above which the co-rotation speed at the Alfven radius will be slower than the Keplerian orbit speed. In this case the matter will accrete rather than be ejected. Magnetic braking will thus be inefficient until $\omega^2 r_\mathrm{A}^3 > GM$, or

$$\dot{M}_{26} < 5.7 \times 10^{-4}\, \omega_3^{7/3}\, \mu_{30}^2, \tag{8}$$

where ω_3 is the angular velocity in thousands of radians per second ($\omega_3 = 1$ implies a period of 2π ms). This turns out to be a very restrictive condition. For a given μ_{30} and ω_3, eq. (6) and (8) give a time, $t_{5,\mathrm{min}}$, when braking can begin. The torque on the neutron star from that point on will be

$$I\dot{\omega} = \mu^2/r_\mathrm{A}^3 = 10^{60} \frac{\mu_{30}^2}{r_\mathrm{A}^3}, \tag{9}$$

with I, the moment of inertia of the neutron star, approximately 10^{45} (Lattimer & Prakash 2001). The integrated deceleration will be

$$\Delta\omega = 250\, \mu_{30}^{2/7}\, t_{5,\mathrm{min}}^{-3/7}. \tag{10}$$

https://doi.org/10.1017/S0074180900196275 Published online by Cambridge University Press

Putting it all together, a 1.4 $M_\odot$ neutron star can be braked to a much slower speed ($\Delta\omega \sim \omega$) by fall back if $\mu_{30} > 78$, 43, or 25 for initial periods of 6, 21, or 60 ms, respectively. If the surface field strength - for a dipole configuration is less than 2×10^{13} G, braking by the propeller mechanism will be negligible in most interesting situations.

However, we have so far ignored all non-magnetic forces save gravity and centrifugal force. A neutron star of age less than one day is in a very special situation. The accretion rate given by eq. (5) is vastly super-Eddington. This means that matter at the Alfven radius will be braked by radiation as well as centrifugal force and the likelihood of its ejection is greater. Fryer, Benz & Herant (1996) have considered neutron star accretion at the rates relevant here and find that neutrinos released very near the neutron star actually drive an *explosion* of the accreting matter. Just how this would all play out in a multi-dimensional calculation that includes magnetic braking, rotation, and a declining accretion rate has yet to be determined, but is obviously a subject worthy of more investigation.

The ejection of material by the propeller mechanism also inhibits the accretion so the process is self limiting. If this is the way most neutron stars are slowed, one might expect a correlation of pulsar period with the mass of the progenitor star. More massive stars experience more fall back and make slowly rotating neutron stars. Interestingly the Crab was probably a star of $\sim$10 $M_\odot$ and may thus have experienced very little fall back. The matter that is ejected by the propeller mechanism in more massive stars could contribute appreciably to the explosion of the supernova and especially its mixing.

5. GRBs and Pulsars - Can One Have Them Both?

We have highlighted an interesting quandary. In order to make GRBs in the collapsar model one needs a specific angular momentum $j > 10^{16}$ erg s, corresponding to a period of $\lesssim$0.5 ms for a neutron star with moment of inertia $\sim 10^{45}$ g cm^2. Other GRB models need only two or three times less. Yet pulsars are estimated to have periods at birth in the range 20 - 100 ms, roughly two orders of magnitude slower. Can reasonable stellar evolution scenarios give both?

First, we note that the circumstances leading to a GRB are special, occurring in only $\sim$ 1% of all core collapse supernovae (roughly 1000 GRBs happen in the universe each day; the supernova rate is of order one per second). The star that dies and makes a GRB must be a WR-star and was very likely influenced by being in a mass exchanging binary. Removing the envelope lessens the torque at the edge of the helium core and allows more rapid rotation at death. But mass loss and magnetic torques during the WR-phase decrease the angular momentum, especially if one uses currently favored loss rates. Reducing those rates, by e.g. $Z_o^{1/2}$ where Z_o is the *initial* metallicity of the star, certainly goes in the right direction and would help to explain why GRBs seem to occur more frequently in the early universe (Stern, Ateia & Hurley 2002), but even this does not go far enough. The torques given by Spruit (2002) and included in the calculations of Heger et al. reported at this meeting rule out the most favored model for GRBs (Table 1). These torques are obviously uncertain, and perhaps one should be pleased to get within an order of magnitude of the desired answer, but they do

https://doi.org/10.1017/S0074180900196275 Published online by Cambridge University Press

scale as the sixth power of the shear $((\frac{r\partial_r\Omega}{\Omega})^6)$. Unless this scaling is itself quite wrong, variations of order factor of 10 in the overall strength will make little difference in the outcome. It may be possible to obtain the necessary conditions for GRBs with reasonable variation of Spruit's parameters, but then isn't one required to use these same parameters in studies of more common supernovae that make pulsars?

Factors that would facilitate the production of collapsars or other GRB models requiring rapid rotation in a massive WR-star would be:

- Decreased mass loss - mass loss removes angular momentum as well as mass. Does decreasing the initial metallicity appreciably slow mass loss for WR-stars?
- The angular dependence of mass loss - if the mass loss is concentrated at the poles as some models (Maeder & Meynet 2000) suggest, less angular momentum is carried away.
- Reduced magnetic torques - Is the formalism of Spruit (2002), based on the interchange instability, correct for massive stars? Are composition gradients more effective at inhibiting angular momentum transport than the default values of parameters in that model would suggest?
- Binary mergers - Scenarios for keeping the helium core rotating rapidly by merger with a binary companion (presumably via common envelope) when the primary is well into helium burning need exploring, but the frequency of such events must be reasonably high.

Perhaps the puzzle is not why GRB progenitors rotate so rapidly as why pulsars rotate so slowly. Either common neutron stars are born with long rotational periods or they are braked. We have discussed here two processes that might brake a young neutron star. Both seem to require magnetic field strengths substantially in excess of 10^{13} G. Interestingly these braking mechanisms would slow a young neutron star, but not a black hole and this at least may be seen as favoring the collapsar model.

This research has been supported by the NSF (AST 02-06111), NASA (NAG5-12036), and the DOE Program for Scientific Discovery through Advanced Computing (SciDAC; DE-FC02-01ER41176). AH is supported, in part, by the Department of Energy under grant B341495 to the Center for Astrophysical Thermonuclear Flashes at the University of Chicago, and a Fermi Fellowship at the University of Chicago.

References

Alpar, M. A. 2001, ApJ 554, 1245

Arras, P., Flanagan, E. E., Morsink, S. M., Schenk, A. K., Teukolsky, S. A. & Wasserman, I. 2003, ApJ 591, 1129

Baade, W. & Zwicky F. 1934, Pub National Acad Sci 20, 259

Berger, E., Kulkarni, S. R. & Chevalier, R. A. 2002, ApJL 577, 5

Chevalier, R. A. 1989, ApJ 346, 847

https://doi.org/10.1017/S0074180900196275 Published online by Cambridge University Press

Colgate, S. A. & White, R. H. 1966, ApJ 143, 626
Duncan, R. C., Shapiro, S. L. & Wasserman, I. 1986, ApJ 309, 141
Frail, D. A., Kulkarni, S. R., Sari, R., Djorgovski, S. G., Bloom, J. S., Galama, T. J., Reichart, D. E., Berger, E., et al. 2001, ApJL 562, 55
Fryer, C. L., Benz, W. & Herant, M. 1996, ApJ 460, 801
Fryer, C. L., Woosley, S. E. & Heger, A. 2001, ApJ 550, 372
Fowler, W. A. & Hoyle, F. 1964, ApJS 9, 201
Hamaan, W.-R. & Koesterke, L. 1998, A&A 335, 1003
Heger, A., Langer, N. & Woosley, S. E. 2000, ApJ 528, 368
Heger, A., Woosley, S. E. & Spruit, H. 2003, ApJ in preparation
Hoyle, F. 1946, MNRAS 106, 343
Illarionov, A. F. & Sunyaev, R. A. 1979, A&A 39, 185
Kaspi, V. & Helfand, D. 2002, in ASP Conf Series 271, ed. P. O. Slane & B. M. Gaensler, San Francisco: ASP, p.3
Kawabata, K. S., Jeffery, D. J., Iye, M., Ohyama, Y. & 27 others 2002, ApJL 580, 39
Lattimer, J. M. & Prakash, M. 2001, ApJ 550, 426
LeBlanc, J. M. & Wilson, J. R. 1970, ApJ 161, 541
Li, Z.-Y. & Chevalier, R. A. 1999, ApJ 526, 716
Lindblom, L., Tohline, J. E. & Vallisneri, M. 2001, Phys. Rev. Lett, 86, 1152
Lin, D. N. C., Woosley, S. E. & Bodenheimer, P. H. 1991, Nature 353, 827
Maeder, A. & Meynet, G. 2000, A&A 361, 159
MacFadyen, A., Woosley, S. E. 1999 ApJ 524, 262
MacFadyen, A., Woosley, S. E. & Heger, A. 2001, ApJ 550, 410
Mestel. L. & Spruit, H. C. 1987, MNRAS 226, 57
Meszaros, P. 2002, ARAA 40, 137
Narayan, R., Piran, T., & Kumar, P. 2001, ApJ 557, 949
Ostriker, J. P. & Gunn, J. E. 1971, ApJL 164, 95O
Piro, L., Costa, E., Feroci, M., Frontera, F., Amati, L., dal Fiume, D., Antonelli, L. A., et al. 1999, ApJL 514, L73.
Piro, L., Garmire, G., Garcia, M., Stratta, G., Costa, E., Feroci, M., Meszaros, P., Vietri, M., et al. 2000, Science 290, 955
Qian, Y. Z. & Woosley, S. E. 1996, ApJ 471, 331
Shapiro, S. L. 2000, ApJ 544, 397
Spruit, H.C. 2002 , A&A 381, 923
Stern, B. E., Atteia, J.-L. & Hurley, K. 2002, ApJ 578, 304
Thompson, T. 2003, preprint.
Thompson, T., Burrows, A. & Meyer, B. 2001, 562, 887
Usov, V. 1992, Nature 357, 472
Vietri, M. & Stella, L. 1998, ApJL 507, L45
Vietri, M. & Stella, L. 1999, ApJL 527, L43
Wheeler, J. C., Yi, I., Höflich, P. & Wang, L. 2000, ApJ 537, 810
Wheeler, J. C., Meier, D. L. & Wilson, J. R. 2002, ApJ 568, 807
Wellstein, S. & Langer, N. 1999, A&A 350, 148
Woosley, S. E. 1993, ApJ 405, 273.

https://doi.org/10.1017/S0074180900196275 Published online by Cambridge University Press