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ORIGINAL ARTICLE

Plasma magnetosphere and spin down of rotating magnetized strange stars in general relativity

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Abstract It has been found that in general relativity slow down due to the energy losses through charged particles outflow in plasma magnetosphere strongly depends on star's compactness parameter and is more faster for the neutron star with comparison to that for the strange star of the same mass. Comparison with astrophysical observations on pulsars spin down precise data may provide important information about star's compactness parameter and consequently an evidence for the strange star existence and, thus, serve as a test for distinguishing it from the neutron star.

Keywords Strange star · General relativity · Spin down · Plasma magnetosphere

Among astrophysical objects which can be useful in investigating the physics under the extreme conditions particular place belongs to radio pulsars (see, for example, Lorimer and Kramer (2005)). According to the magnetospheric models radio pulsars are rotating highly magnetized neutron stars, producing radio emission above the small area of its surface called polar cap. Goldreich and Julian (1969) proved that such a rotating highly magnetized star cannot be surrounded by vacuum due to generation of strong electric field pulling out charged particles from the surface of the star. They proposed first model of the pulsar magnetosphere containing two distinct regions: the region of closed magnetic field lines, where plasma corotates with the star as a solid body, and the region of open magnetic field lines, where radial electric field is not completely screened with plasma particles and plasma may leave the neutron star along magnetic field lines. Radio emission is generated due to continuous cascade generation of electron-positron pairs in the magnetosphere above the polar cap. Thorough research on structure and physical processes in pulsar magnetosphere can be found in works of Goldreich and Julian (1969), Sturrock (1971), Mestel (1971), Ruderman and Sutherland (1975), Arons and Scharlemann (1979), Muslimov and Harding (1997). Although a self-consistent pulsar magnetosphere theory is yet to be developed, the analysis of plasma properties in the pulsar magnetosphere based on the above-mentioned papers provides firm ground for the construction of such a model.

It was shown by a number of authors that effects of general relativity play very important role in physics of pulsars. The effect of general relativistic frame dragging effect in the plasma magnetosphere was investigated in Beskin (1990, 2009), Muslimov and Tsygan (1992), Muslimov and Harding (1997), Mofiz and Ahmedov (2000), and many others, and proved to be crucial for the conditions of particle acceleration in the magnetosphere and, therefore, for generation of radio emission. The effect of the stellar oscillations on plasma magnetosphere in general relativity is recently discussed in Abdikamalov et al. (2009a), Morozova et al. (2010, 2012), Zanotti et al. (2012). From the above mentioned papers it is seen that the general relativistic ef-

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fects in the plasma magnetosphere of pulsars are not negligible and should be carefully considered.

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 (see, for example, Lorimer and Kramer (2005)). 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, outflow of the charged particles in the presence of plasma magnetosphere 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) 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 of and basic facts about neutron stars are recently reviewed by Potekhin (2010).

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, 2005), Madsen (1999), Weber et al. (2009), Xu (2003), Haensel et al. (2007), Alford and Sedrakian (2010), Sedrakian (2010a, 2010b), Cheng et al. (2013).

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. Low mass strange stars are much smaller than neutron stars and 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 (Page et al. 2006). 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 characteristic 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 (∼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.

Here we plan to extend to the magnetospheric case our preceding research (Ahmedov et al. 2012) where the possibility to distinguish neutron star from the strange star using the spin down of pulsar through vacuum magneto-dipolar emission is explored. Actually we plan to compare the spin down features of neutron star and strange star in the presence of the plasma magnetosphere and discuss if 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 plasma magnetosphere formation around strange stars is discussed in the literature (see, for the most recent discussion, Yu and Xu (2011)). Now assuming the presence of plasma magnetosphere around a rotating strange star we plan to study the spin-down of it due to the magnetospheric energy losses through plasma outflow along the open field lines.

The spacetime metric of slowly rotating relativistic star in a coordinate system (t, r, θ, φ) has the following form:

$$ds^2 = -e^{2\Phi(r)}dt^2 + e^{2\Lambda(r)}dr^2 - 2\omega(r)r^2\sin^2\theta dt d\varphi \\ + r^2 d\theta^2 + r^2\sin^2\theta d\varphi^2, \qquad (1)$$

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

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

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

Using expression from the work of Muslimov and Harding (1997) for the total power carried away by the relativistically moving particles one can calculate maximum value for luminosity:

$$(L_p)_{max} = \frac{3}{2}\kappa(1-\kappa)\dot{E}_{rot}, \qquad (3)$$

where

$$\dot{E}_{rot} \equiv \frac{1}{6}\frac{\Omega^4 B_0^2 R^6}{c^3 f_{_R}^2} = \frac{1}{f_{_R}^2}(\dot{E}_{rot})_{Newt}, \\ f_{_R} = -\frac{3R^3}{8M^3}\left[\ln N_{_R}^2 + \frac{2M}{R}\left(1 + \frac{M}{R}\right)\right], \qquad (4)$$

and $(\dot{E}_{rot})_{Newt}$ is the standard Newtonian expression for the magneto-dipole losses in flat space-time approximation, the parameter $\kappa \equiv 2I/R^3$, N_R is the quantity defined at $r = R$, $B_0 = 2\mu/R^3$ is the stellar magnetic field at the pole, μ is the magnetic dipole moment of the star.

Expression (3) could be used to investigate the rotational evolution of the star surrounded by plasma magnetosphere with predominant dipolar magnetic field anchored in the crust which converts its rotational energy into electromagnetic emission through plasma outflow along the open field lines.

The presence of a curved spacetime has the effect of decreasing the rate of energy loss through magnetospheric plasma outflow for the strange star with comparison to that for the neutron star surrounded by plasma magnetosphere by an amount which can be easily estimated to be

$$\frac{(L_{em})_{\rm SS}}{(L_{em})_{\rm NS}} = \frac{[\kappa(1-\kappa)]_{\rm SS}}{[\kappa(1-\kappa)]_{\rm NS}}\frac{(f_{_R}^2)_{NS}}{(f_{_R}^2)_{SS}}\left(\frac{R_{\rm SS}}{R_{\rm NS}}\right)^6. \qquad (5)$$

The expression for the energy loss (3) can also be used to determine the spin-evolution of a pulsar that converts its rotational energy into electromagnetic emission through plasma outflow along the open field lines. Following the simple arguments proposed more than forty years ago (Pacini 1968; Gunn and Ostriker 1969a, 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

$$E_{\rm rot} \equiv \frac{1}{2}\int d^3\mathbf{x}\sqrt{\gamma}e^{-\Phi(r)}\rho\left(\delta v^{\hat{\varphi}}\right)^2, \qquad (6)$$

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 in Rezzolla and Ahmedov (2004), $g_{\alpha\beta}$ are the components of the spacetime metric (1), 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 stationary observers in the stellar interior.

Fattoyev and Piekarewicz (2010, 2012) 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, where p is the pressure of the stellar matter. 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. 2009b; Fattoyev and Piekarewicz 2010; Stergioulas and Living 2003; Worley et al. 2008):

$$\tilde{I} \equiv \int d^3\mathbf{x}\sqrt{\gamma}e^{-\Phi(r)}\rho r^2\sin^2\theta, \qquad (7)$$

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

$$\dot{E}_{\rm rot} \equiv \frac{d}{dt}\left(\frac{1}{2}\tilde{I}\Omega^2\right) = -L_{em}. \qquad (8)$$

Of course, in enforcing the balance (8) 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, when the energy losses due to emission of gravitational radiation will dominate because of the steeper dependence on the angular velocity (i.e. $\dot{E}_{\mathrm{GW}} \propto \Omega^6$).

Expression (8) 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 (3) and (8), it is not difficult to show that

$$(P\dot{P})_{\mathrm{SS}} = \frac{\kappa_{\mathrm{SS}}}{\kappa_{\mathrm{NS}}} \frac{1-\kappa_{\mathrm{SS}}}{1-\kappa_{\mathrm{NS}}} \frac{(f_R^2)_{\mathrm{NS}}}{(f_R^2)_{\mathrm{SS}}} \left(\frac{R_{\mathrm{SS}}}{R_{\mathrm{NS}}}\right)^6 \frac{\widetilde{I}_{\mathrm{NS}}}{\widetilde{I}_{\mathrm{SS}}} (P\dot{P})_{\mathrm{NS}}. \quad (9)$$

Also in this case it is not difficult to realize that general relativistic corrections will be introduced through the magnetic field modification and the stellar moment of inertia.

Considering slowly rotating magnetized compact star one can see that the general relativistic corrections emerging in expression (3) will be partly due to the magnetic field modification at the stellar surface and partly due to the compactness parameter of the strange star.

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 (see e.g. Ginzburg and Ozernoy (1964), Ahmedov and Fattoyev (2008)). 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 the 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 formula (9) 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 slower that the neutron star.

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

$(P\dot{P})_{\mathrm{SS}}/(P\dot{P})_{\mathrm{NS}}$	0.2053	0.2165	0.2199	0.2146
$M/M_\odot$	1.2	1.3	1.4	1.5
R_{SS}, km	7.48	7.62	7.69	7.68
R_{NS}, km	11.75	11.72	11.7	11.68
I_{SS}, $\times 10^{45}$ gm cm^2	0.65	0.74	0.825	0.9
I_{NS}, $\times 10^{45}$ gm cm^2	1.08	1.2	1.36	1.72

The pulsar period for the realistic equation of state as a function of mass is studied by Bejger (2013). The decrease of the pulsar period with the increasing of the mass of the neutron star from $1.2M_\odot$ to $1.6M_\odot$ is about 15% according to Bejger (2013). The changing rate of the pulsar period is much slower than the dependence of the period derivative from the compactness of the star. Steady accretion on to a magnetized and spinning star is possible only if $P > P_{\mathrm{br}}$ ($P_{\mathrm{br}} \sim 50$ ms is the so-called break period for accreting the matter to the stelar surface with the typical parameters of star mass as $M = 1.4M_\odot$ and surface magnetic field as $B = 10^{12}$ G), when the magnetohydrodynamic (e.g. Rayleigh-Taylor and Kelvin-Helmholtz) instabilities occur at the magnetospheric boundary (Xu 2005; Arons and Lea 1976; Elsner and Lamb 1984). Before the onset of the instabilities, the accreting plasma can only penetrate into the magnetosphere by diffusion, with a rate much smaller than $\dot{M}$ (Ikhsanov 2003). The star should then be spun up by a steady accretion torque. The newborn strange stars resulted directly from accretion-induced collapse could rotate quite rapidly, and would spin-down if the accretion rates are not very high (Xu 2005). The results of study of Xu (2005) show that the strange stars surrounded by plasma magnetosphere rotate very rapidly due to the transfer of angular momentum of the accreting matter and consequently millisecond pulsars are rather strange stars than neutron ones. The pulsar period P versus period derivative $\dot{P}$ is astrophysically measured (see, e.g. Harding and Lai (2006), Manchester (2004)) and 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 strange stars surrounded by plasma magnetosphere have less period derivative with compare to the neutron 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 dipolar magnetic field configuration. It is shown that the effect of compactness of strange star on the magnetospheric power loss of the star is nonnegligible (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 in general relativity the strange star will lose less energy than typical rotating neutron star. The obtained dependence may be combined with the astrophysical data on pulsar period slow downs and be useful in further investigations of the possible detection/distinguish of the strange stars.

The total energy loss resulting from the magnetized star causing plasma outflow through the polar cap region, is determined through an integral over the whole polar cap area, and so it depends on both the kinetic energy density of the outflowing plasma and the surface area of the polar cap. Although general relativistic effects lead to some increase in the energy density of the outflowing plasma (due to the increase in the surface magnetic field strength for a given magnetic moment), the area of the polar cap is smaller in general relativity and the increasing the energy density of the outflowing plasma cannot compensate the decrease arising from the shrinking in size of the polar cap. Therefore the total energy losses of the star are significantly smaller in general relativity than in Newtonian theory. Since strange stars have bigger compactness parameter than that of neutron stars the energy loss of the strange stars is much slower.

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 either the isolated or the binary system when it is observed through quasiperiodic oscillations (QPOs). Development of model of QPOs in binary system hosting magnetized oscillating strange star is one of possible extensions of this research. Other development of this study is the construction of electrodynamic model of oscillating strange stars which were discussed, for example, in Chugunov (2006), Watts and Reddy (2007).

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