Plasma Magnetosphere Formation Around Oscillating Magnetized Neutron Stars

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Abstract The notion of death line of rotating pulsars is applied to model of oscillating neutron stars. It is shown that the magnetosphere of typical non-rotating oscillating stars may not contain secondary plasma to support the generation of radio emission in the region of open field lines of plasma magnetosphere.

Keywords Death line; plasma magnetosphere; oscillating neutron stars.

1 Introduction

The model describing formation of the magnetosphere around highly magnetized rotating neutron star was first proposed by Goldreich & Julian (1969). They argued that rotating magnetized neutron star cannot be surrounded by vacuum. Electric field, generated on the surface of the star due to rotation, pulls particles out of the surface and accelerates them along open magnetic field lines. Accelerated particles emit gamma rays due to curvature of magnetic field lines. Gamma rays then produce electron-positron pairs, which in turn accelerate and produce photons again. There arises a chain reaction of multiplication of electrons, positrons and gamma-ray quanta near the surface of polar cap which leads to the formation of the plasma magnetosphere.

There are, however, certain conditions limiting the values of the pulsars rotation period $P$ and the strength of magnetic field $B$ under which formation of the magnetosphere can be realized. Death line is the $P - \dot{P}$ (or $P - B$, or $P - \Phi$) diagram which indicates the region where pulsar can support radio emission from magnetosphere (here $\Phi$ is the potential of accelerating field, $\dot{P}$ means the time derivative of a period). The essence of death line is that beyond certain conditions on the period and surface magnetic field strength of the pulsar sufficient amount of secondary plasma which is responsible for radio emission cannot be generated. In this case either potential drop cannot accelerate the primary particles along magnetic field lines enough to produce high energy gamma rays, or the component of magnetic field perpendicular to gamma ray propagation is not high enough to produce the pair. The mechanism of pair creation and pulsar radio emission is thoroughly described in the papers of Erber (1966), Manchester & Taylor (1977), Ruderman & Sutherland (1975), Medin & Lai (2007).

Since its appearance in 1975 in the work of Ruderman & Sutherland (1975) the notion of death line has been reviewed and revised by many authors (see e.g. Arons & Scharlemann (1979), Chen & Ruderman (1993), Rudak & Ritter (1994)). Numerical approach to the calculation of death line for the case of dipolar magnetic field of rotating neutron star is presented by Muslimov & Harding (2002). Up to now the notion of death line is satisfied well enough and all known radio pulsars are located in the region, which is predicted by theory to be “radio-loud”, i.e. capable to produce radio emission (see Qiao et al. (2003), Zhang et al. (2000)).

Investigation of death line may help in better understanding the mechanism of radio emission from neutron stars; it can serve as a tool for checking various models of pulsar radiation. The works of Zhang et al. (2000), Zhang et al. (1999) are devoted to exploring the model...
dependence of the pulsar death lines where two different types of acceleration models are investigated in detail.

In our research we will study the death line’s formalism for oscillating non-rotating neutron stars by using approach developed by Kantor & Tsygan (2004). Our intention is to show that in the framework of present concepts of death line of pulsar one can predict that oscillating non-rotating typical neutron stars do not produce enough plasma in the region of open field lines to generate radio emission and, therefore, they are radio-quiet. However the oscillating star may have plasma magnetosphere formed in earlier stages of stellar evolution when it was rotating. According to Jones (1980) the cohesive energy of the particles on surface of a pulsar is small to prevent them escape into the magnetosphere under the vacuum electric field. But theory of pulsar activity tells that for producing radio emission there should be continuous processes of plasma formation maintained in the vicinity of the neutron star’s polar cap. This condition is not satisfied on investigated stage of neutron star’s evolution.

2 Death line application to oscillating stars

As it was shown in a number of papers (see Ruderman & Sutherland (1973), Qiao et al. (2003), Manchester & Taylor (1977)) the production of secondary plasma in the open field lines region of the pulsar may be realized if the potential accelerating the primary particle is large enough (for the inverse Compton scattering of thermal photons the Lorentz factor of primary particles must rich \( \gamma > mc^2/2kT \), where \( mc^2 \) is the particle’s rest mass, \( T \) is the temperature of the beam, \( c \) is the speed of light) and if the perpendicular to \( \gamma \)-ray component of magnetic field gets the value

\[
B_\perp = B_c \frac{0.2mc^2}{\hbar \omega} .
\]  

(1)

Here \( \hbar \omega \) is the energy of photon emitted by the primary particle and \( B_c \equiv m^2c^2/e\hbar = 4.414 \times 10^{13} \text{G} \) is the natural quantum mechanical unit for magnetic field strength (\( e \) is the charge of electron). The conditions for pair production are better satisfied at the point \( \eta_0 = 1.5\eta \), where \( \eta \) is the distance from the stellar center (in units of stellar radius) to the place where the gamma ray is emitted and \( \eta_0 \) is the place where the pair is arising. Below this condition the angle between magnetic field and \( \gamma \)-ray is small, up to this condition the strength of magnetic field is low. Using this assumption Kantor & Tsygan (2004) got the expression for the death line of radiopulsars in the following form

\[
\frac{10^{15}(1.5\eta)^3}{B_{12}\gamma mc^2} = \frac{\eta}{2} R ,
\]  

(2)

where \( B_{12} \) is the strength of pulsar magnetic field, normed on \( 10^{12} \text{G} \), \( R \) is the radius of the star.

The accelerating electric field in the region of the open field lines of the pulsar \( E \sim \Omega RB/c \), while corresponding potential drop \( \Phi \sim \Omega BR^2/c \).

Consider now non-rotating neutron star oscillating with the frequency \( \omega_{osc} \). Oscillations of the star are assumed to be toroidal, what means that the components of the oscillation velocity in spherical coordinates \((r, \theta, \phi)\) have the following form

\[
\begin{align*}
\delta v^r &= 0 , \\
\delta v^\theta &= e^{-i\omega_{osc}t} \frac{1}{\sin \theta} \partial_\theta Y_{l m}^m(\theta, \phi) , \\
\delta v^\phi &= -e^{-i\omega_{osc}t} \eta(r) \partial_\theta Y_{l m}^m(\theta, \phi) .
\end{align*}
\]

Here \( \eta(r) \) is the transversal velocity amplitude, oscillation are assumed to be small-amplitude and the magnetic field of the star has dipolar configuration.

Oscillations of the star produce electric field which in analogy with the pulsar’s accelerating electric field can be written as

\[
E_{osc} \sim \frac{\omega_{osc} \xi}{c} B = \frac{\omega_{osc} R}{c} \left( \frac{\xi}{R} \right) B = \frac{\omega_{eff} R}{c} B .
\]  

(4)

The effective frequency of stellar pulsations will be \( \omega_{eff} \sim \xi \omega_{osc} / R \), where \( \xi \) is the amplitude of oscillations.

The physical processes in the magnetosphere of oscillating neutron stars were thoroughly studied by Timokhin et. al. (2000). In particular, it was discussed an important question on formation of the region of open magnetic field lines in the magnetosphere of an oscillating star. It was shown that for every mode of oscillations the angle (on the surface of the star) of the last open field line \( \theta_0 \) should be determined self-consistently using equation for the Alfvenic surface. It was found that for oscillation modes with \( m < 3 \) the angle \( \theta_0 \) is small and expression for the Goldreich-Julian charge density in the approximation of small angles \( \theta \) may be written as

\[
\rho_{GJ} \sim \frac{B_{\|}}{R_c} \cdot \theta^m .
\]  

(5)

Accelerating scalar potential above the surface of the pulsar, which can be found by means of Poisson equation

\[
\nabla \cdot \left( \frac{1}{N} \nabla \Phi \right) = -4\pi (\rho - \rho_{GJ}) ,
\]  

(6)

where \( N \equiv (1 - 2M/r)^{1/2} \) is the gravitational lapse function and \( \rho - \rho_{GJ} \) is the effective space charge density, is proportional to \( \theta_0^2 \) for rotating neutron star. In the case of oscillating magnetized neutron star one can
find by introducing dimensionless angular variable $\theta/\theta_0$ and taking into account angular dependence of $\rho G J$ that scalar potential $\Phi \sim \theta_0^{m+2}$. Consequently, for oscillation modes with $m < 3$ accelerating scalar potential will contain additional small parameter.

Taking into account that oscillation amplitude $\xi$ is about $10^3$ times smaller than radius of star $R$ and assuming that $\theta_0 \sim 10^{-2}$ one can find that potential drop accelerating the primary particles for modes with $m < 3$ will be $10^3 \times 10^{(2m)}$ times smaller with compare to that in the case of rotating neutron stars. The result is that this potential will not be large enough to provide the primary particle with sufficient Lorentz factor to emit gamma ray which would be possible to generate a pair.

Figure 1 illustrates the situation. Dashed curve is the death line for the rotating radiopulsar in frames of the space-charge-limited flow model, adopted from the paper Kantor & Tsygan (2004). Solid line presents the death line for non-rotating oscillating neutron star. It is plotted for real (not effective) values of pulsation periods, which are $\sim 1000$ times shorter than $P_{\text{eff}}$. Using the graph one can see that radioemission from non-rotating stars may be observed only if the frequency of oscillations is rather large. Typical oscillating non-rotating stars with parameters $\omega_{\text{osc}} < 0.5$ kHz and surface magnetic field $B \sim 10^{12}$ G will lie beyond the radio-loud region. It means that plasma may not be produced in the region of open field lines of oscillating non-rotating neutron star’s magnetosphere with typical parameters. It means that vacuum electrodynamic model of oscillating stars McDermott et al. (1984), Muslimov & Tsygan (1986), Rezzolla & Ahmedov (2004)) is more preferable rather than plasma magnetosphere model Timokhin, Bisnovatyi-Kogan & Spruit (2001).

3 Conclusions

Observations of radio emission from a star’s environment are possible only in the case if the magnetosphere of the star is filled with enough amount of secondary plasma. Primary particles, extracted from the surface of the star, generate secondary plasma oscillations resulting in radio photons emission. As it is seen from our results, typical non-rotating oscillating neutron star has not enough conditions to produce secondary plasma and probably may not produce plasma magnetosphere. However magnetars Duncan (1998) with the high surface magnetic fields of order $10^{14}$ G are above solid line from figure 1. Furthermore, there is now observational evidence for stellar oscillations coming from the observation of quasi-periodic oscillations (QPOs) following giant flares of soft gamma-ray repeaters (SGRs).

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Fig. 1  Death lines for rotating radiopulsar (dashed) and for oscillating non-rotating neutron star (solid).
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