Magnetic fields of neutron stars: the AMXP connection

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Abstract. This article briefly reviews our current understanding (or lack thereof) of the evolution of magnetic fields in neutron stars, with an emphasis on the binary systems. In particular, the significance of the newly emerging population of accreting millisecond pulsars (AMXP) is discussed.

Keywords : pulsars: general – stars: magnetic fields – stars: neutron

1.   The neutron star menagerie

In recent years we have been confronted by a variety of apparently disparate observational classes of neutron stars. Fortunately, the processes responsible for energy generation in these 2000+ objects, even though their radiation span almost the entire electromagnetic spectrum, belong basically to three categories. Consequently, the neutron stars can be classified into three types in accordance to the manner of energy generation.

A. Rotation Powered : The classical radio pulsars (PSR), these are powered by the loss of rotational energy due to magnetic braking. Millisecond radio pulsars (MSRP) are simply a sub-class of RPPs, albeit being very bright in γ-rays.

B. Accretion Powered : Accreting neutron stars in HMXBs typically show up as high-magnetic field accretion-powered pulsars (APP). Whereas neutron stars in LMXBs have weak magnetic fields and the emission is usually not pulsed. However, in systems with extremely low rates of mass transfer the neutron stars may show up as bursting X-ray transients (XRT) or the dramatic AMXPs.

C. Internal Energy Powered : A heterogeneous class with objects powered by some form of internal energy. The magnetars are thought to shine due to the decay of their super-strong magnetic fields. The soft gamma-ray repeaters (SGR) and the anomalous X-ray pulsars (AXP) are most likely different evolutionary phases of magnetars themselves. The X-ray bright isolated neutron stars (INS) and the central compact objects (CCO) are most likely powered by their residual thermal energy and/or
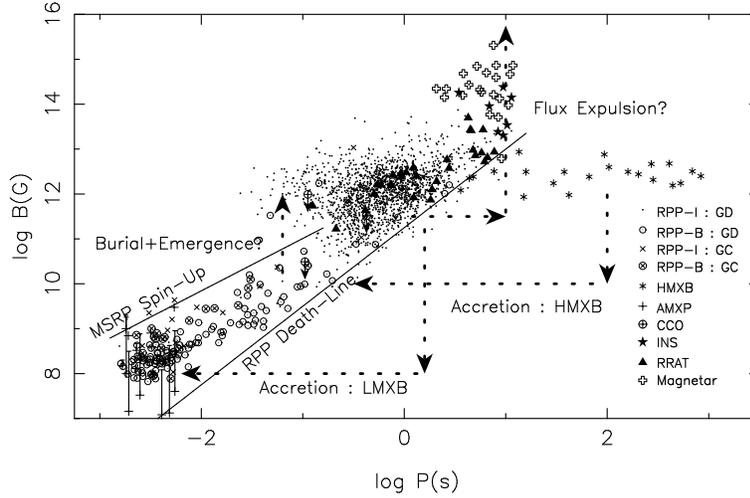

Figure 1. The neutron star menagerie in the $P - B$ plane and possible evolutionary pathways. The data have been obtained from a number of publicly available resources (see Bhattacharya et al. (2013) for detailed references). The range in AMXP field values are due to difference in measurements obtained using different techniques (Mukherjee et al. 2013).

the decay of a strong magnetic field. The rotating radio transients (RRAT), characterised by their powerful single-pulse radio bursts, are suspected to be extreme cases of nulling/intermittent pulsars. Though the nulling pulsars are powered by rotation, the energy source of RRATs is not likely to be the same.

The challenge of neutron star research has always been to find a unifying theme to explain this menagerie. The magnetic field, ranging from 10^8 G in MSRPs to 10^{15} G in magnetars, has been central to this theme. It plays an important role in determining the evolution of the spin, the radiative properties and the interaction of a neutrons star with its surrounding medium. The evolution of the magnetic field is therefore vital to our knowledge of the neutron star physics as a whole.

2.   Evolution of the magnetic field

The magnetic field in a neutron star either evolves spontaneously or as a consequence of material accretion. It has been argued that a physical model of field evolution should satisfy the observational constraints that relatively little magnetic field decay should take place in isolated radio pulsar population, while accretion should be able to reduce the surface field strength by several orders of magnitude (Bhattacharya 2002). However, in modification to this original scenario, a theory of magneto-thermal evolution has recently been developed to understand the evolutionary links between the different types of isolated neutron stars (Pons, Miralles & Geppert 2009).

There is no consensus regarding the generation of the magnetic field in neutron stars. The field could be - (a) a fossil remnant from the progenitor star in the form of

Abrikosov fluxoids of the core proton superconductor (Baym, Pethick & Pines 1969; Ruderman 1972); (b) - generated by the turbulent currents inside the core before it turns superconducting (Thompson & Murray 2001); or (c) - entirely confined to the solid crust generated therein by thermo-magnetic currents (Blandford, Applegate & Hernquist 1983; Urpin, Levshakov & Iakovlev 1986).

However, in most cases the processes responsible for field evolution (for example ohmic dissipation, ambipolar diffusion or Hall drift) can only be effective if the currents supporting the field are located (or are relocated in the course of evolution) in the crustal region which has metal-like transport properties. The simplest and the only mechanism resulting in a permanent decrease of the field strength is ohmic dissipation of the currents. It also successfully explains the MSRP generation via recycling of ordinary radio pulsars in X-ray binaries, where the magnetic field decreases by several orders of magnitude in accretion heated crust.

The basic physics underlying the model of magneto-thermal evolution, invoked for the isolated neutron stars, is also essentially the same. On the one hand the field evolution is sensitively dependent on the transport properties (namely the electrical conductivity) of the crust. Since conductivity is a function of temperature, thermal evolution affects field evolution. On the other hand, the ohmic dissipation of the field generates heat, modifying thermal evolution, reducing conductivity and affecting an even faster dissipation of the magnetic field.

2.1 Isolated neutron stars

A new scenario is emerging out of recent observations linking different types of isolated neutron stars (see Kaspi (2010) for a detailed review). Notice that there is a clear overlap between the high magnetic field ($B > 4 \times 10^{13}$ G) radio pulsars and the magnetars in the $B - P$ diagram (Fig. 1). The magnetar-like X-ray burst exhibited by PSR J1846-0258 ($B = 4 \times 10^{13}$ G) has reinforced the suggestion that such high field radio pulsars are quiescent magnetars. Conversely, it has been suggested that hyper-critical fallback accretion may bury the field to deeper crustal layers thereby reducing the surface field, as seen in the CCOs. Subsequent re-emergence of this buried field could transform a CCO to an ordinary radio pulsar or even to a magnetar. Therefore different combinations of initial spin-period, magnetic field and submersion depth of the field may very well decide whether a neutron star manifests itself as an ordinary radio pulsar, a magnetar or a CCO (Viganò & Pons 2012). Similarly, INSs are observed only in X-ray, despite being isolated objects. It is possible that they are actually similar to the RPPs and are not seen as radio pulsars simply due to the misalignment of emission cones with our lines of sight. The neutron stars with strong magnetic fields are expected to remain at a relatively higher temperature due to field decay. This could then explain the high (compared to ordinary radio pulsars) X-ray luminosity of the INSs. Finally, it has been argued that the anomalous braking index of PSR J1734-3333 signifies an increase in its dipolar surface magnetic field. This is likely driven by the emergence (perhaps glitch-induced) of a stronger field buried un-
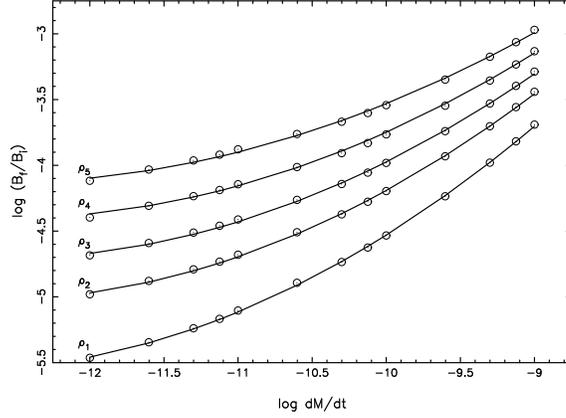
Figure 2. Final surface field as a function of $\dot{M}$ & ρ_c (increasing from ρ_1 to ρ_5).

derneath the surface, with timescales depending on submersion depth (Espinoza et al. 2011). If correct, this process may chart a pathway for the transition from ordinary radio pulsars to magnetars. It appears that different flavors of the isolated neutron stars could, in fact, be intricately connected through various evolutionary pathways.

2.2 Binary neutron stars

Three major physical models have been invoked to explain the evolution of the magnetic field in binary neutron stars, namely - (a) diamagnetic screening of the field by accreted plasma (Cumming, Zweibel & Bildsten 2001; Choudhuri & Konar 2002; Konar & Choudhuri 2004; Payne & Melatos 2004, 2007), (b) spindown-induced flux expulsion (Bhattacharya & Datta 1996; Konar & Bhattacharya 1999b; Konenkov & Geppert 2000, 2001) to the crustal regions, and (c) rapid ohmic decay of the crustal field in an accretion heated crust (Geppert & Urpin 1994; Konar & Bhattacharya 1997, 1999a). The investigation into the consequences of diamagnetic screening have only recently begun in the earnest and we exclude it from the present discussion.

The other two models invoke ohmic decay of the current loops for a permanent decrease in the field strength which happens according to the induction equation, given by -

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) - \frac{\mathbf{c}^2}{4\pi} \nabla \times (\frac{1}{\sigma} \nabla \times \mathbf{B}). \tag{1}$$

In the deeper layers of the crust the field decay is governed essentially by the electrical conductivity σ, and the radially inward material velocity $\mathbf{v}$ ($\propto \dot{M}/\mathbf{r}^2$). In turn, σ is dependent on ρ_c, the density at which the current carrying layers are concentrated, the impurity content Q and the temperature of the crust T_c (again decided by the mass accretion rate $\dot{M}$).

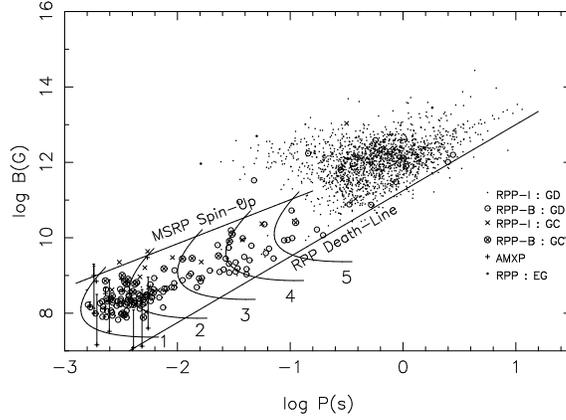Accretion-induced heating reduces σ and consequently the ohmic decay time-

Figure 3. Final surface field and spin-period with currents concentrated at $\rho_c = 10^{13}$ g cm^{-3}. Curves 1 to 5 denote different initial field strengths ($10^{11.5}$ G - $10^{13.5}$ G).

scale inducing a faster decay. At the same time the material movement, caused by the deposition of matter on top of the crust, pushes the original current carrying layers into deeper and denser regions where the higher conductivity slows the decay down. Ultimately the decay stops altogether when the original crust is assimilated into regions with effectively infinite conductivity (Konar & Bhattacharya 1997).

Therefore, the final saturation field of an accreting neutron star depends entirely upon the initial magnetic field, the initial ρ_c and $\dot{M}$ which determines both T_c and $\mathbf{v}$ as can be seen in the left panel of Fig. 2. As is evident, the model of ohmic dissipation is excellent in terms of producing magnetic fields observed in typical MSRPs, starting from ordinary pulsar field strengths.

Location of the magnetic field : The intrinsic uncertainties associated with the model of ohmic dissipation are - a) the impurity content of the crust, and b) the exact location of the current carrying layers. Fortunately, when the crustal temperatures are sufficiently high (as realised in accreting neutron stars) the effect of impurities can be entirely neglected. Consequently, we find that the ohmic dissipation model can be used to constrain the location of the current carrying layers inside a neutron star. We assume that an ordinary neutron star is born with a typical magnetic field of $10^{11.5} - 10^{13.5}$ G. We find that in order to generate the observed population of MSRPs, the original current carrying layers need to be concentrated $\rho_c \gtrsim 10^{13}$ g cm^{-3} as is shown in the right panel of Fig. 3 (Konar, Mukherjee & Bhattacharya 2013).

3. The AMXP-MSRP connection

It has long been understood that the neutron stars are spun up by mass transfer from a stellar companion in an LMXB and are thereby recycled to MSRPs, with an attendant reduction in the magnetic field as discussed in the previous section. The April 1998

	$P_{\text{spin}}^{\text{av}}$ (ms)	B^{av} (10^8 G)	$P_{\text{orb}}^{\text{av}}$ (hr)
MSRP ($P_s \leq 30$ ms) :			
isolated	5.16 (19)	3.45 (19)	
binary	5.32 (65)	2.51 (65)	768 (65)
AMXP :	3.81 (30)	4.93 (14)	0.16 (24)

Table 1. Average surface magnetic field, spin and orbital period of AMXPs and MSRPs. The number of objects in a particular group is within brackets.
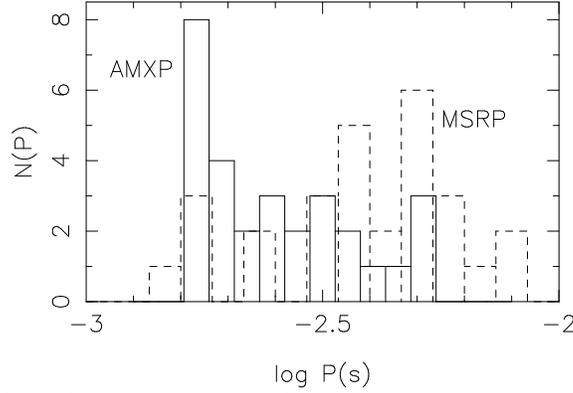

Figure 4. The P_{spin} histogram for AMXPs and isolated MSRPs.

detection of the first AMXP (SAX J1808.4-3658) provided the first direct proof of this model (Wijnands & van der Klis 1998).

The population of AMXPs has been growing rapidly over the last few years, taking the count to 30 (inclusive of standard AMXPs as well as millisecond bursting sources) (Bhattacharya et al. 2013). These objects typically belong to ultra-compact binaries undergoing mass transfer at very low rates from low-mass companions. Though the average P^{spin} of the AMXPs is smaller than that of the millisecond radio pulsars (MSRP), the average B^{surface} tends to be slightly higher in AMXPs (as seen in the above table). It is likely that there exist possible selection effect for high-B objects. And we also need to concede that the uncertainties in the estimates made for the field strength are also rather large.

According to Bildsten & Chakrabarty (2001) objects like SAX-J1808 are progenitors of fast MSRPs with very short orbital periods which have undergone a very long period (Gyr) of accretion at very low rates ($\dot{M} \sim 10^{-11}$ M$_\odot$/yr). However, there appears to be a generic problem associated with the end-products of the AMXPs. It can be seen from table(1) that the average orbital period of the AMXPs is very much smaller than that of the MSRPs. It is true that there exist a bias against detecting MSRPs with very small orbital periods in comparison to AMXPs. But given that many of the AMXPs (including SAX J1808) show *black-widow* traits it is suggested that most of the observed AMXPs would end up as isolated MSRPs. However, a comparison of

the spin-period distribution of AMXPs and the isolated MSRPs show that they are completely mismatched (as seen in the figure above) (Konar et al. 2013).

We conclude that even though the observed population of AMXPs is consistent with pure ohmic dissipation model, it however, does not really mimic the MSRP population. This leaves us with a couple of puzzles regrading the nature of - (1) the real end products of the observed AMXPs, and (2) the progenitor population of the observed MSRPs. It is worth noting that investigations into the nature of binary evolution also suggest that different types of LMXBs may produce different kinds of MSRPs (Chen et al. 2013).

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