Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY LETTERS

Mon. Not. R. Astron. Soc. **425,** L15–L18 (2012) doi:10.1111/j.1745-3933.2012.01292.x

# Understanding the low magnetic field magnetar, SGR 0418+5279, from a magnetized core model

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Accepted 2012 May 29. Received 2012 April 30; in original form 2012 March 16

**ABSTRACT**

We consider the newly found low magnetic field magnetar, SGR 0418+5279, which exhibits flares, in the context of a model recently proposed by us in which magnetars owe their strong magnetic fields to a high baryon density, magnetized core. We calculate the characteristic core size which will give rise to a surface polar field of about $10^{13}$ G, observed for this magnetar. We then estimate the time of transport of the magnetic field to the crust by ambipolar diffusion, and find this time to be roughly consistent with the spin-down age of SGR 0418+5279. Our model suggests that a precise post-flare timing analysis for this magnetar would show a persistent increase in the spin-down rate of $\dot{\nu}$, as observed, for example, in PSR 1846−0258, and in due course a decrease in the braking index, consistent with a post-flare increase in the surface field.

**Key words:** stars: magnetars.

## 1 INTRODUCTION

The recent discovery of an anomalously low magnetic field magnetar (Gogus, Woods & Kouveliotou 2009; Esposito et al. 2010; Horst et al. 2010), SGR 0418+5279, with a surface field of $B \simeq 7.5 \times 10^{12}$ G and a spin-down age of 24 Myr, challenges the conventional wisdom on magnetars. Most magnetars are neutron stars with surface magnetic fields of $10^{14}-10^{15}$ G and spin-down ages of $10^3$–$10^5$ yr. They emit an X-ray luminosity of $10^{34}$–$10^{36}$ erg s$^{-1}$ which is much higher than their rate of rotational energy loss. It is generally accepted that these emissions are powered by magnetic energy (see Merenghetti 2008, for a review).

However, this low magnetic field gamma repeater has been observed to have magnetar-like flares. Furthermore, it has a period, $P \simeq 9.1$ s, a very low value of the time derivative of the period, $\dot{P} \simeq 6 \times 10^{-15}$, and a deduced spin-down age of 24 Myr (Rea et al. 2010). We discuss this magnetar in the context of a model recently proposed by us (Bhattacharya & Soni 2007; Haridass & Soni 2012).

In these works it was shown that it may be possible to explain many unusual features of magnetars if they are born with a highly magnetized core created by strong interactions. Initially the core magnetic field is screened by the surrounding plasma of electrons, protons and neutrons. With the dissipation of the screening currents, the core field is transported by ambipolar diffusion from the core to the crust. It then breaks through the crust to power the magnetar radiative activity. Our model is different from the model of Duncan and Thompson (Duncan & Thompson 1992; Thompson & Duncan 1995), which relies on a *dynamo mechanism* for generating the magnetic field of magnetars.

In Haridass & Soni (2012), we also provided a post-flare timing analysis for PSR 1846−0258 based on the precise timing data of Livingstone, Kaspi & Gavrill (2010) which shows a persistent increase in the spin-down rate of $\dot{\nu}$ as observed for PSR 1846−0258 and a decrease in the braking index (Livingstone et al. 2010). Both are consistent with a post-flare increase in the surface magnetic field that is predicted by our model. We expect a similar phenomenon for SGR 0418+5279.

Such a low magnetic field with large period puts SGR 0418+5279 close to old high field pulsars, which normally do not show flares. An obvious question, then, is where does the energy to power these flares come from. An explanation that has been put forward is that there are toroidal magnetic fields of higher magnitude than the poloidol or dipolar surface fields residing inside the star (Rea et al. 2010). The fields can then have enough energy to power flares but would have different signatures from an emergent core dipolar field (our scenario) which would give enhanced post-flare spin-down – a property of most Soft Gamma Repeaters (SGRs). Therefore, it becomes important to check this from a post-flare timing analysis.

## 2 OUR MODEL

There are three essential features of our model (Haridass & Soni 2012) which clearly distinguish it from the models of Duncan & Thompson (1992), Thompson & Duncan (1995) and Rea et al. (2010). These are (1) creation of a highly magnetized core, (2) a characteristic time during which *ambipolar diffusion* (Goldreich & Reisenegger 1992) carries the core field to the crust (the outgoing field then cleaves the crust and emerges out to the surface) and importantly (3) an *increasing* surface magnetic field after a flare. We now work out these details for SGR 0418+5279.

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### 2.1 The size of the core and the final surface field, $B_f$

The newly discovered high-mass binary PSR J1614−2230 ($M \simeq 2M_s$) (Demorest et al. 2010) has strongly impacted our understanding of the high-density equation of state (EOS) for neutron stars. In contrast to the maximum mass of neutron stars with a soft quark matter core which normally works out to be around $M_{max} \simeq 1.6M_s$ (Cook, Shapiro & Teukolsky 1994, Lattimer & Prakash 2001), the maximum mass of a purely nuclear star governed by the APR EOS of Akmal, Pandharipande & Ravenhall (1998) is $2.2\,M_s$. If we factor in rotation, this mass will be even higher. This is because for stars that are constituted of non-relativistic nucleon matter the EOS is stiffer and the maximum mass can be much higher. Given these facts it is reasonable to conclude that neutron stars are governed by a purely nuclear EOS.

The high-density ground state of matter is not directly accessible in the laboratory but can only be inferred from neutron stars. Ground states can be constructed only variationally – for example, there is no a priori proof for the crystal as a ground state of a metal. For nuclear matter at high density, there are several possibilities. One set of ground states use condensates to lower the ground state energy. There are two sets of condensates that are popular in the literature – kaon condensates and pion condensates. Kaon condensates usually make the EOS too soft to accommodate maximum masses of $M \simeq 2\,M_s$, whereas pion condensates allow for maximum masses of this order (see e.g. Nozawa et al. 1996, for a comparison of kaon condensates and pion condensates in neutron stars). Whereas neutral pion condensates align spins (magnetic moments), kaon condensates do not align spins (magnetic moments). Other possibilities for creating ground states with magnetized cores without pion condensation have been considered by Kutschera & Wojcik (1992) and Haensel & Bonazzola (1996). These works provide a different scenario for creating a core using conventional nuclear physics (Fermi liquid theory) that is independent of pion condensation.

In view of the considerations given below, magnetic moment alignment for the ground states at high density is a very good possibility. Our work (Bhattacharya & Soni 2007; Haridass & Soni 2012) is based on a model which argues that magnetars have larger masses than pulsars and that their higher density cores undergo a strong interaction phase transition to a magnetized ground state of spin-aligned nucleons.

For details on the nuclear EOS, which can give rise to such a magnetized core with a $\pi_0$ condensate ground state, we refer the reader to previous work (e.g. Pandharipande & Smith 1975; Baym 1977; Nozawa et al. 1996; Akmal et al. 1998; Lattimer & Prakash 2001, and references therein) and for EOSs without condensates, the reader is referred to Kutschera & Wojcik (1992) and Haensel & Bonazzola (1996).

We note that the implication of this large mass star, PSR J1614−2230, is that even at five times nuclear density, quark bound states in nucleons (non-relativistic) and nucleon correlations are strong enough that a simple quark matter description will not work. In passing we remark that the results from the RHIC accelerator have also shown that even at high temperature (>300 MeV) the EOS is strongly interacting and cannot be described by simple quark matter.

For illustration, consider a star with a core composed entirely of spin (magnetic moment) aligned neutrons with an average core density of about five times nuclear density ($\simeq 10^{15}$ g cm$^{-3}$). This would result in a uniform core field of $B \simeq 10^{16}$ G (Haridass & Soni 2012). We assume that SGR 0418+5279 is a purely nuclear star with such a magnetized core.

In our model the magnetized core monotonically increases in size and density with the natal mass of the magnetars. We expect that the final unshielded surface field should exhibit this incremental trend. As a matter of fact since the magnetar SGR 0418+5279 is peculiar in having a very low surface magnetic field, we can roughly estimate the size of its core in this scenario from the dipole formula which informs us that the core field drops as $1/R^3$ well outside the core.

Assuming a standard core field, $B_c \simeq 10^{16}$ G, at the core, the surface field $B_f$ can be approximately estimated, using the dipole formula, to be

$$\frac{B_f}{B_c} \simeq \frac{R_c^3}{R_s^3}. \tag{1}$$

Given the value of the final surface field $B_f \simeq 10^{13}$ G and assuming a star radius $R_s$ of 10 km, we find that this magnetar SGR 0418+5279 should have a rather small core of the order of 1 km. In the context of our model this would be the case only if the core field has completely emerged to the surface. Compared with this a typical magnetar with a surface field of $10^{14}$–$10^{15}$ G will have a core of about 3 km.

### 2.2 The time-scale of ambipolar diffusion to transport the magnetic field to the crust

The time-scale of ambipolar diffusion to transport the magnetic field from the core to the crust for a neutron–proton–electron plasma in the interior of a neutron star has been worked out by Goldreich & Reisenegger (1992). Their estimates show that ambipolar diffusion of *poloidal fields* has a dissipation time-scale of $t_{ap} \simeq 10^4 \times B_{16}^{-2} \times T_{8.5}^{-6}$ yr, where $B_{16}$ is the local magnetic field strength in units of $10^{16}$ G and $T_{8.5}$ is the temperature in units of $10^{8.5}$ K, a typical value in the interior of a young neutron star. According to their estimates (Goldreich & Reisenegger 1992), the corresponding time-scale for *toroidal fields* is orders of magnitude smaller. The implications of this for the scenario proposed by Rea et al. (2010) will be discussed shortly.

For ambipolar transport between core and crust, we take an average value for $B$ to be the geometric mean of the field at the core, $B_c \simeq 10^{16}$, and the dipolar value of this field at the inner crust, $B_{crust}$, which is taken to be at a radial distance of $\simeq 8$ km from the centre (this is slightly higher than the surface field $B_f$ which is the field value at the surface which is about $\simeq 10$ km from the centre):

$$B_{crust} \simeq 2 \times 10^{13}\ \mathrm{G}\ (R_{crust} \simeq 8\ \mathrm{km})$$

and

$$B = \sqrt{B_c\, B_{crust}}. \tag{2}$$

For SGR 0418+5279, from the formula given above, this yields a typical ambipolar diffusion time for the dipolar field to reach the crust, $\tau_{ap} \simeq 6 \times 10^6$ yr, provided we assume an interior temperature of $10^{8.5}$ K. Though this is only a rough and ready way to take an average field, note that this is of the same order as the spin-down age of this magnetar.

The question of how such a low field magnetar can keep its interior temperature around $10^{8.5}$ K will be taken up in a following section on the energy budget.

As the strong field moves through the outer crust, mechanical disturbances of the crust are likely to be triggered by the magnetic pressure, leading to glitches and flares. Since the maximum stress that the crust can support is estimated to be $\simeq 10^{27}$ dyne cm$^{-2}$, the crust would be unable to support stresses for magnetic field difference across the crust of $\simeq 10^{13}$ G (Ruderman 1991). This is of the same order as the crustal magnetic field of SGR 0418+5279. The strength of the magnetic field of this star would thus fall at the lower limit for magnetar type fields that can provide for flares that are due to the breaking of the crust by magnetic pressure.

Only after the core magnetic field penetrates the crust does the radiative emission and serious spin-down begin. In our model the surface magnetic field of the magnetar increases with time as the shielding currents dissipate – particularly after a flare. This is contrary to the expectation from other models – that the magnetic field of a magnetar should decrease with time as a consequence of dissipation of magnetic energy. In fact, there may already be evidence in favour of the magnetic field strength increasing with time (Thompson, Lyutikov & Kulkarni 2002). This is further supported by our analysis (Haridass & Soni 2012) of the timing data of Livingstone et al. (Gavrill et al. 2008; Livingstone, Kaspi & Gavrill 2010).

## 3 INTERNAL ENERGY SOURCES, STAR TEMPERATURES AND $L_X$

### 3.1 Energy source with toroidal magnetic field

In Rea et al. (2010), an estimate of the internal magnetic field of the star is made by equating the magnetic field energy, $B^2_{tor}(R^3_s/6)$, to the total integrated X-ray luminosity, $L_X t_{SD}$, where $R_s$ is the radius of the star. Assuming a source distance of 2 kpc and a quiescent luminosity equal to the lowest measured luminosity of $L_X \simeq 6.2 \times 10^{31}$ erg s$^{-1}$, they estimate $B_{tor} \simeq 5 \times 10^{14}$ G as the average field over the 'whole' star. Since the poloidal surface field is known to be $\simeq 10^{13}$G, they conclude that there must be a toroidal field. There are some issues here.

(i) According to Rea et al. (2010), the integrated X-ray luminosity is $L_X t_{SD} \simeq 5 \times 10^{46}$ erg. This is close to the integrated X-ray luminosity emitted by a canonical high field magnetar with a surface polar field, $B_f \simeq 10^{14}$–$10^{15}$ G, a spin-down age of $10^{5(4)}$ yr and $L_X \simeq 10^{34}$–$10^{36}$ erg s$^{-1}$. This implies that in spite of the low surface polar field the internal energy source for this magnetar has the same magnitude as that for canonical high field magnetars.

(ii) No account is taken of the energy loss from neutrino emission. According to estimates (Kaminker et al. 2006), neutrino emission may account for over 90 per cent of the total energy loss. In the above model this energy also comes from the magnetic field. In this case the source would be required to have an energy of over $10\,L_X t_{SD} \simeq 5 \times 10^{47}$ erg, which is of the order of the field energy of the highest magnetic field magnetars.

(iii) An important argument that does not support this scenario is as follows. For normal magnetars, such high *poloidal fields* inside the star will dissipate with a high power output on a typical time-scale of $10^5$ yr given by ambipolar diffusion (Goldreich & Reisenegger 1992). Significantly, Goldreich and Reisenegger also find that for *toroidal fields* this time-scale is much shorter, leading to even higher power output. This is contrary to the finding of low power radiated by this magnetar and also its age.

Given these issues we proceed to a comparison with the expectations from our model outlined in the previous sections.

### 3.2 Our model for energetics

In our model there are actually two different internal energy sources to reckon with.

#### 3.2.1 *Energy release in the phase transition – the transient source*

We have already found that a core radius of about $\simeq$1 km is consistent with the surface magnetic field of SGR 0418+5279. Assuming a neutron density $10^{39}$ cm$^{-3}$ and a typical energy release in the strong interaction phase transition of $\simeq$10 MeV nucleon$^{-1}$ = $1.5 \times 10^{-5}$ erg nucleon$^{-1}$ (Baym 1977; Dautry & Nyman 1979; Soni & Bhattacharya 2006), the total energy released in the phase transition is $E_{PT} \simeq 6 \times 10^{49}$ erg.

For comparison, a canonical magnetar with a core of 3 km would have $E_{PT} \simeq 1.6 \times 10^{51}$ erg.

This is the energy released at the end of the strong interaction phase transition which should occur as the temperature falls below 1 MeV, in a day or two. This would result in higher interior and surface temperature for magnetars compared to pulsars. Such a transient source will produce heating, but due to efficient heat conduction it is not expected that the heat can be retained for the long duration of over $10^7$ yr – the spin-down age of SGR 0418+5279.

In our model, we have another energy source which will give a steady yield of energy. This is the dissipation of the shielding currents and the outward transport of the core magnetic field by ambipolar diffusion.

#### 3.2.2 *The energy release from the shielding currents – the steady energy source*

An estimate of the lower bound on energy stored in magnetic shielding currents is given by the magnetic energy stored in the core field of this magnetar (Haridass & Soni 2012). This energy will be released in the form of neutrinos and radiation as the shielding currents dissipate:

$$E_{MS} = B^2_c \frac{R^3_c}{6},$$
$$E_{MS} \simeq 1.7 \times 10^{46} \text{ erg}.$$

Since this is a lower bound, we introduce a factor $k$ into the above expression as a phenomenological factor to be set by comparison with observed X-ray luminosities:

$$E_{MS} \simeq (k) 1.7 \times 10^{46} \text{ erg}.$$

The energy release rate is given by dividing the total energy release from the core by the time for the ambipolar transport of the magnetic field to the crust, $\tau_{ap} \simeq 6 \times 10^6$ yr.

The amount of energy released per second (power output), $\dot{E}_s$, then works out to be

$$\dot{E}_s \simeq (k) 10^{32} \text{ erg s}^{-1}.$$

It is good to keep in mind that for a conventional magnetar, $E_{MS} \simeq (k) 5 \times 10^{47}$ erg of energy goes into creating the shielding. The time of ambipolar transport of the magnetic field to the crust for canonical magnetars is $\simeq 10^5$ yr. This yields an average energy flux of

$$\dot{E}_s \simeq (k) 10^{35} \text{ erg s}^{-1}.$$

This is about three orders of magnitude larger than the estimated energy flux for SGR 0418+5279.

Given the comparatively low strength of the internal heat source of SGR 0418+5279, it is moot that this source, by itself, can provide sufficient internal heating to give interior temperature of $10^{8.5}$ K. However, it is pertinent to point out that even normal pulsars with polar magnetic fields of $B_f \simeq 10^{12}$ G and iron (Fe) envelopes can maintain a fairly high interior temperature of $\simeq 10^8$ K. Potekhin, Urpin &

Chabrier (2010), in their fig. 1, indicate that for such stars, the interior temperatures are of the order of $\simeq 10^8$–$10^{8.5}$ K, corresponding to surface temperatures of the order of $\simeq 10^{5.8}$–$10^6$ K. In our case we have an additional source of power $\dot{E}_{\rm s} \simeq (k)10^{32}$ erg s$^{-1}$, which may marginally increase the interior temperatures. This will move the curves slightly to the right. We read these features as an indication that we may be at the borderline regime in which ambipolar diffusion can keep the interior temperature around $10^{8.5}$ K.

## 4 POST-FLARE TIMING AS AN IMPORTANT TEST

It is necessary to clearly distinguish between our model outlined above of relatively weaker emergent core magnetic field and that of Rea et al. (2010) which posits strong toroidal magnetic field. Fortunately, the post-flare phenomenon provides an acid test for our model, i.e. the characteristic emergence of the core dipolar field resulting in an enhanced post-flare spin-down – a property of most SGRs. Therefore, it becomes important to check this from a post-flare timing analysis.

A precise post-flare timing analysis for this magnetar could give some important results as found for the 'magnetar' PSR 1846−0258 (Gavrill et al. 2008). A persistent increase in the spin-down rate of $\dot{\nu}$ (as observed for PSR 1846−0258; Livingstone, Kaspi & Gavrill 2010) and in due course a decrease in the braking index (Livingstone et al. 2010) would establish that we have an increasing surface poloidal magnetic field. This would provide more convincing evidence for our model of SGR 0418+5279.

## ACKNOWLEDGMENTS

I would like to thank Sri Kulkarni for attracting our attention to this magnetar and acknowledge N. D. Haridass who was closely involved in a substantial part of this work. I thank the University Grants Commission, ICTP, Trieste, and Centre for Theoretical Physics, Jamia Millia, for support during this work.

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