Part 10

Anomalous X-Ray Pulsars and Magnetars

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Magnetars

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Abstract. I summarize recent observational and theoretical advances in the understanding of the Soft Gamma Repeaters and the Anomalous X-ray Pulsars. Several direct physical arguments point to very strong magnetic fields ($B > 10\,B_{QED} = 4.4 \times 10^{14}$ G) in SGR outbursts. The connection between these two classes of neutron stars is examined. Their persistent X-ray emission and spindown behavior are interpreted in the magnetar model, where a decaying magnetic field dominates all other sources of energy for radiative and particle emission. The response of a magnetic field to the violent motions in a supernova core is also examined, with a focus on mechanisms that may impart unusually large kicks.

1. Introduction

During the last 30 years, a comfortable picture of the Galactic pulsar population emerged: neutron stars are born with largely dipolar magnetic fields of $\sim 10^{11} - 10^{13}$ G, which do not decay significantly unless the star accretes upwards of $\sim 0.1\,M_\odot$ from a binary companion. This picture is based on observations of neutron stars whose pulsed emissions are powered either by rotation, or by accretion. In the first case, there are strong selection effects against observing radio pulsations from a star whose dipole magnetic field is much stronger than $B_{QED} = 4.4 \times 10^{13}$ G. At a fixed age, the spin period $P \propto B_{dipole}$ – after the magnetic dipole torque has pushed P well above its initial value – and the spindown luminosity $I\Omega\dot{\Omega} \propto B_{dipole}^{-2}$. The radio pulsations are also expected to be beamed into an increasingly narrow solid angle, a dramatic example being the 'new' 8.5 s PSR J2144-3933 (Young, Manchester, & Johnston 1999). The upper envelope of the distribution of measured pulsar dipole fields has, nonetheless, increased significantly with the recent discovery of PSRs J1119-6127 and J1814-1744, the second of which is inferred to have a polar field in excess of 10^{14} G (Camilo et al. 2000). The apparent paucity of neutron stars with $B_{dipole} > B_{QED}$ in accreting systems places tighter constraints on their birth rate *if* they have the same distribution of natal kicks as ordinary radio pulsars.

Detection of an isolated neutron star with $B \gg B_{QED}$ becomes much easier if its magnetic field decays quickly, in $10^4 - 10^5$ yr (Thompson & Duncan 1996, hereafter TD96). The observational signatures of this decay include persistent X-ray and particle emissions and, if $B \gtrsim (4\pi\theta_{max}\mu)^{1/2} = 2 \times 10^{14}\,(\theta_{max}/10^{-3})^{1/2}$ G, sudden outbursts triggered by fractures of the rigid crust. (Here μ is the shear modulus and θ_{max} the yield strain in the deep crust.) If the conversion of magnetic energy to X-rays and particles were 100% efficient, the time-averaged output would be $L_X \sim 1 \times 10^{35}$ erg s^{-1} $(B/10\,B_{QED})^2\,(t_{decay}/10^4\ \mathrm{yr})^{-1}$.

The dipolar magnetic fields of ordinary radio pulsars are probably too weak to be transported at a significant rate through the stellar interior (Baym et al. 1969; Pethick 1992; Goldreich & Reisenegger 1992). The heating of the neutron star core by the diffusing field feeds back strongly on the rate of ambipolar diffusion, and above a flux density $B_{core} \sim 10^2\,B_{QED}$ transport occurs on a short timescale $\lesssim 10^4$ yr (TD96; Heyl & Kulkarni 1998). The neutron star then loses $\sim 10^4\,(B_{dipole}/10\,B_{QED})^{-2}$ times more energy to magnetic field decay than to spindown at an age of $\sim 10^4$ yr. In this situation, the internal toroidal (or multipolar) field should significantly exceed the dipolar component. For that reason, the dipole field inferred from spindown does not directly indicate whether the energetic output of a neutron star is dominated by spindown or by magnetic field decay.

Substantial evidence has accumulated in recent years for *magnetars* – neutron stars in which a decaying magnetic field (rather than rotation or accretion) is the dominant source of energy for radiative and particle emission. Magnetars have been associated with the Soft Gamma Repeaters[1] (Duncan & Thompson 1992, hereafter DT92; Paczyński 1992; Thompson & Duncan 1995, hereafter TD95) and with the Anomalous X-ray Pulsars (Thompson & Duncan 1993, hereafter TD93; TD96).

1.1. Soft Gamma Repeaters: X-ray Outbursts

The group of SGRs now comprises four sources of short (~ 0.1 s) and extremely luminous ($L \lesssim 10^{42}$ erg s^{-1}) hard X-ray bursts. Two sources (SGR 1806-20 and SGR 1900+14) been observed to burst more than 100 times, with a very broad range of fluences: $\sim 10^5$ for 1806-20 (Göğüş et al. 1999b) and $\sim 10^4$ for SGR 1900+14 (Göğüş et al. 1999a). The bursts have a power-law distribution of energies, $dN/dE \propto E^{-1.6}$, and a lognormal distribution of waiting times (Hurley et al. 1994; Cheng et al. 1996; Göğüş et al. 1999ab). These properties are very reminiscent of earthquakes and Solar flares, and point directly to an energy source that is internal to the star.

The SGRs are perhaps best known for two giant outbursts on March 5, 1979 (from SGR 0526-66) and August 27, 1998 (from SGR 1900+14). Separated by almost 20 years, these two bursts are nearly carbon copies of each other (Hurley et al. 1999a; Feroci et al. 1999; Mazets et al. 1999 and references therein). They released $\sim 4 \times 10^{44}$ erg and $\sim 1 \times 10^{44}$ erg respectively, and had very similar and striking morphologies. A number of their properties point directly to intense magnetic fields above $10\,B_{QED}$ (Thompson & Duncan 1995, hereafter TD95).

1. Each giant burst was initiated by a very short and intense ($t \sim 0.1$ s) *initial spike*. The luminosity of this spike exceeded the classical Eddington luminosity – above which the outward force due to electron scattering exceeds the

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[1] This talk combined the Soft Gamma Repeaters and the Anomalous X-ray Pulsars due to the unfortunate absence of Jan Van Paradijs. See Norris et al. (1991) for a review of the early SGR literature. I refer here to a representative sample of the more recent discoveries. A separate review (Thompson 2000b) focusses on the bursting behavior of the SGRs in the magnetar model. Mereghetti (2000) provides a more comprehensive review of the AXPs.

force of gravity: $L_{edd} \simeq 2 \times 10^{38}$ erg s^{-1} for a 1.4 $M_\odot$ neutron star – by a factor $3 \times 10^6 - 10^7$ in the case of the March 5 event (Fenimore, Klebesadel, & Laros 1996). It had all the appearance of an expanding $e^\pm$ fireball carrying $\sim 10^{44}$ erg ($T \sim 500$ keV for the March 5 event; Mazets et al. 1999). This peak luminosity is intermediate, on a logarithmic scale, between that of a thermonuclear X-ray flash and the bright γ-ray fireballs that are observed at cosmological distances. The fireball must in fact have been expanding relativistically (TD95).

The most obvious candidate energy source is a magnetic field that experiences a sudden rearrangement. On energetic grounds, the (external) magnetic field must exceed $\sim 10 B_{QED}$ to power $\sim 10^2$ giant outbursts over $\sim 10^4$ yr. If the energy were initially released inside the neutron star (in the form of crustal shear waves or torsional Alfven waves in the liquid core), it would be transmitted into the magnetosphere at a rate $dE_{wave}/dt \simeq \frac{1}{2} B_{dipole}^2 R_{NS}^2 c\,(2\pi\xi\nu/c)^{8/3}$ (Thompson & Blaes 1998). Here, ξ is the harmonic displacement of the magnetospheric footpoints, which excites transverse Alfvén waves at a radius $R_\nu \sim c/3\nu$. Equivalently, $dE_{wave}/dt \simeq 2 \times 10^{44}\,(B_{NS}/10\,B_{QED})^2\,(\xi/0.1\text{ km})^{8/3}\,(\nu/10^3\text{ Hz})^{8/3}$ erg s^{-1}. For example, an elastic distortion of the crust of energy $\sim 10^{44}$ erg corresponds to $\xi \sim 10^{-2}\,R_{NS} \sim 0.1$ km, and the luminosity approaches $10^7\,L_{edd}$ only if $B_{dipole} \sim 10^{15}\,(\nu/10^3\,\text{Hz})^{-4/3}$ G!

Nonetheless, the short ~ 0.1 s duration of the intense initial spike of the March 5 and August 27 events provides direct evidence that internal (rather than external) magnetic stresses trigger these giant outbursts. A 10^{15} G magnetic field will move the core material at a speed $\sim B/\sqrt{4\pi\rho}$ through a distance 10 km in that period of time. By contrast, the fireball resulting from a sudden unwinding of the external field would last only $\sim R_{NS}/c \sim 10^{-4}$ s (TD95).

2. After the initial hard spike, each of the two giant outbursts released an even greater amount of energy in an *extended oscillatory tail.* This component had a softer spectrum but a more stable temperature, even though its luminosity exceeded $\sim 10^4\,L_{edd}$ (e.g. Mazets et al. 1999). In the March 5 outburst it showed a striking 8-second periodicity of a very large amplitude, which was inferred to be the rotation period of the source. The August 27 outburst exhibited a similar 5.16 s periodicity of an even larger amplitude.

A significant fraction of the initial burst of energy appears to have been trapped on closed magnetic field lines. One infers a strong lower bound $B_{dipole} > 2 \times 10^{14}\,(E_{fireball}/10^{44}\text{ erg})^{1/2}(\Delta R/10\text{ km})^{-3/2}\,[(1 + \Delta R/R_{NS})/2]^3$ G to the surface dipole magnetic field (TD95). A simple analytical model of a trapped fireball, cooling by the inward propagation of its cool boundary (TD95), provides a remarkable fit to the extended August 27 lightcurve (Feroci et al. 2000). Further evidence that the X-rays in the soft tail of the August 27 event were released close to the surface of the neutron star comes from the deep modulations at the 5.16 s rotational period of the neutron star. After ~ 30 s, each pulse exhibited 4 sharp subpeaks, with a phase-coherent structure that appears to be the direct imprint of the multipolar structure of the star's magnetic field (Thompson et al. 1999, hereafter T99; Feroci et al. 2000).

1.2. Soft Gamma Repeaters: Persistent Emission and Spindown

The four known SGRs are also persistent X-ray sources of luminosity $10^{35} - 10^{36}$ erg s^{-1} (Rothschild, Kulkarni, & Lingenfelter 1994; Murakami et al. 1994;

Hurley et al. 1999c; Woods et al. 1999b). In two cases persistent periodicites have been detected: $P = 7.47$ s for SGR 1806-20 (Kouveliotou et al. 1998); and $P = 5.16$ s for SGR 1900+14 (Hurley et al. 1999c). This measurement preceded the August 27 event in the case of SGR 1900+14, and agreed with the periodicity detected in the giant outburst. Together with the 8-s periodicity of the March 5 event, these spins are clustered in a remarkably narrow range. The persistent luminosities of the SGRs are also narrowly clustered – an important clue to the source of the X-ray emission that is often overlooked.

In the magnetar model, the long spin periods of the SGRs were ascribed to large torques driven by magnetic dipole radiation (DT92), and by magnetized winds carrying a persistent flux of Alfvén waves and particles (Thompson & Blaes 1998). A key motivation for this model came from the early association between the March 5 burster and the supernova remnant N49 in the LMC (Cline 1982, and references therein): the 8-s periodicity corresponds to a magnetic dipole field of 6×10^{14} G (polar) at an age of $\sim 10^4$ yr. Further evidence that the SGRs are young neutron stars comes from the association of the other three – with varying degrees of certainty – with young supernova remnants (Kulkarni & Frail 1993; Hurley et al. 1999b; Woods et al. 1999b).

Recently, both SGR 1806-20 and 1900+14 have been observed to spin down rapidly, with (coincidentally) nearly the same characteristic age of $P/\dot{P} = 3000$ yr (Kouveliotou et al. 1998, 1999; Marsden, Rothschild, & Lingenfelter 1999; Woods et al. 1999c). The inferred polar magnetic field strength exceeds 10^{15} G in the standard rotating dipole model. However, the measured spindown luminosity $I\Omega\dot{\Omega}$ is smaller by two orders of magnitude than the persistent X-ray luminosity. In this situation, the inferred dipole field of both SGRs is reduced (by a factor of ~ 4) to 4×10^{14} G if the star is a persistent source of Alfvén waves and particles with a luminosity comparable to $L_X \sim 10^{35}$ erg s^{-1} (Thompson & Blaes 1998; Harding, Contopoulos, & Kazanas 1999; T99). These inferred fields lie only a factor ~ 4 above that of the 'new' radio pulsar J1814-1744.

The hyper-Eddington radiative fluxes, regulated temperatures, and collimated X-ray emission seen in the giant outbursts, which all have a simple explanation in terms of Compton scattering and photon splitting in super-QED magnetic fields. Testable predictions of the magnetar model include afterglow from the heated surface of the star following an outburst, and spectral features in the persistent X-ray emission. See Thompson (2000b) for further discussion.

2. Anomalous X-ray Pulsars: SGR and Radio Pulsar Connection

The Anomalous X-ray Pulsars are a group of a half-dozen neutron stars that have been detected through their persistent X-ray pulsations but have never been observed to burst (Mereghetti & Stella 1995; Duncan & Thompson 1995; Van Paradijs, Taam, & Van den Heuvel 1995; Mereghetti 2000). Compared to the SGRs, they have remarkably similiar persistent X-ray luminosities ($L_X \sim 3 \times 10^{34} - 10^{36}$ erg s^{-1}), spin periods ($P \sim 6 - 12$ s), and characteristic ages ($P/\dot{P} \sim 10^3 - 10^5$ yr). At least three are associated with young supernova remnants. This overlap between the SGRs and AXPs in a *three*-dimensional parameter space would be surprising if the two classes of sources were powered by fundamentally different energy sources – e.g. magnetic field decay (TD96) vs.

accretion (van Paradijs, Taam & van den Heuvel 1995) or passive cooling (Heyl & Hernquist 1997). Combining both classes of sources, one roughly estimates the net birth rate of SGRs/AXPs as $\sim 1 \times 10^{-3}$ per year (T99).

The identification of AXPs with inactive magnetars (TD96; Kouveliotou et al. 1998) resolves some of the problems associated with accretion models. If their X-ray emission were powered by accretion from a low-mass binary companion, then the long orbital evolution time – $10^7 - 10^8$ yr if driven by gravitational radiation – combined with the presence of a few AXPs inside SNR of age $\sim 10^4$ yr would imply far more sources in the Galaxy than are in fact observed (TD96). In addition, the peculiarly soft spectra of the AXPs suggests that, if they are accreting at all, they have magnetic fields much weaker than 10^{12} G. Fields that weak can barely provide the spindown torque measured in the AXPs 1E 1048.1+5937 and 1E 1841-045 (Li 1999).

Interest in the connection between the AXPs and radio pulsars has been raised by the recent discovery of PSR J1814-1744, which is positioned near the AXP 1E 2259+586 in the $P - \dot{P}$ plane (Camilo et al. 2000). It should first be noted that the spindown age of 1E 2259+586 ($P/2\dot{P} \sim 2 \times 10^5$ yr) is $\gtrsim 30$ times the age of the supernova remnant CTB 109 near whose center it sits. Since all the other AXPs and SGRs for which this comparison can be made have *shorter* spindown ages, it seems likely that the spindown torque of 1E 2259+586 has decayed, and that over most of its history this AXP sat a factor of ~ 10 higher in the $P - \dot{P}$ plane. Several effects – alignment, field decay, or a previous phase of accelerated spindown – could explain this effect in the magnetar model.

3. Variable Spindown in the SGRs and AXPs

Of all the Soft Gamma Repeater and Anomalous X-ray Pulsar sources, the spindown of the Anomalous X-ray Pulsar 1841-045 is most consistent with simple magnetic dipole radiation (Gotthelf et al. 1999): the spindown age $P/2\dot{P} = 2000$ yr agrees with the estimated age of the surrounding SNR Kes 73, and the spindown is very uniform. The implied (polar) dipole field of 1.4×10^{15} G is a good candidate for the strongest yet measured in any neutron star.

A number of AXPs (1E 2259+586, 1E 1048.1+5937, and 4U 0142+61) have manifestly variable spindown histories. Nonetheless, the spindown of 1E 2259+586 and RXSJ170849-4009 is remarkably smooth over a period of $\sim 10^3$ days (Kaspi, Chakrabarty, & Steinberger 1999), which suggests that the required irregularities in the spindown are concentrated in narrow time intervals. The long term behavior of the spindown of SGR 1806-20 has not yet been determined, but SGR 1900+14 has been observed to spin down persistently for ~ 4 years. Indeed, the characteristic age of SGR 1900+14 is surprisingly short if it has been spun down purely by a magnetic dipole torque, and if it is physically associated with the nearby SNR G42.8+0.6: the required proper motion is $V_\perp \simeq 20,000\,(D/7\ \mathrm{kpc})\,(t/1,500\ \mathrm{yr})^{-1}$ km s^{-1}. (A spurious association leads to an equally unsatisfactory situation: a very young neutron star bereft of a progenitor supernova.) The inconsistency disappears if the spindown of SGR 1900+14 is *temporarily accelerated* with respect to a long-term magnetic dipole trend, by e.g. persistent emission of Alfvén waves and particles (Kouveliotou et al. 1999; T99; Marsden et al. 1999 discuss the possibility that this effect is permanent).

More intriguingly, the spin period of SGR 1900+14 increased by $\Delta P/P = +1 \times 10^{-4}$ above this long term trend within an 80-day interval surrounding the August 27 giant outburst. A transient flow of particles, photons, and Alfvén waves might provide the additional torque – by increasing the magnetic field strength at the light cylinder and by carrying off angular momentum directly – but the constraint on B_{dipole} is severe (T99). The net effect (Thompson & Blaes 1998) is to increase the spindown luminosity to the geometric mean of L_{Alfven} and the standard magnetic dipole luminosity, $I\Omega\dot{\Omega} = \Lambda\, B_{NS}R_{NS}(\Omega R_{NS}/c)^2\,(L_{Alfven}c)^{1/2}$. Subsequent calculations have found the numerical coefficient to be $\Lambda = 2/3$ (Harding et al. 1999) and $\Lambda = \sqrt{2}/3$ (T99). Applying this formula to the August 27 outburst, and normalizing the radiated energy and duration to the observed values ($\sim 10^{44}$ erg and ~ 100 s), one finds $\Delta P/P = 1\times10^{-5}\,(\Lambda/\frac{2}{3})\,(\Delta E/10^{44}\,\mathrm{erg})^{1/2}\,(\Delta t/100\,\mathrm{s})^{1/2}\,(B_{dipole}/10\,B_{QED})$. This falls below the measured value even for $B_{dipole} \sim 10\,B_{QED}$, but a more extended particle flow or an undetected soft X-ray component to the giant burst cannot be ruled out.

As this last formula makes clear, the spindown resulting from the the release of a fixed energy increases with the duty cycle, because at a lower flux the Alfvén radius (and the lever arm) is increased. This means that transient surges in the *persistent* seismic activity in a magnetar would induce transient acceleration of the spindown (Kouveliotou et al. 1998, 1999; T99; see also Marsden et al. 1999). However, the accelerated spindown of SGR 1900+14 does not appear to correlate directly with bursting activity, and the long-term spindown rate appears not to have been perturbed by the August 27 event (Woods et al. 1999c). This observation has the important consequence that the active region of the neutron star must carry a small fraction of the external magnetic energy; hence one deduces a lower bound to the dipole field of $\sim 10\,B_{QED} = 4.4\times10^{14}$ G (T99). It also indicates that low-level, persistent seismic activity, if present, must largely be decoupled from bursting activity. An extended non-thermal radio nebula near SGR 1806-20 (Kulkarni & Frail 1993) has previously been associated with the SGR; but this association has recently been questioned (Hurley et al. 1999d).

Melatos (1999) has recently noted the intriguing possibility that the spindown torque coupled to the asymmetric inertia of the co-rotating magnetic field could be particularly effective at forcing precession in a magnetar. Free precession (which in this model is modulated by the spindown torque) has a period $\tau_{prec} = P/\varepsilon_B = 7\,(P/6\text{ s})\,(B_{core}/10^2 B_{QED})^{-2}$ day, where $\varepsilon_B \simeq 1 \times 10^{-5}(B_{core}/10^2 B_{QED})^2$ is the dimensionless quadrupole distortion of the star by the (toroidal core) magnetic field. Even in the absence of forced radiative precession, free precession will be excited at some level by the giant outbursts, which re-arrange a portion of the neutron star crust on a timescale small compared with τ_{prec} (T99). In general, *the detection of free precession would provide a valuable measure of the internal magnetic field strength, entirely independent of the external dipole component that drives the spindown.* A precession period of days to weeks is predicted by models of magnetic field decay in which only a very strong core field ($B_{core} \gtrsim 10^2\,B_{QED}$) will dissipate significantly on a timescale of $\sim 10^4$ yr (TD96). This test is especially important in light of the detection of radio pulsars with dipole fields within a factor $\sim 3-4$ of those inferred for the two spinning down SGRs, but without the strong X-ray emission of the SGRs and AXPs (Pivovaroff, Kaspi, & Camilo 2000). If by contrast the long term spindown variations of the AXPs (over a period of years) are due to forced radiative precession (Melatos 1999), the quadrupole must be very small ($\varepsilon_B \sim 10^{-7}$). This value is barely consistent (on energetic grounds) with the internal magnetic field needed to power persistent X-ray emission from a magnetar at $L_X \sim 10^{35} - 10^{36}$ erg s^{-1} over 10^4 yr.

3.1. Superfluidity and Glitches

Superfluid-driven glitches are a potential source of spindown irregularities in isolated magnetars. SGRs 1900+14 and 1806-20 have frequency derivatives about one-tenth that of the Vela pulsar. A giant outburst like the August 27 event must involve a large fracture of the crust propagating at $\sim 10^8$ cm s^{-1}, which almost certainly unpins the ^{1}S$_0$ neutron superfluid vortex lines from the crustal lattice. The maximum glitch that could result can be very crudely estimated (TD96) by assuming a characteristic maximum angular velocity difference $\Delta\Omega_{max}$ between the superfluid and lattice, and then scaling to the largest observed glitches (e.g. $\Delta P/P \sim -3 \times 10^{-6}$ in Vela). This gives $|\Delta\Omega/\Omega| \sim \Delta\Omega_{max}/\Omega \propto \Omega^{-1}$ and $|\Delta P/P| \simeq 3 \times 10^{-4}(P/8 \text{ s})$ (TD96).

SGR 1900+14 experienced a transient period increment of $\Delta P/P = +1 \times 10^{-4}$ within an 80-day interval straddling the August 27 giant outburst (Woods et al. 1999c). Could this be a superfluid-driven glitch in spite of the 'wrong' sign? The crust of a magnetar is deformed plastically by magnetic stresses wherever $B \gtrsim (4\pi\mu)^{1/2} \sim 6 \times 10^{15}$ G (TD96). Such a deformation taking place on a timescale short compared to $P/\dot{P}$ will force the pinned vortex lines into an inhomogeneous distribution (with respect to cylindrical radius). The net effect is to *slow* the rotation of the superfluid with respect to the crust. A sudden unpinning event would then tend to *spin down* the rest of the star (T99).

Heyl and Hernquist (1999) estimated the glitch activity in a few variable AXPs, under the assumption that the spindown irregularities are entirely due to glitches of the same sign as pulsar glitches. The required activity is, in fact, quite large: the internal flywheel must carry a much larger fraction of the stellar moment of inertia than the value $I_{sf}/I \simeq 10^{-2}$ which is inferred from the spin history of several young pulsars (Epstein et al. 1999). A further argument against glitches as the dominant source of spindown irregularities comes from the genuine variability in the spindown rate of AXP 1048.1+5937, and the hints of variable spindown in SGR 1900+14 (Woods et al. 1999c). For that reason, it is important to consider alternative mechanisms for spindown variations involving, e.g., acceleration of the torque by persistent Hall fracturing in the crust.

4. Persistent Emission

The persistent X-ray output of the Soft Gamma Repeaters lies within a fairly narrow range of $1 - 10 \times 10^{35}$ erg/s. The output of the AXPs is slightly broader but much softer spectally: whereas the SGRs have predominantly non-thermal spectra with a power-law component $dN/dE \propto E^{-2}$ (Murakami et al. 1994; Hurley et al. 1999c; Woods et al. 1999b), the emission of the AXPs appears to contain both a blackbody component and a (soft) non-thermal component with photon index $\sim 3 - 4$ (Mereghetti 2000, and references therein). These spectral differences suggest that i) dissipation of magnetic energy in a neutron star can product varying persistent X-ray spectra, with hardness correlating strongly with bursting activity; and ii) that more than one mechanism can generate persistent X-ray emission at a level of $\sim 10^{35}$ erg s^{-1}. Four such mechanisms have been proposed, all of which can be expected to operate in an SGR and at least two of which are relevant to the AXPs. We summarize them in turn:

1. *Ambipolar diffusion of a magnetic field through the neutron star core, combined with the increased transparency of the stellar envelope in a strong magnetic field* (TD96; Heyl & Kulkarni 1998). The degenerate charged electrons and protons are tied to the magnetic field lines in the neutron star core. They can be dragged across the background neutron fluid, but only very slowly (Pethick 1992; Goldreich & Reisenegger 1992). Heating of the core feeds back strongly on the rate of ambipolar diffusion (TD96). An intense magnetic field drives an imbalance between the chemical potentials of the electrons, protons and neutrons, $\Delta\mu = \mu_e + \mu_p - \mu_n \simeq B^2/8\pi n_e$, and this imbalance induces β-reactions which heat the core. Above a critical flux density, the heat produced exceeds the heat remaining in the star from its formation, and the core sits at an equilibrium temperature where heating is balanced by neutrino cooling. In practice, this balance is possible only as long as the neutrino emissivity is dominated by the modified-URCA reactions. The very strong temperature-dependence of these reactions translates into a very strong B-dependence of the diffusion rate: $t_{amb} = 10^4\ (B_{core}/7 \times 10^{15}\ \mathrm{G})^{-14}$ yr in a normal n-p-e plasma (TD96). (This timescale depends, of course, on the *core* flux density.) Assuming a magnetized iron envelope, the resulting heat flux through the surface is $L_X(t) = 5 \times 10^{34}\,(t/10^4\ \mathrm{yr})^{-0.3}$ erg s^{-1}. Further time-dependent calculations of ambipolar diffusion through normal n-p-e nuclear matter, including much more detailed modelling of the envelope, are reported by Heyl & Kulkarni (1998).

2. *Hall fracturing in the crust* (TD96). Protons are bound into a rigid Coulomb lattice of nuclei in the neutron star crust. In this situation, the propagation of short-wavelength magnetic irregularities through the crust is driven by the Hall electric field $\vec{E} = \vec{J} \times \vec{B}/n_e ec = (\vec{\nabla} \times \vec{B}) \times \vec{B}/4\pi n_e e$. The polarization of a such a Hall wave rotates, which causes the crust to yield or fracture in a magnetic field stronger than $\sim 10^{14}$ G. A significant fraction of the wave energy is dissipated in this manner – in less than the age t_{NS} of the neutron star – if the turbulence has a short wavelength $\lambda \lesssim 0.1\,(\delta B/B)^{-1/2}(\theta_{max}/10^{-3})^{1/2}$ $(B^2/4\pi\mu)^{-1/4}\,(t_{NS}/10^4\ \mathrm{yr})^{1/2}$ km. (Recall that $(4\pi\mu)^{1/2} = 6 \times 10^{15}$ G in the deep crust.) By contract, large-scale fractures which are capable of triggering giant outbursts require more rapid transport of the magnetic field, which can occur via ambipolar diffusion through the *core*.

Each Hall fracture releases only a small energy, $\Delta E \sim 10^{36}\,(\theta_{max}/10^{-3})^{7/2}$ erg. The cumulative effect is to excite persistent seismic activity with a net output $L_{seismic} \sim 10^{35}\,(\delta B/B)^2\,(B/10^{15}\ \mathrm{G})^2\ (t_{NS}/10^4\ \mathrm{yr})^{-1}$ erg s^{-1} (TD96). The excited seismic waves have a frequency $\nu \sim c_\mu/\lambda \sim 10^4$ Hz, where $c_\mu \sim c/300$ is the shear wave speed in the deep crust. These internal waves couple to transverse (Alfvén) excitations of the magnetosphere at a radius $R_\nu \sim c/3\nu \sim 100\,\lambda$. Only a tiny fraction of the wave energy need be converted to particles to support the associated electrical currents (Thompson & Blaes 1998).

3. *Twisting of the external magnetic field lines by internal motions of the star, which drives persistent electrical currents through the magnetosphere* (T99). The persistent light curve of SGR 1900+14 underwent a dramatic change following the August 27 outburst (Murakami et al. 1999): it brightened by a factor ~ 2.5 and at the same time simplified dramatically into a single large pulse. This change appeared within a day following the August 27 event, indicating that the source of the excess emission involves particle flows *external* to the star (T99). The coordinated rise and fall of the two X-ray pulses of 1E 2259+586 over a period of a few years detected by Ginga (Iwasawa, Koyama, & Halpern 1992) similarly indicates that some portion of its emission is magnetospheric (TD96).

The rate of dissipation due to a twisting of a bundle of field lines (of flux density B, radius a, twist angle θ and length L) can be estimated as follows (T99). The associated charge flow is $\dot{N} \sim \theta B a^2 c/8L$ into the magnetosphere from either end of the twisted field. The surfaces of the SGRs and AXPs are hot enough to emit thermionically for a wide range of surface compositions – even in the presence of $\sim 10^{15}$ G magnetic fields – and so the space charge very nearly cancels. An electric field $\vec{E} \cdot \vec{B} = -(Am_p/Ze)\vec{g} \cdot \vec{B}$ will compensate the gravitational force on the ions; but the same field pushes the counterstreaming electrons to bulk relativistic motion. The net luminosity in Comptonized X-ray photons is $L_{Comp} \sim 3 \times 10^{35} \theta (A/Z)(B/10\, B_{QED})\, (L/R_{NS})^{-1}\, (a/0.5\, R_{NS})^2$ erg s^{-1}. This agrees with the measured value if a few percent of the crust is involved in the August 27 outburst. (Independent evidence for an active fraction this size comes from the unperturbed long-term spindown of SGR 1900+14, and from the expectation of $\sim 10^2$ giant outbursts per SGR in $\sim 10^4$ yr.) This non-thermal energy source will decay in 10-100 years, and so provides a physical motivation for non-thermal persistent X-ray spectra in active burst sources. (Note that the measured increase in the persistent L_X of SGR 1900+14 came entirely in the non-thermal component of the spectrum: Woods et al. 1999a.)

4. Heyl and Hernquist (1997; 1998, and references therein) have explored the interesting possibility that the emission of some AXPs is predominantly due to *passive surface cooling, possibly enhanced by a light H or He composition.* This model is most promising for the AXP 1E 1841-045, but cannot accomodate the variable L_X of 1E 2259+586 or 1E 1048.1+5937. A challenge for this model comes from the very similar spin periods and persistent X-ray luminosities of the active SGRs and the quiescent AXPs. The magnetic dissipation occuring within an active SGR lengthens its *lifetime* as an bright X-ray source (TD96; Heyl & Kulkarni 1998). The observed similarity in L_X and P would have to result from a cancellation between the competing influences of internal dissipation and reduced surface opacity.

5. Origins of Neutron Star Magnetism

The idea of magnetars was motivated by the realization that the violent convective motions in a collapsing supernova core can strongly amplify the entrained magnetic field (Thompson & Duncan 1993, hereafter TD93). The intense flux of neutrinos drives convection both in the central part of the core that is very thick to neutrino scattering and absorption (Pons et al. 1999, and references therein) and in a thin mass shell below the bounce shock where neutrino heating overcomes cooling (Janka & Mueller 1996, and references therein). Balancing hydrodynamic and magnetic stresses, one deduces magnetic fields of $\sim 10^{15}$ G and $\sim 10^{14}$ G respectively (TD93; Thompson 2000a). The convection inside the neutrinosphere has an overturn time τ_{con} of a few milliseconds; the overturn time in the outer 'gain' region is somewhat longer. The inner region will support a large-scale helical dynamo if the core is very rapidly rotating, with $P_{rot} < \tau_{con}$ (DT92), but not otherwise. It is also possible that rapid rotation by itself could amplify a magnetic field (Leblanc & Wilson 1970) through the magnetic shearing instability (Balbus & Hawley 1991) in the absence of convection, if the outermost parts of the collapsing core became centrifugally supported.

A newborn neutron star experiences convection with a dimensionless ratio of convective kinetic energy to gravitational binding energy ($\varepsilon_{con} \sim 10^{-4}$) that is some two orders of magnitude larger than in any previous phase driven by nuclear burning (TD93). (This is the relevant figure of merit because the gravitational binding energy and the magnetic energy are proportional under an expansion or contraction.) For this reason, neutron star magnetic fields are probably not fossils from earlier stages of stellar evolution. The intense flux of neutrinos emanating from the neutron core induces rapid heating and $n - p$ transformations, thereby allowing magnetic fields stronger than $\sim 10^{14}$ G to rise buoyantly through a thick layer of convectively stable material in less than the Kelvin time of ~ 30 s (Thompson & Murray 2000). As a result, the $10^{11} - 10^{13}$ G magnetic moments of ordinary radio pulsars, which do not appear to correlate with the axis of rotation, have a plausible origin (TD93) in a stochastic dynamo operating at slow rotation ($P_{rot} \gg \tau_{con}$). Direct amplification of a magnetic field $\langle B^2\rangle^{1/2}$ within individual convective cells of size $\ell \sim (\frac{1}{30} - \frac{1}{10})\, R_{NS}$ will generate a true dipole of magnitude $B_{dipole} \sim \langle B^2\rangle^{1/2}(\ell^2/4\pi R_{NS}^2)^{1/2} \sim 10^{13}$ G through an incoherent superposition. A similar effect can occur during fallback as convection develops below the accretion shock (Thompson & Murray 2000).

5.1. Large Kicks

There is evidence that some (but not all) SGRs have proper motions approaching ~ 1000 km s^{-1}. The quiescent X-ray source associated with SGR 0526-66 (the March 5 burster) is offset from the center of N49, implying $V_\perp \sim 800\,(t/10^4\,\mathrm{yr})^{-1}$ km s^{-1} perpendicular to the line-of-sight (DT92). Similarly, the association of SGR 1900+14 with G42.8+0.6, if real, implies $V_\perp \sim 3000\,(t/10^4\ \mathrm{yr})^{-1}$. Additional indirect evidence that magnetars tend to have received large kicks comes from the paucity of accreting, strong-B neutron stars. However, it should be emphasized that the proper motions of SGR 1806-20 may be as small as ~ 100 km s^{-1}, and that the projected positions of the AXPs 1E 2259+586 and 1E 1841-045 are close to the centers of their respective remnants.

Since the SGRs already appear to have one unusal property (very strong magnetic fields), one immediately asks if a large kick could be produced by a mechanism that does not operate, or operates inefficiently, in ordinary proto-pulsars. Two mechanisms are particularly attractive if the star is initially a rapid rotator (DT92; Khokhlov et al. 1999; Thompson 2000a): anisotropy in the emission of the cooling neutrinos caused by large scale magnetic spots, which suppress convective transport within the star; and asymmetric jets driven by late infall of centrifugally supported material. The first model is supported by observations of rotating M-dwarfs, which have deep convective zones (like proto-neutron stars) and develop large, long-lived polar magnetic spots: Vogt 1988). One estimates $M_{NS}V_{NS} \sim (E_\nu/c)\,(\tau_{spot}/\tau_{KH})^{1/2}\,(\Delta\Omega_{spot}/4\pi)$, where τ_{spot} is the coherence time of the spot(s) and τ_{KH} the Kevlin time of the star. The corresponding magnetic dipole field is $B_{dipole} \sim 5 \times 10^{14}\,(V_{NS}/1000 \text{ km s}^{-1})\,(\tau_{spot}/\tau_{KH})^{-1/2}$ G. Note that this refers to the dipole field in the *convective* neutron core, and represents an upper bound to the remnant field.

An asymmetric jet provides a more efficient source of linear momentum than does radiation from an off-center magnetic dipole (Harrison & Tademaru 1975), for two reasons: 1) The jet is matter-loaded and the escape speed from a proto-neutron star of radius ~ 30 km is only $\sim \frac{1}{4}$ the speed of light; and 2) a centrifigually supported disk carrying the same amount of angular momentum $(GM_{core}R_{core})^{1/2}\Delta M$ as a hydrostatically supported neutron core can provide much more energy to a directed outflow. The respective energies are $\Delta E \sim GM_{core}\Delta M/2R_{core} = 6 \times 10^{50}(\Delta M/10^{-2}\,M_\odot)\,(R_{core}/30 \text{ km})^{-1}$ erg and $\Delta E \sim \frac{5}{4}G(\Delta M)^2/R_{core} = 10^{48}\,(\Delta M/10^{-2}\,M_\odot)^2\,(R_{core}/30\text{ km})^{-1}$ erg for a 1.4 $M_\odot$ core. The corresponding kick velocity is $\sim 300\,f\,(\Delta M/10^{-2}\,M_\odot)\,(R_{core}/30 \text{ km})^{-1/2}$ km s^{-1}, where f is the fractional asymmetry in the momentum. Only a very energetic jet ($\Delta E \sim 6 \times 10^{51}\,(f/0.3)^{-1}$ erg) can generate a kick of 1000 km s^{-1}.

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