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LETTER TO THE EDITOR

SGRs and AXPs proposed as ancestors of the Magnificent Seven

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ABSTRACT

The recently suggested correlation between the surface temperature and the magnetic field in isolated neutron stars does not seem to work well for SGRs, AXPs and X-ray dim isolated neutron stars (XDINs; specifically the Magnificent Seven or M 7). Instead, by appealing to a color-flavor locked quark star (CFLQS) we find a more natural explanation. In this picture, the heating is provided by magnetic flux expulsion from a crust-less superconducting quark star. Combined with our previous studies concerning the possibility of SGRs, AXPs, and XDINs as CFLQSs, this provides another piece of evidence that these objects are all related. Specifically, we propose that XDINs are the descendants of SGRs and AXPs.

Key words. dense matter – stars: magnetic fields – stars: neutron – X-rays: stars – X-rays: bursts – radiation mechanisms: non-thermal

1. Introduction

Heating of neutron stars by magnetic field decay in the crust has been suggested by Pons et al. (2007) to explain the observed correlation between surface temperature and dipolar magnetic field strength of isolated neutron stars. They define a heating balance line (HBL) in the temperature-magnetic field diagram. Since the soft gamma-ray repeaters (SGRs) and anomalous X-ray pulsars (AXPs) lie well above the HBL line, and the Magnificent Seven (M 7; a group of isolated neutron stars; see for example Haberl 2007) fall well below the line, here we explore an alternative explanation. Our scenario, rather than crustal field decay, involves magnetic flux expulsion from a superconducting crust-less star. The most likely compact star that can provide this is a color-flavor locked quark star (CFLQS). More specifically, we employ strange quark matter in the color-flavor locked (CFL; Rajagopal & Wilczek 2001) phase where quarks of certain color and flavor pair together, resulting in a color superconducting medium. Due to the rotation of the star, the medium develops a vortex lattice, where the star's magnetic field is constrained to reside only inside these vortices (i.e. an Abrikosov lattice).

It is generally accepted that SGRs and AXPs are the same type of objects, and it has been speculated before that X-ray Dim isolated neutron stars (XDINs) are also related (see Treves et al. 2000, for a review). We have previously proposed (Ouyed et al. 2007a, 2007b; Niebergal et al. 2006) that quark stars (QS) in the CFL phase not only exist, but are manifested in the form of these three classes of astrophysical objects (SGRs, AXPs, and a specific group of XDINs named the M 7). Using our CFLQS model, we present further evidence for the relation between SGRs/AXPs and the M 7 based on an analytic prescription for the evolution of the star's effective temperature, $T_{\rm eff}$, and magnetic field strength. This analytic prescription is derived by considering vortex expulsion from the star due to spin-down from magnetic braking. We compare our model with observed $T_{\rm eff}$ vs. B and find a more natural agreement for SGRs, AXPs, and the M 7 than the Pons et al. (2007) model.

The paper is presented as follows: in Sect. 2 we briefly introduce the notion of a CFLQS, the basis of our model, and the resulting vortex lattice formed within. We go on to describe the evolution of this vortex lattice in Sect. 3, and the resulting magnetic flux expulsion due to the quantized relation between the total number of vortices and the star's spin-period. Lastly, in Sect. 4, we discuss XDINs (specifically the M 7) and give evidence for their ancestral link to SGRs/AXPs. We then conclude in Sect. 5.

2. CFL quark stars

We assume that a QS is born with a temperature $T > T_{\rm c}$ ($T_{\rm c}$ is the critical temperature below which superconductivity sets in), and enters a superconducting-superfluid phase (CFL phase) in the core as it cools by neutrino emission (Ouyed et al. 2002; Keränen et al. 2005), and contracts due to spin-down. The CFL front quickly expands to the entire star followed by the formation of rotationally induced vortices, analogous to rotating superfluid ^{3}He (the vortex lines are parallel to the rotation axis; Tilley & Tilley 1990). Via the Meissner effect (Meissner & Ochsenfeld 1933), the magnetic field is partially screened from the regions outside the vortex cores. Now the system will consist of alternating regions of superconducting material with a screened magnetic field and the vortices where most of the magnetic field resides.

As discussed in Ouyed et al. (2004), this has interesting consequences on how the surface magnetic field adjusts to the interior field that is confined in the vortices. In Ouyed et al. (2006) we performed numerical simulations of the alignment of a QS's

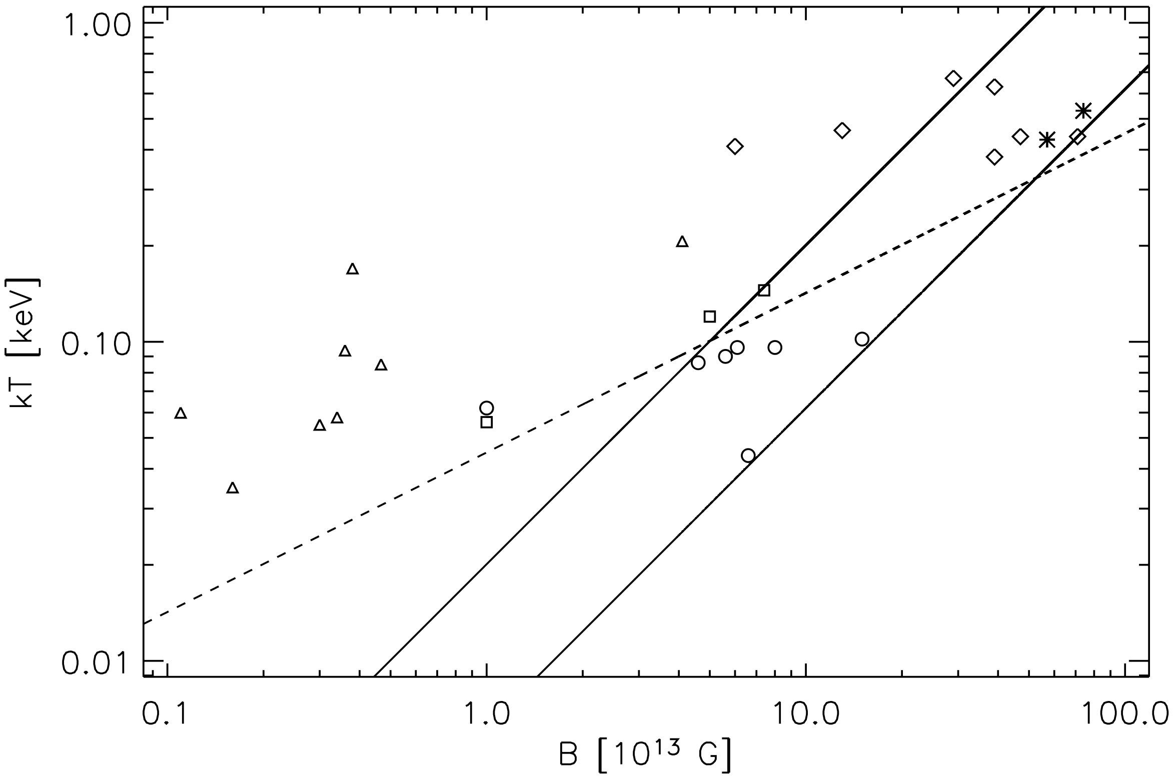

Fig. 1. Effective temperature vs. magnetic field (inferred from cyclotron resonance observations where possible) of isolated neutron stars. The stars and diamonds represent SGRs and AXPs, respectively, while radio-quiet, X-ray dim, isolated stars (the Magnificent Seven) are shown as circles. The remaining objects are isolated radio pulsars with periods $P > 3$ s (squares) and $P < 3$ s (triangles). The dashed line is the *heating balance line* derived by Pons et al. (2007), assuming balance between heating by magnetic field decay and blackbody cooling. The two solid lines are our model of vortex expulsion from a CFL QS (Eq. (5)). The upper and lower lines represent upper ($\Delta R_{\rm km} = 10$, $P_0 = 1.5$ s) and lower ($\Delta R_{\rm km} = 1$, $P_0 = 5$ s) bounds for CFL QSs. We point out that the free parameters in our model are tightly constrained by observations.

exterior field and found that the physics involved was indicative of SGR/AXP activity[1].

3. Magnetic dissipation in the crust vs. flux expulsion

Following the initial magnetic field alignment event is the quiescent phase, where magnetic braking spins-down the QS, causing the outermost vortices to be pushed to the surface and expelled (Ruutu et al. 1997; Srinivasan et al. 1990). The magnetic field contained within these vortices is also expelled and annihilates by means of magnetic reconnection events near the surface of the star, causing energy release, presumably in the X-ray regime. Due to the irregular nature of the reconnection processes, there will be emitting regions that are hotter than others and so the X-ray emission would then be spin modulated. The number of vortices decreases slowly as the QS spins down leading to continuous, quiescent, energy release that can last until the magnetic field is insufficiently strong to produce detectable emission.

This scenario differs to what is expected from neutron stars, wherein the proton and neutron superfluids are thought to compete to push vortices to the surface, where the magnetic field slowly decays as it diffuses through the neutron star's crust (Konenkov & Geppert 2000). Pons et al. (2007) parametrize this field decay and balance it with blackbody cooling, thus attaining an equilibrium temperature ($T_{\rm eff} \propto B^{1/2}$; what Pons et al. referred to as the heat balance line; HBL) below which no neutron stars should be found. However, most of the Magnificent Seven (M 7; e.g. Haberl 2007) are below this proposed temperature (see Fig. 1), or at least require very different physical characteristics than their neutron star counterparts.

In our CFLQS model, because the star possesses only CFL matter and no crust[2], the vortices are efficiently pushed to the surface where the magnetic field contained within decays by reconnection rather than dissipation. Thus, by balancing this heating with blackbody cooling we attain an equilibrium temperature proportional to B, rather than $B^{1/2}$.

This is realized by first considering spin-down due to a rotating, aligned, magnetic dipole (e.g. Mészáros 1992)

$$\frac{\dot{\Omega}}{\Omega} \approx -\frac{B^2 R^6 \Omega^2}{I c^3}. \tag{1}$$

Here, Ω is the spin frequency, $\dot{\Omega}$ is the spin frequency derivative with respect to time, B is the magnetic field strength at the surface of the QS, R is the radius of the QS, I is the moment of inertia, and c is the speed of light. In the aligned-rotator model, the star spins down by magnetospheric currents escaping through the light cylinder. For a neutron star, these currents

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[1] See simulations:
`www.capca.ucalgary.ca/~bniebergal/meissner/`

[2] Although it has been shown that pure CFL matter is rigorously electrically neutral (Rajagopal & Wilczek 2001), other work (Usov 2004, and references therein) indicates that a thin crust is allowed around a QS due to surface depletion of strange quarks. In our model we have assumed no depletion of strange quarks, which implies a bare QS.

are thought to originate in the crust. Instead, in our model, pair production from magnetic reconnection would likely supply the currents (Niebergal et al. 2006).

From the quantization of angular momentum the number of vortices is proportional to the QS's rotation period. As given in Ouyed et al. (2004), for a sphere this relation is given by

$$\frac{\mathrm{d}N_\mathrm{v}}{\mathrm{d}\Omega} \simeq \frac{N_\mathrm{v}}{\Omega}, \tag{2}$$

where N_v is the total number of vortices.

Thus, it is easy to imagine that as the star loses rotational energy and spins down, the QS will lose vortices. The magnetic field contained within these vortices is also released from the QS. This implies that the magnetic field possessed by the QS is dependent on the spin period. However, the rate of spin-down is proportional to the magnetic field squared (cf. Eq. (1)), so the period is also dependent on the magnetic field. Hence, the spin period and magnetic field are coupled, but they can be solved for independently as done by Niebergal et al. (2006), yielding the important relations,

$$\frac{B^2}{\Omega} = \frac{B_0^2}{\Omega_0}$$

$$P = P_0\,(1 + t/\tau)^{1/3}$$

$$B = B_0\,(1 + t/\tau)^{-1/6}\,, \tag{3}$$

where the subscript 0 refers to the initial value at the time of the QS's birth. Also, the characteristic age, τ, in units of years is calculated to be,

$$\tau_\mathrm{yrs} = 5\times10^4\left(\frac{10^{14}\ \mathrm{G}}{B_0}\right)^2\left(\frac{P_0}{5\ \mathrm{s}}\right)^2\left(\frac{M_\mathrm{QS}}{M_\odot}\right)\left(\frac{10\ \mathrm{km}}{R_\mathrm{QS}}\right)^4, \tag{4}$$

where M_QS is the mass of the QS, and R_QS is its radius.

As the magnetic field is forced outside of the star, it decays by reconnection, causing (presumably uneven) heating near the surface. This uneven heating would lead naturally to the spin-modulation of the resulting X-ray emission. Assuming an efficiency of 10% for the conversion from magnetic energy to X-rays due to reconnection, then a simple model of heating balanced with cooling gives an effective equilibrium temperature of the QS to be,

$$kT_\mathrm{eff} \simeq 1.4\times10^{-2}B_{13}\Delta R_\mathrm{km}^{1/4}P_0^{-1/2}\ \mathrm{keV}. \tag{5}$$

In the above equation, B_{13} is the magnetic field strength at the surface of the QS in units of 10^{13} G, ΔR_km is the size of the emitting region in units of kilometers, and P_0 is the initial period of the QS.

In Fig. 1, the two solid lines represent the upper ($\Delta R_\mathrm{km} = 10$, $P_0 = 1.5$ s) and lower ($\Delta R_\mathrm{km} = 1$, $P_0 = 5$ s) bounds for the temperature given by Eq. (5). These bounds cover the likely extent of the parameter space, given that ΔR_km is unlikely to be larger than the QS itself (10 km), and P_0 should not be much less than the SGR/AXP/M 7 period average. Thus, our QS model parameters are very physical, and tightly constrained by observations. The data points are from Pons et al. (2007), as is the dashed line, which represents their HBL temperature for neutron star spin-down combined with a two-parameter best fit for magnetic field diffusion through the crust.

We argue that in the context of the HBL model, the M 7 would require a very different set of parameters from other neutron stars; parameters that should be mostly uniform. In our QS model, the M 7 share a parameter space with SGRs and AXPs, suggesting that the two groups are the same type of objects and differ primarily in age. The other objects in Fig. 1 that do not fall within the bounds of our model are regular neutron stars. Also, there may in fact be more objects in the gap between SGRs/AXPs and the M 7, but they would likely appear like regular X-ray pulsars with no persistent pulsed radio emission, of which there may be some unidentified candidates in the ROSAT catalog.

4. The XDIN, AXP, and SGR link

The M 7 are a class of ~10^6 yrs old stars possessing relatively strong magnetic field strengths (10^{13} to 10^{14} G) and exhibiting a clustering in their observed periods similar to that of AXPs and SGRs. Like AXPs/SGRs they show no persistent pulsed emission in radio wavelengths. They are also characterized by a near perfect blackbody spectrum (Posselt et al. 2007). The near perfect blackbody fits naturally within the framework of our model as the CFLQS is expected to possess no crust, but rather a bare surface. Moreover, the lack of any observed radio pulsations (e.g. Kondratiev et al. 2007) in our model is a necessary consequence of the birth of a CFLQS, which causes the star's interior magnetic field to align with its rotation axis (Ouyed et al. 2006) and its exterior field to assume an aligned dipole configuration. The X-ray emission will still be modulated in our model even though the magnetic field is aligned, due to the irregularity of the magnetic reconnection processes that cause hot-spots on or near the surface.

Although XDINs have previously been speculated to be related to AXPs and SGRs (see Treves et al. 2000, for a review), the most popular neutron star models were unable to explain period clustering and sustainment of the magnetic field. In our CFLQS model, after the QS's field has aligned, it will spin-down through magnetic braking, as described in Eq. (3), and for ages of the order of ~10^6 yrs, we arrive at results indicative of the M 7. As an example, if a CFLQS is born with a radius of 9 km, period of $P_0 = 3$ s, and magnetic field strength of $B_0 = 10^{14}$ G, then by the time it reaches ages estimated for XDINs it will have attained a period of 10 s and its field will have decayed to ~5×10^{13} G (see Fig. 3 in Niebergal et al. 2006).

Hence, by using our model with SGR/AXP parameters we arrive at M 7 parameters after roughly less than a million years, suggesting that age is the primary difference between SGRs/AXPs and the M 7. Also, after roughly 5×10^4 years the magnetic field (and resulting luminosity) begins to drops rapidly in our model, implying no XDIN beyond that age should be detectable, unless it is very close in distance (Niebergal et al. 2006). Recent estimates of distances to the M 7 (Posselt et al. 2007) satisfy this criteria, as the distance varies from roughly 160 to 400 parsecs. These new distance estimates also seem to indicate that the number of currently observable SGRs/AXPs is consistent with the seven observed[3] XDINs, given their ages.

It is worthwhile to point out that, in our model, the dipole magnetic field strength is given by $B_\mathrm{d} = 3\times10^{19}\sqrt{3P\dot{P}}$ G, which is greater than the usual field estimation for neutron stars by a factor of $\sqrt{3}$. Thus, vortex expulsion changes the braking index of a spinning dipole ($n \rightarrow 4$), and results in an extra factor of $\sqrt{3}$ when predicting the star's magnetic field strength from its spin-period and spin-down rate. This extra factor may help account for the discrepancy between the M 7's estimated dipole

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[3] Despite intensive searches for more objects similar to the M 7, none have been found since 2001 (Haberl 2007).

field (using the usual neutron star braking index; $n = 3$) and the observed field using cyclotron resonances (e.g. Haberl 2007).

5. Conclusion

We have shown in this Letter that in the context of our CFLQS model many features of the Magnificent Seven can be explained and evidence for their SGR/AXP ancestry was presented. Specifically the evolution of the effective temperature, the spin-period, and the magnetic field are all predicted for SGRs/AXPs and the M 7 using our CFLQS model. A CFLQS also has the advantage of not possessing a crust, thus its bare surface is able to explain the near featureless spectrum of the M 7 (Pons et al. 2005). The SGR/AXP spectrum is naturally more convoluted as they are much further away, and so would likely suffer from interstellar absorption effects. Other properties of XDINs such as the two-component blackbody, the optical excess, and the absorption lines have been discussed in Ouyed et al. (2007a) in the context of CFLQS (see also Ouyed et al. 2007b). While we have suggested possible evolutionary signatures of QSs among neutron stars, signatures of their birth might have already been seen (Leahy & Ouyed 2007).

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