NATURE OF THE SOFT GAMMA REPEATERS AND ANOMALOUS X-RAY PULSARS

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ABSTRACT. I summarize recent developments in the magnetar model of the Soft Gamma Repeaters and Anomalous X-ray Pulsars, give a critical inventory of alternative models for the AXPs, and outline the improved diagnostics expected from present observational efforts.

1. Introduction

The Soft Gamma Repeaters are young neutron stars detected through their brilliant flashes of X-rays and gamma-rays. Strong physical arguments point to the presence of \( \sim 10^{14} - 10^{15} \) G magnetic fields in these sources. (A detailed analysis of 27 August 1998 flare data is given in Feroci et al. 2001, and of the flare physics in Thompson & Duncan 2001.) The Anomalous X-ray Pulsars have gradually emerged as a class of neutron stars with moderate luminosities \( (L_X \sim 3 \times 10^{34} - 10^{36} \text{ erg s}^{-1}) \) and a narrow range of spin periods \( (P \sim 6 - 12 \text{ s}) \). The AXPs are persistently spinning down, some are observed to vary in brightness, and about half are convincingly associated with young supernova remnants. Remarkably, the SGRs in their quiescent states have similar luminosities and spins to the AXPs, and are spinning down even more rapidly. This overlap between the two classes of sources within a three-dimensional parameter space (in spite of the very different detection methods) motivated the suggestion that both are isolated neutron stars powered by the same energy source: the decay of an ultrastrong magnetic field (Thompson & Duncan 1993, 1996). Recent data suggest two objects as possible ‘missing links’ between the two classes: SGR 0525-66, which has been dormant as a burst source since 1983 and has a soft AXP-like power-law spectrum (Kulkarni et al. 2000); and the anomalous pulsar 1E 1048.1-5937, which has a harder persistent X-ray spectrum than SGR 0525-66, and a noisier spindown torque than the other AXPs (Kaspi et al. 2000). Nonetheless, the observed properties of the AXPs are less constraining than those of the SGRs, and have inspired a number of models over the last decade.

2. Models of the Anomalous X-ray Pulsars

The AXPs were first defined as a group\(^1\) by Mereghetti & Stella (1995). Theoretical models for the AXPs must explain several peculiar properties of these sources: i) the

\(^1\) The name ‘Anomalous X-ray Pulsar’ was coined by Duncan & Thompson (1995) in a conference presentation.
absence of a modulation of the X-ray pulse frequency by binary motion, which is consistent with a low mass helium star, or a very low mass degenerate dwarf companion (Mereghetti, Israel, & Stella 1998); ii) low optical fluxes, \( L_{\text{opt}}/L_X \leq 10^{-3} \) (Hulleman et al. 2000a,b); iii) persistent spindown, \( \dot{P} > 0 \), much larger than the \( \dot{P} \) of radio pulsars, and young characteristic ages \( P/\dot{P} = 4 \times 10^3 - 4 \times 10^5 \) yrs; iv) a wide range of torque noise, with some AXPs spinning down almost as quietly as radio pulsars (Kaspi et al. 1999, 2001); iv) spindown luminosities \( I\Omega \dot{\Omega} \sim 10^{32} - 10^{33} \) erg s\(^{-1}\), some 2-3 orders of magnitude smaller than the X-ray luminosities \( L_X \sim 3 \times 10^{34} - 10^{36} \) erg s\(^{-1}\); and v) the localisation of at least 3 AXPs close to the geometrical centers of young supernova remnants (e.g. Gaensler et al. 2001). See the paper by Israel, Mereghetti, & Stella (these proceedings) for a more complete review.

Here is an inventory of the models for the AXPs, listed in the chronological order in which they were invented. I will indulge in one editorial comment at the beginning: In constructing models, there has sometimes been a tendency to equate the ‘symptoms’ with the underlying ‘disease’. Before the splendid phase-connected spin measurements by Kaspi et al. (of the AXPs) and Woods et al. (of the the SGRs) the only neutron stars showing large torque noise were accreting X-ray binaries and a few young glitching pulsars (such as Vela). The most conservative approach would be to fit the AXP/SGR measurements into one of these classes, and this indeed has been the strongest motivation for the accretion-based torque models. There is, however, a fairly direct argument that we are observing a new mechanism for torque noise in neutron stars. The torque acting on an isolated neutron star is a direct measure of the current flowing through its outer magnetosphere; but the magnetic fields of the SGR sources are time variable (giving rise to the bright X-ray bursts), and so one can also expect the current to be time-variable. The only leap one must make here, with regard to the AXP sources, is to postulate that the magnetic field (and the crust which anchors it) are capable of more gradual deformations, in addition to the sudden yields and fractures which appear to trigger SGR flares. Nonetheless, the patterns of torque noise in the SGRs and AXPs are turning out to be sufficiently similar, that any torque model should be able to accomodate both classes of sources.

i) Massive white dwarfs, formed in white dwarf mergers, now spinning down by magnetic dipole torques. Paczyński (1990) suggested this model for 1E 2259+586, which was recognized early on as a peculiar object (Fahlman & Gregory 1981). The spindown luminosity of a white dwarf is much larger, at fixed \( P \) and \( \dot{P} \), than that of a neutron star, by the ratio of moments of inertia \( I_{\text{wd}}/I_{\text{ns}} \sim 0.3 (M_{\text{wd}}/M_{\text{ns}}) (R_{\text{wd}}/R_{\text{ns}})^2 > 3 \times 10^4 \). The required polar magnetic field is

\[
B_{\text{pole}} R_{\text{wd}}^2 = \frac{9 \times 10^{26}}{\sin \alpha} \left( \frac{P \dot{P}}{10^{-10} \text{ s}} \right)^{1/2} \left( \frac{M_\star}{M_\odot} \right)^{1/2} \left( \frac{I_\star}{M_\star R_{\text{wd}}^2} \right)^{1/2} \text{ G} \text{cm}^2, \tag{1}
\]

from the standard dipole formula with inclination angle \( \alpha \). King et al. (2001) have noted that a binary merger is a promising formation scenario for the white dwarf RE J0317-853 (\( B \sim 4 \times 8 \times 10^8 \) G), but its 725-s spin is very slow for the AXPs (albeit fast for a white dwarf). The questions which hang over the white dwarf interpretation of the AXPs are fairly obvious: why is the radiative area deduced from the thermal component of AXP
emission comparable to that of a neutron star (Perna et al. 2001)? Why are half the AXPs situated close to the centers of supernova remnants, whose kinetic energy greatly exceeds the rotational energy of the white dwarf? Why are the white dwarfs visible only while young, and why the narrow range of spin periods?

ii) Magnetars: neutron stars with decaying $\sim 10^{14} - 10^{15} G$ magnetic fields. Thompson & Duncan (1993, 1996) drew a connection between 1E 2259+58 and the SGR 0525-66, based on their similar spin periods, persistent $L_X$, and residence in $\sim 10^{4}$-yr old SNR. The rapid spindown of the AXPs has a simple interpretation as magnetic dipole breaking, modified by variable magnetospheric currents flowing along the decaying magnetic field (Thompson, Lyutikov, & Kulkarni 2001). A variable X-ray flux also points to active field decay in some sources. The most interesting argument against accretion as the energy source of AXP emission is indirect and comes from the SGR sources: in particular, SGR 1900+14 was detected as a persistent source within $\sim 10^{3}$ s of the August 27 giant flare, and yet the radiative momentum of the flare would excavate any accretion disk and suppress accretion for a much longer period (Thompson et al. 2000).

The limited duration of AXP/SGR activity is consistent with the freeze-out of ambipolar diffusion of the magnetic field through the core of a neutron star after surface photon cooling dominates (Thompson & Duncan 1996; Heyl & Kulkarni 1998). The characteristic timescale is $\sim 10^3$ yrs for an iron surface composition, and $\sim 10^4$ yrs for H/He. However, the observed range of spin periods is surprisingly narrow, given the wide range of characteristic ages exhibited by magnetar candidates: from $P/\dot{P} = 1 - 3,000$ yrs for the spinning down SGRs 1806-20 and 1900+14 (Kouveliotou et al. 1998; 1999) to $P/\dot{P} = 4 \times 10^5$ yrs for 1E 2259+586. This points, in a model-independent manner, to a decay in the torque acting on 1E 2259+586, from its historic average (Thompson et al. 2000). The measured spins are remarkably close to the upward extrapolation of the radio pulsar death line in the $\dot{P} - P$ plane. If the magnetar model were to explain them, it would probably be on the basis of a connection between a pair-loaded current, and the stability of a non-potential magnetic field outside the star.

iii) Low Mass X-ray Binaries. In defining the AXPs, Mereghetti & Stella (1985) suggested that they are accreting neutron stars with very low mass companions. They were motivated by the similarity between the spin periods of the AXPs and the equilibrium spin period $10 \left( B/3 \times 10^{11} G \right)^{6/7} \left( L_X/10^{35} \text{ erg s}^{-1} \right)^{-3/7}$ s of an accreting neutron star whose magnetic field is typical of (in fact, slightly weaker than) a young radio pulsar. In addition, the known LMXB 4U 1626-67 has a spin and X-ray luminosity ($P = 7.7$ s, $L_X \sim 10^{30}$ erg s$^{-1}$) in the AXP range. The X-ray spectrum of 4U 1626-67 is, however, much harder than that of any AXP, and there is an optical counterpart (Chakrabarty 1998). This system also has a feature which is natural in any LMXB model for the AXPs, but is not observed in those sources as presently defined: 4U 1626-67 has exhibited intervals of rapid spin-up as well as spin-down, which is expected as the source is old. The long evolutionary timescale leads more generally to a prediction of too many AXP sources, given the probable association of 3 AXPs with $\sim 10^{4}$-yr old supernova remnants: a binary with a companion of mass $M_2 \sim 0.1 M_\odot$, undergoing Roche-lobe overflow with a luminosity $L_X = G M_\text{NS} \dot{M}/R_\text{NS} = 10^{35}$ erg s$^{-1}$, would evolve on the much longer timescale $M_2/\dot{M} \sim 1 \times 10^{10}(M_2/0.1 M_\odot)(L_X/10^{35} \text{ erg s}^{-1})^{-1}$ yrs. Over-
all, it is not surprising that at least one of the large number of accreting X-ray binaries should happen to overlap the AXP parameter space.

iv) Neutron Stars with Fossil Disks. Some neutron stars may capture a quasi-Keplerian disk after their formation, a scenario which has received renewed interest as a model for the AXPs (Van Paradijs, Taam, & Van den Heuvel 1995; Chatterjee, Hernquist, & Narayan 2000). As was realized after the discovery of the first pulsar planetary system, several evolutionary pathways could result in the formation of such a disk. The accretion rate will generically drop off with time, as the orbiting material spreads outward. If the spin of the neutron star is able to track the equilibrium spin period $P_{eq} \propto M^{-3/7}$ (where the corotation radius is close to the Alfvén radius) then its spin will decrease with time. Li (1999) has noted that in some sources (e.g. 1E 1048.1-5937) the time to return to the equilibrium spin is much longer than the measured characteristic age $\sim P/2\dot{P}$, unless the X-ray emission is significantly beamed and $\dot{M}$ is underestimated. This is not a concern in the case of an old accreting binary with fluctuating $\dot{P}$, but it is if the source is only $\sim 10^4$ years old.

Several questions hang over this model: i) Why are the AXPs so similar to the SGRs in their quiescent states? It has been suggested that the torque is modified by accretion effects in the SGR sources (Marsden et al. 2001), but no cogent connection between accretion and bursting activity has been given. ii) An upper age limit of $\sim 10^4 - 10^5$ yrs could result from the dissipation of the disk (e.g. Chatterjee & Hernquist 2000), but a narrow range of $P$ would seem to require a narrow range of initial disk masses. iii) Optical/IR emission from the portion of the disk exposed to the central X-ray source. The possible detection of an optical counterpart to the AXP 4U 0142+61 with (de-reddened) flux $\sim 10^{-3}$ of the X-ray flux (Hulleman et al. 2000b) conflicts with the expectation of $L_{opt}/L_X \sim 10^{-2}$ (Perna, Hernquist, & Narayan 2000), and the spectrum is much redder than is typical of a LMXB. iv) A basic theoretical question is whether an isolated neutron star, surrounded by a centrifugally supported envelope, is able to lose angular momentum through a propeller and approach corotation with a weak accretion flow. Whether this is possible depends on the angular momentum carried away by each gram of ejected material, the initial spin, and the disposition of the surrounding material (in a disk vs. an extended envelope). Calculations which answer in the affirmative have assumed a disk geometry and a fast initial spin, but have allowed the ejected material to be spun up to corotation with the star – the most optimistic prescription for the propeller (Chatterjee et al. 2000). The critical dipole field, above which the rotation is slowed down to allow accretion, rises from $\sim 10^{13}$ G to more than $10^{15}$ G if one makes a different (weaker) prescription for the propeller: that the angular momentum per gram is that of a Keplerian orbit at the magnetospheric boundary.

3. Magnetars: Recent Developments

The magnetar model for the Soft Gamma Repeater sources and the Anomalous X-ray Pulsars has been reviewed recently (Thompson 2000), and so I will list a few recent theoretical highlights here. A case can be made that we now have a better understanding of the radiative mechanism and the nature of the ‘engine’ in SGR bursts, than has yet been obtained for the more distant cosmological GRBs.
i) Direct Evidence for Trapped Fireballs in SGR Giant Flares. After the initial $\sim 0.5$-s fireball, followed by a $\sim 40$-s phase of irregular pulsations, the X-ray flux in the 27 August giant flare maintained a smooth decline until an abrupt termination at $\approx 380$ s. After averaging over the large-amplitude 5.16-s pulsations, the light curve is well fit by the contracting surface of a trapped fireball, $L_X(t) \approx L_X(0)(1 - t/t_{evap})^3$ (Feroci et al. 2001). Because the shape of the lightcurve is changed by neutrino cooling (which is strongly temperature-dependent), the diameter of the confined $e^\pm$ plasma cannot be much less than 10 km. This leads to a strict lower bound $m/R_{NS}^3 \approx 3 \times 10^{13}$ G on the dipole magnetic moment $m$ of the confining field (Thompson & Duncan 2001). As the X-ray flux declines, the thermal component of the X-ray spectrum maintains a constant temperature $\approx 11$ keV (black body value: Mazets et al. 1999; Feroci et al. 2000), identical to the temperature at which photon splitting freezes out (Thompson & Duncan 1995).

Independent evidence for a trapped fireball comes from a less energetic burst emitted by SGR 1900+14 two days after the 27 August giant flare. The main burst was followed by a faint pulsating tail lasting at least $\sim 10^3$ s, during which the excess flux decreases as $\sim t^{-0.6}$ (Ibrahim et al. 2001). The high temperature of this tail implies a radiative area only $\sim 1$ percent that of a neutron star. This area is consistent with a trapped fireball of a small volume, but an energy density similar to that attained in the much longer pulsating tail of the giant flare. The energy released in this faint tail can be accounted for by heating of the outer crust through $e^-$-captures, while it was compressed under the fireball pressure (Ibrahim et al. 2001).

ii) Thermal Stability of Magnetized Pair Plasmas, and Short SGR Bursts. The trapped fireball model requires that energy is released fast enough into the magnetosphere to create a plasma in local thermodynamic equilibrium. A steady balance between heating and radiative cooling from the (optically thick) plasma could be maintained if the rate of injection of energy were less than $\sim 10^{42} (R/10$ km) erg s$^{-1}$ within a volume $R^3$ (Thompson & Duncan 2001). We know that LTE can be achieved in the giant flares, because their peak luminosities exceed $\sim 10^{44}$ erg s$^{-1}$ during the initial $\sim 0.5$-s transient. Similarly, one infers that the injection was fast enough to reach LTE in the main, bright component of the 29 August burst. Nonetheless, the question remains open as to whether an LTE fireball actually forms in the much more common short SGR bursts, which have a characteristic $\sim 0.1$-s duration much shorter than the 3.5-s duration of the 29 August burst (Göğüş et al. 2001). In a steady state, the heated electrons cool primarily by Compton upscattering O-mode photons (which maintain a Wien distribution and have a large scattering cross-section $\sim \sigma_T$ in an ultra-strong magnetic field). The net result is an anti-correlation between hardness and luminosity (Thompson & Duncan 2001) which is qualitatively similar to that observed in the short bursts (Göğüş et al. 2001).

iii) Passively Cooling, Ultramagnetized Neutron Stars. The transparency of the outer envelope of a neutron star is increased slightly in the presence of a strong magnetic field, which led to the suggestion that some AXP may be passively cooling neutron stars without active magnetic field transport (Heyl & Hernquist 1997). This model is simple enough for detailed calculations of the angular and spectral distributions of the cooling X-ray flux to be compared with AXP data. Gravitational bending of the photon trajectories tends to reduce pulsed fractions (Psaltis, Özel, & DeDeo 2000). In addition,
the spectrum will differ from a pure blackbody, as the result of the strong asymmetry between the opacities of the two X-ray polarization modes, which might explain some of the soft, high energy power-law tails obtained in AXP spectral fits (Özel 2001). It is worth keeping in mind that two effects will bias the number of observed sources toward those with active magnetic field decay: external currents are more efficient at generating X-rays than is deep heating; and the lifetime of a magnetar as a thermal X-ray source is lengthened, by an order of magnitude, by the decaying field (Thompson & Duncan 1995; Heyl & Kulkarni 1998).

iv) Magnetar Electrodynamics. The persistent emission of the active SGRs has a hard, power-law spectrum and correlates directly with X-ray burst activity (Woods et al. 2001). A strong magnetic field will heat the interior of a neutron star, and also drive electrical currents through its exterior (Thompson & Duncan 1996). The lowest energy deformation of the crust, extending over a scale of kilometers, involves a predominantly rotational motion, which will twist up the external magnetic field. Detailed force-free models of twisted, current-carrying magnetospheres have been constructed by Thompson, Lyutikov & Kulkarni (2001). They have the remarkable property that the optical depth to resonant cyclotron scattering depends directly on the twist angle, but not on the mass, charge, or radius of the scattering particle. As a result, the smooth pulse profile emerging in SGR 1900+14 after the 27 August giant flare (Woods et al. 2001) has a simple explanation through the formation of an extended scattering screen at the electron cyclotron resonance, which for electrons sits at \( R/R_{NS} \simeq 10(B_{pole}/10^{14} \, \text{G})^{1/3}(\hbar \omega/\text{keV})^{-1/3} \) in magnetar-strength fields. In addition, multiple resonant scattering will generate an extended high-energy tail in the persistent X-ray spectrum, and allow large pulse fractions in AXP sources. The field decreases more slowly with radius than a pure dipole, but only slightly, so that the polar surface fields inferred from the measured \( \dot{P} \) and \( P \) of the SGR sources are reduced by a factor 3 – 10 compared with respect to the classical magnetic dipole model.

4. Observational Tests and their Theoretical Implications

In the next few years, the following observational efforts can be expected to throw further light on the true nature of the SGR/AXP sources.

i) Optical counterparts to the SGRs and AXP. Besides the possible detection \( L_{opt}/L_X \sim 10^{-3} \) for 4U 0142+61 (with a peculiar spectrum: Hulleman et al. 2000), there is an interesting upper limit for 1E 2259+586 (Hulleman et al. 2000a) and SGR 0525-66 (Kaplan et al. 2001). High extinctions may limit further progress on the SGR sources, but the prospects are good for improving optical identifications of the AXP by making use of improved X-ray localizations. Strong constraints on accretion will be obtained – either through flux limits; or from the spectral distribution of the measured optical/IR emission, combined with the cross-correlation between the X-ray and optical fluxes.

ii) Connection between the SGR/AXPs and nearby cooling neutron stars. The SGRs and AXP fade as X-ray sources after \( \sim 10^4 – 10^5 \) yrs, but little is known about the further evolution of their X-ray flux and spectrum. The nearby soft X-ray pulsars RX J0420.0-5022, RX J0720.4-3125, and RBS1223 have similar spin periods (22.7, 8.37, and 5.2 s) to the SGRs/AXPs, but much lower X-ray luminosities. It is difficult to
make unambiguous predictions about the field decay occurring in a magnetar after it begins photon cooling, because the heating quickly becomes dominated by the crustal magnetic field. Measurements of spindown in these sources will provide crucial input to the physical modelling.

**iii) Ion cyclotron features: emission vs. absorption?** Detailed calculations of cooling neutron star atmospheres in very strong magnetic fields ($B = 10^{14} - 10^{15}$ G) show that broad absorption features are possible at the fundamental ion cyclotron resonance (Zane et al. 2001; Ho & Lai 2001). Nonetheless, the persistent emission of the SGRs and some AXPs has a strong non-thermal component which, if interpreted in terms of stationary magnetospheric currents, implies a significant amount of surface heating – much of which could be re-radiated through an emission line (Thompson, Lyutikov, & Kulkarni 2001).

**iv) Torque variations in the SGR/AXP sources.** Our picture of torque variations in the SGR and AXP sources is still murky: the level of torque noise is sometimes not much higher than radio pulsars (Kaspi et al. 1999), but at other times the torque can vary by at least a factor $\sim 2$ over periods of months to years (Woods et al. 2000; Paul et al. 2000; Kaspi et al. 2000). It appears so far that variations in the persistent output (and bursting emission) do not correlate directly with torque variations. Whether there is some hysteresis between the two, or whether they are completely uncorrelated, has important implications for the physical mechanism and can only be determined by redoubling the efforts at phase-connected timing (Kaspi et al. 1999, 2000; Woods et al. 2000). These monitoring campaigns are especially important if, as argued above, the variable torque of the SGRs and AXPs is a distinct physical phenomenon from that encountered in accreting binaries or glitching radio pulsars.

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