**Abstract.** Recent measurements of the spin-down rates of soft gamma ray repeaters (SGRs) and anomalous X-ray pulsars (AXPs) have been interpreted as evidence that these objects are “magnetars”: neutron stars spinning down by magnetic dipole radiation, but with a magnetic field two orders of magnitude larger than that of ordinary neutron stars. We discuss the evidence disfavouring this interpretation. We argue that, instead, the observations support the hypothesis that SGRs and AXPs are neutron stars that have suffered a transition into a denser form of nuclear matter to become, presumably, strange stars or quark stars.

1. Introduction

Consider a neutron star (NS) of radius $R$, with a magnetic field $B_p$ at the magnetic poles, spinning with a period $P$. If the star’s magnetic moment is misaligned with the spin axis by an angle $\alpha$, electromagnetic energy is emitted at a rate (see, e.g., Shapiro & Teukolsky 1983 and references therein.)

$$\dot{E} = -\frac{B_p^2 R^6 \Omega^4 \sin^2 \alpha}{6 c^3}, \quad (1)$$

with $\Omega = 2\pi/P$ the angular velocity. If the NS is observed as a pulsar, its period can be measured as a function of time. Let the NS have a moment of inertia $I$ and let $\dot{P}$ be the rate at which its period decreases. The magnetic field required to explain the slow-down rate by magnetic dipole radiation (MDR) is:

$$B_p = \left(\frac{6 c^3 I}{4 \pi^2 R^6 \sin^2 \alpha}\right)^{1/2} \sqrt{\dot{P}} P. \quad (2)$$

For a “canonical” NS, $M \sim 1.4 M_\odot$, $R \sim 10$ km and $I \sim 10^{45}$ g cm$^2$, so that $B_p = 6.4 \times 10^{19} \sin^{-1} \alpha \sqrt{\dot{P} P}$ Gauss, with $P$ the period in seconds. Young radio pulsars...
such as the Crab pulsar are fast-rotating NSs with an estimated surface magnetic field $B_p \sim 10^{13}$ Gauss. They fit the picture whereby their observed slow-down rates are due to the MDR of their rotational energy.$^1$

All observed slowly-rotating pulsars, of period $P > 5$ s, exhibit very peculiar properties. Four of them are known to emit occasional short bursts of radiation peaking at tens of keV energies, and are classified as “Soft Gamma-ray Repeaters” (SGRs). Six other “Anomalous X-ray Pulsars” (AXPs) persistently emit X-rays, but they are quiet at radio wavelengths. Some of these objects’ observational parameters are listed in Tables I and II. Their rotational energy loss $\dot{E}_{\text{rot}} = I \Omega \dot{\Omega}$ is insufficient to power their observed radiation, suggesting the magnetic field energy $E_m \sim B_p^2 R^3/12$ as an alternative source. Both SGRs and AXPs are located in directions close to those of supernova remnants (e.g., Cline, et al. 1982; Kulkarni & Frail 1993; Vasisht et al. 1994; Hurley, K. et al. 1999; Vasisht et al. 1997a; Vasisht et al. 1997b; Gaensler, Gotthelf & Vasisht 1999) that are observable for only tens of thousands of years. The association with SNRs would imply that these peculiar stars are too young to have spun-down by MDR to their current periods, if they were born rotating as fast as the Crab pulsar, the Vela pulsar or any other young pulsar (the ones also associated with SNRs), and if they also have characteristic radio-pulsar magnetic fields: $B \sim 10^{13}$ Gauss.

The values of $P$ and $\dot{P}$ for SGR 1806$-20$ and SGR 1900+14 were recently measured (Kouveliotou et al. 1998; Kouveliotou et al. 1999; Woods et al. 1999) and are listed in Table I. They imply, by use of Eq. 2, magnetic fields in excess of $10^{15}$ Gauss. With the information displayed in Table II, similarly large fields can be deduced for AXPs (e.g., Gotthelf et al. 1999; Israel et al. 1999). Magnetic fields of this enormous intensity can explain the rapid slow-down of SGRs and AXPs and can store enough energy to power their emissions during their active lifetime (Duncan and Thompson 1992; Thompson and Duncan 1995; Thompson and Duncan 1996). Not surprisingly, the discovery of SGRs and AXPs with fast spin-down rates was reported as the observational discovery (Kouveliotou et al. 1998; Kouveliotou et al. 1999) of hypermagnetized neutron stars, or magnetars (Duncan and Thompson 1992; Thompson and Duncan 1995; Thompson and Duncan 1996).

In this paper we discuss the observational evidence implying that SGRs and AXPs are not magnetars (Dar 1999a; Marsden et al. 1999; Dar 1999b). We contend that the mechanism producing their observed rapid slow-down is not MDR, but relativistic particle emission along the magnetic axis, be it in the form of jets (Dar 1999b) or of winds (Harding et al. 1999). We argue that the locations and estimated ages of SGRs, when compared to those of their associated SNRs, strongly suggest that “something” happened to these NSs well after they were born. Their inferred X-ray emitting surface areas, sig-
significantly smaller than those of a “canonical” neutron star, point in the same direction. For the source of the emitted energy we do not have an explicit model; we conjecture that the energy gained by steady gravitational contraction can power both the quiescent X-ray emission and the star quakes that produce “soft” gamma ray bursts (Ramaty et al. 1980). A phase transition from a conventional neutron star into a strange star or a quark star (Dar 1999a) can explain, we shall argue, all of the properties of SGRs and AXPs.

2. Critique of the magnetar model

The magnetar model of SGRs cannot explain their ages, locations and occasional increases in spin-down rate (Dar 1999a, Marsden et al. 1999). The ages of SGRs, if estimated from their magnetic spin-down rate, are much smaller than the ages of the remnants of the supernovae in which they were born: an age crisis. The location of SGRs relative to the centre of their associated remnant implies that they move with unacceptably large peculiar velocities: a separation crisis. Sudden increases in $\dot{P}$ require inexplicable jumps in the energy stored by the magnetic field: an energy crisis.

A pulsar with initial spin period $P_i$ and constant moment of inertia, whose rotational kinetic energy $E_{\text{rot}} = I \Omega^2/2$ powers the MDR, has an age, $t$, shorter than the “characteristic age”, $\tau_s$:

$$
t = P \frac{2 \dot{P}}{P^2} \left(1 - \frac{P_i^2}{P^2}\right) \leq \tau_s = \frac{P}{2 \dot{P}}.
$$

An age estimate independent from the above “magnetic braking” age is provided by the time elapsed since the parent supernova event took place. The ejecta from SNe expand freely to a radius $R_{\text{SNR}} \propto t$, as long as the mass of the swept-up ambient medium is smaller than the mass of the ejecta. When they are comparable, the SNR enters a “Sedov-Taylor phase” during which $R_{\text{SNR}} \propto t^{2/5}$. Finally, for a swept up mass superior to the ejected mass, the SNR cools radiatively and $R_{\text{SNR}} \propto t^{2/7}$. The expansion velocity and the size of SNRs, as well as their X-ray temperatures, are commonly used to estimate their ages (see, e.g., Shapiro & Teukolsky 1983 and references therein).

In Table I we list the characteristic ages $\tau_s$ of SGRs, and the ages of the SNRs where they were presumably born. For the two SGRs whose slow-down rate $\dot{P}$ has been measured (1806-20 and 1900+14), Eq. 3 results in $\tau_s \approx 1400, 1300$ y, respectively. This upper limit is significantly smaller than the estimated age of their SNRs, which is larger than $5 \times 10^3$ and $10^4$ y, respectively. This age crisis of the magnetar model would recur for SGR 0529-66 and 1627-41, if their slow-down rate is similar to that of the other two known SGRs.

The characteristic ages of SGR 1806-20 and 1900+14 also imply a separation crisis. SGR 1806+20, if it was born at the centre of SNR G10.0-0.3 (Hurley et al. 1999b) and is
less than \( \tau_\ast \approx 1400 \text{ y} \) old, must have travelled with a sky projected velocity larger than \( v_\perp \approx 5500 \text{ (D/14.5 kpc) \ km s}^{-1} \) to its present location (Kulkarni et al. 1994). With its similar \( \tau_\ast \), SGR 1900+14, if associated to SNR G42.8+0.6 (Vasisht et al. 1994), must have travelled at \( v_\perp \sim 27000 \text{ (D/7 kpc) \ km s}^{-1} \), or faster, to where it is (Hurley et al. 1999c; Hurley et al. 1999d). The same argument, applied to SGR 0526-66 and 1627-41 at their current locations (Cline et al. 1982; Hurley et al. 1999a), would result in lower limits of \( v_\perp \sim 22000 \) and \( \sim 4000 \text{ km s}^{-1} \), respectively, if their spin-down rates and implied ages turned out to be akin to the measured ones. These magnetar-model velocities are too large, compared to the mean observed \( v_\perp \sim 350 \pm 70 \text{ km s}^{-1} \) of pulsars (e.g., Lyne and Lorimer 1994), and in particular of young pulsars such as the Crab pulsar \( (v_\perp \approx 170 \text{ km s}^{-1}, \text{ Caraveo and Mignani 1999}) \) and the Vela pulsar \( (v_\perp \approx 70 \text{ km s}^{-1}, \text{ Nasuti et al. 1997}) \).

In the magnetar model of SGRs the radiation-energy source is the magnetic field energy \( E_M \sim B_p^2 R^3/12 \sim 10^{47} \text{ erg} \), for \( B_p = 10^{15} \text{ Gauss} \) and \( R = 10 \text{ km} \). Magnetic braking implies that the pulsar’s surface field is \( B_p^2 \propto \dot{P} \), an increase in \( \dot{P} \) implies a commensurate increase in magnetic energy. The spin-down rate of SGR 1900+14 roughly doubled from \( \dot{P} \sim 6 \times 10^{-11} \) to \( \dot{P} \sim 13 \times 10^{-11} \) around the time of its large flare on 27 August 1998 (Woods et al. 1999a, Marsden et al. 1999). How to explain a sudden doubling of a huge magnetic energy? This is the energy crisis. As the magnetic energy is consumed and the field weakens, the pulsar’s spin-down rate should decrease, contrary to observation: yet another problem for the magnetar scenario (Marsden et al. 1999).

For AXPs the magnetar model faces similar difficulties. AXPs 1709-40 and 1E 1048-5937 have spin-down ages (9 ky and 4.6 ky) shorter than the estimated age of their associated SNRs (20 ky and 10 ky), hinting at an age crisis. The projected sky velocities required to move these objects from the centres of their associated SNRs (G346.6-0.2 and G287.8-0.5) to their observed positions are 2100 km s\(^{-1}\) and 2300 km s\(^{-1}\), a separation crisis. Observed jumps in the spin-down rate of AXPs 1E1048.1-5937 and 1E2259+58, akin to the one in SGR 1900+14, entail an energy crisis. For AXP 1E 2259+586 (Corbet et al. 1995), the magnetic energy inferred from its spin-down rate, \( E_B \approx 2 \times 10^{45} \text{ erg} \), is insufficient to power its steady X-ray luminosity, \( L_X \approx 8 \times 10^{34} \text{ erg s}^{-1} \), over its characteristic age, \( \tau_\ast \sim 1.5 \times 10^5 \text{ y} \). Also, a magnetic field this large would be inconsistent with the absorption features observed by ASCA in its X-ray spectrum (Corbet et al. 1995), if interpreted as cyclotron lines.

The magnetar model of SGRs and AXPs is not successful: alternatives are called for.
3. Spin-Down by Relativistic Jets

There is evidence for the emission of relativistic particles by SGRs. In the case of SGR 1806-20, the non-thermal quiescent X-ray emission and the highly suggestive radio images (Vasisht et al. 1995; Frail et al. 1997) provide compelling evidence for steady relativistic particle emission, perhaps in the form of relativistic jets. A fading radio source is seen within the localization window of SGR 1900+14; it has been interpreted as a short-lived nebula powered by relativistic particles ejected during the intense high energy activity in late August 1998 (Frail et al. 1999). The emission of relativistic particles along the magnetic axis can be the dominant mechanism for the braking of slowly-rotating pulsars with normal magnetic fields (Dar 1999b, see also Harding et al. 1999), for which magnetic braking is inefficient. Magneto-hydrodynamic calculations of pulsar braking by particle emission are a formidable task, but simple estimates (Dar 1999b) will suffice here.

Let $L_{RP}$ be a pulsar’s luminosity in the form of relativistic particles escaping from the magnetic poles along the open magnetic lines. The emitted particles co-rotate with the magnetic field up to a radius $r_e \approx \left( \frac{3 c B_p^2 R^6}{2 L_{RP}} \right)^{1/4}$, at which their pressure ($L_{RP}/[12\pi c r^2]$) becomes comparable to the magnetic pressure ($B_p^2 R^6/[8\pi r^6]$ for a dipole field). Beyond this point a particle of mass $m$ and Lorentz factor $\gamma$ is no longer entangled in the magnetic field and it escapes, carrying away an angular momentum $\gamma m \Omega r_e^2 \sin^2 \alpha$.

The resulting rate of rotational energy loss is

$$\dot{E}_{\text{rot}} = I \Omega \dot{\Omega} \approx - \left( \frac{3 L_{RP}}{2 c^3} \right)^{1/2} B_p R^3 \Omega^2 \sin^2 \alpha,$$

(4)

which yields an exponential decline, $E_{\text{rot}}(t) = E_{\text{rot}}(0) \exp(-t/\tau_s)$, with a characteristic time:

$$\tau_s = \frac{P}{2 P} = \frac{I}{B_p R^3 \sin^2 \alpha} \left( \frac{c^3}{6 L_{RP}} \right)^{1/2}.$$

(5)

For a conventional $B_p = 10^{13}$ Gauss, $R = 10$ km, $L_{RP} = 10^{37}$ erg s$^{-1}$, and $\sin \alpha \approx 1$, the characteristic slow-down time is $\tau_s \sim 2000$ y, scaling as $1/R$ at fixed $B_p R^2$, and consistent with the characteristic slow-down times of SGRs and AXPs.

Relativistic particle emission may also be the dominant spin-down mechanism in pulsars rotating faster than SGRs and AXPs. A comparison between Eq.4 and Eq.1 shows that slowing-down by relativistic jets becomes faster than slowing-down by MDR when

$$P \geq \left( \frac{4\pi^2 B_p R^3}{54 c^3 L_{RP}} \right)^{1/2}.$$

(6)

For $B_p = 10^{13}$ Gauss, $R = 10$ km, and $L_{RP} = 10^{37}$ erg s$^{-1}$, slowing-down by emission of relativistic jets is faster than by MDR if $P > 60$ ms. But, for $B_p = 10^{13}$ Gauss, $L_{RP} < 10^{37}$ erg, and $P < 100$ ms, $r_e \sin \alpha$ becomes larger than the radius of the light cylinder, $r_c = c/\Omega$, and relativistic particles of energy $E$ that stop co-rotating with the
pulsar at \( r_c \) carry away an angular momentum \( E/\Omega \), so that the total rate of angular momentum loss by particle emission is \( \dot{L} \approx L_{\text{RP}}/\Omega \), i.e.,

\[
\dot{E}_{\text{rot}} \approx L_{\text{RP}}, \quad \tau_s \approx E_{\text{rot}}/L_{\text{RP}}.
\] (7)

The relation \( \dot{E}_{\text{rot}} = L_{\text{RP}} \) is well satisfied, for instance, by the Crab pulsar, for which \( \dot{E}_{\text{rot}} = 1\Omega \dot{\Omega} \approx 5 \times 10^{38} \text{ erg s}^{-1} \), coinciding exactly with the estimated energy input to the Crab nebula (Manchester and Taylor 1997), presumably supplied by relativistic particles from the pulsar.

The gamma-ray bursts and radio flares of SGRs are presumably produced by bursts of relativistic particles. If relativistic particle emission induces the observed spin-down, \( \dot{P} \) should increase during these periods of activity. Indeed, the spin-down rate of SGR 1900+14 doubled during its intensive burst activity in 1998, after which it seems to resume its “quiescent” long-term value (Woods et al. 1999a), as shown in Fig. 1.

4. What powers SGRs and AXPs?

If, unlike in the magnetar model, the energy reservoir of SGRs and AXP is not magnetic, what can it be? A NS whose internal heat, magnetic field and/or angular momentum are diminishing as it radiates, may undergo a phase transition (see, e.g., Shapiro & Teukolsky 1983 and references therein) and collapse to a strange star (SS) or a quark star (QS). Gravitational energy release during the subsequent slow contraction of the cooling and spinning-down star may power SGRs and AXPs (Dar 1999a). The equation of state of nuclear matter, or even that of quark matter at supernuclear densities, has not yet been derived from first principles. Yet, simple considerations indicate that the possible phase transitions of NSs into SSs and QSs ought to be taken seriously.

Naively approximate the pressure of cold nuclear matter at NS densities by that of a non-relativistic degenerate Fermi gas of nucleons. Ignoring general-relativistic corrections, the radius and central density \( \rho_c \) of a self-gravitating gas of neutrons of total baryonic mass \( M \) and zero angular momentum are then given by the polytropic Emden-Lane solution of the hydrostatic equation:

\[
R \approx 15.1 \left( \frac{M}{M_\odot} \right)^{-1/3} \text{ km},
\]

\[
\rho_c \approx 6 \dot{\rho} \approx 0.83 \times 10^{15} \left( \frac{M}{M_\odot} \right)^2 \text{ g cm}^{-3}.
\]

In this simplest of models, low mass NSs should indeed be made of neutrons, but as \( M \) is increased past 1.27\( M_\odot \), \( \rho_c \) increases until the central Fermi energy \( E_F = (\hbar^2/8m_n)(3\rho_c/\pi m_n)^{2/3} \) exceeds \( (m_\Lambda - m_n) c^2 \). At this point, it is favourable for the strangeness changing weak process \( n \to \Lambda \) (or \( ud \to su \)) to start transforming neutrons.
at the top of the Fermi sea into (initially pressureless) \( \Lambda \)'s at the bottom of the sea. This reduces the pressure, causes contraction and increases \( \rho_c \), initiating a run-away reaction that stops only as the \( n \) and \( \Lambda \) chemical potentials equalize, i.e. until \( E_F(n) - E_F(\Lambda) \approx c^2 (m_\Lambda - m_n)(1 - GM(r)/r) \), where \( M(r) \) is the mass enclosed within \( r \).

At the central densities of the strange stars of the previous paragraph, the nucleons would be so snuggly packed that their “individuality” would be in doubt. But it has been argued (Alford et al. 1998; Berges et al. 1999 Rapp et al. 1999; Wilczek 1999; Li et al. 1999) that cold nuclear matter, compressed to high nuclear densities, converts into a much denser superfluid and superconducting Bose-condensate of spin zero diquarks. Cooper pairing of quarks reduces their pressure and would trigger a gravitational collapse that, if it does not proceed all the way to a black hole, would stop only when the squeezed size of the pairs increases their internal energy above their binding energy.

A neutron star may be born with a temperature, a magnetic field and/or an angular momentum that prevent its transition to a strange- or quark-matter state. As the star ages, it may reach a point at which a transition to a denser state of matter is favourable. The collapse would reheat the star to some extent; we conjecture that the gravitational energy made available by its subsequent slow cooling and contraction can power SGRs and AXPs (estimates of the effect are difficult, since quantities such as the heat conductivity are notoriously hard to predict). For a pulsar which is mainly supported by the Fermi pressure of non-relativistic degenerate fermions contraction can power a total luminosity:

\[
L \approx \frac{2}{7} \left( \frac{G M^2}{R} \right) \frac{\dot{R}}{R}.
\]  

For a canonical pulsar mass \( M = 1.4 \, M_\odot \) and a radius \( R = 10 \, \text{km} \), a contraction rate of \( \dot{R} \sim 20 \, \mu\text{m} \, \text{y}^{-1} \) (a tiny \( \dot{R}/R \sim 2 \times 10^{-9} \, \text{y}^{-1} \)) is sufficient to provide the inferred total luminosity of SGRs and AXPs, \( L \leq 10^{37} \, \text{erg} \, \text{s}^{-1} \).

5. Extra evidence and hints in favour of collapsed NSs

The gravitational collapse of pulsars to strange or quark stars may offer explanations for some puzzling observations: the anomalously small effective surfaces of AXPs, the origin of short duration gamma-ray bursts, the shape of some SNRs and the large peculiar velocities of old pulsars.

The X-ray spectra of SGRs and AXPs in quiescent periods have been interpreted as the Wein tail of black-body radiation from their surface. The Stefan-Boltzman law, \( L_X = 4\pi R^2 \sigma T^4 \) (or \( L_X \approx 1.3 \times 10^{37} \, \text{erg} \, \text{s}^{-1} \), for \( R = 10 \, \text{km} \) and \( T = 1 \, \text{keV} \)) yields effective surface areas significantly smaller than expected for a NS, \( A_{NS} \approx 4\pi \times 10^{2} \, \text{km}^2 \). The AXP data are summarized in Table II, normalized to the measured distances (analysis of the corresponding data for SGRs is complicated by their time variability and not
well determined temperatures). All inferred areas are $\sim20\%$ of the expectation. It would be difficult to attribute this systematic effect to errors in the observations. Effective areas smaller than expected may be due to non-uniform surface temperatures. But, more interestingly, they can be real and reflect the small radii of SSs or QSs.

Does the transition from a neutron star to a denser star have directly observable signatures? The answer may be guided by analogies with observed phenomena, a detailed model would be very hard to develop. The gravitational binding energy release --of $\mathcal{O}(10^{53})$ ergs-- would be mainly emitted as a neutrino burst, as in the Type II explosion that first begat the NS. The collapse of a NS core into a denser object should be accompanied by the ejection of the outer layers, and be more similar to a Type I SN explosion than to Type II, Ib or Ic events, for which the ejected mass is much larger and consists mainly of light elements. The ejecta should be mildly relativistic and deposit their energy in the interstellar medium at a fast rate, giving rise to a short-lived SNR, rich in Fe-group elements. The collapsing material may, as in active galactic nuclei, acquire an accreting toroidal structure and emit highly relativistic and collimated jets. These jets, if they point in our direction, may produce gamma-ray bursts (Dar 1999a; Dar and Plaga 1999).

If collimated jets produce cosmological gamma-ray bursts, their kinetic energy must be $E_k \sim 10^{52}$ erg, i.e. comparable to the kinetic energy of the SNR from the SN event in which the NS was originally born. With that much energy, the jets may distort the first SNR in a recognizable manner. Radio observations expose a vast range of SNR shapes (see, e.g., Whiteoak and Green 1996). While very young SNRs have a simple expanding geometry, most older SNRs have a distorted and complicated appearance, which has been traditionally attributed to their expansion into an inhomogeneous interstellar medium. However, some SNRs have striking properties which require explanation either in terms of jets (Manchester 1987; Rozyczka 1993; Gaensler 1998) or --if not due to accidental superpositions-- in terms of a second explosion (Aschenbach 1998; Aschenbach et al. 1999; Gaensler 1999). A second gravitational collapse, which produces a second bang and emits relativistic jets along the rotation axis may explain the puzzling morphology of many SNRs (Dar and De Rújula, in preparation).

In the collapse of a neutron star, an imbalance in the momenta of oppositely ejected jets can impart a natal kick to the resulting SS or QS. This may explain the large observed velocities of “old”, slowly-rotating pulsars. Millisecond pulsars and young pulsars have small velocities (e.g., Toscano et al. 1999); their youth and large angular momentum may have temporarily prevented their collapse (for millisecond pulsars this may also be a selection effect: they are found in binary systems and only with a small natal velocity could they remain bound and be spun up by mass accretion).
6. Outlook

We have contended that SGRs and AXPs do not have the anomalously large magnetic fields postulated in the magnetar model to be the cause of their fast spin-down and the energy reservoir of their emitted radiation. Instead, we argued that the spin-down is caused by relativistic particle emission and we conjectured that the power supply is the gravitational energy released by contraction, resolving the conundrum associated with the large observed jumps in spin-down rate.

Independently of the strength of their magnetic field, the well measured SGRs and AXPs are truly puzzling: their spin-down ages are much smaller than the age of the SNRs with which they are associated, and the distance they must have travelled during their lifetime implies an unacceptable velocity. The hypothesis that these neutron stars have suffered a delayed transition to a denser type of constituency resolves these problems: the measured spin-down ages date back only to the stars’ “second birth”. This hypothesis also explains why the star’s surfaces, as extracted from their X-ray emission, turn out to be smaller than expected for a conventional NS, and why the morphology of some of their associated SNRs hints at a double bang. If the second birth gives a new kick velocity to the NS, its direction should be uncorrelated to the centre of the SNR, as in the Vela pulsar.

Most observed pulsars are not in binary systems and are not SGRs or AXPs. These conventional pulsars have periods averaging to 1/2 s, significantly shorter than the periods listed in Tables I and II. Their characteristic spin-down ages, on the other hand, are longer, typically $10^7$ years. With such long lifetimes, and if a good fraction of the rate of core-collapse supernova (roughly one per century in our galaxy) results in pulsars, one would expect to detect some $10^5$ of these objects, while only about $10^3$ are actually observed. But, if within some $10^5$ years a good fraction of these NSs –depending on their mass, rotation period and magnetic field– were to suffer a transition into a denser object, the observed numbers of supernovae, conventional pulsars, SGRs and AXPs would fall into a consistent picture. A star freshly reborn after a phase transition could be an SGR, whose longer period is explained by rapid spin-down. In turn, SGRs could convert into AXPs after a period of bursting activity. As the AXPs cool and spin down, they should become slowly rotating, radio-quiet, X-ray-dim pulsars. Many of these dim pulsars should still be present in the neighbourhood of their SNRs. Very sensitive X-ray searches are required to discover their presence there.

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### Table 1

**SOFT GAMMA RAY REPEATERS [SGRs]**

| Pulsar       | SNR      | P (s) | \(P \) (Gauss) | \(v \) (km s\(^{-1}\)) | \(\tau \) (ky) | \(\tau_{SNR} \) (ky) | \(S_{\perp} \) (pc) | \(v_{\perp} \) (km s\(^{-1}\)) |
|--------------|----------|-------|-----------------|-----------------|----------------|-----------------|----------------|----------------|
| SGR 1806-20\(^b\) | G10.0-0.1 | 7.47  | \(8.3 \times 10^{-11}\) | \(1.6 \times 10^{15}\) | 1.4  | > 5  | 8.3d\(_{15}\) | 5500d\(_{15}\) |
| SGR 1900+14\(^c\) | G42.8+0.6 | 5.16  | \(6.1 \times 10^{-11}\) | \(1.1 \times 10^{15}\) | 1.3  | > 10 | 36d\(_{7}\) | 27000d\(_{7}\) |
| SGR 1627-41\(^d\) | G337.0-0.1 | 6.41  | \(\ldots\) | \(\ldots\) | > 5  | 5.4d\(_{11}\) | 5400d\(_{11}\)/\(\tau_3\) |
| SGR 0525-66\(^e\) | N49      | \~ 8  | \(\ldots\) | \(\ldots\) | > 5  | 22  | > 22 | 22000/\(\tau_3\) |

\(^a\) \(B_p\) values are for \(\sin \alpha = 1\). Distances \(d_x\) are in units of \(x\) kpc. \(\tau_3\) is the age of the SGR in ky.

\(^b\) Atteia et al. 1987; Kulkarni & Frail 1993; Kouveliotou et al. Ref. 1994; Kulkarni et al. 1994; Murakami et al. 1994; Sonobe et al. 1994; Kouveliotou et al. 1998 and references therein.

\(^c\) Kouveliotou et al. 1994; Vasisht et al 1994; Kouveliotou et al. 1999; Woods et al. 1999a; Hurley et al. 1999 and references therein.

\(^d\) Woods et al. 1999b; Hurley et al. 1999a and references therein.

\(^e\) Mazets et al. 1979; Cline et al. 1982; Marsden et al. 1996 and references therein.

### Table 2

**ANOMALOUS X-RAY PULSARS [AXPs]**

| Pulsar       | P (s) | \(P \) (Gauss) | \(kT \) (keV) | \(L_X \) (\(10^{35}\) erg s\(^{-1}\)) | \(A_X \) \((4\pi \times 10^{2} \text{km}^2)\) |
|--------------|-------|-----------------|---------------|-----------------|----------------|
| 1E 1841−045\(^b\) | 11.76 | \(4.1 \times 10^{-11}\) | \(1.4 \times 10^{15}\) | 0.55 | \(3d_{7}^{2}\) | 0.25d\(_{7}^{2}\) |
| 1E 2259+586\(^c\) | 6.98  | \~ 5 \times 10^{-13} | \(1.2 \times 10^{14}\) | 0.41 | \(0.8d_{4}^{2}\) | 0.22d\(_{4}^{2}\) |
| 4U 0142+615\(^d\) | 8.69  | \~ 2 \times 10^{-12} | \(2.6 \times 10^{14}\) | 0.39 | \(0.7d_{4}^{2}\) | 0.24d\(_{4}^{2}\) |
| 1E 1048−5937\(^e\) | 6.44  | \~ 1.5 \times 10^{-11} \> 6.3 \times 10^{14} | \(~ 6.3 \times 10^{14}\) | 0.64 | \(5.4d_{10}^{2}\) | 0.23d\(_{10}^{2}\) |
| RX J170849−4009\(^f\) | 11.00 | \(~ 2 \times 10^{-11}\) | \(9.5 \times 10^{14}\) | 0.40 | \(10d_{10}^{2}\) | 0.17d\(_{10}^{2}\) |
| PSR J1844-0258\(^g\) | 6.97  | \ldots | \ldots | 0.64 | \(3d_{15}^{2}\) | 0.15d\(_{15}^{2}\) |

\(^a\) \(B_p\) values are for \(\sin \alpha = 1\). All X-ray luminosities are in the \(\sim 1 – 10\) keV energy band as corrected for absorption by Gotthelf and Vasisht 1998. The distances \(d_x\) are in units of \(x\) kpc.

\(^b\) Vasisht & Gotthelf 1997

\(^c\) Iwasawa et al. 1992; Corbet et al. 1995; Parmar et al. 1998 and references therein.

\(^d\) Mereghetti & Stella 1995; White et al. 1996; Israel et al 1999 and references therein.

\(^e\) Oosterbroek et al. 1998; Mereghetti et al. 1997; Corbet & Mihara 1997 and references therein.

\(^f\) Sugizaki et al. 1997

\(^g\) Torii et al. 1998; Gaensler et al. 1999 and references therein.
Fig. 1.— The period of SGR 1900+14 as a function of time (Woods et al. 1999a), as measured by RXTE (squares), BeppoSAX (triangles), ASCA (circles) and BSA (crosses). The lines are linear fits to the X-ray periods of the SGR before June 9, 1998 ($\dot{P} = 6.1 \times 10^{-11}$), between June 9 - August 27, 1998 ($\dot{P} = 1.3 \times 10^{-10}$), and after August 27, 1998 ($\dot{P} = 6.1 \times 10^{-11}$). Between June 9-August 28, the “averaged” spin-down rate has changed by a factor $\sim 2.2$ as a result of a continuous or sudden braking.