

## HIGH MAGNETIC FIELD PULSARS AND MAGNETARS: A UNIFIED PICTURE

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### ABSTRACT

We propose a unified picture of high magnetic field radio pulsars and magnetars by arguing that they are all rotating high-field neutron stars, but have different orientations of their magnetic axes with respect to their rotation axes. In strong magnetic fields where photon splitting suppresses pair creation near the surface, the high-field pulsars can have active inner accelerators while the anomalous X-ray pulsars cannot. This can account for the very different observed emission characteristics of the anomalous X-ray pulsar 1E 2259+586 and the high field radio pulsar PSR J1814-1744. A predicted consequence of this picture is that radio pulsars having surface magnetic field greater than about  $2 \times 10^{14}$  G should not exist.

*Subject headings:* stars: magnetic fields - stars: neutron - pulsars: general - pulsars: individual: PSR J1814-1744, 1E 2259+586

### 1. INTRODUCTION

There is growing evidence that two sub-groups of objects, namely soft  $\gamma$ -ray repeaters (hereafter SGRs) and anomalous X-ray pulsars (hereafter AXPs) are magnetars (e.g. Kouveliotou et al. 1998, 1999; Hurley et al. 1999; Mereghetti & Stella 1995; Wilson et al. 1999; Kaspi, Chakrabarty & Steinberger 1999), a type of objects with dipolar magnetic fields much stronger than the critical magnetic field (Duncan & Thompson 1992; Paczynski 1992; Usov 1992; Thompson & Duncan 1995, 1996). These objects occupy a unique phase space in their combination of long, monotonically increasing periods and high period derivatives, and are believed to be a distinct species from the normal radio pulsars in that most of them are radio quiet, except for a possible detection of radio emission from SGR 1900+14 (Shitov 1999; Shitov, Pugachev & Kutuzov 2000). However, the recent Parkes multi-beam radio pulsar survey (e.g. Manchester et al. 2000; Camilo et al. 2000b) discovered three pulsars with dipolar field strength higher than the critical value (i.e. high magnetic field pulsars, hereafter HBPs); and one of them, PSR J1814-1744, has spin parameters quite similar to the AXP 1E 2259+586 (Camilo et al. 2000; Kaspi et al. 2000). Furthermore, a search of the archival X-ray data from the HBP PSR J1814-1744 indicates that the upper limit of the X-ray luminosity of this pulsar is approximately 1/10 that of 1E 2259+586; this led to the suggestion that HBPs and AXPs may have distinct evolutionary paths, despite their proximity in period-period derivative phase space (Pivovarov, Kaspi & Camilo 2000). Here we propose a possible interpretation of the distinct emission properties of the HBPs and AXPs (especially PSR J1814-1744 and 1E 2259+586) using a simple geometric effect.

### 2. THE INTERPRETATION

Pulsar radio emission is believed to be due to some kind of coherent emission processes in an electron-positron pair plasma. Therefore pair production from a pulsar

inner magnetosphere is the essential condition for pulsar radio emission. The apparent lack of pulsed radio emission from the known SGRs and AXPs has been attributed to the possible pair production suppression by photon splitting, a third-order QED process that may become important in strong magnetic fields above the critical field (Baring & Harding 1998, 2000). However, the discovery of PSR J1119-6127, PSR J1726-3530, and PSR J1814-1744 (Camilo et al. 2000a; Kaspi et al. 2000, see also, <http://www.atnf.csiro.au/~pulsar/psr/pmsurv/pmwww/pmpsrs.db>) above the photon splitting “death line” (Baring & Harding 1998) raises questions concerning how photon splitting suppresses pair production. The close clustering of PSR J1814-1744 and the AXP 1E 2259+586 in the  $\dot{P} - P$  phase space makes the problem more severe.

Such a behavior could be understood in a simple, unified picture when the properties of pulsar inner accelerators are taken into account, assuming that photon splitting can completely suppress pair creation in magnetic fields exceeding  $\sim 10^{14}$  G. Baring & Harding (2000) found that pair creation is completely suppressed only if all three modes permitted by QED operate, i.e. photons polarized both parallel and perpendicular to the field can split, which we will assume throughout this letter. Rotating magnetized neutron stars are unipolar inductors that generate huge potential drops

$$\Phi \sim \frac{B_p R^3 \Omega^2}{2c^2} = (1.0 \times 10^{13} \text{V}) \left( \frac{B_p}{10^{14} \text{G}} \right) \left( \frac{P}{8\text{s}} \right)^{-2} R_6^3 \quad (1)$$

across the open field line region, where  $B_p$  is the dipolar magnetic field strength at the pole,  $R$  is the star radius, and  $\Omega$ ,  $P$  are the rotation velocity and the period of the pulsar, respectively. Under certain conditions a part of or even the total amount of this potential will drop across a charge-depleted region (or a gap) formed in the polar cap area of the pulsar. Depending on the boundary condition at the surface, there are two kinds of inner accelerators,

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i.e., the space-charge-limited flow (hereafter SCLF) type accelerator, which is formed by a self-regulated flow due to free extraction of the charged particles from the neutron star surface (Arons & Scharlemann 1979; Harding & Muslimov 1998), and the vacuum (hereafter V) type gap, which is formed due to strong binding of the charged particles within the surface (Ruderman & Sutherland 1975). There are two important differences between these two types of accelerators (see Zhang, Harding & Muslimov 2000, for a comparison between the two models). First, SCLF gaps could be extremely long and narrow because the potential drop only increases mildly with the gap height so that pair formation fronts (PFFs) could be formed at much higher altitudes, especially when the parallel electric field within the gap is saturated (Harding & Muslimov 1998; Zhang & Harding 2000). A V gap, on the other hand, usually has a height less than the polar cap radius mainly due to the quadratic form of the gap potential-height relation, and the maximum potential is achieved when the gap height  $h \sim r_{\text{pc}}/\sqrt{2}$ , where  $r_{\text{pc}}$  is the polar cap radius (Ruderman & Sutherland 1975; Zhang et al. 2000). Second, the cessation of a V gap requires a pair formation avalanche within the gap, which requires pair production at both the top and the bottom of the gap (Ruderman & Sutherland 1975). A SCLF gap, however, only requires a steady PFF at the top of the gap<sup>2</sup>.

These features have important implications for whether photon splitting can completely suppress pair production. Since photon splitting is only important in strong fields, it does not suppress pair production at higher altitudes where the local field strength is considerably degraded ( $B(r) \propto r^{-3}$ , where  $r$  is the radius in spherical coordinates), even if the near surface field is super-strong. Since a SCLF accelerator could be long and narrow, particles within the gap can keep accelerating. Though the  $\gamma$ -rays produced near the surface by these primary particles will split to lower frequency photons, those produced at higher altitudes will eventually undergo pair production in the less intense fields. For a V gap, however, the gap is usually pancake-shaped, and there is no significant degradation of the field at the gap top with respect to the gap bottom. Even if in some cases (usually near the death line, Zhang et al. 2000) the gap could be long so that the field at the top is less intense, the gap still can not breakdown because pairs can not be formed at the bottom. Thus if the surface field strength is super strong, very likely, such a V gap simply does not form, since a gap solution with boundary condition [ $E_{\parallel}(z=0) \neq 0$ ,  $E_{\parallel}(z=h) = 0$ ] can not be realized. We therefore conclude that *in magnetar environments where photon splitting effectively suppresses pair production at the surface, only SCLF-type accelerators could be formed; V-type accelerators can not develop*. Numerical simulations (Baring & Harding 2000) show that the pair yields drop steeply with increasing magnetic field when photon splitting starts to suppress pair production, which means that at the top of the SCLF gap when pair production starts to overcome photon splitting the pair production rate also rises steeply to provide copious pairs for radio emission. Here we assume that *in magnetar environments, radio emission is possible if a SCLF accelerator is formed*.

<sup>2</sup>Although a lower PFF at the gap bottom can also be formed sometimes in the SCLF model (e.g. Harding & Muslimov 1998), this is never obligatory.

We now discuss the condition for a SCLF gap to develop. The essential point is to investigate whether free ejection of charged particles from the surface is possible, and this depends on (1) the binding energy of the charged particles, and (2) the surface temperature. Let us first discuss a type of neutron star in which the angle between the rotation axis and the magnetic axis is larger than  $90^\circ$ , or  $\boldsymbol{\Omega} \cdot \mathbf{B}_p < 0$ . We call such rotators “anti-parallel rotators” (hereafter APRs) although the axes are not strictly anti-parallel. In such rotators, a force-free magnetosphere requires that the polar cap region is filled with positive charges, and the positive ions from the surface are expected to flow out. The composition of the neutron star surface is uncertain, but it is probably composed of  $^{56}\text{Fe}$ . Although there is a large uncertainty in calculating the binding energy of Fe ions, in magnetar environment, it is likely that a magnetic metal could be formed, and the cohesive energy could be approximated  $\Delta\epsilon \simeq (26.0\text{keV})(B_p/10^{14}\text{G})^{0.73}$  (Abrahams & Shapiro 1991; Usov & Melrose 1995, 1996), and the critical temperature for thermionic emission of the ions is (Usov & Melrose 1995)

$$T_i \simeq (1.0 \times 10^7 \text{K}) \left( \frac{B_p}{10^{14} \text{G}} \right)^{0.73}. \quad (2)$$

The surface temperature of a magnetar is connected to the core temperature by, e.g.,  $T_s \simeq (0.87 \times 10^6 \text{K})(T_c/10^8 \text{K})^{0.55} g_{14}^{0.25}$  (Gudmundsson, Pethick & Epstein 1983, where  $g_{14}$  is the surface gravity of the neutron star in units of  $10^{14} \text{cm s}^{-2}$ ). The balance of neutrino cooling and various magnetic heating yields the core temperature to be  $T_c \sim 6 \times 10^8 \text{K}$  which insensitively depends on the age of the magnetar (Thompson & Duncan 1996). This approach gives a rough estimate of the surface temperature of  $T_s \sim 2.3 \times 10^6 \text{K}$ . From the observational approach, the surface temperature could be estimated from the quiescent X-ray luminosity of magnetars,  $L_x$ , by

$$T_s \simeq (4.8 \times 10^6 \text{K}) \left( \frac{L_x}{10^{35} \text{erg s}^{-1}} \right)^{1/4} \left( \frac{R}{10 \text{km}} \right)^{-1/2}. \quad (3)$$

Both estimations show that the surface temperature is not hot enough for thermionic emission of the ions, and that a SCLF accelerator can not develop. With  $T_s \sim 3 \times 10^6 \text{K}$ , the condition for a SCLF gap, i.e.,  $T_s \geq T_i$ , is  $B_p^i \leq 1.9 \times 10^{13} \text{G}$ , which is well below the photon splitting death line for surface emission (Baring & Harding 1998)

$$B_p \simeq (5.7 \times 10^{13} \text{G}) P^{2/15}. \quad (4)$$

Field emission of ions, which is possibly important when thermionic emission is unimportant, can also be neglected, since the maximum parallel electric field at the surface  $E_{\parallel}(\text{max}) = (2\Omega B_p/c)(r_{\text{pc}}/\sqrt{2}) \sim 5.7 \times 10^9 (\text{V cm}^{-1}) B_{p,14} (P/8\text{s})^{-3/2} (R/10\text{km})^{3/2}$  is much smaller than the critical parallel field required to pull out the ions,  $E_{\parallel}(\text{cri}) \simeq (8 \times 10^{12} \text{V cm}^{-1})(\Delta\epsilon/26\text{keV})^{3/2}$  (Usov & Melrose 1995). Here  $r_{\text{pc}} \sim R(\Omega R/c)^{1/2}$  is the radius of the polar cap, and  $B_{p,14} = B_p/(10^{14}\text{G})$ . Therefore, for APRs

above the photon splitting death line (4), the magnetospheres of magnetars are very likely to be dead, with no active inner accelerators.

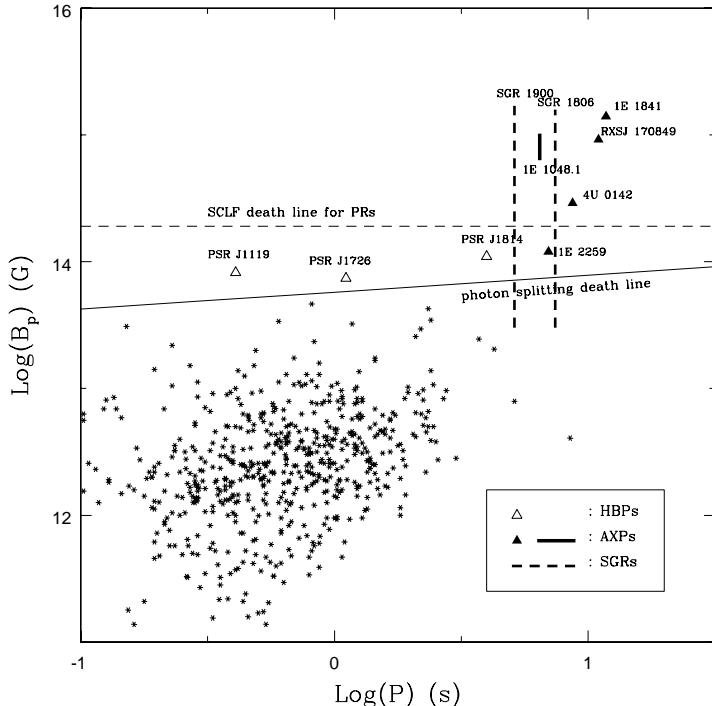


FIG. 1.— A  $B_p - P$  diagram of some radio pulsars and known magnetars. The spin parameters of the HBPs are from Kaspi et al. (2000) and <http://www.atnf.csiro.au/~pulsar/psr/pmsurv/pmwww/pmpsrs.db>. The spin parameters of the AXPs and SGBs are from Mereghetti & Stella (1995), Wilson et al. (1999), Mereghetti (1999), and Kouveliotou et al. (1998). Triangles mean precise measurements of unvarying  $\dot{P}$ . Variations of  $\dot{P}$  data for AXP 1E 1048.1-5937 follows Mereghetti (1999) and Paul et al. (2000). The upper ends of the two bars for the two SGRs are estimated by assuming pure dipolar spin-down, while the lower ends are estimated by assuming that spin-down is dominated by a continuous wind of luminosity  $10^{37} \text{ erg s}^{-1}$  following Harding et al. (1999). The solid line is the photon splitting death line for surface emission (Baring & Harding 1998), which acts as the radio emission death line of the APRs. The dashed line (SCLF death line for PRs) acts as the radio emission death line for the PRs.

We now investigate the opposite case that the neutron stars have inclinations less than  $90^\circ$ , i.e.,  $\Omega \cdot \mathbf{B}_p > 0$ . With the same convention, we call such kind of objects parallel rotators (hereafter PRs). In such neutron stars, negative charges are expected to fill the polar cap region, and electrons from the surface are expected to be pulled out. The binding energy of electrons is roughly the Fermi energy of the electrons, which reads  $\epsilon_F \simeq (5.0 \text{ keV})(Z/26)^{0.8} B_{p,14}^{0.4}$  (Usov & Melrose 1995). And the critical temperature for thermionic emission of the electrons is

$$T_e \simeq (2.3 \times 10^6 \text{ K}) \left( \frac{Z}{26} \right)^{0.8} \left( \frac{B_p}{10^{14} \text{ G}} \right)^{0.4}, \quad (5)$$

where  $Z$  is the atomic number ( $Z = 26$  for Fe) (Usov & Melrose 1995). Assuming that the fields of the HBPs decay in a similar way to that of the AXPs, they should also have typical surface temperatures of  $T_s \sim 3 \times 10^6$  K. By comparing the temperature  $T_e$  to  $T_s$  in magnetar environ-

ments, the condition for thermionic emission of electrons (and hence for a SCLF accelerator to form for a PR), i.e.,  $T_s \geq T_e$ , is thus

$$B_p^e \lesssim 1.9 \times 10^{14} \text{ G}. \quad (6)$$

It is notable that thermionic emission of the electrons is possible at a much higher field strength than the field strength  $B_p^i$  for the thermionic emission of ions. There is a large phase space in the high  $B$  regime where pair production is still allowed at higher altitudes when a SCLF accelerator is formed, even though it is above the photon splitting death line for surface emission. We emphasize that such a conclusion only holds for PRs, and it is interesting to note that such rotators are originally proposed as “anti-pulsars” in the Ruderman & Sutherland (1975) vacuum gap model.

A  $B_p - P$  diagram of the HBPs, AXPs, SGRs, as well as some of the other known radio pulsars is shown in Fig.1, in which the photon splitting death line and the SCLF accelerator “death line” for PRs are also plotted. Polar surface magnetic field is calculated by  $B_p = 6.4 \times 10^{19} \sqrt{P\dot{P}}$  G (Shapiro & Teukolsky 1983; Usov & Melrose 1995). Note that besides the observed variation of  $\dot{P}$  for SGR 1900+14 and 1E 1048.1-5937, there are even more uncertainties in inferring  $B_p$  from the spin-down parameters of SGRs, since a general spin-down formula also includes the contribution from the winds (Harding, Contopoulos, & Kazanas 1999). Therefore, in some cases we adopt a bar instead of a point to denote an object in Fig.1. An important fact is that the three newly-discovered HBPs are located in the phase space defined by the photon splitting and PR SCLF death lines, which means that they could be theoretically radio loud if they are PRs. The AXP 1E 2259+586 also lies in this regime but is clearly radio quiet, and we argue that it is an APR. Thus the discrepancy between AXPs and HBPs in this picture is simply due to a geometric effect.

Another question is why PSR J1814-1744 is quiet in X-rays, in contrast to 1E 2259+586. Quiescent emission from magnetars is interpreted as due to magnetic field decay (Goldreich & Reisenegger & 1992; Thompson & Duncan 1996; Heyl & Kulkarni 1998). The quiescent X-ray luminosity should satisfy

$$L_x \leq \dot{E}_B \simeq (1/6) B_p^2 R^3 / \tau_d, \quad (7)$$

where  $\dot{E}_B$  is the magnetic energy decay rate, and  $\tau_d$  is the decay time scale, which is model dependent (Goldreich & Reisenegger 1992; Heyl & Kulkarni 1998) and  $B$  dependent. Note that  $E_B = (1/12) B_p^2 R^3$ , and  $\dot{B} \sim B/\tau_d$  have been adopted. In the general case of a field permeating the core, ambipolar diffusion is the dominant decay mechanism when the field strength is in the magnetar regime. For the solenoidal ambipolar decay mode, the decay timescale is  $\tau_d(\text{ambip}, \text{s}) \sim (3 \times 10^5 \text{ yr}) L_5^2 T_{c,8}^2 B_{p,14}^2$ , thus the quiescent X-ray luminosity is limited to

$$L_x(\text{ambip}, \text{s}) \lesssim 1.8 \times 10^{32} \text{ ergs s}^{-1} B_{p,14}^4 R_6^3 L_5^{-2} T_{c,8}^{-2}. \quad (8)$$

Here  $T_{c,8} = T_c/10^8$  K,  $R_6 = R/10^6$  cm, and  $L_5$  is a characteristic length scale of the flux loops through the outer core in units of  $10^5$  cm (Goldreich & Reisenegger 1992). Note that the right side is proportional to

$B_p^4$ . Observed quiescent X-ray luminosities of all other AXPs do not contradict (8) except for 1E 2259+586, which gives an upper limit on the X-ray luminosity of  $L_x(1E2259) \lesssim 3.7 \times 10^{32} \text{ergs s}^{-1}$ , while observations show that  $L_x(1E2259, \text{obs}) \sim 5 \times 10^{34} \text{ergs s}^{-1}$ . For PSR J1814-1744, on the other hand, (8) gives  $L_x(\text{J1814}) \lesssim 2.6 \times 10^{32} \text{ergs s}^{-1}$ , which is consistent with the upper limit from the archival observations,  $L_x(\text{J1814, obs}) < 3.8 \times 10^{33} \text{ergs s}^{-1} [\sim (1/13)L_x(1E2259, \text{obs})]$ , Pivovarov et al. 2000<sup>3</sup>. Thus the non-detection of bright X-rays from PSR J1814-1744 is not a surprise if neutron star magnetic fields are of core-origin. The discrepancy between PSR J1814-1744 and 1E 2259+586 must then be attributed to the peculiarity of 1E 2259+586. To interpret the quiescent emission of this AXP, one needs to assume either a much faster field decay mechanism (e.g. magnetic fields are of crustal origin and the Hall cascade effect dominates the field decay, Colpi, Geppert & Page 2000) or much stronger multipole fields near the magnetic pole (Baring & Harding 2000). In fact, the age of the associated supernova remnant (SNR) CTB 109 ( $t_{\text{SNR}} \sim 3 - 20 \text{ kyr}$ ) (Parmar et al. 1998) is much younger than the characteristic age of the AXP 1E 2259+586 ( $t_c \sim 2.3 \times 10^9 \text{ yr}$ ) and  $\tau_d(\text{ambip, s})$ . If one assumes  $\tau_d \sim t_{\text{SNR}}$  for this pulsar, the high  $L_x$  is then consistent with eq.(7).

### 3. DISCUSSIONS

In this letter we discuss possible formation of the inner accelerators in a magnetar environment for the first time and come to a unified picture for AXPs and HBPs by arguing that they are all rotating high-field neutron stars, but have different orientations of the magnetic axes with respect to the rotation axes. If photon splitting suppresses pair creation near the surface, the HBPs can have active inner accelerators while the AXPs can not.

This suggestion may also have implications for another type of magnetar, i.e., the SGRs. These objects react much differently from the AXPs by exhibiting irregular short bursts and occasional giant flares, which are inter-

preted as crust cracking and large-scale magnetic field reconnection, respectively, within the framework of the magnetar model (Thompson & Duncan 1995). It remains unclear whether they are experiencing a different evolutionary stage than that of AXPs or whether they are intrinsically different objects. Only two of them (SGR 1806-20 and SGR 1900+14) have  $\dot{P}$  measurements, but determination of their dipolar magnetic fields is complicated by the contribution of the relativistic winds to the spin-down (Harding et al. 1999). It is notable that the constraints of both the SNR age and the magnetar energy requirements lead to a polar field  $B_p(\text{SGR}) \sim 10^{14} \text{ G}$  (Harding et al. 1999), which may lie below the SCLF death line for PRs. Thus they may also have active inner accelerators if they are actually PRs. Here we suggest a possibility that SGRs might also have active accelerators while AXPs do not, and the active behaviors of SGRs may have some connections with their inner accelerators. For example, the constant extraction of electrons from the pole may somehow more frequently trigger instability within the crust. One expectation of this scenario is pulsed radio emission from the SGRs, which may account for the pulsed radio emission from SGR 1900+14 (Shitov 1999; Shitov et al. 2000).

Theoretically, the question of whether photon splitting occurs in all three modes permitted by QED or only in one mode in superstrong magnetic fields is difficult to tackle. If radio pulsar surveys discover any pulsar above the SCLF death line for PRs (the dashed line in Fig.1), these pulsars must have active V gaps with pair breakdown near the surface. This would strongly imply that only one mode of photon splitting occurs in fields above a few times  $10^{14} \text{ G}$ , and thus sheds important light on a fundamental physics process. It is worth noting that the location of the SCLF death line for PRs depends on the surface temperature of the neutron star, so that the location of the dashed line in Fig.1 may rise or drop. Thus detections in both radio and X-ray bands are desirable.

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<sup>3</sup>Note that this luminosity upper limit implies a surface temperature above what we have assumed to derive the SCLF death line for PRs (eq.[6]).

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