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ORIGINAL ARTICLE

Spin down of rotating compact magnetized strange stars in general relativity

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Abstract We find that in general relativity slow down of the pulsar rotation due to the magnetodipolar radiation is more faster for the strange star with comparison to that for the ordinary neutron star of the same mass. Comparison with astrophysical observations on pulsars spindown data may provide an evidence for the strange star existence and, thus, serve as a test for distinguishing it from the neutron star.

Keywords Compact stars · Strange star · General relativity · Spin down

1 Introduction

The study of electromagnetic fields of magnetized compact objects is an important task for several reasons. First one can obtain information about such stars through their observable characteristics, which are closely connected with electromagnetic fields inside and outside the relativistic stars. Magnetic fields play an important role in the life history of majority astrophysical objects especially of compact relativistic stars which possess surface magnetic fields of 10^{12} G and $\sim 10^{14}$ G in the exceptional cases for magnetars (see e.g. Ginzburg and Ozernoy 1964; Duncan and Thompson 1992; Thompson and Duncan 1993). The strength of compact star's magnetic field is one of the main quantities determining their observability, for example as pulsars through the magneto-dipolar radiation. Electromagnetic waves radiated from the star determine energy losses from the star and therefore may be related with such observable parameters as period of pulsar and it's time derivative.

The second reason is that one may test various theories of gravitation through the study of compact objects for which general relativistic effects are especially strong. Considering different matter for the stellar structure one may investigate the effect of the different phenomena on evolution and behavior of stellar interior and exterior magnetic fields. Then these models can be checked through comparison of theoretical results with the observational data. The third reason may be seen in the influence of stellar magnetic and electric field on the different physical phenomena around the star, such as gravitational lensing and motion of test particles.

The majority of neutron stars are known to have large angular velocities, and in the case of radio pulsars one can directly measure their speed of rotation. It is also observed that, on average, their rotation tends to slow down with time, a phenomenon that is explained by emission of electromagnetic waves or, in some conditions, by the emission of gravitational waves or other processes. This should be the case during most of the life of the neutron star when it is observed as pulsar. Since 1967 (Hewish et al. 1968)

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pulsars play a role of relativistic astrophysical laboratory where the fast rotation, the extreme density of matter and the high magnetic field are realized. Topical problems in the physics and basic facts of neutron stars are reviewed by Potekhin (2010). Magnetospheric structure surrounding a rotating, magnetized neutron star has been studied by Morozova et al. (2008).

Neutron stars provide a natural laboratory to study extremely dense matter. In the interiors of such stars, the density can reach up to several times the nuclear saturation density $n_0 \simeq 0.16\ \mathrm{fm}^{-3}$. At such high densities quarks could be squeezed out of nucleons to form quark matter. The true ground state of dense quark matter at high densities and low temperatures remains an open problem due to the difficulty of solving nonperturbative quantum chromodynamics (QCD). It has been suggested that strange quark matter that consists of comparable numbers of u, d, and s quarks may be the stable ground state of normal quark matter. This has led to the conjecture that the family of compact stars may have members consisting entirely of quark matter (so-called strange stars) and/or members featuring quark cores surrounded by a hadronic shell (hybrid stars). The physics of strange matter is reviewed for example by Glendenning (2000), Weber (1999), Madsen (1999), Weber (2005), Weber et al. (2009), Xu (2003), Haensel et al. (2007), Alford and Sedrakian (2010), Sedrakian (2010a, 2010b), Weber et al. (2010), Huang et al. (2010), Negreiros et al. (2010), Lorimer and Kramer (2005), Shen et al. (2005), Bejger and Haensel (2002).

The possibility of existence of stable self-bound strange matter could have important consequences for neutron stars: some compact, dense stars could be strange stars. Discovery of a strange star in the universe would be a confirmation of the validity of our present theory of the structure of matter. In view of this, we should look for the signatures of strange stars. Univocal and detectable signature of strange star would be a key to its possible detection. Low mass strange stars are much smaller than neutron stars. There is no lower limit for strange star mass.

Observationally, it is very challenging to distinguish the various types of compact objects, such as the strange stars, hybrid stars, and ordinary neutron stars. Newly born strange stars are much more powerful emitters of neutrinos than neutron stars. Their early cooling behavior is dominated by neutrino emission which is a useful probe of the internal composition of compact stars. Thus, cooling simulations provide an effective test of the nature of compact stars. However, many theoretical uncertainties and the current amount of data on the surface temperatures of neutron stars leave sufficient room for speculations. However, this property is also characteristics of the neutron star with a large quark core.

Another useful avenue for testing the internal structure and composition of compact stars is astroseismology, i.e., the study of the phenomena related to stellar vibrations. Pulsations of newly born strange star are damped in a fraction of second: after this time copious neutrino flux from them should not show pulsating features. Unfortunately, the same would be true for the neutrino emission from a neutron star with a large quark core.

Photon cooling of bare strange star could be significantly different from that of neutron stars. If quark surface is not an extremely poor emitter of photons, then absence of insulating crust could lead to a relatively fast photon cooling. In principle, a well established upper limit of surface temperature of neutron star-like object of known age, which is well below the estimates for an object with crust, could be a signature of a bare strange star. A neutron star-like object with crust which is 10 y old cannot have a surface temperature lower than 10^6 K. Unfortunately, surface (black-body) emission flux decreases as a fourth power of temperature and at the present day with X-ray satellite detector it is very difficult to detect an object of 10 km radius at 100 pc (typical distance to the nearest observed point X-ray sources) if its surface black body temperature is quite low. However the recent observation of radio-quiet, X-ray bright, central compact objects (CCOs) shows that the spectra of these objects can very well be described by a one- or two-component blackbody model, which would indicate unusually small radii ($\sim$5 km) for these objects Becker (2009). Such small radii can only be explained in terms of self-bound stellar objects like strange quark matter star.

The search for the detectable signatures of strange stars should be continued. After all, chances of producing strange matter in our laboratories are negligibly small compared to those for its creation during 10^{10} years in the immense cosmic laboratory of the universe.

Here in this short note we will be concerned with the possibility to distinguish neutron star from the strange star from the spin down of pulsar. From the observation of the spin down of a pulsar we compare the spindown features of neutron star and strange star and discuss whether astrophysical observations could be useful to prove the validity of the strange matter hypothesis.

If strange stars are born in some supernova explosions then because of enormous electric conductivity of strange matter they should possess huge frozen-in magnetic field (Haensel 1987). In this respect strange stars could be used as models of pulsars. The calculation of electric conductivity σ of strange matter has been done by Haensel et al. (2007). Charge transport in strange matter is dominated by quarks. The value of conductivity σ is determined by the color-screened QCD interaction $\sigma = 10^{29} \mathrm{T}_{10}^{-2}\ \mathrm{s}^{-1}$ and it is only several times larger than electric conductivity of normal neutron star matter of the same density and temperature. In the case of neutron star matter the charge carriers are electrons.

The magnetic field of strange stars will decay due to ohmic dissipation of currents strange matter. For the dipole magnetic field the decay time is (see e.g., Landau and Lifshitz 1982)

$$\tau_D \cong \frac{4\sigma R^2}{\pi c^2}, \qquad (1)$$

and for $T < 10^9$ K and $R = 10$ km one can get $\tau_D > 4 \times 10^{11}$ yr. The ohmic dissipation of magnetic field in a strange star is thus negligible.

Now we plan to study the spin-down of a rotating strange star due to magnetodipolar electromagnetic emission. Assume that the oblique rotating magnetized star is observed as radio pulsar through magnetic dipole radiation. Then the luminosity of the relativistic star in the case of a purely dipolar radiation, and the power radiated in the form of dipolar electromagnetic radiation, is given by Rezzolla and Ahmedov (2004)

$$L_{em} = \frac{\Omega_R^4 R^6 \widetilde{B}_0^2}{6c^3} \sin^2 \chi, \qquad (2)$$

where tilde denotes the general relativistic value of the corresponding quantity, subscript R denotes the value of the corresponding quantity at $r = R$ and χ is the inclination angle between magnetic and rotational axes. In this report we will use the spacetime of slowly rotating relativistic star which in a coordinate system (t, r, θ, φ) has the following form:

$$ds^2 = -e^{2\Phi(r)}dt^2 + e^{2\Lambda(r)}dr^2 - 2\omega(r)r^2\sin^2\theta dt d\varphi + r^2 d\theta^2 + r^2\sin^2\theta d\varphi^2, \qquad (3)$$

where metric functions Φ and Λ are completely known for outside of the star and given as:

$$e^{2\Phi} = \left(1 - \frac{2M}{r}\right) = e^{-2\Lambda}, \qquad (4)$$

$\omega = 2J/r^3$, $J = I(M, R)\Omega$ is the total angular momentum of the star with total mass M and moment of inertia $I(M; R)$, Ω is the angular velocity of the star.

For the interior of the star the metric functions strongly depend on equation of state and were widely discussed in the literature (see, e.g. Fattoyev and Piekarewicz 2010; Geppert et al. 2000; Page et al. 2000). In particular, the function $\Lambda(r)$ is related to mass function $m(r) = \int_0^r 4\pi\rho r'^2 dr'$:

$$e^{2\Lambda} = \left(1 - \frac{2m}{r}\right)^{-1}. \qquad (5)$$

Function $\Phi(r)$ can be determined from evaluating the following integral (see, Fattoyev and Piekarewicz 2010, for more details):

$$\Phi(r) = \frac{1}{2}\ln\left(1 - \frac{2M}{r}\right) - \int_r^R \frac{m(x) + 4\pi x^3 p(x)}{x^2(1 - 2m(x)/x)} dx, \qquad (6)$$

where $p(x)$ is the pressure profile over the parameter $0 \le x \le R$.

When compared with the equivalent Newtonian expression for the rate of electromagnetic energy loss through dipolar radiation (Landau and Lifshitz 1987; Pacini 1967, 1968)

$$(L_{em})_{\text{Newt.}} = \frac{\Omega^4 R^6 B_0^2}{6c^3} \sin^2 \chi, \qquad (7)$$

it is easy to realize that the general relativistic corrections emerging in expression (2) are due partly to the magnetic field amplification at the stellar surface

$$\frac{\widetilde{B}_0}{B_0} = \frac{\widetilde{B}_0 R^3}{2\mu} = f_R, \qquad f_R = -\frac{3R^3}{8M^3}\left[\ln N_R^2 + \frac{2M}{R}\left(1 + \frac{M}{R}\right)\right], \qquad (8)$$

and partly to the increase in the effective rotational angular velocity produced by the gravitational redshift

$$\Omega(r) = \Omega_R \frac{N_R}{N} = \Omega_R \sqrt{\left(\frac{R - 2M}{r - 2M}\right)\frac{r}{R}}, \qquad (9)$$

i.e. $\Omega = \Omega_R N_R = \Omega_R \sqrt{1 - 2M/R}$ when $r \to \infty$, where $N = (1 - 2M/r)^{1/2}$ is the lapse function.

Expression (2) could be used to investigate the rotational evolution of magnetized neutron stars with predominant dipolar magnetic field anchored in the crust which converts its rotational energy into electromagnetic radiation. First detailed investigation of general relativistic effects for Schwarzschild stars has been performed by Page et al. (2000), who have paid special attention to the general relativistic corrections that needed to be included for a correct modeling of the thermal evolution but also of the magnetic and rotational evolution.

Overall, therefore, the presence of a curved spacetime has the effect of increasing the rate of energy loss through dipolar electromagnetic radiation for the strange star with comparison to that for the neutron star by an amount which can be easily estimated to be

$$\frac{(L_{em})_{\text{SS}}}{(L_{em})_{\text{NS}}} = \left(\frac{f_R}{N_R^2}\right)^2_{\text{SS}} \Big/ \left(\frac{f_R}{N_R^2}\right)^2_{\text{NS}}. \qquad (10)$$

The expression for the energy loss (2) can also be used to determine the spin-evolution of a pulsar that converts its rotational energy into electromagnetic radiation. Following the simple arguments proposed more than forty years ago (Pacini 1968; Gunn and Ostriker 1969a; Gunn and Ostriker 1969b), it is possible to relate the electromagnetic energy loss L_{em} directly to the loss of rotational kinetic energy $E_{\rm rot}$ defined as

$$E_{\rm rot} \equiv \frac{1}{2}\int d^3\mathbf{x}\sqrt{\gamma}e^{-\Phi(r)}\rho(\delta v^{\hat{\varphi}})^2, \tag{11}$$

where ρ is the stellar energy density and factor γ is defined as follow:

$$\gamma = \left[-g_{00}\left(1+g_{ik}\frac{\delta v^i\delta v^k}{g_{00}}\right)\right]^{-1/2} \simeq e^{-\Phi},$$

$\delta v^i = dx^i/dt$ is the three velocity of conducting medium defined by Rezzolla and Ahmedov (2004), $g_{\alpha\beta}$ is the components of the spacetime metric (3), Greek indices run from 0 to 3, Latin indices from 1 to 3, and hatted quantities $(\delta v^{\hat{i}})$ are defined in the orthonormal frame carried by the static observers in the stellar interior.

Fattoyev and Piekarewicz (2010) have shown that having generated an equation of state it is easy to find pressure $p(r)$ and density $\rho(r)$ profile. In most physical models considered in the literature, for example in the paper of Fattoyev and Piekarewicz (2010) the ratio p/ρ in the crust lies in the interval $(4 \div 5)\times 10^{-3}$. As one moves towards the center of the star this ratio could increase to as large as 10%. However the moment of the inertia is very sensitive to the matter density/pressure in the crust of the star and one can assume that the condition $p/\rho \ll 1$ will approximately satisfy. This is suitable in the most physical situations and one can introduce the general relativistic moment of the inertia of the star as (see, e.g. Rezzolla and Ahmedov 2004; Abdikamalov et al. 2009; Fattoyev and Piekarewicz 2010; Stergioulas 2003; Worley et al. 2008):

$$\widetilde{I} \equiv \int d^3\mathbf{x}\sqrt{\gamma}e^{-\Phi(r)}\rho r^2\sin^2\theta, \tag{12}$$

whose Newtonian limit gives the well-known expression $I \equiv (\widetilde{I})_{\rm Newt.} = \frac{2}{5}MR^2$, the energy budget is then readily written as

$$\dot{E}_{\rm rot} \equiv \frac{d}{dt}\left(\frac{1}{2}\widetilde{I}\Omega^2\right) = -L_{em}. \tag{13}$$

Of course, in enforcing the balance (13) we are implicitly assuming all the other losses of energy (e.g. those to gravitational waves) to be negligible. This can be a reasonable approximation except during the initial stages of the pulsar's life, during which the energy losses due to emission of gravitational radiation will dominate because of the steeper dependence on the angular velocity (i.e. $\dot{E}_{\rm GW} \propto \Omega^6$).

Expression (13) can also be written in a more useful form in terms of the pulsar's most important observables: the period P and its time derivative $\dot{P} \equiv dP/dt$. In this case, in fact, using expression (2) and (13), it is not difficult to show that

$$(P\dot{P})_{\rm SS} = \left(\frac{f_R^2}{N_R^4}\right)_{\rm SS}\left(\frac{f_R^2}{N_R^4}\right)^{-1}_{\rm NS}\frac{\widetilde{I}_{\rm NS}}{\widetilde{I}_{\rm SS}}(P\dot{P})_{\rm NS}. \tag{14}$$

Also in this case it is not difficult to realize that general relativistic corrections will be introduced through the amplification of the magnetic field and of the stellar angular velocity, as well as of the stellar moment of inertia.

Considering slowly rotating magnetized neutron star one can see that the general relativistic corrections emerging in expression (2) will be partly due to the magnetic field amplification at the stellar surface and partly to the increase in the effective rotational angular velocity produced by the gravitational redshift.

General-relativistic treatment for the structure of external and internal stellar magnetic fields including numerical results has shown that the magnetic field is amplified by the monopolar part of gravitational field depending on the compactness of the relativistic star. Thus for a given compact star, the effects of general relativity on electromagnetic luminosity can be characterized only by the single compactness parameter M/R which is different for the neutron and strange star.

Let us mention so called canonical neutron star model used by many authors. This artificial model does not imply any specific EOS, but just assumes the typical values of M and R: $M = 1.4\ M_\odot$, $R = 10$ km. Using the data for the mass, the radius, the moment of inertia of neutron stars and strange stars from the recent paper Bagchi (2010) we have calculated the ratio of spin down of neutron star to one of the strange star on the base of formula (14) for the compact stars of the different masses. Results are summarized in the Table 1 from where one can see that the strange star is spinning down approximately 5 times faster that the neutron star.

Table 1 The dependence of the ratio $(P\dot{P})_{\rm SS}/(P\dot{P})_{\rm NS}$ from the different parameters of the compact object: mass (in units of solar mass), radii and moment of inertia of the Strange ($R_{\rm SS}$, $I_{\rm SS}$) and Neutron ($R_{\rm NS}$, $I_{\rm NS}$) stars. Data for strange and neutron stars are obtained from the recent paper by Bagchi (2010)

$(P\dot{P})_{\rm SS}/(P\dot{P})_{\rm NS}$	4.34463	4.53723	5.1094	6.16863
$M/M_\odot$	1.2	1.3	1.4	1.5
$R_{\rm SS}$, km	7.48	7.62	7.69	7.68
$R_{\rm NS}$, km	11.75	11.72	11.7	11.68
$I_{\rm SS}$, $\times 10^{45}$ gm cm^2	0.65	0.74	0.825	0.9
$I_{\rm NS}$, $\times 10^{45}$ gm cm^2	1.08	1.2	1.36	1.72

The pulsar period P versus period derivative $\dot{P}$ is astrophysically measured (see, e.g. Harding and Lai 2006; Manchester 2004) distinguishes the different classes of pulsars. According to the astrophysical observations the majority of pulsars have the periods of 1 s and period derivatives of 10^{-16} to 10^{-14}. Since period derivatives are in the range of about two orders one may conclude that the neutron stars have less period derivative with compare to the strange stars.

In the present paper we considered the general relativistic effects on the electromagnetic luminosity of a rotating magnetic strange star which is produced due to the rotation of the strange star with the inclined dipolar magnetic field configuration. It is shown that the effect of compactness of strange star on the electromagnetic power loss of the star is non-negligible (may have the order of tens percents of the value for the neutron star) and may help in future in distinguishing the strange star model via pulsar timing observations.

As an important application of the obtained results we have calculated energy losses of slowly rotating strange star and found that the strange star will lose more energy than typical rotating neutron star in general relativity. The obtained dependence may be combined with the astrophysical data on pulsar period slowdowns and be useful in further investigations of the possible detection/distinguish of the strange stars.

Recently Lavagetto et al. (2005a, 2005b) have shown important role of the general-relativistic effects in the evolution of low-mass X-ray binaries hosting a neutron star and of millisecond binary radio pulsars. In particular the formula for the energy released by magnetodipolar rotator obtained by Rezzolla and Ahmedov (2004) has been applied for the angular momentum loss by the neutron star at the pulsar phase of the evolution. The general relativistic formulas for the electromagnetic energy released by oscillating star can be used for the oscillation energy loss by the neutron star in the binary system when it is observed through quasiperiodic oscillations (QPOs). Development of model of QPOs in binary system hosting magnetized oscillating neutron star is other possible extension of this research.

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