FOSSIL DISKS & PROPELLER SPINDOWN OF SGR/AXPS

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\textbf{ABSTRACT.} We have shown that the interstellar media which surround the progenitors of SGRs and AXPs were unusually dense compared to the environments around most young radio pulsars. This environmental correlation argues strongly against the current magnetar model for SGRs and AXPs. We suggest instead that they are neutron stars with sub-critical magnetic fields and are spun down rapidly by “propeller” torques from fossil disks formed from the fallback of supernova ejecta. We show that this hypothesis is consistent with the observed properties of these enigmatic objects, and we compare the propeller and magnetar models for SGR and AXPs.

1. Introduction

Two lines of thought exist as to the nature of Soft Gamma-ray Repeaters (SGRs) and Anomalous X-ray Pulsars (AXPs). On the one hand, Thompson and Duncan (1995) propose neutron stars with super-critical ($>10^{14}$ Gauss) magnetic fields, which spin-down the stars and power the gamma-ray bursts. On the other hand, several authors (van Paradijs et al. 1995; Alpar, 2000; Chatterjee, Hernquist & Narayan, 2000; Marsden et al. 2001 [MLRH]) propose neutron stars with typical pulsar magnetic fields ($\sim 10^{12}$ Gauss), which are spun down by magnetospheric “propeller” torques from fallback or fossil disks.

The association with visible supernova remnants has long been recognized (e.g. Cline et al. 1982), and recently reaffirmed (MLRH; Figure 1 and Table I), as the primary evidence for the SGR/AXP’s relatively young ages, which together with their unusually long periods, distinguished them as a unique class of pulsars. MLRH have now shown from an analysis of the SNRs associated with SGR/AXPs, that essentially all ($\sim 80\%$) of them occur in the Warm phase of the ISM. This is very unexpected, since observations of extragalactic Type II/Ibc SN (van Dyk, Hamuy & Filippenko 1996), Galactic SNRs (Higdon & Lingenfelter 1980) and young pulsars (MLRH), all show (Table I) that only a small fraction ($< 20\%$) of all the neutron star producing Type II/Ibc SN actually occur in the Warm phase of the ISM, whereas the bulk ($> 80\%$) of them occur instead in the more tenuous ($n \sim 0.001$ cm$^{-3}$) Hot phase. Consequently, something about the dense ISM environment shapes the character of the SGR/AXPs and makes them different from the more common neutron star population of radio pulsars.
Fig. 1. The radius of the SGR and AXP supernova remnant shells as a function of their age (from Marsden et al. 2001). The solid lines denote SNR expansion trajectories in the free expansion, Sedov, and radiative phases in a wide range of ISM densities. The dotted lines denote the tracks of neutron stars born at the origin of the supernova explosion with varying space velocities. The data show that these objects are unusual in that they are all preferentially formed in the denser (> 0.1 H cm$^{-3}$) Warm phases of the interstellar medium (ISM), where <20% of all neutron star forming supernovae occur. As can be seen, the data are very robust even though there are large uncertainties in the SNR ages.
The unusually dense phases of the interstellar medium in which the SGR/AXPs are born confine the progenitor winds and rapidly slow the supernova ejecta, initiating a reverse shock, which in turn reverses the flow of the innermost ejecta for capture by the nascent neutron star. Inflow of this material provides an additional torque along with magnetic dipole radiation (MDR) to rapidly spindown the initially fast rotating neutron star to very slow (several second) periods in $\sim 10^4$ years. Here we show that the effects of such rapid spindown can also provide the energy for the observed bursts through plate-tectonic driven crustal subduction and phase transitions.

The unexpected occurrence of most, and perhaps all, of the SGR/AXPs in the denser phases of the ISM effectively rules out the magnetar model of their origin, since in that model supercritical magnetic fields are an intrinsic property of the neutron star with no plausible relation to the external environment. It has been suggested that magnetars might form from progenitors with the largest angular momentum, so that they might only be formed from the most massive stars, which, because they evolve most rapidly, may explode preferentially in the denser regions where they were formed. But this suggestion is not tenable, since pulsar observations (e.g. Cordes & Chernoff 1998) show that there is no correlation between spin period and magnetic field strength, and observations of giant star formation regions show that only the most massive stars in the first of several generations of star formation explode in the dense cloud environment while most of those formed in later generations explode in the hot, low density environment of the superbubble created by the earlier supernova explosions (e.g. McKee & Williams 1997).

### Table I

OCCURRENCES IN THE WARM AND HOT PHASES OF THE ISM

| Source                  | WISM(%)$^a$ | HISM(%)$^b$ |
|-------------------------|-------------|-------------|
| Extragalactic Supernovae$^c$ | <20         | >80         |
| Galactic Supernovae$^d$  | 10±10       | 90±10       |
| Young Pulsars$^e$        | 31±14       | 69±21       |
| SGR/AXPs$^e$             | 83±26       | 17±12       |

$^a$Percentage in the Warm ISM ($n \geq 0.1$ cm$^{-3}$)

$^b$Percentage in the Hot ISM ($n \sim 0.001$ cm$^{-3}$)

$^c$van Dyk, Hamuy & Filippenko (1996) as discussed in Marsden et al. (2001)

$^d$Higdon & Lingenfelter (1980) as discussed in Marsden et al. (2001)

$^e$Marsden et al. (2001)

2. Propeller Spindown from Fossil Disks

Propeller spindown models of the SGR/AXPs, on the other hand, can be strongly influenced by the circumstellar environment. The rapid spindown rates, young ages inferred from the SNR ages, long spin periods clustered around 5-10 s, and $\sim 10^{35}$ erg/s x-ray luminosities can all be explained by models involving the propeller effect on inflowing
material (Illarionov & Sunyaev 1975) as the dominant spindown torque. Since no binary companions have been detected around SGR/AXPs, the infalling material must come from fossil disks which can spindown the neutron star on time scales of 1-10 kyr.

Fossil disks may be formed from the supernova ejecta being pushed back toward the star by the reverse shock, which can actually reverse the flow of the slowest moving inner ejecta (Truelove & McKee 1999), pushing it back toward the nascent neutron star to form a disk. The occurrence of “pushback” disks will depend on the strength of the reverse shock, which forms in the Sedov phase of the SNR expansion from the interaction between the supernova blast wave and the external gas and is thus strongly affected by the density of the circumstellar ISM. These disks are most likely to form around neutron stars born from the more massive progenitors in the dense phases of the ISM which confine the progenitor winds much nearer the star, so that the expanding SN ejecta can sweep up gas and develop both forward and reverse shocks much more rapidly. Such a situation can be seen in evolution of the ejecta from SN 1987A, which is surrounded by very dense ($n \sim 10^2$ to $10^3$) gas from confined progenitor winds (e.g. Chevalier & Dwarkadas 1995) and has already entered the Sedov phase dramatically slowing the forward shock from 30,000 km/s to only 3,000 km/s within 10 yrs of the explosion. For such densities the pushback process should begin at a “reversal time” of 400 to 800 yr with an expected (Truelove & McKee 1999) pushback mass of $\sim 0.4 M_\odot$ for a total ejecta mass of $10 M_\odot$. Only a very small fraction of the pushed back ejecta is needed to form a fossil disk with the $10^{-6} M_\odot$ required to explain the spindown of SGR/AXPs via the propeller mechanism.

The fossil disk will exert a spindown torque on the neutron star, if the inflow rate is low and the magnetic field is strong, so that the majority of the inflowing material is accelerated away in a bipolar wind which carries off angular momentum from the magnetosphere, and hence from the neutron star itself (e.g. Illarionov & Sunyaev 1975). For typical radio pulsar magnetic fields of $10^{12}$ Gauss, the observed 6–12 s spin period range of SGR/AXPs is naturally explained by mass infall rates at the magnetospheric boundary of $4-20\times10^{15}$ g/s. Such rates can also account for the observed x-ray luminosities of $\sim 10^{35}$ ergs/s if only about 5-25% of the infalling material actually reaches the neutron star surface.

Propeller spindown from such disks can also easily account for the observed number of SGR/AXPs. From the Galactic neutron star birth rate (1/40 yr$^{-1}$), the fraction of neutron star progenitors in the warm dense ISM (<0.2), and the fraction of such progenitors (>20 $M_\odot$) that suffer mass loss sufficient to form a pushback disk (0.1), MLRH estimate that the number of SGR/AXPs formed in the last 30 kyr should be <15, which is quite consistent with the observed number of 12.

Propeller spindown can also explain many other quiescent aspects of the SGR/AXPs in a natural manner. This includes spindown ages comparable to the ages of the associated SNRs, the narrow range of spin periods, the relatively low luminosities, and the lack of prolonged periods of spin-up. Moreover, we suggest that the exceedingly rapid spindown of these neutron stars provides both the energy and mechanism for the very energetic bursts seen from SGRs.
3. Mechanisms and Energetics of SGR Bursts from Propeller Spindown

The similarities between the size-intensity distributions (Cheng et al. 1996) and other features (Palmer 1999) of SGR bursts and earthquakes suggests that the physics of these two phenomena may be similar. With this in mind, the magnetar model postulates that the majority of SGR bursts are crust cracking events caused by the diffusion and possible decay of the superstrong magnetar field. As exemplified by the Earth, however, a superstrong magnetic field is not required to excite crustal quakes, and one simple source of SGR bursts is quakes caused by neutron star plate tectonics (Ruderman 1991), driven by the rapid spindown of these objects. This process is illustrated in Figure 2. Rapid spindown should cause segments of the neutron star's crust to be cracked and dragged toward the rotational equator by pinned superfluid vortices. Subduction of crustal material will occur as plates collide and will release gravitational energy as the subducted crust undergoes compressional phase transitions deep in the interior of the star. The largest, deepest quakes on the Earth are caused by compressive phase transitions of subducted crust. Vibrations excited by this process will be transmitted into magnetospheric Alvén waves which accelerate particles — producing x-ray/gamma-ray emission.

The energy released in the subduction process can be estimated and compared with that of the most energetic SGR bursts. The subduction of relatively light crust into the dense interior of the star will eventually result in one or more phase transitions, when blocks of low density crust are transformed into much denser interior phases. The resulting decrease in volume of the subducted material will cause settling of the overlying material, releasing gravitational energy and exciting vibrations throughout the neutron star. The gravitational energy released in this process by the settling of $\Delta M$ of overlying material dropping by $\Delta R$ is $\Delta E_g \approx (GM^2/R_*) (\Delta M/M_*) (\Delta R/R_*)$, where $M_*$ and $R_*$ are the mass and radius of the neutron star.
or $5 \times 10^{53} (\Delta M / M_r) (\Delta R / R_r)$ ergs. Thus for a crustal block of area equal to a fraction $A$ of the surface of the star and thickness $r = \Delta R / R_r$ undergoing a phase transformation, compressing it as little a 10%, at a fractional depth $d = D / R_r$, the overlying mass is $\Delta M \approx A d M_r$ and $\Delta R \approx 0.1 r R_r$, so that the gravitational energy released is $5 \times 10^{43} A r^{-3} d^{-3} r^{-3}$ ergs, even for all of the fractions as small as $10^{-3}$. This energy is easily sufficient (e.g. Cheng et al. 1996) to power a single typical SGR burst with an x-ray production efficiency of a few percent or less. The superbursts, with isotropic energy releases of $\sim 10^{44}$ ergs (e.g. Ramaty et al. 1980), require larger sections of the crust to participate (or possibly a deeper core phase transition; e.g. Ellison & Kazanas 1983), but they are still explainable by this mechanism. Thus the release of gravitational energy by spindown induced phase transitions can explain the energetics of SGR bursts.

The mean gravitational energy density $(GM^2 / R^2)_* / V_*$ of $\sim 10^{35}$ erg cm$^{-3}$ of subducted material in a neutron star greatly exceeds the magnetar magnetic energy density in the same volume unless the mean stellar magnetic field is unrealistically strong ($> 10^{18}$ G). Thus gravitational energy is a much more plausible source of SGR burst energy than magnetic energy.

Other characteristics of SGR bursts can similarly be explained in terms of canonical neutron star parameters and conventional neutron star physics. A superstrong magnetic field, for example, is not required to explain the short durations of SGR bursts, which can be explained quite easily in terms of the storage time for energy in the neutron star crust (Blaes et al. 1989). The $\sim 100$ s duration of the rare SGR superbursts can be plausibly attributed to the gravitational radiation timescale from a vibrating neutron star (Ramaty et al. 1980). The spectral hardness and luminosity of SGR bursts can be explained by a synchrotron cooling model (Ramaty, Bussard, & Lingefeltter 1981). Magnetar-strength magnetic fields are not required in this model, as illustrated by the following argument based on the March 5th 1979 superburst from SGR 0526–66. This burst had a peak luminosity of $L_p \sim 5 \times 10^{44}$ erg/s, but the synchrotron cooling time of the vibrationally-heated electrons in a $\sim 10^{12}$ Gauss field is only $t_s \sim 2 \times 10^{-16} \gamma^{-1} s$, where we have assumed a relativistic gamma factor of $\gamma = 5 \gamma_5$ for the emitting electrons (e.g. Rybicki & Lightman 1979). This means that only $L_p t_s \sim 10^{29}$ ergs of electrons are emitting at any one time, which can easily be confined into only a 1 m cube by the $10^{12}$ Gauss field. Finally, a thin fossil disk could survive the intense photon flux from even the strongest SGR bursts, because the total energy deposited in the disk from a burst would be less than the gravitational binding energy of the disk for typical disk parameters.

4. Conclusion

We have shown that propeller spindown from fossil disks can explain many of the features of SGRs and AXPs. The lack of binary companions, rapid spindown, and SGR burst energetics and spectra can also be explained by the magnetar model. But several very important properties — clustered spin periods, SNR ages, dense environments, and quiescent energetics — which are easily explained by the propeller disk model, have not been explained in the context of the magnetar model. These distinguishing characteristics are listed in Table II.
As mentioned previously, the clustering of SGR and AXP spin periods in the range $5 - 12$ s is evidence of a characteristic spin period, which is a natural consequence of propeller spindown from a fossil disk (Chatterjee & Hernquist 2000). There can be no spin equilibria in magnetars, however, since magnetars can only spindown (Harding, Contopoulos, & Kazanas 1999). Therefore if AXPs and SGRs were magnetars, the clustering of their spin periods would have to be a coincidence, which is extremely unlikely. Similarly, the association of SGRs and AXPs with middle age ($\sim 10$ kyr) SNRs is at odds with their $\sim 1$ kyr MDR timing ages if they are magnetars\footnote{The effects of Alfvén wind torques (Harding, Contopoulos, & Kazanas 1999) and magnetic field decay (e.g. Colpi et al. 2000) in magnetars would only increase this age discrepancy.}. Propeller spindown can explain the MDR age discrepancies in SGRs and AXPs (Chatterjee, Hernquist, & Narayan 2000) and other sources (Marsden, Lingenfelter, & Rothschild 2001a,b), while providing a link between SGRs/AXPs and other isolated neutron stars. As discussed above, the environments of SGRs and AXPs also very strongly favor the propeller disk model, while no plausible argument has been found as to how the development of magnetars could be affected by their environment. Finally, the broadband quiescent emission from SGRs (Kaplan et al. 2001) and AXPs (Hulleman et al. 2000a) would require large scale magnetar fields of $> 10^{15}$ Gauss to supply the necessary energy. Such extremely large magnetic fields would greatly exacerbate the magnetar age problem discussed above, because of the extremely rapid spindown caused by the magnetic torques. Assuming an x-ray efficiency of only 1%, the propeller disk model requires a disk mass of $\sim 10^{-5} M_\odot$ to power the SGR and AXP quiescent emission for a lifetime of 10 kyr. This is a very small fraction of the ejecta mass pushed back by the reverse shock in a massive Type II SN in the denser ISM.

| SGR/AXP Property       | Propeller Model | Magnetar Model |
|------------------------|-----------------|----------------|
| Clustered Spin Periods?| Yes             | No             |
| SNR Ages?              | Yes             | No             |
| Dense Environments?     | Yes             | No             |
| Quiescent Energetics?   | Yes             | No             |

Although the propeller disk model is quite successful in explaining the properties of SGRs and AXPs, there are two important issues that need to be addressed. The first issue concerns the multiwavelength emission from pushback disks, which should manifest itself primarily at infrared wavelengths as result of the high fraction of refractory dust grains from the heavy supernova ejecta. Because of the high grain content, standard gas disk spectra (e.g. Perna, Hernquist, & Narayan 2000) are not applicable in this case, since the bulk of the disk energy will be radiated at wavelengths longer than the optical,
where restrictive upper limits have been obtained for some of these objects (Hulleman et al. 2000b; Kaplan et al. 2001). Sensitive IR observations of the nearby SGRs and AXPs are needed before serious constraints can be placed on the propeller disk model. Secondly, the recently noted correlation between the spectra and spindown torques of SGRs and AXPs (Marsden & White 20001) needs to be explained in terms of the two theoretical models for SGRs and AXPs. Models of accreting neutron star spectra can produce spectra with the blackbody plus soft power law shape characteristic of SGRs and AXPs, but it is unclear if the spectral hardness increases with spindown torque as indicated by the observations. Similarly, detailed calculations of the quiescent spectra of magnetars have yet to be done.

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