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Whither Strange Pulsars ?

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ABSTRACT

Both neutron stars and strange stars are capable of supporting fast rotations observed in pulsars. On the basis of this it has been argued that some of the pulsars could be strange stars. We investigate whether strange stars can sustain characteristic pulsar magnetic fields ($10^8 - 10^{13.5}$ Gauss) over astronomically significant time-scales. Furthermore, we check whether strange stars fit into the general scenario of field evolution of pulsars. It is found that as far as the evolution of the magnetic field is concerned the strange pulsar hypothesis runs into serious difficulties to explain the observational data.

1 INTRODUCTION

Strange Quark Matter (SQM), composed of u, d and s quarks, may probably be the ultimate ground state of matter (Farhi & Jaffe 1984, Witten 1984). If meta-stable at zero pressure this phase might exist in the central region of a compact object (white dwarfs, neutron stars) stabilized by the high pressure (Glendenning, Kettner & Weber 1995). If however, SQM is absolutely stable at zero pressure the existence of *Strange Stars* (with or without a thin hadronic crust) is a possibility. It has been found that the stable range of mass ($1M_\odot - 2M_\odot$) for strange stars is quite similar to that for neutron stars. Furthermore, in this range the radii of strange stars are not very different from those of the standard neutron stars (Haensel, Zdunik & Schaefer 1986). Since, the range of stable rotation periods sustainable by these two types of stars are obviously similar, there has been speculations that perhaps some or all of the pulsars are strange stars instead of neutron stars (Alcock, Farhi & Olinto 1986).

Considerable effort has been spent to distinguish strange stars from neutron stars observationally (for detailed reviews see Lu 1998, Madsen 1998a, 1998b and references therein) - one of the important difference being the minimum period of rotation. Though the neutron stars also have a minimum Keplerian rotation period in the sub-millisecond range non-radial instabilities would slow the star down well before such small periods could be attained. In strange stars, however, sub-millisecond rotation could be easily stabilized due to the large bulk viscosity (Madsen 1992). Therefore, a sub-millisecond pulsar would most probably be a strange star.

It has also been believed that the strange stars, in which the direct URCA reactions can proceed, would cool much faster than the neutron stars, cooling via modified URCA, and therefore should have a smaller surface temperature at a given age. But with the revival of direct URCA processes in the neutron stars (Lattimer et al. 1991) and a possible suppression of direct URCA in the strange stars (Schaab et al. 1997) - it is now almost impossible to differentiate the two on the basis of their thermal history.

As yet there is no definite observational characteristic to distinguish a strange star from a neutron star. In the present work, we take a critical look at the *strange pulsar* hypothesis from the point of view of the evolution of the magnetic field in strange stars. In this context we investigate :

(i) the maximum field strength sustainable by strange stars,
(ii) the possible current configurations supporting the field, and
(iii) the evolution of such fields in isolated as well as accreting strange stars.

We compare our results with the following observational facts concerning the nature of the pulsar magnetic fields, namely :

- Pulsar magnetic fields range from $\sim 10^8 - 10^{13.5}$ G (probably up to 10^{15} G with the discovery of the magnetars).
- Isolated pulsars with high magnetic fields ($\sim 10^{11} - 10^{13.5}$ G) do not undergo any significant field decay during their lifetimes (Bhattacharya et al. 1992; Wakatsuki et al. 1992, Lorimer 1994, Hartman et al. 1997).
- The fact that binary pulsars, as well as millisecond and globular cluster pulsars which almost always have a binary history, possess much lower field strengths suggests that significant field decay occurs only as a result of the interaction of a neutron star with its binary companion (Bailes 1989). Recently, it has been shown that a decrease in field strength can also occur due to the pulsar accreting from interstellar medium (Wang 1997, Popov & Konenkov 1998).
- The crustal model of pulsar (neutron star) magnetic field seems to be more likely from recent work on field evolution (Geppert & Urpin 1994, Urpin & Geppert 1995, 1996, Konar & Bhattacharya 1997, 1999a).

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2 MAGNETIC FIELD OF STRANGE STARS

2.1 maximum field strength

For strange stars without a crust the maximum field strength is limited by the naive condition of gravitational stability ($P_{grav} \gtrsim P_{\rm mag}$) and is $\lesssim 10^{18}$ G. But it has been shown that for fields larger than $\sim 4.4 \times 10^{13}$ G in the core of a proto-neutron star the deconfinement transition is strongly suppressed. This would prevent the formation of a strange star in a supernova collapse with a field value higher than that (Ghosh & Chakrabarty 1998). On the other hand, if a strange star forms via the deconfinement conversion of an accreting neutron star (Olinto 1987) then the maximum field strength would be that applicable for the neutron stars (believed to be $\sim 10^{15}$ G - the maximum field supportable by the neutron star crust). A $1.4 {\rm M}_{\odot}$neutron star requires to accrete $\sim$0.5 ${\rm M}_{\odot}$or more to attain the deconfinement density ($\rho_{\rm deconfine} \sim 8\rho_{\rm nuc}$) at the centre for the quark-to-hadron deconfinement transition to take place (Cheng & Dai 1996). Accretion of $0.5{\rm M}_{\odot}$is possible only if the neutron star has a low mass companion (Bhattacharya & van den Heuvel 1991, Verbunt 1993). And it has been shown that the magnetic field of a neutron star decays by several orders of magnitude under such conditions.

For a strange star with a hadronic crust, though, the maximum field is determined by the shear stress of the crust ($\sigma_{\rm shear} \gtrsim P_{\rm mag}$). The maximum density at the bottom of the crust of a strange star is that of the neutron drip ($\rho_{\rm drip} \sim 4 \times 10^{11} {\rm g\,cm}^{-3}$) (Glendenning 1997). The shear stress for a given density is $\sigma_{\rm shear} \sim \mu\theta$ where θ is the dimensionless strain (Ruderman 1991). The shear modulus, μ, is given by :

$$\begin{aligned} \mu &= \frac{0.3(Ze)^2}{a^4} \\ a &\sim (\frac{a}{m_a A})^{-(1/3)}, \end{aligned}$$

where (Z, A) correspond to the equilibrium nuclide at density ρ and m_a is the atomic mass unit (Ashcroft & Mermin 1976). Assuming $\theta_{\rm max} \sim 10^{-2}$ (Ruderman 1991) we obtain the maximum field supportable by the strange star crust to be :

$$B_{\rm max} \sim 5 \times 10^{13} {\rm G}. \tag{1}$$

The equilibrium nuclide has been calculated using the data from Itoh et al. (1984). Hence, the maximum possible field that strange stars can have is $\sim 5 \times 10^{13}$ G. Therefore, even though this range is sufficient for ordinary pulsars - it falls far short of the field strength of exotic objects like magnetars.

2.2 field configuration

According to the presently accepted models of strange stars, they have two clearly distinct regions - a quark core and a thin crystalline nuclear crust separated by a dipole layer of electrons (Glendenning & Weber 1992). Since no currents can flow across a dipole layer the currents, supporting a magnetic field, either reside entirely within the quark core or are completely confined to the nuclear crust. The dipole layer acts like a physical separator between the two regions. Being a stationary charge configuration, however, it does not screen any interior magnetic field. In what follows, we show that the crustal currents would not be long lived enough to sustain a magnetic field over typical pulsar life-times.

The evolution of the magnetic field is governed by the equation :

$$\frac{\partial \vec{B}}{\partial t} = -\frac{c^2}{4\pi} \nabla \times (\frac{1}{\sigma} \times \vec{\nabla} \times \vec{B}), \tag{2}$$

where σ is the electrical conductivity of the medium. The equation is diffusive in nature with the ohmic dissipation time-scale being, $\tau_{\rm ohmic} \sim \frac{4\pi}{c^2} \sigma L^2$, where L is the system dimension. The electrical conductivity of the solid crust is calculated according to the formula, $\sigma^{-1} = \sigma_{\rm ph}^{-1} + \sigma_{\rm imp}^{-1}$, where $\sigma_{\rm ph}$ is the phonon scattering conductivity (Itoh et al. 1984) and $\sigma_{\rm imp}$ is the impurity conductivity (Yakovlev & Urpin 1980). We assume Baym-Pethick-Sutherland equation of state to be valid in the entire crust where density is less than the neutron drip density (Bay, Pethick & Sutherland 1970).

The conductivity increases monotonically with density. Therefore the currents survive for the longest time if they are concentrated at the maximum density, i.e. at the bottom of the crust where $\rho \sim \rho_{\rm drip}$. The temperature at the bottom of the crust for a strange star, similar to a neutron star, is equal to that of the isothermal core. At an age of $\sim 10^5$ years the core temperature is $\sim 10^7$ K (Madsen, 1997). Accordingly, the conductivity at the neutron drip density is $\sim 8 \times 10^{25} s^{-1}$. It must be noted that we assume the impurity content of the crust to be zero. Since the effect of a non-zero impurity would be simply to decrease the ohmic dissipation time-scale further. As the crust and the core are physically separated by the intervening dipole layer, the length-scale of the current diffusion is simply the thickness of the crust which is of the order of 100 meters. With this we find that :

$$\tau_{\rm ohmic} \sim 3 \times 10^6 {\rm years}. \tag{3}$$

The typical lifetime of isolated pulsars is $\sim 10^8$ years whereas the millisecond pulsars probably remain active for more than 10^9 years. Clearly, in a strange star a crustal field dissipates away on far too shorter a time-scale. Therefore, for a strange star to function effectively as a pulsar, the currents supporting the field must reside in the quark core.

3 FIELD EVOLUTION

The behaviour of the magnetic field the quark core would again be governed by equation (2), where σ now stands for the electrical conductivity of the three-component (u,d,s) plasma. Assuming the quarks to be massless in this phase, the conductivity is :

$$\sigma \sim 6 \times 10^{25} (\frac{\alpha_c}{0.1})^{-3/2} T_{10}^{-2} \frac{n_B}{n_{B0}} s^{-1}, \tag{4}$$

where α_c is the QCD coupling constant, T_{10} is temperature of the isothermal core in units of 10^{10} K, n_B is the number density of baryons and n_{B0} is the nuclear baryon number density. Here we take the radius of the star ($\sim$ 10 km) as the length-scale since the currents can diffuse through the entire core, the average baryon density to be $\sim 8n_{B0}$ (since the radial variation in n_B is negligible) and the QCD coupling constant to be equal to 0.1.

Isolated Strange Stars - An isolated strange star undergoes a steady cooling and at an age of $\sim 10^5$ years attains an isothermal core temperature of $\sim 10^7$ K. For this temperature $\tau_{\rm ohmic} \sim 10^{17}$ years. It is evident that the current loops would live forever and much longer than is required for a strange star to function as a pulsar.

Accreting Strange Stars - There has been sufficient observational indication for the field decay of an accreting pulsar - accreting either from a binary companion or from interstellar matter. The main effect of accretion is to raise the temperature of the star. Unfortunately, no calculation for the thermal evolution of an accreting strange star is available. But the strange star thermal evolution should be at least as fast as (if both cool by the same process) or faster (if neutron stars cool by modified URCA whereas the strange stars cool by direct URCA reaction) than that of the neutron stars. Therefore, the temperature of an accreting strange star is equal to or less than that for an accreting neutron star. Using the neutron star temperature in this case then would give us a lower limit (since conductivity increases with a decrease in temperature) to the ohmic dissipation time-scale. It is believed that the maximum temperature reached in the core of an accreting neutron star is $\sim 10^9$ K corresponding to an accretion rate of $\sim 10^{-9}$ $M_\odot$ yr^{-1}(Miralda-Escude et al. 1990) which gives $\tau_{\rm ohmic} \sim 10^{13}$ years. Therefore, this completely rules out the possibility of any field reduction even in an accreting strange star.

4 DISCUSSION

There has been arguments that when a 1.4 $M_\odot$neutron star accretes approximately ~ 0.5 $M_\odot$the density at the centre exceeds the deconfinement density and the entire material at densities below neutron drip gets converted to SQM. This gives rise to a strange star of mass ~ 2 $M_\odot$which is already very close to its stability limit (Glendenning 1997). Nevertheless, it has recently been shown that long before such a transition can take place the magnetic field would decay to a low value at which it would be stabilized because the current loops the regions of effectively infinite conductivity (Geppert & Urpin 1994, Urpin & Geppert 1995, 1996, Konar & Bhattacharya 1997, 1999a,b). Subsequent conversion would affect a further increase of the conductivity without giving rise to any change in the field strength. However, such a strange star would undoubtedly harbour a chromo-magnetic field due to the existence of current loops in the SQM. Therefore, possible observational signatures of a chromo-magnetic field would decidedly distinguish a strange star from an ordinary neutron star.

In conclusion we note that there is as yet no compelling arguments in favour of strange pulsars vis-a-vis neutron stars to function as pulsars. In fact, the evolution of magnetic field in strange stars do not fit the pulsar field evolution scenario, as indicated by observations, at all. A likely alternative to strange stars may perhaps be the hybrid stars with extended regions of quark-hadron mixed phase (Glendenning 1996). Since the transport properties of such phases have not yet been investigated it is not possible to comment upon the nature of the magnetic field in such systems. However, if a strange star does exist then observation of its chromo-magnetic field might identify them definitively.

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