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Origin of Magnetar-Scale Crustal Field in PSR J1852+0040 and 'Frozen' Magnetars

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Abstract

We discuss the origin of strong crustal magnetic field in one of central compact objects (CCOs)—a neutron star PSR J1852+0040 in the supernova remnant Kes 79. Taking into account its relatively long present day spin period we conclude that the field could not be generated via a dynamo mechanism. If this neutron star indeed is a magnetar with field submerged during a strong fall-back episode, then it argues against the dynamo field origin in magnetars. Otherwise, Kes 79 is not a close relative of normal magnetars. A discovery of an anti-magnetar with a millisecond period and strong crustal field identifiable, for example, due to large pulse fraction, would be the proof of the dynamo field origin. Existence of such sources is in correspondence with the present standard picture of neutron star unification. However, the fraction of magnetars with submerged fields can be small—few percent of the total number of CCOs.

Keywords: magnetic field – physical data and processes – pulsars: general – pulsars: individual (PSR J1852+0040) – stars: magnetars – stars: neutron

1 INTRODUCTION

Magnetars are neutron stars (NSs) whose energy budget is dominated by dissipation of electric currents supporting magnetic fields. Known objects of this type have strong fields: poloidal (in particular, dipolar) or/and toroidal. The origin of these strong fields is still not clear.

In their foundational paper, Duncan & Thompson (1992) proposed that strong fields are enhanced via a dynamo mechanism. This scenario requires rapid initial rotation of an NS. Field of the order of 10^{15} G can be reached if the initial spin is $\sim$1 msec[1]. This is a strong prediction that potentially can be tested.

Vink & Kuiper (2006) studied supernova remnants (SNRs) with magnetars to check if traces of additional energy release due to a rapidly spinning down magnetar can be found. Indeed, a young magnetar is a very powerful source with a luminosity $L \sim 9.6 \times 10^{48}\ B^2{}_{15} P^{-4}{}_{\mathrm{msec}}$ erg s^{-1}. Such objects were even considered as central engines of gamma-ray bursts (Usov 1992). Though no additional energy input in magnetars' SNRs has been found (Vink & Kuiper 2006), still this result does not exclude the original scenario by Duncan & Thompson (1992). Note also, that alternatives related to fossil fields (Ferrario & Wickramasinghe 2006) have been seriously criticised (Spruit 2008), as just a small fraction of the total stellar magnetic flux can end in an NS.

Unfortunately, due to a rapid spin-down and field decay, initial periods of magnetars are quickly 'forgotten'. However, there is a situation, when the initial period can be 'frozen'. This is related to strong fall-back which results in burying of the magnetic field (Muslimov & Page 1995; Ho 2011; Viganò & Pons 2012; Bernal, Page, & Lee 2013). Such an NS—magnetar inside, anti-magnetar outside—can be a Rosetta stone for understanding the origin of strong magnetic fields. Potentially, an NS in the SNR Kes 79 could be such an object.

The NS in Kes 79 (PSR J1852+0040) belongs to the class of so-called 'anti-magnetars'(Halpern & Gotthelf 2010). It has a spin period $p = 0.105$ s, $\dot{p} = 8.7 \times 10^{-18}$, and so the polar magnetic field for an orthogonal rotator is about 6.2×10^{10} G. The SNR age is estimated as $\sim 6 \times 10^3$ years. The source has one peculiar feature: large (64%) pulse fraction. Shabaltas & Lai (2012) show that large pulse fraction of the NS in Kes 79 can be explained if its magnetic field in the crust is very strong: few $\times 10^{14}$ G. In their study, the authors assumed that the strong component of the field is the toroidal one. Potentially, this opens two possibilities. First, despite its

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[1] However, as the physical situation is very complicated, this was never studied in details in realistic computer simulations.

young age, the NS in Kes 79 is an analogue of so-called low-field magnetars (see a review in Turolla & Esposito 2013). Second, both components are strong, and they have been significantly submerged due to a strong fall-back episode (Geppert, Page, & Zannias 1999 called such sources 'hidden magnetars'). Below, we analyse how this can be used to put constraints on the origin of magnetars' magnetic field.

2 ANALYSIS AND ESTIMATES

The process of fall-back on a newborn magnetar can be a very complicated one. However, in this section, we apply simple formulae to perform a qualitative analysis of the consequences of such a process.

At first, we recall that accretion on the surface of an NS can be prohibited either by a relativistic wind (so-called *ejector* stage), or by a rapidly rotating magnetosphere (*propeller* stage), see a detailed description of stages, for example, in Lipunov (1992). Transition between stages can be formalised in terms of critical spin periods (back transitions can not be symmetric, and so corresponding critical periods can be different, also additional conditions can be important, but we do not discuss here situations not applicable to the fall-back case).

The first one, p_{E}, corresponds to the transition ejector→propeller. The second, p_{A}, corresponds to the transition propeller→accretor. We are interested mainly in the latter one, as the fall-back we are interested in, is strong enough to switch off the pulsar.

$$p_{\mathrm{A}} \approx 20\mu_{32}^{6/7} \left(\frac{M}{\mathrm{M}_\odot}\right)^{-5/7} \left(\frac{\dot{M}}{\mathrm{M}_\odot \mathrm{yr}^{-1}}\right)^{-3/7} \mathrm{msec}. \quad (1)$$

Here, μ is the magnetic moment of an NS, M is its mass, and $\dot{M}$ is the accretion rate. We use standard accretion formulae for the adiabatic index $\gamma = 5/3$. Chevalier (1989) in his estimates used $\gamma = 4/3$ (a radiation-dominated envelope). However, as can be seen from his Eqs. (4.22) and (5.2) for fields of the magnetar scale, the magnetosphere can start to be important for $\gamma = 4/3$, too. So in the case of a rapidly rotating NS, the propeller stage can appear for reasonable accretion rates also for this value of the adiabatic index.

If the initial dipole magnetic field is strong and the spin period is short, then accretion is possible only for a very large accretion rate $\sim 100\mathrm{M}_\odot\ \mathrm{yr}^{-1}$. Such rates are not unexpected. For example, Chevalier (1989) estimated the accretion rate for SN1987A as $350\mathrm{M}_\odot\ \mathrm{yr}^{-1}$ (lower values about tens of solar masses per year also have been reported by other authors).

Bernal et al. (2013) demonstrated that for such strong fall-back the field is rapidly (∼100 msec) submerged. Then it can diffuse out on a time scale of thousands or tens of thousand years (Ho 2011; Viganò & Pons 2012). While the field is submerged, the NS appears as an anti-magnetar. Rotation braking is very slow in this case. The spin period is nearly constant, frozen. A similar situation appears if the initial dipolar field was small, but the toroidal is large. In this case, the accretion gates are opened even for lower $\dot{M}$. Discovery of an anti-magnetar with a large crustal field and a millisecond-scale spin period would be a proof for a dynamo-mechanism field origin. Oppositely, PSR J1852+0040 (with its large spin period) most probably represents a counter example.

In PSR J1852+0040, the present day spin period is nearly the same as the initial one because $\dot{p}$ is low due to the low field and the relatively long spin period. And it is easy to estimate that no spin-down mechanism (magneto-rotational or similar ones, propeller, interaction with a disc, etc.) can slow the rotation from few milliseconds down to 100 msec in a very short time before the field is buried.

One of the most effective spin-down mechanisms ever discussed was proposed by Shakura (1975) (see a list of other spin-down formulae for the propeller stage in Lipunov & Popov 1995):

$$d(I\omega)/dt = \omega \dot{M} R_{\mathrm{A}}^2. \quad (2)$$

Here, R_{A} is the magnetospheric (Alfven) radius, $\omega = 2\pi/p$ is the spin frequency, and I is the moment of inertia of an NS. Eq. (2) can be rewritten as

$$dp/dt = \dot{M} R_{\mathrm{A}}^2 p/I = \quad (3)$$

$$= 8.6 \times 10^{-5} \left(\frac{\dot{M}}{100\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}}\right)^{3/7} p\,\mu_{32}^{8/7} \left(\frac{M}{\mathrm{M}_\odot}\right)^{2/7}.$$

Despite the exponential spin-down during this stage, field submergence (as numerical experiments indicate) happens so rapidly that the period cannot be increased by a factor ∼100. Obviously, normal magneto-dipole spin-down is less effective, and a newborn magnetar cannot be slowed down significantly due to this mechanism.

We conclude that a strong crustal toroidal magnetic field in Kes 79 could not be generated with a dynamo mechanism.

3 DISCUSSION

Shabaltas & Lai (2012) comment that the field configuration they obtained can not be a unique one which explains the large pulse fraction of PSR J1852+0040. This means that we cannot be sure if the dipolar component of the field was strong before the fall-back episode, or not.

Bernal et al. (2013) mention that the accretion of magnetised matter can modify the magnetic field of a NS, reducing the dipolar component while making the general shape of the field configuration more complicated. If this is the case for PSR J1852+0040, then it can be much different from normal magnetars. Even if the strength of toroidal field in the crust is high, the total energy of the field can be orders of magnitude smaller than in magnetars (Viganò, Pons, & Miralles 2012). Probably, an effective dynamo mechanism is not necessary in this case. Then accretion could start for 100 msec period even for relatively low accretion rates.

High accretion rates normally result in a large total accreted mass, comparable with the mass of the crust. Roughly, the mass of the crust is accreted in one hour for the rate $\dot{M} = 100\,\mathrm{M}_\odot\ \mathrm{yr}^{-1}$:

$$\Delta M \sim M_{\mathrm{crust}} \left(\frac{\dot{M}}{100\,\mathrm{M}_\odot \mathrm{yr}^{-1}}\right)\left(\frac{\Delta t}{1\ \mathrm{hour}}\right).$$

The total accreted mass can be up to few tenths of solar mass (Chevalier 1989). An NS which experienced such strong fall-back episode can so much more massive that it follows a different cooling history. In all scenarios, massive NSs are colder (Yakovlev & Pethick 2004; Page et al. 2004; Blaschke, Grigorian, & Voskresensky 2004). As far as the NS in Kes 79 is a hot source, then an additional heating mechanism is required. It can be easily provided due to rapid magnetic field decay in the crust, as the field is confined in a narrow layer (see, for example, Geppert et al. 1999).

It would be important to estimate for PSR J1852+0040 the total amount of accreted matter. This can allow the calculation of the maximum accretion rate during the fall-back. Then all estimates above can be made in a more robust way.

As a determination of initial spin periods for known magnetars[2] is impossible, a promising way to get solid arguments in favour of the dynamo mechanism hypothesis is to find a real 'frozen magnetar'. In the modern picture of unified NS population (see, for example, Pons, Viganò, & Geppert 2012 for description of different possibilities and evolutionary histories, especially their Figure 2 for evolutionary tracks), such sources are quite natural. However, they must be relatively rare.

Magnetars form up to 10% of all NSs as both observations and population synthesis studies indicate (see Gill & Heyl 2007, and also Popov et al. 2010 for a unified description of magnetars, pulsars and cooling NSs, and references therein). If we assume that the submergence of the magnetic field happens in magnetars as often, as in other NSs, and that central compact objects (CCOs) are NSs with submerged fields, then the number of 'frozen' magnetars is $\lesssim$10% of the number of CCOs. However, it is natural to assume that the larger the fields, the more difficult it is to bury them. Then, the fraction of 'frozen magnetars' is even lower. In addition, if magnetars are born in binary systems where spin of the progenitor was increased due to interaction with the companion (Popov & Prokhorov 2006; Bogomazov & Popov 2009), then the amount of fall-back can be smaller as a significant parts of the outer layers of the star are already removed (this was mentioned, for example, by Chevalier 1989). The problem of identification (the detectability of millisecond periods for complicated field topology in the crust, pulse profiles, etc.) can also prevent easy discovery of 'frozen magnetars' (but see a recent discussion in Perna et al. 2013). On the other hand, an additional energy source—field decay —can help such sources to stay bright for a longer time, which favours their discovery (Heyl & Kulkarni 1998).

4 CONCLUSIONS

The CCO in Kes 79 has a relatively long spin period (0.1 s) and might have a strong crustal field (Shabaltas & Lai 2012). We argue that this field could not be generated by a dynamo mechanism as, on one hand, known mechanisms of NS spin-down applicable in the case of this source cannot slow down rotation form $\sim$ msec to the present day period before the field is buried, on the other—the present day low field also excludes a significant spin-down during the lifetime of the source. Discovery of a 'frozen magnetar'—a CCO-like source with a millisecond period and indications of a strong crustal field—would be a strong argument in favour of the dynamo mechanism scenario by Duncan & Thompson (1992).

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