RX J1856.5-3754 as a possible Strange Star candidate.

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Abstract RX J1856.5-3754 has been proposed as a strange star candidate due to its very small apparent radius measured from its X-ray thermal spectrum. However, its optical emission requires a much larger radius and thus most of the stellar surface must be cold and undetectable in X-rays. In the case the star is a neutron star such a surface temperature distribution can be explained by the presence of a strong toroidal field in the crust (Pérez-Azorín et al. 2006; Geppert et al. 2006). We consider a similar scenario for a strange star with a thin baryonic crust to determine if such a magnetic field induced effect is still possible.

Keywords RX J1856.5-3754 · Strange Star · Neutron Star

1 Introduction

Quark stars have long ago been proposed as an alternative to neutron stars (Itoh 1970). The “strange matter hypothesis” (Witten 1984) gave a more precise theoretical formulation for their existence: that at zero pressure three flavor quark matter, i.e. with u, d and s quarks, has a lower density per baryon than nuclear matter and would hence be the true ground state of baryonic matter. These stars are now called “strange stars” (Alcock et al. 1986; Haensel et al. 1986) and share many similarities with neutron stars: they can have similar masses, have similar radii in the observed range of masses, similar cooling histories and, to date, it has been practically impossible to conclusively prove or disprove their existence (for recent reviews, see Weber 2005; Page et al. 2006; Page and Reddy 2006).

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One possible distinctive property of a strange star could be a small radius. Given the impossibility to treat quark-quark interactions from first principles, i.e. starting from QCD, at densities relevant for compact stars, only simplified models are possible and results are, naturally, model dependent. However, several classes of such models do predict small radii, \(5 < R < 10 \text{ km}\) at masses \(\sim 1.4M_\odot\) (see, e.g., Dey et al. 1998; Hanauske et al. 2001), and all models predict very small radii, \(\lesssim 5 \text{ km}\) at masses \(\ll 1M_\odot\). Hence, measurement of a compact star radius giving a radius \(\lesssim 10 \text{ km}\) directly allows a claim for a strange star candidate.

The “Magnificent Seven” (Haberl 2007) arouse great expectations to measure compact star radii with high enough accuracy to put strong constraints on the dense matter equation of state. In particular, fits of the observed soft X-ray thermal spectrum of RX J1856.5-3754 (Pons et al. 2002) pointed to a very small radius and lead to the claim that this object may be a strange star (Drake et al. 2002). However, observations in the optical band allowed the identification of the Rayleigh-Jeans tail of a second component of the surface thermal emission, corresponding to a lower temperature and much larger radius than the component detected in the X-ray band. An interpretation of these results is that the surface temperature of the star is highly non-uniform (Pons et al. 2002; Trümper et al. 2004), possibly due to the presence of a strong magnetic field. Models of surface temperature distribution with purely poloidal magnetic fields (Page 1995; Geppert et al. 2004) do predict non-uniform surface temperature distributions, but such inhomogeneities are not strong enough to produce such small X-ray emitting regions surrounded by large cold regions detectable in the optical band as observed. However, inclusion of a toroidal component of the magnetic field, confined to the neutron star crust, has a dramatic effect (Pérez-Azorín et al. 2006; Geppert et al. 2006; see also Pons 2007; Page 2007): this field component inhibits heat from the stellar core to flow to the surface through most of the crust, except for small domains surrounding the magnetic axis, and results in highly non-uniform surface temperature distributions producing good fits to the observed thermal spectra, from the optical up to the X-ray band.
These models of small hot regions, detected in the X-ray band, surrounded by large cold regions, detected in the optical band, which allow to reproduce the entire observed thermal spectrum and results in large radii for the star are in contradiction with the proposed strange star interpretation of RX J1856.5-3754, which was based on the small radius detected in the X-ray band. Here we want to push the discussion one step further: are these highly non-uniform surface temperature distributions, assuming they are real, incompatible with a strange star model? We consider strange stars having a thin crust, composed of normal bayonic matter, with a strong magnetic field. Since a strange star crust can, at most, reach the neutron drip density, it is much thinner than the crust of a normal neutron star and the specific question is: can such a thin layer produce the surface temperature distributions deduced from observation?

2 The Strange Star Models

We will consider strange star models built on the MIT-bag inspired equation of state of Farhi and Jaffe (1984) which has three parameters: the QCD coupling constant \( \alpha_s \), the bag constant \( B \) and the strange quark mass \( m_s \) (u and d quarks are treated as massless). Figure 1 illustrates four families of such strange matter models; by varying the parameters, these equations of state allow the production of a wide range of models, from very compact stars up to very large ones. It is important to notice from this figure that, depending on the assumed parameters of the model, strange stars can have large radii and thus, although a small radius measurement is a strong argument in favor of a strange star, a large radius is not an argument against a strange star.

On top of the quark matter, a thin crust can exist as long as the electron density within it is smaller than that in the quark matter (AXcock et al. 1986). Such a baryonic crust is, however, much thinner than a neutron star crust as illustrated in Figure 2.

Following the neutron star models presented by Geppert et al. (2006) we consider dipolar magnetic fields with three components (Figure 3): a poloidal one maintained by currents in the quark core, \( \mathbf{B}^{\text{pol}} \), a poloidal one maintained by currents in the baryonic crust, \( \mathbf{B}^{\text{crust}} \), and a toroidal one maintained by currents in the baryonic crust, \( \mathbf{B}^{\text{tor}} \). The separation between currents in the crust and in the core is motivated by the likely fact that quark matter forms a Maxwell superconductor (Alford 2001; Page and Reddy 2006): at the moment of the phase transition, occurring very early in the life of the star, superconductivity will prevent any current in the crust from penetrating the core while currents in the core will become supercurrents and be frozen there. Moreover, flux expulsion due to the star’s spin-down can also significantly increase the crustal field at the expense of the core field.

The importance of the crustal field is that its field lines are forced to be closed within the crust and hence it has a very large meridional component \( B_\theta \), compared to the core component. Due to the classical Larmor rotation of electrons, a magnetic field causes anisotropy of the heat flux and the heat conductivity becomes a tensor whose components perpendicular, \( \kappa_\perp \), and parallel, \( \kappa_\parallel \), to the field lines become

\[
\kappa_\perp = \frac{\kappa_0}{1 + (\Omega B / \tau)^2} \quad \text{and} \quad \kappa_\parallel = \kappa_0
\]

where \( \kappa_0 \) is the conductivity in the absence of a magnetic field, \( \Omega_B \) the electrons cyclotron frequency and \( \tau \) their collisional relaxation time. The large values of \( B_\theta \) in the crust have the effect of inhibiting radial heat flow except in regions close to the magnetic axis where \( B_\theta \) dominates over \( B_r \) (Geppert et al. 2004).

3 Strange Stars - Results

We performed heat transport calculations using the 2D code described in Geppert et al. (2004) which incorporates the ther-
nal conductivity anisotropy described by Eq. [1]. Details of the crust microphysics are as described in Geppert et al. (2004, 2006). We consider a strange star model with a radius of \( \sim 11 \) km and a baryonic crust of thickness \( \sim 250 \) m for a 1.4 \( M_\odot \) mass. The two poloidal components of the magnetic field are parametrized by \( B_{\text{core}} \) and \( B_{\text{crust}} \) which are the strengths of the corresponding field components at the surface of the star along the magnetic axis so that, ideally, \( B_{\text{core}} + B_{\text{crust}} \) would be the dipolar field estimated from the star’s spin-down. Notice that the maximum value of \( B_{\text{core}} \) in the crust is only slightly larger than \( B_{\text{core}} \) while maximum values of \( B_{\text{crust}} \) are up to almost 100 times larger than \( B_{\text{crust}} \) due to its large tangential component, \( B_{\theta} \), resulting from the compression of the field within the narrow crust. The strength of the toroidal field is parametrized by \( B_{\text{tor}} \), defined as the maximum value reached by \( B_{\text{tor}} \) within the crust. We keep \( B_{\text{core}} \) at 10\(^{13} \) G and vary \( B_{\text{crust}} \) and \( B_{\text{tor}} \).

We display in Figure 3 the resulting crustal temperature profiles for several typical values of \( B_{\text{crust}} \) and \( B_{\text{tor}} \). One sees that, independently of the strength of the poloidal component, \( B_{\text{tor}} \) needs to reach 10\(^{15} \) G to have a significant effect, a result similar to what was obtained by Geppert et al. (2006) for the neutron star case. However, independently of the value of \( B_{\text{tor}} \), once \( B_{\text{crust}} \) reaches 10\(^{13} \) G highly non-uniform temperature profiles develop in the thin strange star crust: such profiles are sufficiently non-uniform to produce the wanted surface temperature distribution, i.e. small hot regions surrounded by extended cold ones.

### 4 Discussion and Conclusions

The optical + X-ray spectrum of RX J1856.5-3754, when fitted with blackbodies, requires two components with very different temperatures and emitting areas. The implied highly non-uniform surface temperature distribution can be physically justified by the introduction of a very strong magnetic field, whose supporting currents are mostly located within the star’s crust. We have shown here that, similarly to the neutron star case, such field configurations can be found in the case of a strange star, despite the shallowness of its baryonic crust. However, the strength of these fields, either the toroidal component \( B_{\text{tor}} \) or the crust anchored poloidal one \( B_{\text{crust}} \) must reach strengths close to, or above, 10\(^{15} \) G to produce the desired temperature anisotropy. Similarly to the neutron star case, such surface temperature distributions impose severe, but not unrealistic, restrictions on the orientation of either the observer or the magnetic field symmetry axis with respect to the rotation axis to explain the absence of pulsations (Braje and Romani 2002; Geppert et al. 2006).

That the thin strange star crust can support such huge field strengths is an open question, but a positive answer seems doubtful as some simple estimates illustrate. The magnetic shear stress, \( B_{\theta} B_{\phi}/4\pi \), reaches 10\(^{26} \) dyne cm\(^{-2} \) in the crust when \( B_{\text{crust}} \) reaches 10\(^{13} \) G, which is comparable or higher to the maximum value sustainable by a crust of thickness \( \Delta \sim 200 \) – 300 m (Ruderman 2004): violent reajustments of the crust are expected but have yet to be observed in any of the “Magnificent Seven”. Moreover, the ohmic decay time in the low density crust is relatively short, less than 10\(^5 \) yrs (Page et al. 2000), and the presence of such a strong field in a \( \sim 10^7 \) yrs old star would require an initial crustal field about two orders of magnitude higher when the star was young. (However, the highly non-linear evolution of coupled strong poloidal and toroidal magnetic fields remains to be studied under such conditions).

We have also adopted the very ingenuous assumption that the surface emits as a perfect blackbody. A condensed matter surface may simulate a blackbody spectrum (Turolla et al. 2004; Pérez-Azorín et al. 2005; van Adelsberg et al. 2005) but such models still require strong fields to produce a non-uniform temperature distribution (Pérez-Azorín et al. 2006). However, other interpretations are possible, such as a thin atmosphere atop a solid surface (Motch et al. 2003; Ho et al. 2007) which may be able to reproduce both the optical and X-ray spectra without invoking strongly non-uniform temperatures and can be applied as well to strange stars with a crust as to neutron stars since they only consider the very surface of the star.

In conclusion, the crustal field scenario, which is successfull when applied to neutron star models in order to explain the observed thermal spectrum properties of RX J1856.5-3754, can be “successfully” applied to a strange star model but requires such a huge magnetic field confined within a thin crust that its applicability is doubtful. It is hence difficult to conciliate the observed, from optical to X-ray, properties of RX J1856.5-3754 with a strange star interpretation unless these are due exclusively to the emitting properties of its surface.

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**Fig. 4** Crustal temperature profiles for various strange star magnetic field structures according to the model parameters (see text for details). The radial aspect of the crust has been stretched by a factor of 15 in order to clearly show the thermal structure. The upper right profile shows the field lines of the poloidal component $B_{core} + B_{tor}$ (white lines) and the intensity distribution of the toroidal component $B_{tor}$ (in colours).

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