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PSR 0943+10: A BARE STRANGE STAR?

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ABSTRACT

Recent work by Rankin & Deshpande strongly suggests that there exist strong “microstorms” rotating around the magnetic axis of the 1.1 s pulsar PSR 0943+10. Such a feature hints that most probably the large-voltage vacuum gap proposed by Ruderman & Sutherland (RS) does exist in the pulsar polar cap. However, there are severe arguments against the formation of the RS-type gap in pulsars, since the binding energies of both the ^{56}Fe ions and the electrons in a neutron star’s surface layer are too small to prevent thermionic ejection of the particles from the surface. Here we propose that PSR 0943+10 (and probably also all of the other “drifting” pulsars) might be bare strange stars rather than normal neutron stars, in which the “binding energy” at the surface is merely infinity for the case of either a “pulsar” or an “antipulsar.” It is further proposed that identifying a drifting pulsar as an antipulsar is the key criterion for distinguishing strange stars from neutron stars.

Subject headings: elementary particles — pulsars: general — pulsars: individual (PSR 0943+10) — stars: neutron

1. INTRODUCTION

A wealth of observations has been collected for pulsars since their discovery more than 30 years ago. However, some important discrepancies still remain in our understanding of the particle acceleration mechanisms, the emission processes, and even the nature of pulsars. It is commonly agreed that there exists an inner accelerator near the magnetic polar cap region of a pulsar, but two subclasses of models appear in the literature. The space-charge–limited flow models (Sturrock 1971; Arons & Scharlemann 1979; Arons 1983; Muslimov & Tsygan 1992; Harding & Muslimov 1998) assume a free ejection of particles of either charge sign from the star surface. Another type of model, however, assumes that certain particles (usually ions) could be bound in the surface layer of the star, so that a vacuum gap can form and can keep breaking down to generate “sparks” continuously (Ruderman & Sutherland 1975, hereafter RS75; Usov & Melrose 1995 and 1996, hereafter UM95 and UM96, respectively; Zhang & Qiao 1996; Zhang et al. 1997b). Both subclasses of models have some observational support, and it is very likely that different kinds of accelerators may exist in different pulsars.

Maybe the strongest observational support for the Ruderman & Sutherland (RS)–type vacuum gap model is the regular “drifting” of the subpulses observed in some of the pulsars. In such a model, the sparks produced by the inner-gap breakdown provide the source of the subpulses, and the $\boldsymbol{E} \times \boldsymbol{B}$ drift that is due to the lack of charges within the gap causes the observed drifting phenomena. In their original paper, RS75 have treated the “drifting/sparking” process carefully in a detailed calculable way in order to get the predicted value of P_3 to be directly comparable to the observations. This was not done by any other models hitherto known.

However, the RS model encounters severe theoretical criticisms that, taken together, are known as the so-called “binding-energy problem.” Even if it has been modified by different ways, either by introducing partial screening of the parallel electric fields (UM95; UM96) or by reducing the gap height with an inverse Compton scattering–induced breakdown (Zhang & Qiao 1996; Zhang et al. 1997b), the formation of such vacuum gaps is still suspected since calculations using various methods show that the binding energy of the ^{56}Fe ions is much lower than what is required to maintain a vacuum gap or simply that there is no binding at all (e.g., Flowers et al. 1977; Müller 1984; Jones 1986; Neuhauser, Koonin, & Langanke 1987; Kössl et al. 1988). Furthermore, the RS model is only viable for the case of an antiparallel rotator, i.e., $\boldsymbol{\Omega} \cdot \boldsymbol{B} < 0$, which they defined as a “pulsar.” In such a geometry, positive charges are expected to dwell on the polar cap, and a vacuum gap could be formed if positive ions *could* be bound within the molecular lattice of the star layer. For a parallel rotator with $\boldsymbol{\Omega} \cdot \boldsymbol{B} > 0$, however, copious negative electrons could flow freely out from the surface, so that a vacuum gap will never form. This is referred to as an “antipulsar” in RS’s terminology.

Recently, Deshpande & Rankin (1999) have developed a technique for “mapping” the pattern of polar cap sparks or “microstorms.” They studied the typical drifting pulsar PSR 0943+10 while applying this technique and came to a clear map of the polar cap–sparking pattern of this pulsar (Rankin & Deshpande 1998; Deshpande & Rankin 1999; for popular report, see Glanz 1999). Their results strongly suggest that the RS vacuum gap does exist in this pulsar’s polar cap. Vivekanand & Joshi (1999) also came to a similar conclusion independently by studying the competing drifting subpulses in PSR 0031−07, and they argued that “there is a genuine need to reinvestigate the theoretical basis of this model” (RS model). All these results again pose the question of how certain charged particles can be bound in the star surface. The question becomes more severe if the drifting pulsar can be identified as an antipulsar.[6]

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[6] PSR 0943+10 was reported to be an antipulsar in Rankin & Deshpande (1998), but this conclusion is not solid (J. M. Rankin 1999, private communication).

On the other hand, another kind of astrophysical object, the strange star, has been widely discussed (e.g., Witten 1984; Alcock, Farhi, & Olinto 1986). Trying to find criteria for distinguishing strange stars from neutron stars is not only an interesting topic in astrophysics but will also exert an important impact on the fundamental physics. However, there seems to be no evident criteria since strange stars are analogous to neutron stars in many aspects (for a recent review, see Lu 1998). Specifically, the canonical strange-star models all invoke a solid crust that is composed of normal matter (Alcock et al. 1986; Glendenning & Weber 1992; Huang & Lu 1997). This makes strange stars indistinguishable from neutron stars in appearance. Hence, all the difficulties faced by the RS vacuum gap model for neutron stars still remain.

Recently, Xu & Qiao (1998, hereafter XQ98) proposed that a magnetosphere similar to the one for a neutron star could also be formed outside a bare strange star, so that bare strange stars can act as pulsars as well. Here we will show that an RS-type vacuum gap can be well formed above the surface of a bare strange star both for the case of $\boldsymbol{\Omega} \cdot \boldsymbol{B} < 0$ *and* for the case of $\boldsymbol{\Omega} \cdot \boldsymbol{B} > 0$ (antipulsar). We suggest that PSR 0943+10 and other drifting pulsars might be bare strange stars rather than normal neutron stars (NSs).

2. BINDING ENERGY PROBLEM IN RS MODEL FOR NEUTRON STARS OR STRANGE STARS WITH CRUSTS

The essential condition of the RS vacuum gap model is that certain charged particles could be bound in the star surface, so that a boundary condition of $\boldsymbol{E} \cdot \boldsymbol{B} \neq 0$ is satisfied at the surface. In their original work, RS75 have set two criteria to judge whether or not ions are bound in the surface. These two criteria were later more evidently presented by UM95: (1) whether thermionic emission is important (i.e., whether the surface temperature is in excess of a critical "unbound" temperature) or (2) whether field emission is important (i.e., whether the parallel electric field is in excess of a critical unbound field value). Both the critical temperatures and the critical electric fields are determined by the work functions of the particles. For electrons, the work function is just their Fermi energy, which reads $w_{e,\,\mathrm{NS}} = \epsilon_\mathrm{F} = (2\pi^4\hbar^4 c^2/e^2B^2m_e)\, n_e^2 \simeq 1.03 \times 10^{-63} B_{12}^{-2} n_e^2$, where n_e is the electron number density (Ruderman 1971; Flowers et al. 1977; UM95). For ^{56}Fe ions, the work function is the cohesive energy per ion in the *assumed* magnetic metal, which is quite uncertain since this small number is the difference of two large numbers (e.g., Müller 1984). UM95 has adopted $w_{i,\,\mathrm{NS}} = \Delta\epsilon_c \simeq (0.9\ \mathrm{keV}) B_{12}^{0.73}$ following Abrahams & Shapiro (1991). However, the error of the calculation is on the order of this value itself. Thus, it is possible that there might be no cohesive energy at all.

For thermionic emission to be important, the critical temperature is calculated by equating the current density due to thermionic emission, which is proportional to $\exp(-w/kT)$ (see eq. [12] of RS75 and eq. [2.10] of UM95), with the Goldreich-Julian (1969) charge current density $n_\mathrm{GJ} ec$, where $n_\mathrm{GJ} \simeq \Omega B/(2\pi ce)$. For the case of a parallel rotator ($\boldsymbol{\Omega} \cdot \boldsymbol{B} > 0$, i.e., an antipulsar), electrons are expected to be pulled out from the surface. Adopting the density at surface as $\rho \simeq (4 \times 10^3\ \mathrm{g\ cm^{-3}}) B_{12}^{6/5} A_{56} Z_{26}^{-3/5}$ and noticing $n_e = \rho/m_p\,(Z/A)$, the work function of electrons is then ~0.8 keV. Thus, the critical temperature for electron thermion ejection is $T_{\mathrm{cri},\,e} \simeq (3.7 \times 10^5\ \mathrm{K}) Z_{26}^{4/5} B_{12}^{2/5}$ (UM95; UM96). For an antiparallel rotator ($\boldsymbol{\Omega} \cdot \boldsymbol{B} < 0$, i.e., a pulsar), however, the potential difference at the pulsar polar cap tends to pull ^{56}Fe ions from the surface, if the star is a neutron star or a strange star with a crust. With $w_{i,\,\mathrm{NS}} \sim 0.9$ keV, one can get $T_{\mathrm{cri},\,i} \simeq (3.5 \times 10^5\ \mathrm{K}) B_{12}^{0.73}$ (UM95; UM96).

Given the work function (w) and $E_\parallel$, another particle ejection mechanism is the field emission, which is a quantum mechanical tunneling effect and is only relevant when thermionic ejection is unimportant. Again, by equating the current density of the tunneling with the Goldreich-Julian density, one gets the critical field to pull certain particles out via field ejection (UM95), $E_{\parallel,\,\mathrm{cri}} \simeq (6 \times 10^{10}\ \mathrm{V\ cm^{-1}})\,(w/1\ \mathrm{keV})^{3/2}$, where w is the work function of the particle.

In the RS model, the parallel electric field at the surface is $E_\parallel = 2\Omega Bh/c$, where h is the gap height. With equation (22) of RS75, one gets $E_{\parallel,\,\mathrm{CR}} \simeq (6.3 \times 10^8\ \mathrm{V\ cm^{-1}}) B_{12}^{3/7} P^{-4/7}$, which is smaller than $E_{\parallel,\,\mathrm{cri}}$ for most cases. It was found that the inverse Compton scattering (ICS)–induced cascade gaps usually have much smaller gap heights, potentials, as well as surface electric fields (Zhang & Qiao 1996; Zhang, Qiao, & Han 1997a; Zhang et al. 1997b). With equation (12) of Zhang et al. (1997a), we get even smaller parallel electric fields as $E_{\parallel,\,\mathrm{ICS}} \simeq (1.4 \times 10^8\ \mathrm{V\ cm^{-1}}) P^{-2/3}$ for the "resonant" ICS-induced gaps. Thus, usually field emission is not important for the charge ejection of both the electrons and the ions.

The thermion ejection, however, is important for both cases. The pulsar polar cap temperature could be estimated self-consistently by the feedback of the inward particle streams, which is $T = (\gamma m_e c^2 \Omega B/2\pi e\sigma)^{1/4}$ by assuming a Goldreich-Julian density, where $\sigma = 5.67 \times 10^{-5}$ ergs cm^{-2} K^{-4} s^{-1} and γ is the typical Lorentz factor of the primary particles accelerated within the gap. This turns out to be $T_\mathrm{CR} \simeq (3.1 \times 10^6\ \mathrm{K}) B_{12}^{3/14} P^{-2/7}$ for the curvature radiation (CR)–induced gap model (RS75) and $T_\mathrm{ICS} \simeq (1.5 \times 10^6\ \mathrm{K}) P^{-1/3}$ for the ICS-induced gap model (using eq. [14] of Zhang et al. 1997a), which are much higher than $T_{\mathrm{cri},\,e}$ and $T_{\mathrm{cri},\,i}$. Furthermore, hot polar caps with temperatures greater than 10^6 K have been observed (e.g., Wang & Halpern 1997). This makes the thermionic ejection of both electrons and ions important in most cases and is referred as the binding-energy problem of the RS-type vacuum gap model. This conclusion is more robust for antipulsars, and also the large error bar of the ion cohesive energy leaves only a little room for the solution of the binding-energy problem for pulsars.

The critical temperatures $T_{\mathrm{cri},\,e}$ and $T_{\mathrm{cri},\,i}$ could be raised in stronger magnetic fields. Thus, UM95 and UM96 developed a modified RS-type model that operates in strong-field pulsars with $B \geq 0.1B_c \sim 4.4 \times 10^{12}$ G, where $B_c \simeq 4.4 \times 10^{13}$ G is the critical magnetic field. However, in their "self-consistent" model, the gap is still not completely a vacuum since they invoked a partial screening of $E_\parallel$ so as to keep the inflow current from heating the surface to above the critical temperatures. Although they did not discuss the "sparking" and "drifting" process in such a model, the results should be quite different from RS's predictions.

3. PSR 0943+10 AS A BARE STRANGE STAR

Rankin & Deshpande (1998) and Deshpande & Rankin (1999) show that, at least for PSR 0943+10, the drifting and sparking patterns just closely match the prediction of the RS model. In fact, J. M. Rankin wrote that the RS model "is the only reasonably complete explanation for the hot spots at the moment" (Glanz 1999). However, the above-mentioned binding-energy problem makes it difficult to understand the formation of an RS gap in this pulsar if the pulsar is a neutron star or a strange star with a crust. Even the modified partial screening gap model proposed by UM95 and UM96 could not solve it since PSR 1943+10 has a relatively long period of 1.1 s and a moderate surface field strength of 2.0×10^{12} G (or 4.0×10^{12} G as UM95 and UM96 argued), which is well located outside the self-consistent region of UM95 and UM96 (region 2 in Fig. 1 of UM96). We will show here that a sound answer could be obtained if this pulsar is actually a "bare strange star" (BSS).

The main objection to BSSs acting as pulsars lies in the superstrong electric fields near the star surfaces (Alcock et al. 1986). However, XQ98 show that the electric field that is due to the nonneutral effect of strange stars near a bare strange star's surface actually decreases rapidly. A handy calculation using Alcock et al.'s equation (14) shows that the parallel electric field strength will drop from the high value of $\sim 5 \times 10^{17}$ V cm^{-1} down to 10^{10} V cm^{-1} within a height of $z_c \sim 10^{-7}$ cm, where rotation-induced electric fields begin to dominate (XQ98). By defining an "effective" BSS surface at z_c, a magnetosphere like that of a normal neutron star could be formed right above this effective surface within a short timescale once some high-energy γ-ray seeds ignite a pair-production cascade (XQ98). Hence, a BSS can act as a pulsar.

The key advantage of such a BSS model is that a BSS can completely prohibit both the thermionic and field ejections of any charged particles from the surface to occur. In other words, the binding energy of the particles on the pulsar surface is merely infinity. For the case of $\boldsymbol{\Omega} \cdot \boldsymbol{B} < 0$ (the pulsar case), this conclusion is just as straightforward, since the positive charges within the surface are *u* quarks rather than ions. The homopolar-generated strong fields are solely negligible with respect to the strong interaction operating between the quarks. Thus, essentially $w_{q,\,\rm BSS} \rightarrow \infty$. For the case of $\boldsymbol{\Omega} \cdot \boldsymbol{B} > 0$ (the antipulsar case) in a BSS, the situation is a little bit more complex. The interaction preventing electrons from ejection is also the electromagnetic force. However, by defining the effective surface of BSS at z_c, the picture could be simplified. At the effective surface, the homopolar field strength is just equal to the "binding" field strength, so that the "field-ejection" condition fails below it. The "thermionic-ejection" condition, on the other hand, also fails just slightly below the effective surface. This is because the electric fields increase rapidly inward below z_c, so that the binding energy of the electrons at z, $w_{e,\,\rm BSS} = \int_{z_c}^{z} (dV/dz)dz$, also increases rapidly. Note again that the thermionic emission current density is proportional to $\exp(-w/kT)$ (RS75; UM95) and that the critical temperature is defined by equating this current density with the Goldreich-Julian density; then the critical temperature in this BSS case is just proportional to $w_{e,\,\rm BSS}$, and therefore it also increases tremendously slightly below the effective surface. As a result, only a very thin layer of electrons could be thermionically ejected, and these contribute a negligible current density, so that a vacuum gap analogous to the RS-type gap could be formed.

There are some differences between this sort of gap (rooted to a BSS) and the original RS gap (rooted to a NS). The key point is that besides the homopolar-generated electric field, there is also an intrinsic electric field that is due to the attraction of the strange quark matter from the BSS. However, the rapidly decreasing behavior of this intrinsic or background field (Fig. 1 in XQ98) makes it play a negligible role. Thus, we can safely say that a gap rooted to a BSS can reproduce completely all the features of the RS model, and with this we can interpret the work of Deshpande & Rankin (1999) successfully. In this sense, we suggest that PSR 0943+10 might be a bare strange star rather than a normal neutron star. As shown above, this argument is more promising if it can be inferred from the observations that the star is an antipulsar. We further suggest that other drifting pulsars (e.g., Rankin 1986) might also be BSSs, since most of them have similar periods and surface field strengths as PSR 0943+10, and that the binding-energy problem could not be released if their gaps are rooted to neutron stars or strange stars with crusts.

4. CONCLUSION AND DISCUSSION

We have shown in this Letter that the lack of theories that try to solve the binding-energy problem of the RS model rooted to a neutron star has led us to present the idea that PSR 0943+10 as well as other clearly drifting pulsars might be bare strange stars. Although the argument in favor of the BSS model is indirect, it seems that this is the only hitherto known sound model that solves the binding-energy problem completely.

There are some arguments against the formation of the BSSs or even strange stars. In their pioneer paper, Alcock et al. (1986) simply state that "a bare strange star may readily accrete some ambient material" since "the universe is a dirty environment." Although firmly concluding that all accreting X-ray pulsars have crusts, they admitted, however, that "the situation with radio pulsars is harder to assess" and that "the rotating magnetosphere is likely to prevent fluid accretion." Thus, as long as the fallback materials do not form a crust during the supernova explosion when a strange star is born, the BSS could remain bare for a sufficiently long period of time before its rotation becomes too slow to prevent materials from dropping onto its polar cap. Usually, at this stage, the pulsars have died out across the "death lines" or "death valleys" (RS75; Chen & Ruderman 1993; Qiao & Zhang 1996). Thus, it is plausible to say that observed pulsars could be BSSs.

Perhaps the most severe argument against the existence of strange stars is the "glitching" phenomena observed in some pulsars, which is commonly interpreted as the starquakes that occur in the solid crust. Even for strange stars with solid crusts, Alpar (1987) argued that the observed magnitude of $\Delta\Omega/\Omega \sim 10^{-2}$ to 10^{-3} poses a strong objection to such an idea, since strange stars' crusts are not thick enough. These arguments are not in conflict with our idea that drifting pulsars might be BSSs. By comparing the samples of the drifting pulsars (Table 2 of Rankin 1986) with the samples of the glitching pulsars (Table 6.2 of Lyne & Graham-Smith 1998), we found that, remarkably, all other drifting pulsars were never observed showing this glitching behavior except for PSR 0525+21, which is one of the few pulsars with a surface magnetic field higher than 10^{13} G. In such a high field, a UM96-type gap or even a RS75-type gap could be formed in a *neutron star* surface, since the binding energies are greatly enhanced. Furthermore, the glitching behavior might also be interpreted by the BSS models, and, if stable, low-baryon number strangelets could exist and form a solid crust (Benvenuto & Horvath 1990). Thus, observed glitches "should not be used to dismiss the possibility of strange stars" (Madsen 1999).

Another possible objection to our idea may come from the strong thermal X-ray emissions from drifting pulsars, since the bare quark matter surface of a strange star is a very poor radiator itself. Spectral analysis of some spin-powered X-ray pulsars (e.g., Becker & Trümper 1997, 1999 [updated version]) reveals that the X-ray spectra can be fitted by either power-law radiation (with a nonthermal magnetospheric origin), thermal emission from the full surface (mainly due to the cooling or the internal heating), thermal emission from the hot polar cap (due to inner-gap or outer-gap heating), or a combination of the above two or three components. Our model actually predicts that *the full surface thermal emission from the drifting pulsars should be strongly suppressed*. Four pulsars, i.e., Vela, Geminga, PSR 0656+16, and PSR 1055−52, are observed showing strong thermal emission from the full surface. But they are not drifting pulsars, and thus our idea cannot be dismissed. Future X-ray observations and spectral analyses on drifting pulsars will either prove or dismiss the idea that drifting pulsars are BSSs.

The final question is whether or not a strange star could be formed in the supernova explosion. No definite answer is available yet. Nevertheless, as argued in XQ98, the birth of a strange star rather than a neutron star could enhance both the successful possibilities of a supernova explosion and the energy of the revived shock wave, because of the additional energy source of the phase transition from two-flavor quark matter to three-flavor quark matter (Dai, Peng, & Lu 1995).

In principle, a BSS model can mend the RS vacuum gap model, and make it to have a much more solid foundation. The existence of such a gap can benefit the ICS model of pulsars (Qiao & Lin 1998), which can thus help us interpret naturally the long-identified pulsar “core” emission (Rankin 1983; Lyne & Manchester 1988).

The idea presented here also adds one more criterion for distinguishing strange stars from neutron stars. As shown above, the arguments in favor of the BSSs are more promising for the antipulsar case. Unfortunately, the drifting direction does not depend on whether the star is a pulsar or an antipulsar. Thus, seeking other observational methods to tell the sense of the magnetic pole of a pulsar is essential. We propose here that *finding and identifying a drifting antipulsar will be a strong argument in favor of the existence of the* (*bare*) *strange stars in nature*.

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