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FORMATION OF VERY STRONGLY MAGNETIZED NEUTRON STARS: IMPLICATIONS FOR GAMMA-RAY BURSTS

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ABSTRACT

Neutron stars with unusually strong magnetic dipole fields, $B_{\rm dipole} \sim 10^{14}$–$10^{15}$ G, can form when conditions for efficient helical dynamo action are met during the first few seconds after gravitational collapse. Such high-field neutron stars, "magnetars," initially rotate with short periods ~ 1 ms, but quickly lose most of their rotational energy via magnetic braking, giving a large energy boost to the associated supernova explosion. Several mechanisms unique to magnetars can plausibly generate large (~ 1000 km s^{-1}) recoil velocities. These include magnetically-induced anisotropic neutrino emission, core rotational instability and fragmentation, and/or anisotropic magnetic winds.

Magnetars are relatively difficult to detect because they drop below the radio death line faster than ordinary pulsars, and because they probably do not remain bound in binary systems. We conjecture that their main observational signature is gamma-ray bursts powered by their vast reservoirs of magnetic energy. If they acquire large recoils, most magnetars are unbound from the Galaxy or reside in an extended, weakly bound Galactic corona. There is evidence that the soft gamma repeaters are young magnetars.

Finally, we note that a convective dynamo can also generate a very strong dipole field after the merger of a neutron star binary, but only if the merged star survives for as long as ~ 10–100 ms.

Subject headings: gamma rays: bursts — magnetic fields — pulsars: general — stars: neutron

1. INTRODUCTION

A neutron star undergoes vigorous convection during the first ~ 30 s after its formation (Burrows 1987; Burrows & Lattimer 1988). When coupled with rapid rotation, this makes the star a likely site for dynamo action. We have studied such neutron star dynamos in detail elsewhere (Thompson & Duncan 1991, hereafter TD). A key parameter for the success of both α^2 and α-Ω dynamos is the Rossby number Ro, defined as the ratio of the rotation period P to the convective overturn time $\tau_{\rm con}$. In a turbulent fluid with Ro of order unity or less, the amplification of a magnetic field by helical motions is not suppressed by turbulent diffusion, and an efficient dynamo results. Larger Rossby number flows make less effective mean-field dynamos.

For convection driven by the large neutrino flux from the star, mixing-length theory implies that the overturn time of a convective cell is only $\tau_{\rm con} \sim 1 F_{39}^{-1/3}$ ms near the base of the convection zone, where $F = F_{39} \times 10^{39}$ ergs cm^{-2} s^{-1} is the convective heat flux (TD). The Rossby number is therefore $Ro \sim 1(P/1 \text{ ms})$. The initial rotation period of a pulsar is constrained by accurate measurements of the age of a surrounding supernova remnant and by limits on the amount of rotational energy deposited in the remnant. Both the Crab pulsar and the pulsar formed in SN 1987A (if it exists) almost certainly had initial rotation periods P_i much greater than 1 ms, indicating that an efficient mean-field dynamo did not operate in these objects. Nonetheless, some presupernova stellar cores may have sufficient angular momentum that they spin near breakup velocity, $P_i \gtrsim 1$ ms, following collapse. Such rapid rotators are also likely to form when white dwarfs undergo accretion-induced collapse (AIC) (Narayan & Popham 1989).

We have argued[1] that the dipole field of an ordinary pulsar born with $P_i \gg 1$ ms is generated either (*a*) during the vigorous, high Rossby number convective episode which follows the formation of the neutron star, or (*b*) in the progenitor star, during low Rossby number, main-sequence core convection (TD). In case (*a*), the dynamo amplifies the mean field on the scale of the energy-bearing turbulent eddies, but not on larger scales in a slowly rotating ($Ro \gg 1$) neutron star. A stellar dipole field of strength $\sim 10^{12}$–10^{13} G naturally arises as the incoherent sum of many small dipoles of size $\sim l_P$ and strength $\sim B_{\rm sat}$, where $l_P \sim \frac{1}{3} - 1$ km is the pressure scale height and $B_{\rm sat} = (4\pi\rho)^{1/2} l_P/\tau_{\rm con} \simeq 10^{16} F_{39}^{1/3}$ G is the dynamical saturation field strength (TD). In case (*b*), the value of $B_{\rm sat}$ in the main-sequence convective core corresponds to a field $\simeq 10^{14}$ G after compression to nuclear density, more than sufficient to account for observed pulsar fields.

A neutron star born with $P_i \sim 1$ ms (hence $Ro \sim 1$) can support an efficient α-Ω dynamo. How strong is the dipole field generated? Neutron stars generally form with a significant degree of differential rotation (e.g., TD). The associated free energy is $E_{\Omega i} \sim 10^{52}(P_i/1 \text{ ms})^{-2}$ ergs. In principle, fields as strong as 3×10^{17} $(P_i/1 \text{ ms})^{-1}$ G can be generated as the

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[1] As stellar evolution progresses, the Rossby number and Mach number of the convective motions both increase. Thus, the earliest phase of convection is the most promising site for a mean field dynamo, but the last stage is capable of generating the largest magnetic stresses. The key unresolved theoretical question concerns the viability of a small-scale, high Rossby number dynamo. For example, the rms field in the upper convection zone of the Sun approaches the local saturation strength (Goldreich et al. 1991), but it is not clear whether this requires *spontaneous* local growth of a small seed field, independent of the global solar dynamo.

differential rotation is smoothed by growing magnetic stresses. After the available free energy is released in the outermost parts of the star, vigorous convection continues to generate much stronger magnetic fields than any previous phase of stellar convection (in the sense that when B approaches $B_{\rm sat}$, the ratio of magnetic to gravitational binding energy is much larger [TD]).

These results suggest that an α-Ω dynamo operating in a neutron star born with $P_i \sim 1$ ms might generate a dipole field *much* stronger than 10^{13} G. We can compare this field to that of an ordinary pulsar by considering both scenarios for the origin of pulsar magnetism mentioned above. In case (*a*), the dipole field varies roughly as the square of the coherence length of the surface field (TD). In a star born with rapid ($P_i \sim 1$ ms) differential rotation, the wrapping of field lines around the star by the shear motion allows the formation of larger scale magnetic structures. The resulting increase in the strength of the dipole field may approach a factor $(R_\star/l_P)^2 \sim 10^2$, where $R_\star$ is the stellar radius. In case (*b*), a neutron star with $P_i \sim 1$ ms will acquire a dipole field

$$\frac{B_{\rm dipole}(\text{magnetar})}{B_{\rm dipole}(\text{pulsar})} \simeq \frac{B_{\rm sat}(\text{neutron star convection zone})\,R_{\rm ns}^2}{B_{\rm sat}(\text{main-sequence core convection})\,R_{\rm ms}^2} \sim 10^2\,, \qquad (1)$$

where $R_{\rm ms}$ is the radius of the innermost $\approx 1.4\,M_\odot$ on the main sequence and $R_{\rm ns}$ is the radius of the resulting neutron star. (We should caution that a main-sequence convective core extends over ~ 1 pressure scale height, whereas a neutron star convective zone extends over 5–6 scale heights [Burrows & Lattimer 1988], so the ratio of the dipole field to the rms field is expected to be smaller in the latter case.) Scenarios (*a*) and (*b*) both lead to the following conclusion: unusually *strong* dipole fields are probably generated in young neutron stars with $P_i \sim 1$ ms. In particular, AIC of a weak-field white dwarf does *not* necessarily produce a weak-field neutron star. From here on, we refer to such a highly magnetized neutron star as a *magnetar*.

A significant fraction of the differential rotation is damped in a protomagnetar by growing magnetic stresses on a time scale no longer than ~ 10 s. Magnetic torques continue to spin down the star after convection ceases, releasing the remaining rotational energy on the spin-down time scale $\tau_{\rm SD} \simeq 0.6 B_{15}^{-2}(P_i/1\text{ ms})^2$ hr, where $B_{15} \equiv (B_{\rm dipole}/10^{15}\text{ G})$. Note that $\tau_{\rm SD}$ is less than the shock break-out time, so supernovae which form magnetars will be brighter than average, and their remnants will carry more kinetic energy.

Magnetars attain rotation periods *long* compared to those of radio pulsars relatively early in their lives: e.g., $P \gtrsim 10$ s after only $10^4 B_{15}^{-2}$ yr. They evolve to the "death line" beyond which their magnetospheres become charge-starved on a time scale $\sim 6 \times 10^5 B_{15}^{-1}$ yr, when their periods are $P \geq 70 B_{15}^{1/2}$ s (e.g., Ruderman 1987). This may enhance their subsequent gamma-ray emission (Blaes et al. 1989) and may explain why gamma-ray burst (GRB) sources are radio-quiet.

A large recoil could be imparted to a magnetar in several ways. One possibility is that the star undergoes some form of anisotropic mass loss.[2] For example, a young magnetar rotates close to the critical angular velocity for nonaxisymmetric gravitational radiation instabilities (Chandrasekhar 1970). A mass $\simeq 1 \times 10^{-2}\,M_\odot$ ejected at the escape velocity from a radius 20 km would impart a $\sim 10^3$ km s^{-1} recoil to the star. A related possibility is that the young magnetar ejects a significant amount of material in an anisotropic magnetized wind or jet (§ 3.2 below; LeBlanc & Wilson 1970; Symbalisty 1984). Even in the absence of mass loss, off-center magnetic dipole radiation will generate a kick $V_{\rm rocket} = \epsilon E_{\Omega i}/Mc \simeq 400(\epsilon/0.16)(P_i/1\text{ ms})^{-2}$ km s^{-1}, where $\epsilon = 0.16$ is the maximum possible anisotropy factor (Harrison & Tademaru 1975).

A second class of recoil mechanism is anisotropic neutrino emission, which can be induced in a number of ways by a strong magnetic field. A fractional anisotropy in the radiated scalar momentum, $\delta p/p \sim 0.03$ would produce a $\sim 10^3$ km s^{-1} recoil. Neutrino emission from a millisecond rotator is generally peaked along the rotation axis (Janka & Mönchmeyer 1989). We now outline some mechanisms that could induce a small hemispheric asymmetry.

A significant fraction of the heat flux in a newborn neutron star is carried by convection. A strong ($B \sim B_{\rm sat} \sim 10^{16}$ G) magnetic field locally suppresses convective energy transport and thus depresses the neutrino flux at the stellar surface, creating the neutron star analog of sunspots. Dark spots of size λ, persistence time τ, and covering factor f induce a recoil larger than 10^3 km s^{-1} if $(\lambda/R)^2(\tau/t_{\rm cool})f \sim (\delta p/p)^2 \gtrsim 10^{-3}$, where R is the stellar radius and $t_{\rm cool} \sim 3$ s is the neutrino cooling time. For comparison, individual spots of size $\lambda \sim R$ appear on some rapidly rotating magnetic main-sequence dwarfs (Haisch, Strong, & Rodonò 1991).

A uniform magnetic field can also induce anisotropic neutrino emission via weak interaction effects. As shown by Vilenkin (1979), the mean-free time for neutrino electron scattering is altered in the presence of a magnetic field by the factor $\tau^{\nu e}/\tau_0^{\nu e} = 1 + a(e/E_e^2)\boldsymbol{V}_\nu \cdot \boldsymbol{B}$, where e is the electron charge, E_e is the electron fermi energy near the surface of last scattering, V_ν is the neutrino velocity, and a is a flavor-dependent combination of weak coupling constants. (We use units with $\hbar = c = 1$). This implies a momentum-loss asymmetry parallel to the field of

$$\frac{\delta p}{p} = \frac{aeB}{E_e^2}\left(\frac{\tau^\nu}{\tau^{\nu e}}\right) \sim 0.02 B_{15}\left(\frac{a}{0.3}\right)\left(\frac{E_e}{5\text{ MeV}}\right)^{-2}\left(\frac{\tau^\nu/\tau^{\nu e}}{0.3}\right), \qquad (2)$$

where τ^ν is the effective mean-free time due to all processes. The net stellar recoil occurs in the direction $\hat{\boldsymbol{\Omega}}$ of the rotation axis, and is smaller by a factor cos $(\hat{\boldsymbol{\Omega}} \cdot \boldsymbol{B}/B)$. It directly adds to (or subtracts from) the recoil generated by neutrino starspots. A magnetic anisotropy of similar, but probably somewhat smaller, magnitude occurs in neutrino emission by β processes (Dorofeev, Rodionov, & Ternov 1985). This is a global manifestation of parity-breaking in the weak interactions.

Most of the kick mechanisms considered above are totally ineffective for pulsars ($B_{\rm dipole} \sim 10^{12}$–$10^{13}$ G and $P_i \gtrsim 10$ ms), becoming important only in the magnetar regime ($B_{\rm dipole} \sim 10^{15}$ G and/or $P_i \sim 1$ ms). Of these mechanisms, only neutrino starspots might contribute significantly to observed ~ 100 km s^{-1} pulsar recoils, since fields of strength $B \sim B_{\rm sat}$ are probably generated on small scales in protopulsars (TD). This mechanism is difficult to quantify, but it plausibly produces larger recoils in neutron stars with larger scale magnetic structure, contributing to the observed correlation between pulsar proper motions and $P\dot{P} \propto B_{\rm dipole}^2$ (e.g., Cordes 1986).

An additional recoil is imparted during binary disruption

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[2] An observational signature of this would be anisotropic, high-velocity outflow outside the associated supernova remnant. Near the LMC remnant N49, which contains the angular error box of the 1979 March 5 burster, a large-scale flow is present (Mathewson et al. 1983), but the association of this flow with the remnant is uncertain. (See also Mathewson & Clark 1973.)

(Bailes 1989); this may be especially strong for magnetars forming via AIC in close binaries.

2. OBSERVATIONAL EVIDENCE FOR MAGNETARS

2.1. *The Soft Gamma Repeaters*

The angular position of the 1979 March 5 burst coincided with the supernova remnant N49 in the LMC. The burst was modulated on a period of 8.00 ± 0.05 s for over 20 cycles (e.g., Cline 1982), and its spectrum contained an emission line at 440 MeV, consistent with a pair annihilation line redshifted from a neutron star surface. The periodic modulation was probably due to rotation since it contained "pulse" and "interpulse" features that underwent roughly exponential decay on distinct time scales. This source has subsequently emitted short bursts with a soft spectrum, and thus is known as a "soft gamma repeater" (SGR).

If the source of the 1979 March 5 burst is indeed a neutron star, as this evidence indicates, then this star has some peculiar properties, consistent with those expected of a magnetar. Equating the spindown age $t = P/2\dot{P}$ with the age of the SN remnant, $t_4 \times 10^4$ yr where $0.6 < t_4 < 1.6$ (Shull 1983), yields $\dot{P} \approx 1.27 \times 10^{-12} t_4^{-1}$. Approximating the spindown torque as being due to magnetic dipole radiation (Pacini 1967; Gunn & Ostriker 1969) implies, for an 8 s rotation period, a surface dipole field $B \simeq 6 \times 10^{14} t_4^{-1/2}$ G, in the magnetar regime.

The recoil velocity of the N49 object can be estimated from the displacement of the position error box from the nebula center (Cline et al. 1982). This implies a *transverse* velocity in the range $V_{\rm trans} = (920 \pm 530) t_4^{-1}$ km s^{-1}, and an expected recoil velocity $V = (3/2)^{1/2} V_{\rm trans} = (1100 \pm 650) t_4^{-1}$ km s^{-1}. If the localized source of X-rays in the burst error box gives the location of the star (Rothschild et al. 1992), then $V = (800 \pm 160) t_4^{-1}$ km s^{-1}. It is doubtful that the star could have remained bound in a binary system after suffering a recoil this large.

If the N49 neutron star does *not* have an unusually strong dipole field (i.e., if $B \lesssim 10^{13}$ G), then it must have been born rotating several hundred times more slowly than a typical pulsar, with a recoil velocity $\sim$3–10 times higher, and with a peculiar propensity to burst. In the magnetar model, these distinguishing characteristics are derived from the single hypothesis that the star was initially a fast rotator.[3]

The detection of two other SGRs at low Galactic latitudes indicates that the N49 object is not the only star of its kind in the Galaxy and Magellanic Clouds. In fact, given the age of the N49 nebula, a rough bound on the formation rate of neutron stars with properties similar to the N49 object in the Galaxy and LMC is $\Gamma \gtrsim 10^{-4}$ yr^{-1}.

The proper motions of other SGRs are not known. If we assume that a significant fraction of the SGRs have large ($V \sim 1000$ km s^{-1}) proper motions like the N49 object, then *there exists a population of* $\geq 10^4$ *such objects in the Galactic halo within a distance* ~ 100 kpc. If these stars continue to burst with roughly the same luminosity over $> 10^7$–10^8 yr, they constitute a halo population of GRB sources.[4] Note that magnetars receive kicks via a number of mechanisms which are ineffective for stars with fields and rotation periods characteristic of ordinary young pulsars (§ 1), and possibly only a small fraction receive kicks small enough to remain localized in the disk or in the near halo.

It is often assumed that the SGRs are completely distinct from the classic GRB sources, but the two phenomena have many similarities and are not discontinuous in their spectral properties (Epstein 1989). If the SGRs are young magnetars, as we have argued, then their bursting characteristics should evolve with time. Evidence that the SGRs are in a transient phase of frequent burst activity is provided by the sequence of SGR bursts from the N49 source following the 1979 March 5 event, and its apparent cessation in 1983 (Golenetskii, Ilyinskii, & Mazets 1984; Norris et al. 1991).

2.2. *Evidence for Long Rotation Periods*

Ginga satellite observations have revealed "tails" of X-ray emission lasting for $\sim 10^2$ s following some GRBs (Yoshida et al. 1989; Murakhami et al. 1991). These late X-rays exhibit a strong overall trend of decreasing intensity and spectral hardness, suggesting a cooling object, but in many cases the intensity rises to a second, spectrally soft maximum after ~ 50 s. For an example, see Figure 1 of Yoshida et al. (1989), which shows two peaks in the 14–370 keV time-trace of GB870303, separated by 33 s. The soft X-ray trace has coincident peaks, *and* a third peak with similar width, also delayed by 33 s. This time structure is also evident in the hardness ratio. Note the monotonic decrease in hardness of the three peaks. We suggest that the 33 s periodicity is due to rotation.

In order to account for this time structure *without* rotation, one must invoke discrete energy injection events of progressively diminishing hardness, with the coincidence that the successive peaks are evenly spaced in time with comparable widths. The theoretical problem of producing hard gamma spectra with little thermal degradation would then be more severe.

GB870414 (in the same figure) also shows a spectrally soft recurrence after 47 s. The *Hakucho* satellite found an X-ray emission tail following GB811016, which showed a strong overall trend of softening, but with a 4 σ increase in counts in the lowest energy band at 70 s after the burst peak (Katoh et al. 1984).

It is possible that bursting stars with $P \simeq 30$ s are very old, spun-down pulsars which have retained 3×10^{12} G dipole fields for nearly a Hubble time; alternatively, they may be young magnetars with an age $\simeq 5 \times 10^4 B_{15}^{-2}$ yr. Periods longer than 10^2 s could only be reached by pulsars with $B_{\rm dipole} > 10^{13}$ G. Finally, we note that a blackbody fit by Yoshida et al. to the final stages of X-ray emission in the burst GB870303 implies a distance $D \approx 10(l/10$ km) kpc (where l is the radius of the "hot spot" on the stellar surface) and suggests that the source is associated with the Galaxy.

3. CONCLUSIONS AND DISCUSSION

3.1. *Galactic or Cosmological Bursts?*

Compton Observatory observations of the GRB distribution (Meegan et al. 1992) have bolstered suggestions that the bursts come from cosmological distances (e.g., Paczyński 1991). Because of the many well-known observations which indicate

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[3] Some magnetic white dwarfs have been discovered with rotation periods in excess of 1 yr (e.g., Schmidt 1989). However, the progenitors of neutron stars are distinguished from the progenitors of white dwarfs, in that the convective envelope which forms on the slowly rotating red giant branch does *not* penetrate into the material that later forms the compact object, implying that core-envelope magnetic braking is comparatively inefficient.

[4] Lingenfelter & Higdon (1991, hereafter LH) note that SGRs make a significant contribution to the excess of Konus burst counts at low $V/V_{\rm max}$. This is consistent with the model outlined here.

that at least some classical GRBs arise from neutron stars,[5] it is—in our opinion—probably safe to say that the cosmological burster model might only work in a hybrid scenario, with a fraction of classical GRBs coming from within the Galaxy. Furthermore, there is another phenomenon, the SGRs, which is not clearly discontinuous in its properties from all other GRBs, and which probably originates in our Galaxy.

In this *Letter* we have outlined a physical scenario for the formation of highly magnetized neutron stars ("magnetars"). We have indicated several mechanisms which could impart a large recoil to these stars at birth, sufficient to escape from the Galactic disk. An independent argument, based on the observed recoil and age of the soft gamma repeater in N49, suggests that there exists a population of $> 10^4$ of aged SGRs throughout the Galactic halo within a radius 100 kpc, and many more at greater distances. It is natural to identify this old SGR population with the theoretical magnetars, especially since the magnetic field of the N49 star inferred from spindown is $B_{\rm dipole} \simeq 6 \times 10^{14}$ G.

Let us briefly consider the possibility that these stars are sources of classical GRBs. Magnetars contain a tremendous reservoir of magnetic energy, $3 \times 10^{47} B_{15}^2$ ergs, and GRBs could be triggered by magnetic reconnection, like stellar flares (Sturrock 1986). The energy required[6] for a burst of the minimum fluence $\sim 10^{-7}$ ergs cm^{-2} detectable with BATSE is only $1 \times 10^{41}(\Delta\Omega/4\pi)$ ergs if it originates at a distance $D = 100$ kpc and is beamed into a solid angle $\Delta\Omega$. The presence of hard (> 1 MeV) photons in GRB spectra implies that if the bursts originate in neutron stars with $\sim 10^{15}$ G dipole fields, then the hard photons are generated high in the magnetosphere and/or are narrowly beamed along field lines (cf. Ho, Epstein, & Fenimore 1990).

Flares are triggered in magnetically active main-sequence stars when convective motions displace the footpoints of the field sufficiently to create tangential discontinuities, which undergo catastrophic reconnection. Similar reconnection events probably occur in magnetars, where the footpoint motions are driven by a variety of diffusive processes. For example, the component of the field anchored in the crust of a neutron star undergoes Hall drift (Goldreich & Reisenegger 1992, hereafter GR). However, most of the field generated by an α-Ω dynamo in a rapidly rotating neutron star is likely to thread the stellar core. The core field evolves on an uncertain, perhaps very long, time scale (e.g., GR). Models of flarelike bursts involving pair cascades in subcritical magnetic fields produce reasonable gamma-ray spectra (Preece 1990; Sturrock, Harding, & Daugherty 1989), but these models have not yet been extended to the case of supercritical fields.

Even if magnetars accounted for a significant fraction of GRBs, there could also exist a local disk population of faint sources that are presently detectable only at distances less than 1 scale height (LH), although these sources cannot account for a majority of bursts without violating the observed trend of decreasing slope in the source counts with decreasing fluence (Mao & Paczyński 1992). For example, nearby spun-down pulsars may be the source of bursts with claimed detections of cyclotron absorption lines in a $\sim 10^{12}$ G field, as suggested by the distance limit $D < 200$ pc found by Lamb, Wang, & Wasserman (1991).[7] If all GRBs are magnetically powered, then lower field disk stars would plausibly emit much fainter bursts.

Current bounds on the anisotropy of GRB sources place significant—but perhaps not prohibitive—constraints on any Galactic halo model for GRB sources (Brainerd 1992). What is the expected spatial distribution of magnetars? Since a star moving at $V \sim 10^3$ km s^{-1} reaches a distance 100 kpc in only $\sim 1\%$ of the Hubble time, magnetars bound to the Galaxy will dominate the halo population if only $\sim 1\%$ of magnetars receive kicks smaller than the escape velocity. A model of the angular distribution and source counts of GRBs emitted by magnetars must take into account evolutionary trends in the luminosity, frequency, hardness, and beaming of the bursts, and correlations of these properties with the proper motion.[8]

We emphasize that *whether magnetars are responsible for most GRBs or not, they probably do exist, and they very plausibly account for the SGRs.* Thus magnetars could play a supporting role in *cosmological* GRB scenarios by explaining the SGRs, which have positions clearly indicating a Galactic origin.

3.2. *Dynamo in a Naked Neutron Star: Implications for Cosmological GRBs*

The same dynamo mechanism that we discussed in § 1 will operate in the hot, rapidly rotating star formed from the merger of a neutron star binary,[9] but recent calculations suggest that these objects collapse to black holes in ~ 1 ms (Rasio, Shapiro, & Teukolsky 1991). Amplification of the field to $B \sim B_{\rm sat}$ would require at least O(10–100) overturns of the convective cells, corresponding to ~ 10–100 ms. Thus, AIC provides a more promising route to a very strongly magnetized neutron star which is not clothed by a large column of supernova ejecta. The magnetic energy generated inside such a star could be converted to gamma rays outside the star via a number of mechanisms discussed in TD, but it is difficult to avoid a significant amount of baryonic pollution (cf. Paczyński 1990). In addition, the star will lose energy to magnetic torques, $\sim 10^{50}\, B_{15}^2$ ergs in the first 10 s. This energy is not quite sufficient to power a gamma-ray burst at cosmological distances (redshift $z \sim 1$), unless the magnetic wind is highly collimated into a jet. Shock waves in such a jet are capable of accelerating nonthermal particles at large distances from the star, and thence generating some hard gamma rays via Compton upscattering and pion decay, although the efficiency of these processes is uncertain. Hydrodynamical instabilities in a relativistic jet are also capable of causing fluctuations in the gamma ray flux on millisecond time scales. We conclude that

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[5] Namely (1) pair annihilation lines with neutron star–like redshifts, (2) cyclotron lines, (3) thermal X-ray tails with Galactic distance limits, (4) bounds on recurrence times from archival plates, (5) complex variability of bursts on millisecond time scales. In general, the combination of rapid variabilities, hard spectra, and enormous energy fluxes make a difficult burden for cosmological models to bear (Schmidt 1978; Cavello & Rees 1978).

[6] The field of a magnetar carries sufficient energy to power the very bright 1979 March 5 event (5×10^{44} ergs at the distance of the LMC, assuming isotropic emission; Mazets et al. 1979). Dissipation of magnetic energy could also account for the localized X-ray emission which may come from the N49 neutron star (Rothschild et al. 1992).

[7] This bound is based on the magnetic Eddington limit and on the assumption that the absorption occurs near the neutron star surface. Note that X-ray pulsar observations indicate that 10^{12} G surface fields can persist in pulsars for at least 10^8 yr (e.g., Verbunt, Wijers, & Burm 1990).

[8] For example, neutrino magnetic recoil due to weak parity-breaking predicts $V \propto B_{\rm dipole}$. Since the magnetic energy density powering GRBs goes as B^2, there might exist a strong positive correlation of burst luminosity (or other burst properties) with V.

[9] Although somewhat distinct from the main subject of this *Letter*, the physics discussed in this section is closely related.

this possibility deserves further investigation if some bursts prove to be cosmological.

3.3. *An Observational Test for Magnetars*

Being endowed with intense dipole fields, young magnetars should emit pulsed radiation with very long periods out to the "death line" at $P \sim 70 B_{15}^{1/2}$ s. By contrast, the maximum observable period of normal pulsars with $B_{\rm dipole} \sim 3 \times 10^{12}$ G is about 4 s; thus, *young* magnetars should emit pulses in a novel range of periods.

We can get a preliminary estimate of the luminosity in long-period pulses using the empirical formula $L_{\rm pls} = 4.3 \times 10^6 \dot{P}^{1/3} P^{-1}$ mJy kpc^2 (Narayan & Ostriker 1990). This is a fit to the known radio pulsar population, and so extrapolation into the magnetar regime is uncertain. Nevertheless, this formula implies that $L_{\rm pls} = 90 B_{15}^{-2/3} t_4^{-2/3}$ mJy kpc^2 for a magnetar with age $t_4 \times 10^4$ yr and pulse period $P = 13 t_4^{1/2} B_{15}$ s. Detection of long-period pulses from an isolated neutron star would provide evidence for an extremely strong dipole field, although a measurement of the period derivative would be needed for corroboration.

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