Is the high mass binary pulsar PSR J 1614-2230 a latent magnetar?

Vikram Soni

ABSTRACT

We consider the newly found high mass and low magnetic field binary pulsar PSR J1614-2230 in a model in which magnetars owe their strong magnetic fields to a high baryon density, magnetized core. In our magnetar model all neutron stars above a certain threshold mass are magnetars. This confronts us with the very basic paradox as to why this high mass star, PSR J1614-2230, remains a pulsar and shows no magnetar characteristics. This is a star that has acquired its large mass by accretion from its binary companion over 5 gigayears.

In this work we show that the maximum rate of energy gain from the strong interaction phase transition from this slow accretion does not allow for high enough interior temperature for ambipolar transport of the magnetic field to the surface of the star and thus the PSR J 1614-2230 remains latent and does not become an emergent magnetar.

Key words: Neutron Stars, Magnetars.

1 INTRODUCTION

Generally, magnetars are neutron stars with surface magnetic fields (10^{14(15)} G) a thousand times larger than that of an average pulsar. The magnetars have spin down ages of 10^3 – 10^5 years. Over this period, they emit a quasisteady radiative luminosity of 10^{34} - 10^{36} erg/s. Some of them emit repeated flares or bursts of energy typically of 10^{41} – 10^{44} erg. The periods of magnetars fall in a surprisingly narrow window of 5-12 s (see (Merenghetti 2008) for a review). For conventional magnetars with large periods, the energy emitted in both quiescent emission and flares far exceeds the loss in their rotational energy. The most likely energy source for these emissions is their magnetic energy (Duncan & Thompson 1992, Thompson & Duncan 1993), yet there is no evidence of a decrease in their surface magnetic fields with time (Thompson et al. 2002).

There have been many attempts to explain some of this physics of which the most popular is the magnetar model of Duncan and Campbell (Duncan & Thompson 1992, Thompson & Duncan 1993), which is otherwise known as the dynamo mechanism for magnetars. This model requires the collapse of a large mass progenitor to a star which starts life with a period close to a millisecond. Such a fast rotation can amplify the inherited pulsar valued field of 10^{12} G to 10^{15} G. However, as pointed out in earlier works (Bhattacharya & Soni 2007, Haridass & Soni 2010), several observations on magnetars are hard to understand from such a model.

These works were 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. In these works (Bhattacharya & Soni 2007, Haridass & Soni 2010) 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 the strong interaction. Initially the core magnetic field is screened by the surrounding plasma of electrons, protons and neutrons. As the screening currents dissipate the core field is transported first from the core to the crust and then from the crust to the surface (Haridass & Soni 2010) powering the enhanced X-ray flux and enhancing the surface magnetic field.

In this magnetar model all neutron stars above a certain threshold mass are magnetars. This confronts us with the puzzle of why the binary pulsar, PSR J1614-2230, whose mass has been recently determined (Demorest et al. 2010) to be ≃ 2 solar masses, remains a pulsar and shows no magnetar characteristics. In this work we show that the rate of energy gain from the accretion induced strong interaction phase transition does not allow for high enough interior temperature for ambipolar transport of the magnetic field and thus the PSR J 1614-2230 remains latent.
2 THE MODEL

Pulsars, which have radii of $\approx 10^{10} - 10^{12}$ G, are believed to inherit such fields from their progenitors, which are stars of radius $\approx 10^6$ km and magnetic fields of $\approx 1 - 10^7$ G due to ‘conservation’ of magnetic flux during stellar collapse (Woltjer 1964).

Our starting point, to make the distinction between pulsars and magnetars, is that pulsars exist up to some threshold mass $M_T$ and central density. For larger masses and consequently higher central density, the core of neutron stars undergo a phase transition giving rise to magnetars. When the core density exceeds about three times the nuclear density new and interesting phases may appear.

As the core magnetization grows in time, the magnetic field of the core will initially be screened by the highly conducting exterior plasma in accordance with Lenz’s law. Eventually the Lenz (screening) currents dissipate establishing the full dipolar field due to core magnetization outside the core. In the process of this dissipation, energy is carried away from the star as thermal effects, neutrino emission etc. A central feature of our model is that there is a characteristic time during which ambipolar diffusion (Goldschmidt & Reisenegger 1992) carries the core field to the crust with copious neutrino emission. The emerging magnetic field then cleaves the crust, increasing resistivity and the shielding currents get dissipated to power the radiative emissions from magnetars.

3 THE NEW 2 SOLAR MASS BINARY NEUTRON STAR

In this work we consider the recently reported (Demorest et al. 2010) discovery of highest mass neutron star, the binary pulsar PSR J1614-2230, using the precision technique of Shapiro delay (Demorest et al. 2010). It has a low field, $B = 1.8 \times 10^8$ G, no enhanced X-ray flux and no flares and a spin down age of $5 \times 10^9$ years, associated with recycled pulsars. Additionally, PSR J1614-2230, has an orbital period of 8.7 days with the final mass of the donor (white dwarf) being $\approx 0.5 M_s$. In our model, for all neutron stars above a certain threshold mass, magnetar characteristics emerge when a high density magnetized core is created at birth by the strong interaction. However, this is a star that has acquired its large mass by accretion from its binary companion, which also spins it up to a period of 3.15 milliseconds, over 5 gigayears. We will demonstrate here that this is the reason that, PSR J1614-2230, does not show magnetar features.

4 EQUATION OF STATE, FAST ROTATION AND THE MAXIMUM MASS OF THE STAR

The spun up binary, PSR J1614-2230, $(M \approx 2M_s)$ has a period of 3.15 milliseconds. A neutron star with such rapid rotation will have an enhanced maximum mass, due the strong centrifugal forces that push out matter in the star and counteract gravity.

For non relativistic fermions, like neutrons, the fermi pressure goes as density to the fifth power and can effectively counteract gravity to form stable stars. For relativistic quark matter ground states the fermi pressure goes as density to the fourth, which is not strong enough to hold off gravity and results in an instability that sets the maximum mass of the star. Stars with quark matter cores have yet another problem; they have a stiff non relativistic neutron exterior pushing in a softer relativistic quark interior - an unstable situation. In this case a star with a quark core is stable only if the nuclear matter to quark matter transition takes place in a small window at low pressure (Soni & Bhattacharya 2006).

It is also for this reason that most neutron stars with quark matter cores and in particular with meson condensates have smaller maximum allowed masses. In the absence of rotation, the maximum mass of neutron stars with a quark matter core normally works out to be around $M_{\text{max}} \approx 1.6 M_s$ as recorded in the compilation of Lattimer and Prakash (Lattimer & Prakash 2001) and observed by Demorest et al (Demorest et al. 2010). This was also confirmed in the results of (Soni & Bhattacharya 2006).

Cook et al (Cook et al. 1999) have looked at the allowed masses of rotating neutron stars using mass shed and radial instability limits. With a fast rotation that corresponds to a period of a few milliseconds, the maximum mass of a star with a soft equation of state EOS (for example, a quark matter core), could be raised to $M_{\text{max}} \approx 1.8 M_s$, still falling well short of PSR J1614-2230, $(M \approx 2M_s)$.

The existence of such a large mass neutron star would then eliminate all typical soft equations of state associated with quark matter (with/without condensate) interiors.

In contrast, the maximum mass of a purely nuclear star governed by the APR equation of state of Akmal et al (Akmal et al. 1998) is $2.2 M_s$. If we factor in rotation this mass will be even higher. It may then not be unreasonable to expect that a star governed by APR equation of state EOS, even with a pion condensate, could have a mass of 2 solar masses.

For details on the nuclear equation of state, with a $\pi_0$ condensate we refer the reader to previous work and references therein (Dutra & Nyman 1974; Baym 1977; Akmal et al. 1998; Soni & Bhattacharya 2006). Other possibilities for creating magnetized cores without pion condensation have been considered by Kutschera and Wojcik (Kutschera & Wojcik 1992) and by Haensel and Bonazzola (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.

We assume that PSR J1614-2230 is a purely neutron star with a magnetized core. We will now turn to our model.
stars which have magnetic cores that are created by a high density phase transition.

5 MAGNETAR BY BIRTH OR ACCRETION

Neutron stars with a large mass could result either (i) from the core collapse of a rather massive star or (ii) by heavy accretion onto a neutron star in a binary system. In either case, if the final mass exceeds $M_{\text{max}}$, a magnetic core will form. Will one expect to see a magnetar in all such situations? The answer depends on the details of the thermal structure in the neutron star interior.

(i) A newly born neutron star in a stellar collapse has a very hot interior, facilitating ambipolar diffusion and allowing the strong field to emerge at the surface in a short time.

The time scale of ambipolar diffusion to transport the magnetic field to the crust for a neutron, proton, electron plasma in the interior of a neutron star, have been worked out by Goldreich and Reisenegger (Goldreich & Reisenegger 1992). Their estimates show that ambipolar diffusion has a dissipation time scale of $t_{\text{ap}} \approx 10^3 - B_{16}^{-2} \cdot T_{8.5}$ years, 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$^8$ K, a typical value in the interior of a young neutron star. The more massive the neutron star, the larger will be the size of the magnetic core and the quicker will the strong field emerge to the surface.

(ii) A neutron star accumulating matter via accretion, on the other hand, is old and its interior is relatively cold. Heating due to the accretion process is not expected to raise the interior temperature above $10^{10}$ K. As we show in what follows, the extreme temperature sensitivity of the ambipolar diffusion rate will then delay the emergence of the field at the surface, perhaps for such a long time that the magnetar property would never be visible. This may be the reason why the surface magnetic field of PSR J1614-2230 remains low (<Demorest et al. 2010>) despite its mass growing to a large value.

6 FEATURES OF AN ACCRETED NUCLEAR MATTER MAGNETAR WITH A MAGNETIZED CORE

1) To begin with, let us deal with the question if this binary star, PSR J1614-2230, was born a magnetar. In the context of our model this means, did it have a large enough mass at birth to have a magnetized core.

If it was born with a magnetized core its surface magnetic field would be large, $B > 10^{13}$ gauss, and like the other magnetars, would have emerged at the surface in $\sim 10^{5-6}$ years, which is not the case. We can conclude that PSR J1614-2230 was not born a magnetar.

2) As pointed out by van den Heuvel (van den Heuvel 2011) if an accreted neutron star was born with a typical pulsar mass $\sim 1.4M_\odot$ then its short pulse (milliseconds period) could be the result of a long lasting mass accretion of at least $\sim 0.1M_\odot$. However, if this was the case for PSR J1614-2230, it would imply an abnormally large mass accretion, $\sim 0.6M_\odot$ of mass. The larger the mass accreted the larger the spin up - in this case the star should have spun up to a period less than a millisecond.

Van den Heuvel (van den Heuvel 2011) also points to another scenario that can arise from a large mass progenitor, $M > 19M_\odot$. In this scenario, which he considers more likely for PSR J1614-2230, the star can be born with a mass larger than $\sim 1.7M_\odot$. In this case the accreted mass would be of the order of $0.2 - 0.3$ solar mass, which is more reasonable. Independently, Lin et al. (Lin et al. 2011) have carried out extensive simulations of an accreted neutron star which acquires its mass from high mass X ray binary. Given the parameters of PSR J1614-2230, an orbital period of 8.7 days and the final mass of the donor (white dwarf) of $\approx 0.5M_\odot$, they find that this can only happen if the initial neutron star mass is of the same order, $\sim 1.7M_\odot$.

It is then probable that PSR J1614-2230 is to be understood as a purely nuclear star with an initial mass of at least, $M \approx 1.7M_\odot$. If it starts life below the threshold mass of a magnetar, it follows that the threshold mass for a (nuclear) magnetar is $M_T > 1.7M_\odot$. With an observed mass of almost 2 solar masses, it follows that PSR J1614-2230 can pick up at most, $0.2 - 0.3$ solar mass by accretion from its companion.

3) The total mass energy added to the star must then be less than $0.3 \cdot M_\odot \approx 0.6 \cdot 10^{33}$ gm.

Since the star was not born a magnetar, only a fraction of this accreted mass would go into making the magnetized core. We note that conventional (born not accreted) magnetars, with a substantial core of radius, $R_c \approx 2 - 3km$ and an average density of $10^{15}$ gm/cc, would have a core of mass $M_c \approx 0.03M_\odot$. For PSR J1614-2230, we must take account of the fact that accretion is accompanied by spin up to millisecond periods which reduces the nucleon density ($\approx \text{Haensel et al.}$) in the core. It is then likely that the high density ($\approx 10^{15}$ gm/cc) core mass have an upper limit of $M_{\text{core}} \approx 0.03 - 0.06 \cdot 10^{33}$ gm.

Taking a typical energy release in the strong phase transition (eg. to a pion condensed core) of $\approx 10$ Mev/nucleon = $1.5 \cdot 10^{-5}$ erg/nucleon (Dautry & Nyman 1979, Baym 1974, Akmal et al. 1998, Soni & Bhattacharya 2000), the total energy release from the core works out to, $\approx 10^{33}$ ergs (upper limit).

4) Now, accretion keeps adding mass to the core as the star builds up in a time scale set by its age. In contrast to born magnetars the strong interaction phase transition happens gradually over the age of the star and so the energy release thereof. Given the electromagnetic opacity of the surrounding plasma it will heat up the rim of the core and allow for neutrino emission. It would well be that less than one percent of the energy released will be converted (Kaminker et al. 2006, Zdunik et al. 1992) to heat. In this case from a total $\approx 10^{33}$ ergs of energy we may have a leftover balance of $\approx 10^{30}$ ergs. Of this balance a part will be used in generating the core magnetic field and the shielding currents that screen it.

5) For a magnetised core of $2 - 3$ km and a magnetic field of $B \approx 10^{16}$ gauss the magnetic energy contained in the core is $E_{\text{core}} \approx 10^{46}$ erg.

A similar but somewhat larger amount of energy sits in...
the screening currents that shield the core. Note that the magnetic energy is of the same order as the balance energy left after accounting for the loss from neutrino emission. These screening currents dissipate during the age of the star. An estimate of the average energy flux is given by dividing the total screening current energy release by the age of the star - 5 Gigayears.

\[ \dot{E}_s \simeq 10^{38(31)} \text{ ergs/sec} \]

6) It is good to keep in mind that for a conventional magnetar with a similar core a similar energy release happens rather quickly via the strong interaction as the core formation is completed shortly after the star is born. This energy heats up the interior of the star and a large fraction may be emitted as neutrinos. Also, an amount of energy of order, \( E_{\text{mag}}^{\text{imp}} \simeq 10^{48(49)} \) erg, goes into creating the core magnetic field and the consequent shielding. However, now the shielding currents get dissipated in \( \simeq 10^5 \) years. This yields an average energy flux of

\[ \dot{E}_s \simeq 10^{35(36)} \text{ ergs/sec} \]

which can give rise to (Kaminker et al. 2006) interior temperatures of \( 10^{5.5} \) K, required for efficient ambipolar diffusion in conventional magnetars.

This is at least four orders of magnitude larger than the energy flux from PSR J1614-2230. It would appear that the energy flux of from PSR J1614-2230 may not be able to sustain interior temperatures of \( 10^5 \) K.

7) Let us next look at the internal temperatures of regular accreting, spun up neutron stars without any additional heating sources in the interior (without any magnetic cores and dissipation of shielding currents). The authors of reference (Zdunik et al. 1992) have looked at interior temperatures of accretion based spun up neutron stars with and without pion condensed cores to find that the accreted neutron stars with pion condensed interiors cool faster and have interior temperatures of less than \( 10^5 \) K, whereas stars with normal n,p,e interiors can have slightly higher interior temperatures of up to \( 10^8 \) K.

Such temperatures for spun up accretion pulsars are also indicated by the work of Potekhin et al. (Potekhin et al. 2010). They find that pulsars with accreted material envelopes are different from normal pulsars with iron (Fe) envelopes - the former having smaller interior temperatures than the latter as evidenced in their Fig 1 (Potekhin et al. 2010). For regular accreted pulsars they indicate surface temperatures in the range of \( T \simeq 10^{5-6} \) K (Potekhin et al. 2010) and interior temperatures of \( T_i \simeq 10^{7-8} \) K.

7 THE TIME SCALE OF AMBIPOLAR DIFFUSION TO TRANSPORT THE MAGNETIC FIELD TO THE CRUST

The dissipation time scale of ambipolar diffusion to transport the magnetic field to the crust for a neutron, proton, electron plasma, in the interior of a neutron star, have been estimated by Goldreich and Reisenegger (Goldreich & Reisenegger 1992).

\[ t_{ap} \simeq 10^4 \cdot B_{16}^{-2} \cdot T_{8.5}^{-1.5} \text{ years} \]

This star has a very large core magnetic field and yet does not manifest as a magnetar. The reason for this has to then be the internal temperature not reaching a high enough value for ambipolar diffusion to be effective. Recall, that from the above formula, the time of transport by ambipolar diffusion goes inversely as the sixth power of the temperature.

For an accreting star, with a magnetised core, we have magnetic fields of \( 10^{15} \) G at the core surface and fields of \( 10^{14(15)} \) G at the surface of the star. If we take the mean field in the interior of the star to be \( 10^{15} \) G and mean interior temperature to be, \( \simeq 10^5 \) K, then the ambipolar diffusion formula gives a typical travel time of \( \simeq 10^5 \) years to reach the surface. This is larger than the age of the star. In our model this completes the understanding of why the magnetar core fields for spun up, accreted magnetars like, PSR J1614-2230, are not manifest.

8 ACKNOWLEDGEMENTS

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

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