Oscillating neutron star as a pulsar

A.N. Timokhin

Sternberg Astronomical Institute,
Universitetskij pr. 13, 119992 Moscow, Russia
e-mail: atim@sai.msu.ru

Abstract
Pulsar "standard model" of rotating magnetized conducting sphere surrounded by plasma is generalized in its essential parts for the case of oscillating star. Goldreich-Julian charge density, electromagnetic energy losses as well as polar cap scenario of particle accelerations are considered. Despite similarities, there are substantial differences between magnetospheres of rotating and oscillating stars. Distortion of particle acceleration mechanism in radiopulsars by neutron star oscillations, excited by a strong glitch, for example, is discussed.

Keywords: stars:neutron – stars:oscillations – pulsars:general

1 Introduction

Neutron stars (NS) are probably the most densest objects in the Universe. It is of the great interest for fundamental physics to study their internal structure, because the matter inside the NS is under extreme physical conditions (huge density, pressure, magnetic fields), which can not be reproduced in laboratory conditions, at least in the near future. The only way to get information about the internal structure of a celestial object is to study its proper oscillations, i.e doing some kind of seismology. Such investigations would be in principle possible if two things are present: an effective mechanism for excitations of oscillations and a physical process causing changes in radiation of the celestial object due to its oscillations. NS are observed both as isolated objects (radiopulsars) and as members of binary systems (X-ray binaries). In the second case it will be very difficult to connect some observational features with proper oscillations of the NS itself, because there are a bunch of non-stationary processes connected with accretion of matter on to NS. Because of this, revealing NS oscillations in radiation of radiopulsar seems to be more promisingly. In the latter case glitches could play a role of excitation mechanism for neutron star oscillations. Almost the whole pulsar radiation is formed in the magnetosphere, so in order to be able to reveal signatures of NS oscillation in the pulsar radiation it is necessary to know how pulsar magnetosphere will be distorted by star oscillations. In this work we are considering the magnetosphere of an oscillating neutron star and trying to reveal physical mechanisms able to produce observable signatures of stellar oscillations. We consider the main properties of oscillating NS magnetosphere and
2 Goldreich-Julian charge density

As it was firstly shown by Goldreich and Julian \cite{goldreich1969}, magnetosphere of a NS is filled with charged particles. In the last thirty years model of rotating magnetized conducting sphere surrounded by non-neutral plasma became the standard model for radiopulsars. Despite difficulties of this model \cite{1970ApJ...160..821T} it is the only model describing, at least qualitatively, main properties of pulsar phenomena. According to this model, charge density of the magnetospheric plasma compensates the longitudinal electric field caused by NS rotation. The knowledge of this, so-called Goldreich-Julian, charge density allows one to study particle acceleration and emission mechanism. In the case of oscillations, charge density in the magnetosphere should compensate longitudinal electric field caused by motion of the NS surface. So, in order to make prediction about observational signatures of stellar oscillations it is necessary to generalize standard pulsar model for the case of arbitrary oscillations of the NS. Formalism of such generalization was proposed by Timokhin, Bisnovatyi-Kogan and Spruit \cite{2005ApJ...626..351T}.

We have looked for configuration of electric field $\vec{E}$ in the magnetosphere of oscillating NS such that it is orthogonal to the NS's magnetic field $\vec{B}$:

$$\vec{E} \cdot \vec{B} \equiv 0 \quad (1)$$

everywhere in the magnetosphere. Charge density supporting this electric field is the Goldreich-Julian (GJ) charge density connected with NS oscillations:

$$\rho_{\text{GJ}} = -\frac{1}{4\pi} \nabla \cdot \vec{E}. \quad (2)$$

In \cite{2005ApJ...626..351T} solution for GJ charge density for toroidal oscillation modes has been constructed. It turned out that for a half of all oscillation modes smooth charge density distribution in the whole magnetosphere could exists only if a strong current with density

$$j \approx \rho_{\text{GJ}} c \left( \frac{c}{\omega_r} \right) \quad (3)$$

is flowing along closed magnetic field lines ($\rho_{\text{GJ}}$ is the GJ charge density associated with oscillations, $\omega$ is oscillation frequency, $r$ – radius in spherical coordinate system, and $c$ is the speed of light). In this work we have constructed solution for GJ charge density for spheroidal oscillation modes, covering the most interesting physical oscillation modes ($p$-, $g$-, $r$- modes). Similar to the case of toroidal oscillations, only a half of all spheroidal modes have smooth solution without presence of a strong current flowing in the magnetosphere. This has an important implication for possible observations of NS oscillations, because this (non-stationary) current will flow in the closed field lines regions, which are invisible in radiopulsars. Hence, radiation could be produced in initially ’dead’ regions of pulsar magnetosphere. On the other hand, this will cause very rapid damping of modes producing strong magnetospheric currents.
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Figure 1: Difference between the charge density of space charge limited flow and the local Goldreich-Julian charge density along magnetic field lines in the polar cap region is shown (in arbitrary units) for three spheroidal modes with different \((l, m)\): \((64,14)\) – by the upper solid line, \((54,14)\) – by the middle solid line, \((54,2)\) – by the lower solid line. The same quantity for aligned rotator is shown by the dashed line. \(x\)-axis shows the distance \(r\) from the center of the NS in units of the NS radius \(r_{NS}\). For each oscillation mode this difference is shown along the field line where a local maximum of corresponding \(\rho_{GJ}\) is achieved. It was assumed that all modes have the same velocity amplitude and the latter is equal to the linear velocity at the equator of the aligned rotator.

3 Distortion of particle acceleration mechanism in pulsar

In open field line regions near magnetic poles Goldreich-Julian charge density associated with oscillations for both toroidal and spheroidal modes with \(l > 1\) decreases with \(r\) more rapidly than the density of particles flowing away from the polar cap. Moreover, the difference between charge density of outflowing particles and the GJ charge density increases with increasing of both \(l\) and \(m\) (see. Fig. 1). In the most popular model of space charge limited flow, where particles freely escape the surface of the NS \([4]\), this would lead to formation of a "decelerating" electric field, accelerating particles back to the NS. If this field will be of compatible strength with accelerating field due to pulsar rotation, then for a half oscillation period the resulting accelerating electric field will be stronger or weaker than in unperturbed pulsar, when rotational and oscillation GJ charge densities have different and the same signs correspondingly. This will lead to variations in both spectrum and intensity of pulsar radiation after a strong glitch. For oscillation modes with large \(l\) the corresponding GJ charge density decreases more steeper with \(r\) than GJ charge den-
sity of rotating star [3]. Because of this and increase of $\rho_{GJ}$ with $(l, m)$, decelerating electric field due to star oscillations with $l, m$ large enough could be of compatible strength with the rotational accelerating field even for surface oscillation velocity much lower than the velocity of rotation. If decelerating electric field is stronger than accelerating field due to NS rotation (such a, rather artificial, case is shown in Fig. 3), then on field lines close to a local maxima of $\rho_{GJ}$ particle acceleration will be periodically suppressed. To be able to make quantitative predictions about the threshold of oscillation velocity amplitude above which oscillation of the NS could be detected in pulsar radiation pattern one need to perform detailed investigation of electromagnetic cascade development in the polar cap region. This is outside the scope of the current work and will be subject of further investigations.

4 Electromagnetic energy losses of oscillating star

Oscillating star looses energy through electric current flowing across magnetic field lines in the open filed line regions. Accepting as an estimation for the current density $j \approx \rho_{GJ} c$ and considering self-consistently the position of the last closed field line we have got estimations for the electromagnetic energy losses of an oscillating star (see [5], where detailed consideration for toroidal modes are given). In contrast to the case of rotating star, where electromagnetic energy losses due to current flow are well described by the magnetodipolar formula, in the case of star oscillating in modes with $l > 1$ energy losses have another dependency on oscillation frequency than energy losses in vacuo and depend on oscillation velocity magnitude. For rotating oscillating star, where the position of the last closed filed line is set by rotation, damping time of oscillations substantially differs from estimations based on vacuum formulas too.

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