

THE FUNDAMENTAL PLANE FOR RADIO MAGNETARS

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ABSTRACT

High magnetic fields are a distinguishing feature of neutron stars and the existence of sources (the soft gamma repeaters and the anomalous X-ray pulsars) hosting an ultra-magnetized neutron star (or magnetar) has been recognized in the past few decades. Magnetars are believed to be powered by magnetic energy and not by rotation, as with normal radio pulsars. Until recently, the radio quietness and magnetic fields typically above the quantum critical value ($B_Q \simeq 4.4 \times 10^{13}$ G), were among the characterizing properties of magnetars. The recent discovery of radio pulsed emission from a few of them, and of a low dipolar magnetic field soft gamma repeater, weakened further the idea of a clean separation between normal pulsars and magnetars. In this Letter we show that radio emission from magnetars might be powered by rotational energy, similarly to what occurs in normal radio pulsars. The peculiar characteristics of magnetars radio emission should be traced in the complex magnetic geometry of these sources. Furthermore, we propose that magnetar radio activity or inactivity can be predicted from the knowledge of the star's rotational period, its time derivative and the quiescent X-ray luminosity.

Subject headings: X-rays: star — stars: neutron — stars: magnetar

1. INTRODUCTION

The radio emission from pulsars has been studied in detail in the past decades, and it is believed to be powered by the star's rotational energy ($L_{\text{rot}} = 4\pi^2 I \dot{P}/P^3 \sim 3.9 \times 10^{49} \dot{P}/P^3 \text{ erg s}^{-1}$, where $I \sim 10^{45} \text{ g cm}^2$ is the star moment of inertia, P and \dot{P} the rotational period (in seconds) and period derivative). A key ingredient to activate the radio emission is the acceleration of charged particles, which are extracted from the star's surface by an electrical voltage gap. The voltage gap forms due to the presence of a (mainly) dipolar magnetic field co-rotating with the pulsar, and extends up to an altitude of $\approx 10^4 \text{ cm}$ with a potential difference $> 10^{10}$ statvolts. Primary charges are accelerated by the electric field along the magnetic field lines to relativistic speeds and emit curvature radiation. Curvature photons are then converted into electron-positron pairs in the strong magnetic field and this eventually leads to a pair cascade which is ultimately responsible for the coherent radio emission we observe from radio pulsars (Goldreich & Julian 1969; Ruderman & Sutherland 1975).

Under the usual assumption of dipole magneto-rotational braking, the polar magnetic field of neutron stars is given by

$$B_p = (3 I c^3 \dot{P} P / 2\pi^2 R^6)^{1/2} \sim 6.4 \times 10^{19} \sqrt{P \dot{P}} \text{ G}, \quad (1)$$

where $R \sim 10^6 \text{ cm}$ is the neutron star radius. On the other hand, the electric potential of pulsars (for slow rotators) can be approximated as (Ruderman & Sutherland 1975)

$$\Delta V = 2 \pi^2 B_p R^3 / c^2 P^2 \sim 4.2 \times 10^{20} \sqrt{\dot{P}/P^3} \text{ statV}. \quad (2)$$

In the last two decades two new classes of pulsars were discovered, with properties much at variance with those of radio pulsars, namely the soft gamma repeaters (SGR) and the anomalous X-ray pulsars (AXP). SGRs were discovered as flaring sources by large field-of-view X-ray and gamma-ray instruments. AXPs, instead, were observed as steady, radio-quiet X-ray sources with slow rotational periods (a few seconds). Despite their apparently different properties, the detection of powerful bursts from AXPs (Gavriil et al. 2002), as well as the discovery of persistent X-ray emission and slow rotational periods from SGRs (Kouveliotou et al. 1998), has by now highlighted the connections among the two groups, and was instrumental in establishing their common magnetar nature (Thompson & Duncan 1995, 2001; Mereghetti 2008).

Until recently, the defining observational properties of magnetars were: 1- lack of radio emission, possibly due to the quenching of the pair cascade by photon splitting in their super-strong field (Baring & Harding 1998); 2- persistent X-ray luminosities exceeding rotational energy losses ($L_x > L_{\text{rot}}$), clearly indicating that these sources are powered by magnetic energy rather than rotation (Thompson & Duncan 1995); 3- non-thermal emission in the X-ray spectrum, interpreted as produced by resonant cyclotron upscattering in the current-loaded twisted magnetosphere (Thompson et al. 2002); and 4- surface dipolar magnetic fields exceeding the quantum critical value for electrons ($B_Q = m_e^2 c^3 / e \hbar \sim 4.4 \times 10^{13} \text{ G}$).

SGRs and AXPs are now known to exhibit transient X-ray and gamma-ray outbursts on timescales of months to years, during which an energy up to $\sim 10^{44} \text{ erg}$ is released. Since the discovery in 2003 of such transient outbursts (Ibrahim et al. 2004), 5 new magnetars (over a total of about 20 confirmed class members) have been discovered by means of their X-ray transient activity and thanks to the current X-ray all-sky monitors (the Swift and Fermi satellites; see Rea & Esposito (2011) for a recent review).

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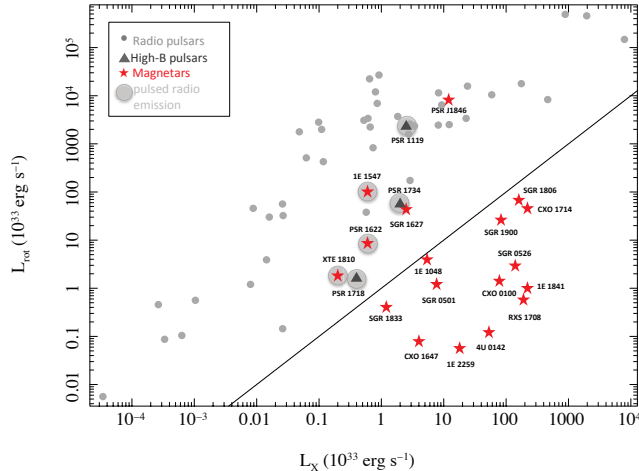


FIG. 1.— X-ray luminosity versus the spin-down luminosity for all pulsars having a detected X-ray emission (grey filled circles), high-B pulsars (filled triangle), and the magnetars (red stars). Grey shaded circles mark the magnetars and high-B pulsars with detected pulsed radio emission, and the solid line shows $L_x = L_{\text{rot}}$. X-ray luminosities are calculated in the 0.5–10 keV energy range, and for variable sources refer to the quiescent emission state.

With the discovery of transient magnetars many of the previously established properties of SGRs/AXPs had to be revised: 1- they can be radio-loud, though also transient in their radio emission (Camilo et al. 2006); 2- during the quiescent state their spin-down luminosity can exceed the X-ray luminosity; 3- they can have purely thermal spectra; and 4- their surface dipolar magnetic field can be as low as a few times 10^{12} G, in line with rotation-powered pulsars (Rea et al. 2010). In light of this, the idea that the physics involved in these sources is completely set apart from that of normal radio pulsars became arguable, as already hinted by the discovery of radio pulsars with magnetic fields reaching into the magnetar range (Camilo et al. 2000; McLaughlin et al. 2003). However, the exact extent of the connection between radio pulsars and magnetars has been so far a matter of debate. In this respect, the understanding of magnetar radio emission is crucial in obtaining a complete picture of the neutron star population as a whole.

2. RADIO EMISSION FROM MAGNETARS

The detection of pulsed radio emission from the magnetar XTE J1810–197 (Camilo et al. 2006; $B_p \sim 2.1 \times 10^{14}$ G) opened a new perspective in the study of such strongly magnetized sources, and the physics of their magnetosphere. For many months, XTE J1810–197 was found to be the strongest radio pulsar in the Galaxy at frequencies above 20 GHz. Its radio emission was highly variable in intensity and pulse-profile morphology on several timescales, and it likely started around a year after the X-ray outburst onset and then declined in a few years (Camilo et al. 2006, 2007a; Lazaridis et al. 2008; Serylak et al. 2009).

Pulsed radio emission was later discovered to follow the X-ray outbursts of the magnetar 1E 1547–5408 (Camilo et al. 2007b; $B_p \sim 2.2 \times 10^{14}$ G). This source showed three X-ray outbursts in the past 5 years. Between the last two events, radio emission was observed to decline, and rise again after the onset of the subsequent X-ray outburst, with a delay of at least a few days (Camilo et al. 2009; Burgay et al. 2009).

Very recently yet another radio-pulsed magnetar has been discovered. PSR 1622–4950 ($B_p \sim 2.8 \times 10^{14}$ G) was the

first magnetar discovered in the radio band, with the identification of its X-ray counterpart following later (Levin et al. 2010). In this case the peak of the X-ray outburst was probably missed (Anderson et al. 2011), and its dim X-ray emission is currently fading off, as expected from a magnetar returning to its quiescent state.

Beside the magnetars reported above, no other source of the class has shown evidence of radio activity (Burgay et al. 2006; Crawford et al. 2007; Lazarus et al. 2011).

The main properties of the radio-pulsed emission of these sources are: 1- a delay in the appearance of the radio emission after the X-ray outburst onset; 2- variable pulse profiles and radio flux on a timescale from minutes to days; 3- decay of the average radio flux as the X-ray outburst decays; 4- flat radio spectrum over a wide range of frequencies (spectral index $\alpha \sim 0$). These characteristics appear at variance with those of the radio pulsars having large magnetic fields ($B_p \sim 5 - 9 \times 10^{13}$ G; Camilo et al. 2000; McLaughlin et al. 2003; Ng & Kaspi 2011), which have radio properties in line with those of typical rotation-powered pulsars (i.e. more stable pulse profile morphology, steep radio spectra, and long-term flux stability).

No complete theory for the ephemeral radio-pulsed emission observed in outbursting magnetars has been put forward so far, although a few theoretical works started to address this issue (Beloborodov 2009; Thompson 2008b). Large observational efforts are on-going to understand when and which magnetar will emit radio-pulsed emission, or be radio-quiet. So far it was argued that whatever the mechanism is, it should differ from that of rotation-powered radio pulsars, and that any magnetar undergoing an outburst could in principle emit radio waves. In the following we show that this might not be the case, and only magnetars with certain characteristics would show radio pulsed emission.

3. RESULTS

In Figure 1 we plot the quiescent X-ray luminosity (in the 0.5–10 keV energy range) versus the spin-down luminosity, for all known magnetars (Rea & Esposito 2011), X-ray bright high-B radio pulsars (Ng & Kaspi 2011) and X-ray-emitting rotation-powered radio pulsars (Becker 2009). The first interesting feature which emerges from this comparison is that all radio emitting magnetars have a spin-down luminosity larger than their X-ray luminosity, in line with the rotational powered radio pulsars. In particular, radio magnetars and high-B radio pulsars tend to fill the gap between normal pulsars and canonical magnetars.

In Figure 2 (left) we plot the electric potential gap (as from Eq. 2) versus the X-ray efficiency L_x/L_{rot} , defined as the ratio of the quiescent X-ray luminosity (in the 0.5–10 keV energy range) to the spin-down luminosity, for the same sources as for Figure 1. The X-ray conversion efficiency has been interpreted as the capacity of the pulsar in converting rotational energy into X-ray emission (Possenti et al. 2002; Vink et al. 2011). For radio-quiet magnetars, it strongly suggests that spin-down luminosity cannot be the “main” responsible of the X-ray emission, which is in fact likely dominated by magnetic energy. On the other hand, the value of the potential gap relates to the ability of the pulsar in extracting and accelerating particles in the polar cap to power the cascade process eventually responsible for the radio emission.

From Figure 2 (left) it is clear that the potential gap of magnetars is in line with that of rotational powered pulsars, although a decay trend is visible (see below for further details).

We note that two objects, PSR J1846–0258 and

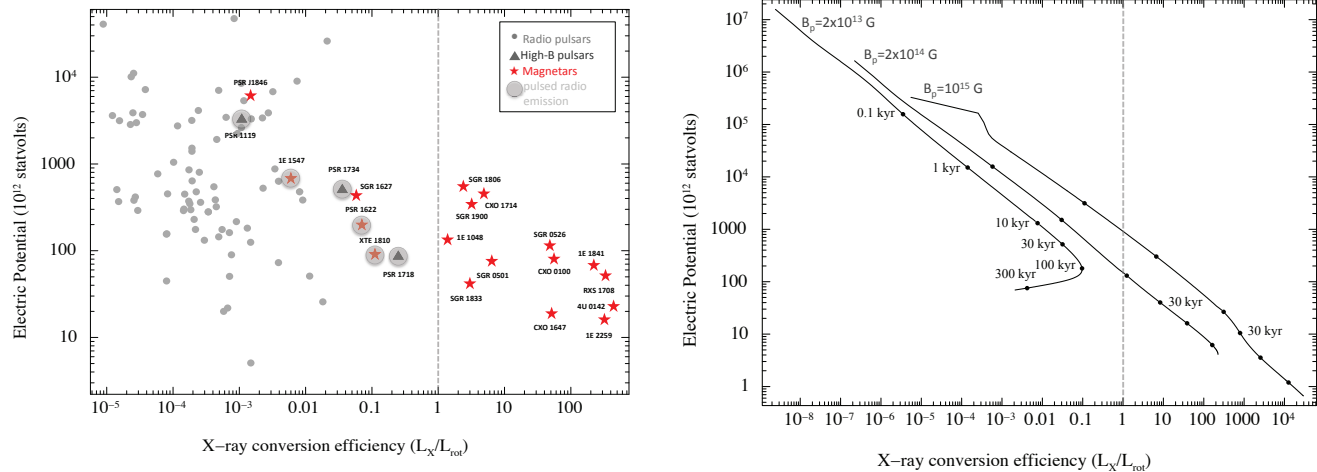


FIG. 2.— *Left panel:* Fundamental plane for radio magnetars: Electric potential gap as a function of the L_x/L_{rot} ratio for the same sources as in Figure 1. *Right panel:* Evolution of the potential gap versus the X-ray conversion efficiency for neutron stars with three initial magnetic field values. The time-steps superimposed to the evolution lines are the same for all lines. See text for details.

SGR 1627–41, appear at first sight as possible outliers in the otherwise clear trend shown in Figure 1 and 2. In principle, one could appeal to beaming effects to explain why these 2 magnetars are not detected in radio (among those with $L_x/L_{\text{rot}} < 1$). However, we note that so far all radio emitting magnetars (for which X-ray pulsations are detected) showed a good X and radio phase-alignment and broad profiles in the two bands (0.2–0.5 in phase; Serylak et al. 2009). Hence, assuming that all magnetars share similar X/radio properties, there would be good chances for the radio beam to be observable since X-ray pulsations are clearly detected. We then rather think that there are other (more likely) alternatives to explain the current non-detection in radio.

PSR J1846–0258 is the youngest pulsar (900 yrs) that showed magnetar-like activity (Gavriil et al. 2008; Kumar & Safi-Harb 2008). Deep radio searches were performed during its 2006 magnetar-like outburst and about 18 months later. If the radio emission of PSR J1846–0258 parallels that of XTE J1810–197, the source should have become radio bright sometime after the X-ray outburst and then continue to fade, reaching in 18 months a flux lower than the $\sim 5 \mu\text{Jy}$ upper limit (at 1.9 GHz) derived by current observations. If its radio emission was similar to those of other radio magnetars, current deep radio observations would have probably missed it (Archibald et al. 2008). The source distance is still uncertain, ranging from 5 to 21 kpc (Becker et al. 1984; Leahy & Tian 2008), which reflects in a large uncertainty in the source dispersion measure (DM); the entire Galactic DM in this direction is $\sim 1470 \text{ pc cm}^{-3}$ (using the NE2001 model; Cordes & Lazio 2002). Furthermore, this pulsar lies in a very dense supernova remnant (Kes 75). In such an environment the detection of any radio-pulsed emission is very difficult.

Searches for radio emission from SGR 1627–41 have been recently performed following its 2008 X-ray outburst (Camilo et al. 2008; Esposito et al. 2009). No radio emission has been detected, but the large distance ($\sim 11 \text{ kpc}$), large column density along the line of sight ($N_{\text{H}} \sim 10^{23} \text{ cm}^{-2}$; which corresponds to a $\text{DM} \sim 1150 \text{ pc cm}^{-3}$ using the NE2001 model), and the time of the observations (close to the outburst peak) make the non-detection quite un-constraining. We conclude that the two apparent outliers to the general trend de-

picted in Figure 1 and 2, have no associated radio emission yet because they are unfavorably affected by distance, scattering, or lack of sensitive observations at the time their pulsed radio emission was possibly expected to be brighter.

The correlation of the potential gap with the X-ray conversion efficiency in magnetars and high-B pulsars (see Figure 2 left) can be interpreted as a natural consequence of the pulsar evolution. To explain this effect, we plot in Figure 2 (right) three evolutionary tracks corresponding to different magneto-thermal models, obtained with the code of Pons et al. (2009), to which we refer for further details on the physical processes involved. The values of the dipolar field B_p at birth are 2×10^{13} , 2×10^{14} , and 10^{15} G (internal toroidal components are 0, 2×10^{14} , and 10^{16} G , respectively). These are chosen as representative cases of a high-B pulsar, a moderate magnetar, and an extreme magnetar (see e.g. Pons & Perna 2011 for a detailed discussion of how the luminosity and timing properties depend on the initial field configuration). We took for all the models a short initial period ($P = 0.01 \text{ s}$), choosing a longer initial period would only shift the lines in the plots towards earlier ages. From these results, we can conclude that the magneto-thermal-rotational evolution of neutron stars born with a high magnetic field, say $> 5 \times 10^{13} \text{ G}$, results in their clustering in a diagonal, relatively narrow band. Along the evolution, they cross the $L_x/L_{\text{rot}} = 1$ line very early, and spend the rest of their lives in the *radio pulsar inactivity* region. Typically, an extreme field object crosses the line in less than 1 kyr. This fast motion on the fundamental plane explains the lack of magnetars in the upper left part of the diagram. Lower field pulsars, on the contrary, reach a turning point before the critical line, thus staying in the left side of the diagram where radio pulsar activity is expected.

4. DISCUSSION

We have shown that radio emitting magnetars have in quiescence $L_x/L_{\text{rot}} < 1$, as rotation-powered pulsars. An X-ray efficiency greater than one was all along considered as a basic property to define a magnetar (see e.g. Mereghetti 2008), but this does not hold as such anymore. In magnetars with a small L_x/L_{rot} ratio, particle acceleration and the subsequent ignition of the cascade process could proceed as for normal pul-

sars (Medin & Lai 2010), successfully reaching the open-field line region and generating pulsed radio emission. This means that their radio emission might basically follow the same rules as for normal radio pulsars, with rotational energy driving pair creation through a cascade, rather than being related to the magnetic energy budget.

However, while the magnetic field of normal pulsars is dominated by its dipolar component, in magnetars an important contribution from higher order multipoles and a toroidal component is expected in both, the internal and external field. This complex magnetic geometry is believed to be ultimately responsible for their bright X-ray emission, their high surface temperature, their bursting and glitching behavior as well as their outburst activity (Thompson & Duncan 2001; Thompson et al. 2002; Beloborodov 2009). Furthermore, the toroidal geometry is also what is believed to drive the differences in radio properties between radio magnetars and radio pulsars. In fact, even if the physical mechanism driving these emissions might possibly be similar, the actual radio emission appear at a first glance somewhat different. The rapid variability, broad pulses, and unusually hard radio spectra of magnetars are consistent with them having a twisted magnetosphere which is dominated by strongly variable currents and large plasma densities interfering/interacting with the pair cascade (Thompson 2008b). In radio pulsars the plasma density relates to the square of the emitted radio frequency (Ruderman & Sutherland 1975). The flat spectra of radio magnetars is then in line with magnetospheric densities orders of magnitude larger than in normal pulsars, as theoretically predicted (Thompson et al. 2002; Nobili et al. 2008) and estimated from the X-ray spectra (Rea et al. 2008; Zane et al. 2009). Changes in the magnetospheric density (i.e. during the outburst decay) might also affect the torque on the neutron star, as it has been observed in radio-emitting magnetars (Camilo et al. 2007a), as well as in some radio pulsars (Kramer et al. 2006).

From Figure 1 it is clear that the high spin-down power is not the only ingredient for magnetars to show or not radio emission: the X-ray luminosity also plays a crucial role (i.e. SGR 1806–20 has a higher \dot{L}_{rot} than XTE J1810–197 or 1E 1547–5408, but it is not radio pulsed; see Figure 1). One possibility to explain the crucial role of the X-ray luminosity is noting that this is mainly related to the toroidal component of the magnetar. In particular, it might be that radio-emitting magnetars and high-B radio pulsars have systematically lower toroidal fields than the canonical radio-quiet magnetars. This might also be in agreement with the former being fainter, and with a softer X-ray spectrum, during quiescence. A lower crustal toroidal field, in fact, results in less heating produced by Joule dissipation in the star crust, and hence lower surface temperatures. In this picture a possible explanation for the absence of radio emission in the brightest magnetars, is a disruptive interaction between the particle cascades triggered by the acceleration of particles in the electric gap, and the powerful currents forming as a consequence of the largely twisted external magnetic field (Thompson 2008a,b; Beloborodov 2009).

Although the exact relation between the crustal and magnetospheric B_{tor} components is not known yet, it may be surmised that stars with a larger internal reservoir of helicity (hence brighter X-ray luminosities) are able to continuously feed it to the magnetosphere, sustaining a long-lasting twist. The absence of radio-pulsed emission from magnetars with high toroidal fields can then be explained if the particle cas-

cades cannot reach the open-field lines due to the powerful currents forming as a consequence of the twisted magnetosphere.

Another possibility might be a reduction in the surface voltage gap due to pair creation by non-resonant scattering of high-energy X-rays photons and collisions between gamma-ray and thermal X-ray photons (Thompson 2008b). A typical (temperature dependent) reduction of a factor ≈ 10 –50 in the gap voltage is expected for a surface temperature $kT > 0.1$ keV. Interestingly, SGRs/AXPs have surface temperatures ≈ 0.2 – 0.6 keV.

In both these scenarios, the connection of magnetar radio emission with their X-ray outburst activity is straightforward. X-ray outbursts are interpreted as sudden changes in the magnetic topology, which results in an increase of the magnetospheric twist, stressing and heating the crust, and replenishing the magnetosphere with charge (Thompson et al. 2002). Around the outburst peak, the twist, the surface temperature and the magnetospheric charge density attain their largest values. In this environment, the pair cascades fail to propagate outside screened by the large currents, and/or the increase in the surface temperature can reduce drastically the gap voltage. No radio emission is then expected to be detected soon after the outburst onset.

During the outburst decay the magnetosphere untwists, the surface cools, and radio-pulsed emission may appear. In particular, the same mechanism which is inhibiting radio emission from the canonical magnetars at all times, is also responsible for the delay in the activation of radio-emission after the onset of an X-ray outburst. Once the radio emission is active again, the large particle density in the magnetosphere, inheritance of the increased magnetic twist which caused the outburst, provides an additional contribution to pair cascade process, hence producing a much brighter radio emission. As the outburst decays toward quiescence the magnetosphere progressively untwists, the charge density decreases, and the radio flux decays.

Given the above scenarios, we argue that radio emission may be present at all times in magnetars with $L_{\text{x}}/L_{\text{rot}} < 1$, but during quiescence might be detectable only for close objects, while it gets too dim in other sources (as e.g. XTE J1810–197).

5. CONCLUSIONS

In this Letter we discuss the radio emission from magnetars, and its connection with rotation-powered radio pulsars. Our results can be used to establish if a newly discovered magnetar will show pulsed radio emission or not. To this end, only the period, period derivative, and an estimate (or an upper limit) of its quiescent luminosity are needed (e.g. from available X-ray all sky surveys). These values will allow to evaluate the electric gap voltage (see Eq. (2)), and the ratio $L_{\text{x}}/L_{\text{rot}}$. If the electric gap voltage is large enough, and $L_{\text{x}}/L_{\text{rot}} < 1$, then radio pulsed emission should be present, and the source eventually detected, if its environment and distance allow such a detection. If the new source will have $L_{\text{x}}/L_{\text{rot}} > 1$, it will be radio-quiet, regardless of it showing or not X-ray outburst activity.

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