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Formation of plasma magnetosphere of neutron stars

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Magnetized neutron stars as extremely compact and massive objects have an important place around neutron stars observed as sources of radio pulsars, anomalous X-ray pulsars, and recurrent soft gamma-rays by testing various theories of gravity in the strong field regime and estimating and constraining various parameters of these theories. helps to better understand the physics of energy processes involved. It is also important to examine alternative theories of gravity. Although general relativity has been tested in many astrophysical processes and is consistent with observations and experiments, the tests have usually been performed in the weak field regime. This leaves unanswered whether the theory of general relativity is sufficient to fully describe the physics of compact gravitational objects.

I. INTRODUCTION

Compact astrophysical gravitational objects such as black holes and neutron stars (NSs) can play a role of relativistic laboratories to test the gravitational theories in the strong-field regime and which in particular can be observed as X-ray binaries, radio pulsars, soft gamma ray repeaters, etc. Radio pulsars are associated with isolated rotating highly magnetized neutron stars. The first, electrodynamics vacuum model of a rotating magnetized Newtonian star emitting electromagnetic radiation has been developed by Deutsche in his pioneering paper.[1] However, Goldreich and Julian [2] have justified that a rotating highly magnetized star cannot be surrounded by vacuum due to the generation of strong electric field pulling out charged particles from the surface of the neutron star. That is, the rotation of a strongly magnetized, highly conducting neutron star spontaneously creates a charged magnetosphere around itself. The strong magnetic field together with rotation of the star generates a very strong radial-component electric field $E_{\|} \sim 10^{10}$–$10^{12} V/cm$ on the surface of the star that forces charged particles to escape from the surface of the star and form a plasma magnetosphere around the star. Plasma charges, in turn, partially screen the radial electric field and E×B drift sets them into corotation with the star. The magnetosphere charge density which would be necessary for complete screening of E is called the co-rotation charge density or the Goldreich–Julian (GJ) density. In the region of the polar cap, magnetospheric charge does not screen parallel electric field completely, which results in continuous flow of accelerated charged particles from the surface of the polar cap responsible for later generation of radio emission from the region. It has been first proposed the model of the pulsar magnetosphere containing two distinct regions[2]: the region of closed magnetic field lines, where plasma corotates with the neutron 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 the magnetic field lines. Radio emission is generated due to continuous cascade generation of electron–positron pairs in the magnetosphere above the small area of its surface called polar cap. Analytical research on the structure and physical processes in pulsar magnetosphere depending on

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the models for the particles production and generation can be found in the literature [2]-[6]. The current numerical study is performed in, based on [7] and [8]. In fact, strong gravity effect plays an important role in the physics of pulsars and magnetars. [9]

II. PLASMA MAGNETOSPHERE OF ROTATING NEUTRON STARS

Although the rotating dipole model discussed above provides explanations for many of the observed properties of pulsars, it is based on the hypothesis that the rotator is in vacuum. As shown by Goldreich and Julian (1969), this is rather unrealistic, and the EF induced by the rotation of the magnetic moment is sufficient to pull-out charges from the stellar surface. These will then corotate with the star, forming the so-called “magnetosphere”. Many models have followed the original aligned rotator model by Goldreich and Julian (1969). However, because the latter contains the most important features which have then been shared also by more complex (and realistic) models, I will briefly describe it. Consider therefore a perfectly conducting rotating sphere threaded by an external dipolar magnetic field given by

$$\mathbf{B}_{ext} = B_p r^3 \left(\frac{\cos\theta}{r^3}\mathbf{e}_r + \frac{\sin\theta}{2r^3}\mathbf{e}_\theta \right) \tag{1}$$

Because of the perfect conductivity ($i.e.\sigma \to \infty$) in the stellar interior, Ohm’s law will be

$$\frac{\mathbf{j}_{int}}{\sigma} = 0 = \mathbf{E}_{int} + \frac{\mathbf{\Omega}\times\mathbf{r}}{c} \times \mathbf{B}_{int} \tag{2}$$

so that the interior Emagnetic fields are mutually orthogonal [$i.e.(\mathbf{E}\cdot\mathbf{B})_{int} = 0$]. Assuming now that no surface currents are present, the continuity across the stellar surface of the normal and tangential components of the magnetic field indicate that the form of the interior Emagnetic fields is

$$\mathbf{B}_{int} = B_p \left(\cos\theta\mathbf{e}_r + \frac{\sin\theta}{2}\mathbf{e}_\theta \right) \tag{3}$$

$$\mathbf{E}_{int} = \frac{\Omega R B_p \sin\theta}{c} \left(\frac{\sin\theta}{2}\mathbf{e}_r - \cos\theta\mathbf{e}_\theta \right) \tag{4}$$

Similarly, by requiring the continuity of the tangential EF we obtain

$$E^{\theta}_{ext} = -\frac{\Omega R B_p \sin\theta}{c} \frac{\partial}{\partial\theta} \left(\frac{\sin^2\theta}{2} \right) \tag{5}$$

Stated differently, the rotation of the magnetic dipole moment induces a quadrupolar electric field. Note that the EM in the exterior could well not be orthogonal and, in particular

$$(\mathbf{E}\cdot\mathbf{B})_{ext} = -\frac{\Omega R}{c} B_p^2 \left(\frac{R}{r}\right)^7 \cos^3\theta, \tag{6}$$

so that the external EF component parallel to the magnetic field will be

$$\left(\frac{\mathbf{E}\cdot\mathbf{B}}{|\mathbf{B}|}\right)_{ext} \sim \frac{\Omega R}{c} B_p \sim 2\times 10^8 \left(\frac{1sec}{P}\right) \left(\frac{B_p}{10^{12}G}\right) \tag{7}$$

The electric force acting on charged particles at the stellar surface is $\sim e\mathbf{E}_{ext}$ and is far larger than the corresponding gravitational one

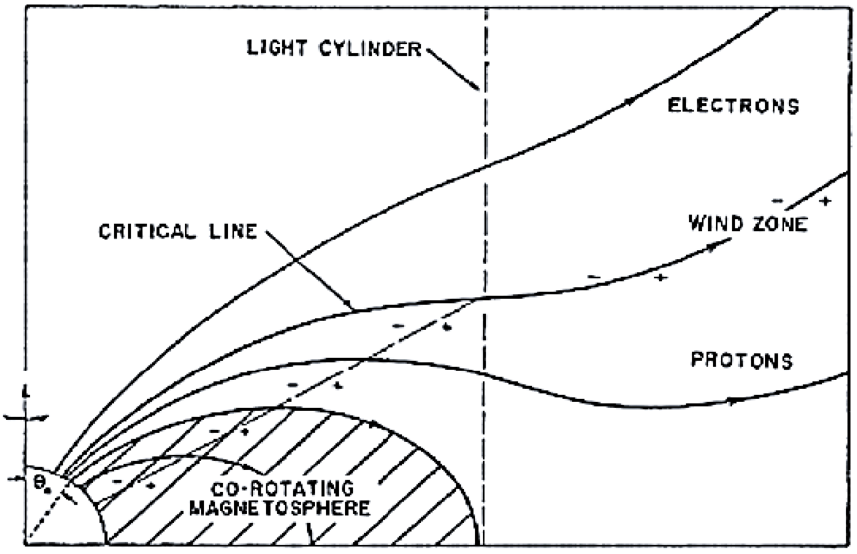

FIG. 1: Schematic representation of the magnetosphere and magnetic field lines in the aligned rotator model (from Goldreich & Julian 1969).

$$\frac{electricforce}{gravitationalforce} \sim \frac{e\Omega R B_p/c}{GMm_e/R^2} \sim 10^9. \tag{8}$$

As a result, charged particles will be extracted from the stellar surface and will fill the magnetosphere, which corotates rigidly with the star.

$$\rho_e = \frac{1}{4\pi} \bigtriangledown \cdot \mathbf{E} = \frac{1}{2\pi c} \mathbf{\Omega} \cdot \mathbf{B} \tag{9}$$

Because of corotation, the magnetic field lines of the magnetosphere will be closed out to “light cylinder” $r_c \equiv c/\Omega$. The magnetic field lines that cross are open and deflected back to form a toroidal magnetic field. Charged particles are accelerated along these lines ($\mathbf{E} \cdot \mathbf{B} \neq 0$) and stream out to infinity, producing the pulsed emission observed. As a final comment, it is useful to underline that the estimates on the strength of the magnetic field coming from the lines in the spectra of X-ray pulsars and from the spin-down measurements are in general agreement. However, new evidence is now mounting that the two observations may be sensitive to two distinct magnetic fields (either at the surface or at large distances from it) and that the two magnetic fields can also be considerably different. It is now important to discuss how the intense magnetic field can be produced, and for this a minimal approach to the equations of magnetohydrodynamics is necessary.

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