Gamma Ray Burst Central Engines

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Abstract. I review aspects of the theory of long-duration gamma-ray burst (GRB) central engines. I focus on requirements of any model; these include the angular momentum of the progenitor, the power, Lorentz factor, asymmetry, and duration of the flow, and both the association and the non-association with bright supernovae. I compare and contrast the collapsar and millisecond proto-magnetar models in light of these requirements. The ability of the latter model to produce a flow with Lorentz factor $\gamma \sim 100$ while simultaneously maintaining a kinetic luminosity of $\sim 10^{50}$ ergs s$^{-1}$ for a timescale of $\sim 10 - 100$ s is emphasized.

Keywords: Gamma Ray Bursts, Outflows, Nucleosynthesis, Accretion, Magnetars, MHD

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INTRODUCTION

Models for the central engine of long-duration gamma ray bursts (GRBs) are highly constrained by the character of the prompt emission and the afterglow, and — at least in some cases — the fact of an associated supernova (SN). There is little diversity among models for the central engine and essentially all can be simply classed as a rotating compact object that drives an asymmetric relativistic outflow.

The “collapsar” model as described in [1] and developed in [2, 3] proposes that GRBs arise from the collapse of rapidly rotating Type-Ibc progenitors. A black hole forms with an accompanying accretion disk and drives a collimated relativistic outflow along the axis of rotation via either neutrino heating or magnetic stresses.

The “millisecond proto-magnetar” model posits a newly formed rotating neutron star (spin period $P \sim 1$ ms) with surface magnetic field of magnetar strength ($B \sim 10^{15}$ G), cooling via neutrino radiation on the Kelvin-Helmholtz timescale, $t_{KH} \sim 10 - 100$ s, and driving a neutrino-heated magneto-centrifugal wind [4]. Proto-magnetars might be produced by rotating Type-Ibc progenitors, the accretion-induced collapse of a white dwarf, the merger of two white dwarfs, and/or (potentially) the merger of two neutron stars [5]. Thus, they may trace both young and old stellar populations. See also [6, 7, 8].

Here, I compare and contrast some of the basic elements of and requirements on the collapsar and proto-magnetar models. I focus on the fact that a viable central engine must simultaneously realize a collimated flow with Lorentz factor in the range $100 \lesssim \gamma \lesssim 1000$, on a $10 - 100$ second timescale, while producing a kinetic luminosity of $\sim 10^{50}$ ergs s$^{-1}$. While many models have been proposed that can in principle meet these requirements, the proto-magnetar model realizes them quantitatively.
THE PROGENITOR: ANGULAR MOMENTUM

**Collapsar.** The model is that of a central black hole, formed by core-collapse of a massive star, with a centrifugally-supported disk. The latter requirement sets the minimum angular momentum required for the collapsar mechanism: \( j_{\text{min}} \approx 1.5 \times 10^{16} M_3 \text{ cm}^2 \text{ s}^{-1} \) is required for disk formation at the ISCO of a maximally-rotating \( M_3 = M/3 M_\odot \) black hole. For a disk that extends to larger radius and/or a non-maximal black hole, \( j_{\text{min}} \) increases. The models of [2] that produce a strong “Ni wind,” which is needed to power the bright associated Type-Ibc SN lightcurve have \( j \sim 10^{17} \text{ cm}^2 \text{ s}^{-1} \).

**Proto-Magnetar.** The proto-magnetar model does not require disk formation. Instead, it posits the existence of a neutron star with a large-scale magnetic field of strength \( B \sim 10^{15} \text{ G} \), mass \( M_{1.4} = M/1.4 M_\odot \), radius \( R_{10} = R/10 \text{ km} \) and spin period of order \( P_1 = P/1 \text{ ms} \) [4]. In a detailed set of calculations, [9] find that (depending on \( B \)) \( P \lesssim 2 \text{ ms} \) is required to produce conditions favorable for a GRB, implying a minimum specific angular momentum for the pre-collapse iron core of \( j_{\text{min}} \approx 3 \times 10^{15} R_{10}^2 P_1^{-1} \text{ cm}^2 \text{ s}^{-1} \). This is a factor of 5 smaller than \( j_{\text{min}} \) for the collapsar model, and a factor of \( \sim 30 \) smaller than the model of [2] that launches a disk wind. In absolute terms, a spin frequency (\( \Omega \)) corresponding to \( P \sim 2 \text{ ms} \) is relatively small, just \( \sim 25\% \) of breakup, \( \Omega_{\text{max}} \sim (GM/R^3)^{1/2} \).

The additional requirement on the proto-magnetar model is that the neutron star must generate or be born with a magnetar-strength field. That large \( B \) might accompany small \( P \) was proposed by [10, 11], who argued that when \( P \) becomes shorter than the convective overturn timescale (Rossby number < 1) neutron stars undergo strong dynamo action, producing a magnetar. A weakness of the proto-magnetar model is that a strong poloidal field is assumed to exist without being generated self-consistently (e.g., [4, 12]). In absolute terms, the energy associated with a \( 10^{15} \text{ G} \) field is much less than the rotational energy (\( B_{\text{eq, rot}} \sim [4\pi \rho R^2 \Omega^2]^{1/2} \sim 2 \times 10^{17} \rho_{14}^{1/2} R_{10} P_1^{-1} \text{ G} \), where \( \rho_{14} = \rho/10^{14} \text{ g cm}^{-3} \)) of the neutron star and/or the total energy carried in convective motions during \( t_{\text{KH}} \).

**Summary.** \( j_{\text{min}} \) for collapsars is significantly larger than for proto-magnetars. If a progenitor stellar population evolves in such a way as to produce conditions favorable for a collapsar, it is hard to see how it should not produce progenitors with smaller specific angular momentum in the range needed to power proto-magnetar-driven GRBs. Perhaps in this way collapsars represent an extremum of the GRB population and proto-magnetars more continuously connect with the SN population.

THE FLOW: KINETIC POWER & LORENTZ FACTOR

In the internal shock model, it is important that the flow that generates the GRB achieve \( 100 \lesssim \gamma \lesssim 1000 \) while simultaneously producing a kinetic luminosity of \( \sim 10^{50} \text{ ergs s}^{-1} \) on a \( t \sim 10 - 100 \text{ s} \) timescale. Reference [13] writes that ‘A nagging question in all these models is what produces the ’observed’ ultra-relativistic flow? How are \( 10^{-5} M_\odot \) of baryons accelerated to an ultra-relativistic velocity with \( \gamma \sim 100 \) or larger? Why is the baryonic load so low? Why isn’t it lower? There is no simple model for that. An ingenious theoretical idea is clearly needed here.” See the lucid and concise discussion in [14] of the physics that sets the upper and lower limits on \( \gamma \).

**Collapsar.** There have been few attempts to derive the Lorentz factor self-consistently in the collapsar model. Reference [2] showed that \( \bar{\nu} \bar{\nu} \) annihilation above
the poles of the black hole results in efficient energy deposition, generating very large specific entropy and high relativistic enthalpy. It is natural that the flow should then accelerate to relativistic velocities, as in\(^\text{[15, 16]}\). A collimated relativistic flow might also be accelerated via magnetic stresses along the rotational axis, producing a highly Poynting-flux-dominated jet. Calculations of the global structure of accretion disks indicate that the polar funnel does realize very large magnetization, \(\sigma\), the magnitude of which is limited only by numerics as the pole becomes essentially baryon-free\(^\text{[17]}\). It has been suggested that cross-field neutron diffusion might set the asymptotic Lorentz factor in an otherwise baryon-free jet\(^\text{[18]}\); however, see\(^\text{[19]}\).

There is little doubt that the flow above the pole of a rotating black hole will become highly relativistic as a result of either neutrino energy deposition or magnetic stresses, or both. The question is, does the collapsar model simultaneously produce a jet with \(100 \lesssim \gamma \lesssim 1000\) and \(\dot{E} \sim 10^{50}\text{ergs s}^{-1}\)? What is the time-evolution of \(\gamma\), and how does it relate to the time-dependence of the accretion rate? These questions are as yet unanswered and they represent the largest single gap in the collapsar model of GRBs.

**Proto-Magnetar.** Regardless of the mechanism of core-collapse SNe, neutron stars are born hot — with a central temperature of \(10\)’s of MeV — and they radiate their gravitational binding energy in neutrinos as they cool, contract, and deleptonize on the Kelvin-Helmholtz timescale of \(t_{\text{KH}} \sim 10 – 100\text{s}\)\(^\text{[20, 21]}\). During this epoch, neutron stars drive thermal neutrino-heated hydrodynamical winds\(^\text{[22, 23]}\). For a neutron star with \(M = 1.4\text{M}_\odot, R = 10\text{km},\) rotation frequency \(\Omega\), and and a magnetar-strength magnetic field, the mass-loss rate during \(t_{\text{KH}}\) is given approximately by\(^\text{[23, 4, 9]}\)

\[
\dot{M}(t) \approx 10^{-6} L_{\nu_{e,51}}^2(t) \exp[\Omega^2(t)^2/\Omega_\text{c}^2] \text{M}_\odot \text{s}^{-1},
\]

where the total neutrino luminosity \(L_{\nu}\) is indexed by the \(\nu_{e}\) luminosity \(L_{\nu_{e,51}} = L_{\nu_{e}}/10^{51}\text{ergs s}^{-1}\) (typically \(L_{\nu} \sim 5L_{\nu_{e}}\)) and it has been assumed that \(L_{\nu_{e}} \propto \langle \epsilon_{\nu_{e}} \rangle^4\), where \(\langle \epsilon_{\nu_{e}} \rangle\) is the average energy. The normalization of eq. \((1)\) and its \(L_{\nu}\)-dependence follow from the physics of the weak interaction, and, in particular, the cross-section for the charged-current processes \(\nu_e n \leftrightarrow pe^-\) and \(\nu_{e}p \leftrightarrow ne^+\)\(^\text{[22, 23]}\). This physics is a significant part of the answer to the questions posed by\(^\text{[13]}\) at the beginning of this section in the proto-magnetar model. The exponential factor in equation \((1)\) accounts for the enhancement by magneto-centrifugal forces when \(B\) and \(\Omega\) are large \((\Omega_\text{c} \approx 2300 L_{\nu_{e,51}}^{0.08}\text{rad s}^{-1}\)\(^\text{[6]}\)). For \(P \lesssim 2\text{ms}\) this factor becomes important\(^\text{[4]}\).

One of the most important components of the proto-magnetar model is that as the neutron star cools \(L_{\nu}\) decreases on a timescale \(t_{\text{KH}}\)\(^\text{[20, 21, 7, 4]}\). As a result of equation \((1)\), \(\dot{M}\) decreases concomitantly. For this reason, for fixed surface magnetic field strength, the wind becomes increasingly magnetically-dominated and relativistic as a function of time. This is quantified by the magnetization at the light cylinder \((R_L = c/\Omega \sim 50P_1 \text{km})\):

\[
\sigma_L(t) = B(R_L)^2/[4\pi \rho (R_L)c^2] \approx \dot{M}(t)^{-1}.
\]

At early times of order \(\sim 1\text{s}\) after the SN shock is launched \(L_{\nu}\) is high enough that the wind is primarily driven by neutrino heating, \(\dot{M}\) is large, \(\sigma_L\) is less than unity, and the flow is non-relativistic. As \(L_{\nu}\) decreases, the wind becomes increasingly magnetically-dominated and it transitions to non-relativistic, but magneto-centrifugally dominated. On
a few-second timescale, $\sigma_L$ becomes larger than unity and the wind becomes Poynting-flux dominated. It becomes increasingly so on a timescale $t_{KH}$. If we assume that there is efficient conversion of the magnetic energy to bulk kinetic energy (via, e.g., magnetic dissipation; see [24]), then the asymptotic Lorentz factor of the wind is $\gamma \sim \sigma_L$.

As an example, in the models of [9] (see, e.g., Fig. 1 of [25]), we find that $\sigma_L \approx 100$ at $t \approx 20$ s, when $\dot{E} \approx 10^{50}$ ergs s$^{-1}$, for a proto-magnetar with $B = 3 \times 10^{15}$ G and $P = 1$ ms. Thus, proto-magnetars drive relativistic flows with the kinetic luminosity, timescale, and Lorentz factor appropriate for producing GRBs.

The time evolution of the system is governed by perhaps the single most significant input to the proto-magnetar model: the time evolution of $L_\nu$ and $\langle \varepsilon_\nu \rangle$: as $L_\nu$ decreases, $\dot{M}$ decreases (eq. 1), $\sigma_L$ increases (eq. 2), and, because $\dot{E}$ scales with a positive power of $\dot{M}$ [4, 12, 9], it decreases. The cooling epoch eventually ends, $L_\nu$ and $\dot{M}$ drop precipitously, and the proto-magnetars transitions to more “pulsar”-like. As recently shown by [19], the fact that $\sigma_L(t) \sim \gamma(t)$ increases monotonically with time throughout $t_{KH}$ implies high radiative efficiency in the internal shock model for the prompt emission.

In [4, 9, 19] we have taken $L_\nu(t)$ and $\langle \varepsilon_\nu \rangle(t)$ from [21], informed by the early-time calculations of, e.g., [26]. However, the models of [21] are for non-rotating non-magnetic proto-neutron stars and it is possible that models including these effects (more appropriate for proto-magnetars) will change $L_\nu(t)$ and $\langle \varepsilon_\nu \rangle(t)$ quantitatively.

Summary. The ability of the proto-magnetar model to link $L_\nu$, $\dot{M}$, $\dot{E}$, and $\sigma_L \sim \gamma$ and their mutual time-dependence is a significant strength of the model and may allow it to be ruled out or (potentially) confirmed for some subsets of the global GRB population.

THE EXPLOSION: (NON-)ASSOCIATION WITH SUPERNOVAE

Several events link GRBs and SNe directly (e.g., GRB 030329 & SN 2003dh; [27]). Conversely, there are cases for which firm limits on an associated SN ($M^{[56]}_{\text{Ni}} < 10^{-3} - 10^{-4} M_\odot$) can be established (e.g., 060505, 060614; [28, 29, 30]).

Collapsar. The collapsar model provides an explanation for both the association and non-association with SNe. High angular momentum cores produce extended collapsar disks, which launch non-relativistic winds as in [2]. Calculations taking into account the electron fraction ($Y_e$) changing charged-current interactions show that even though the midplane of the disk is neutron-rich, the outflow becomes de-neutronized with $Y_e \approx 0.5$, which then produces the $^{56}\text{Ni}$ needed to power a SN lightcurve. In contrast, low angular momentum cores that do not produce extended disks might not drive Ni winds, although a relativistic jet above the poles is potentially possible. Both scenarios require a young stellar population. This is qualitatively different from the proto-magnetar model.

Proto-Magnetar. Some proto-magnetars may be formed from the collapse of a Type-Ib/c progenitor. In this scenario, one imagines that the SN mechanism in some form (e.g., the “neutrino mechanism” [31]) launches a SN shock with $\sim 10^{51}$ ergs that produces $^{56}\text{Ni}$ via explosive nucleosynthesis. This would explain the presence of an accompanying SN, but not the bright character of some GRB-SNe. If $^{56}\text{Ni}$ in excess of that produced in non-GRB Type-Ibc SNe is indeed required in some cases (see [32]) there are two ways in which it might be produced by proto-magnetars: (1) some of the initial rotational energy of the core may be tapped rapidly via magnetic stresses, enhancing the SN shock energy as it is launched [26, 33] and/or (2) as the initial slow
SN shockwave is moving outward it is shocked by the subsequent, highly-energetic proto-magnetar wind, again enhancing the shock energy [4]. Depending on the angular distribution of the wind kinetic energy, the latter option requires that $\gtrsim 10^{51}$ ergs is extracted from the proto-magnetar on a $\lesssim 1 - 2$ s timescale.

Proto-magnetars (and their GRBs) may also be formed by the accretion-induced collapse of white dwarfs and the merger of white dwarfs. In this scenario there is no explosive nucleosynthesis, essentially no $^{56}$Ni yield, and no accompanying SN [9, 19]. Proto-magnetar GRBs could then potentially trace both relatively young and old stellar populations. This is qualitatively different from the collapsar model.

**Summary.** The $^{56}$Ni yields of non-GRB Type-Ibc SNe are presumably generated by explosive nucleosynthesis. It would be remarkable if an entirely different mechanism — i.e., the Ni wind from a collapsar disk — was responsible for $^{56}$Ni production in GRB-SNe given the quantitative similarity between the $^{56}$Ni yield distributions of GRB-SNe and non-GRB-SNe [12]. Yet, this possibility is not excluded. A potentially more natural explanation is that the similarity in $^{56}$Ni yields between GRB-SNe and non-GRB-SNe evidences the same underlying physical mechanism. The proto-magnetar model provides a simple and natural way of understanding this, as well as the association and the non-association of SNe with some GRBs. It further allows for a simple interpretation of the continuum in properties between the explosive events of non-GRB-SNe and the GRB population itself (see, e.g., Fig. 5 of [34]): the diversity in $B$ and $\Omega$ for neutron stars at birth leads to a diversity in the amount of matter accelerated to relativistic velocities and the energy and distribution of energy as a function of $\gamma$ for the explosion as a whole.

**ASYMMETRY: BEAMING & COLLIMATION**

**Collapsar.** Because of the geometry of the system, the collapsar model provides a natural explanation for how the flow becomes highly-collimated, whether driven by neutrino energy deposition [2] or magnetic stresses [17].

**Proto-Magnetar.** The kinetic luminosity of a relativistic Poynting-flux-dominated proto-magnetar wind emerging into vacuum is distributed broadly around the equatorial plane [12]; production of a jet is not trivial. However, work by [25, 35] shows that the interaction between the outflow and both the overlying stellar progenitor and the preceding SN shock acts to tightly collimate the relativistic flow. The mechanism was suggested in the GRB context by [36], based on models of [37]. At radii much larger than $R_L$, the toroidal component of the wind magnetic field ($B_\phi$) is much larger than its poloidal component. The wind shocks on the exploding stellar envelope and produces a relativistically hot, quasi-hydrostatic bubble. If $B_\phi$ is large enough, the bubble expands in the polar direction as a result of both hoop stress at the equator and the confinement of the bubble by the overlying stellar envelope. The result is a relativistic jet. The models of [35] indicate that little of the incident wind energy is coupled to the “spherical” component of the explosion (the SN) and, therefore, the asymptotic Lorentz factor of the jet reflects the Lorentz factor of the incident proto-magnetar wind.

**Summary.** Based on analogy with observed jets in AGN and X-ray binaries it may be argued that the picture of collimation in the collapsar scenario is more natural than that for the proto-magnetar. Nevertheless, [25, 35] provide a compelling picture of proto-magnetar wind collimation. A major focus of future work on the proto-magnetar model
will be to understand the interaction of the wind on the progenitor and the potential feedback on the wind itself if, for some parameters, the reverse shock propagates inside the fast, Alfvén, and slow magnetosonic surfaces [35].

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