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Particle acceleration in polar cap region of neutron stars in modified gravity

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In this work, we investigate charged particles dynamics and their acceleration along open field lines coming from polar cap of rotating magnetized neutron stars due to accelerating electric field in frame of modified gravity. In the presence of the MOG parameter the charged particles reach their maximum energy at small distances than in general relativistic case n the presence of MOG parameter, the accelerated electrons from the surface of the star radiate at the distances closer to the surface than in general relativity and pair production process starts much earlier. Also, we study charged particles trajectories on the polar cap region of the magnetized neutron star for the different values of MOG parameter. We show that with increase of the MOG parameter the steps of the trajectory of the particle decreases due to the decreasing of polar cap size in the presence of MOG parameter in comparison with the general relativity. It implies electromagnetic radiation beam so-called jet phenomena smooths as the increase of the MOG parameter.

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I. INTRODUCTION

The rotating neutron stars due to their extreme properties can play a role of the relativistic laboratories and testing the alternate theories of gravity versus GR in the strong field regime through a comparison of electromagnetic fields and particle acceleration processes with the precise measurement of the pulsar's basic parameters. As for formation of plasma magnetosphere along open lines exterior to the neutron stars is concerned, it explains the electromagnetic radiation of the neutron star due to the radiative processes of the accelerated particles [1–5] ejected from its surface at the polar cap. On the other hand, the observed spin down of radio pulsars measured with high precision is related to the loss of kinetic energy of rotation of the neutron star through electromagnetic radiation of radio pulsars [6, 7]. Ignoring the decay of stellar magnetic field due to high conductivity of the stellar matter, the decrease in angular velocity causes a decrease in accelerating induced electric field near the surface, which cuts the chain reaction [8, 9] of plasma magnetosphere formation while pulsar can no longer radiate and disappears from radio observation[10]. This phenomenon is usually explained via the so-called radio pulsar death line in the two-dimensional magnetic field versus time derivative period of rotation plane [11–15]. Throughout this work we use signature $(-,+,+,+)$ for the space-time and geometrized unit system $G_{\rm N} = c = 1$ (However, for an astrophysical application we have written the speed of light explicitly in our expressions). Latin indices run from 1 to 3 and Greek ones from 0 to 3.

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II. CHARGED PARTICLE ACCELERATION IN THE POLAR CAP

One of the most mysterious unsolved questions of pulsar physics is the exact mechanism of the origin of polar cap radiations. One likely scenario was described above: magnetospheric charges are accelerated along open magnetic field lines (which are concentrated at the poles) and radiate γ-rays that subsequently generate the electron-positron pairs in the strong magnetic field. The primary beam and the pair plasma combined provide the mechanism of the electromagnetic radiation. This motivates the studies of the equations of motion of relativistic charged particles in the plasma magnetosphere of the slowly rotating magnetized neutron stars.

The equation of motion of a m-mass charged particle with charge e in an electromagnetic field has the following form [1]

$$\frac{dv^\mu}{d\tau} + \Gamma^\mu_{\nu\lambda} v^\nu v^\lambda = \frac{e}{m} F^{\mu\nu} v_\nu \ , \tag{1}$$

where $v^\mu = dx^\mu/d\tau$ is four-velocity of the particle, $\Gamma^\mu_{\nu\lambda}$ are Christoffel symbols for a given spacetime metric and τ is an arbitrary affine parameter. Since open field lines area (the polar cap) is small (with an angular size of $\sim 5^\circ$), we can use the small angle ($\theta \ll 1$) approximation for the polar cap region. Taking that into account the equations (1) and (**??**) can be rewritten as [1]

$$\begin{aligned} &\frac{N^2(\eta;\epsilon,\alpha)}{s^2}\frac{d}{ds}\left(s^2\frac{d\phi}{ds}\right) - \frac{l(l+1)}{s^2}\phi = \frac{B}{B_0}\left(\frac{j}{V} - \bar{j}\right) \ , \\ &\frac{d}{ds}\left(N(\eta;\epsilon,\alpha)\gamma\right) = \frac{1}{N^2(\eta;\epsilon,\alpha)}\frac{d\phi}{ds} \ , \end{aligned} \tag{2}$$

here l is the multipole number and the Lorentz factor γ is defined as

$$\gamma \equiv -v^\mu u_\mu = \frac{1}{\sqrt{1-V^2}} \ , \tag{3}$$

where u^μ is the four-velocity of fiducial observer, $V^i \equiv v^\mu h^i_\mu/\gamma$ is the 3-dimensional spatial velocity with the projection tensor $h^{\alpha\beta} \equiv g^{\alpha\beta} + u^\alpha u^\beta$, and for convenience we introduced the following normalized variables [1]

$$\begin{aligned} j &\equiv -\frac{2\pi N(s)\rho(s)}{\Omega B(s)} \ , \qquad \phi(s) \equiv \frac{e}{m}\Phi(s) \ , \\ \bar{j} &\equiv -\frac{2\pi N(s)\rho_{\rm GJ}(s)}{\Omega B(s)} \ , \quad s \equiv \sqrt{\frac{2\Omega B e}{mc^2}}\, r \ , \end{aligned}$$

where $B \equiv |\mathbf{B}| = B^{\hat{r}} + \mathcal{O}(\theta^2)$, Φ is the scalar potential of the electromagnetic field and ρ is the charge density on the stellar surface. In order to clarify the relationship between j and $\bar{j}$ at $\chi = 0$, we expand j in power series for small parameter $y = r/R - 1$ up to the first order in the following form [1]

$$\bar{j} \simeq \bar{j}_R \left[1 + \frac{3\omega_R}{\Omega}\frac{y}{1+\alpha}\right] \ , \tag{4}$$

where $\bar{j}_R = 1 - \frac{\omega_R}{\Omega}\frac{1}{1+\alpha}$, with $\omega_R = \omega(r = R)$. It is clear that the presence of nonzero MOG parameter provides additional radial dependence too $\bar{j}$. In Fig. 1 the dependence of Lorentz γ-factor of the accelerating relativistic charged particles on dimensionless height ($y = \eta - 1$) for different values of MOG parameter α is illustrated. Fig. 1 shows that in both cases ($j = 0.99 j_{\rm GJ}$ and $j = 1.01 j_{\rm GJ}$) Lorentz γ-factor starts to decrease at certain distances as the value of MOG parameter increases. From Fig. 1 we can see that the velocity of the charged particle is zero at closer points in comparison with GR. One can conclude that in the presence of the parameter α the charged particles reach their maximum energy at small distances than in general relativistic case. In the case $j < \bar{j}$ (at the top panel in Fig.1) the maximum value of the Lorentz factor reaches up to about 60, it means that ($50 \lesssim \gamma \lesssim 10^4$) the regime corresponds to resonance in Compton scattering in which the scattering cross-section increases significantly and thus the energy loss of the accelerated charged particle is high. Then the accelerated electrons/positrons radiate γ-rays through inverse Compton scattering with the energy enough to create $e^\pm$ pairs, i.e. $E_\gamma \geq 2m_e c^2$, in turn, the γ-rays start pair production $\gamma \to e^+ + e^-$ in the magnetic field of the star. In the presence of MOG parameter, the accelerated electrons from the surface of the star radiate at the distances closer to the surface than in general relativity and pair production process starts much earlier, because the charged particles are accelerating under two different forces: those

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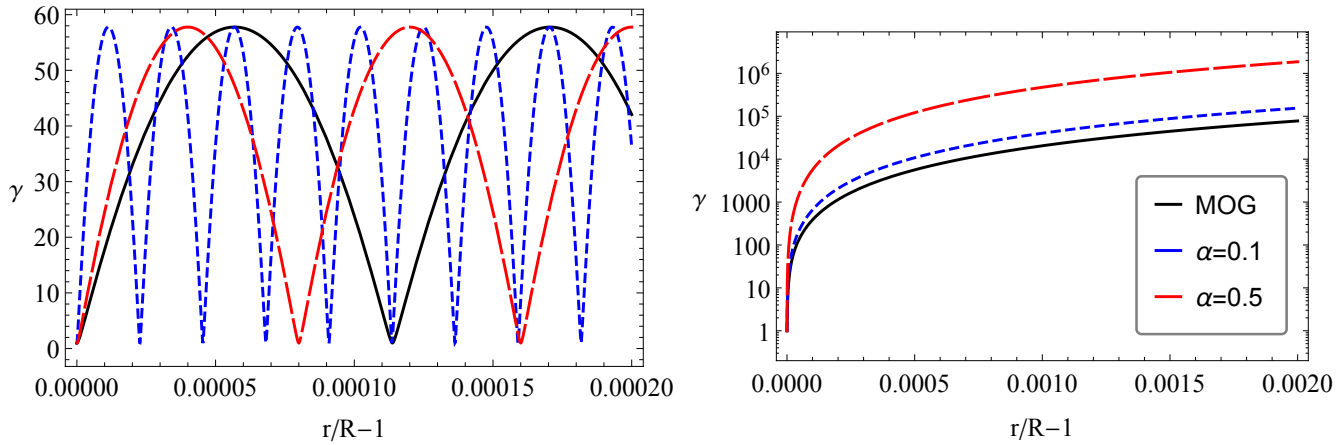


FIG. 1: Numerical solution of equations (2) and (2) for the Lorentz factor γ with different values of MOG parameter for the typical neutron star with mass $M = 2$km, radius $R = 10$km and period $P = 1$ms at the value of multipole number $l = 2$ and $\gamma_{\rm R} = \gamma_{\rm (r=R)} = 1.000001$. Top panel for the case when $j = 0.99 j_{\rm GJ}$, bottom panel for the case when $j = 1.01 j_{\rm GJ}$. In both panels gray line corresponds to GR (α) case, blue lines for $\alpha = 0.5$ and red one is for $\alpha = 1$.

of the accelerating electric field and the gravitational field of the central object. Here we test the effects of the MOG parameter on γ factor for the accelerating charged particle in a typical neutron star's polar cap region. In $j > \bar{j}$ case (the bottom panel in figure 1) the value of the Lorentz factor at large distances reaches to more than 10^6 and the curvature radiation dominates being a source of ultra-high/high energy γ photons.

According to Ref. [1] we can have

$$\frac{d\theta(\eta)}{d\eta} = \frac{B^{\hat{\theta}}}{B^{\hat{r}}} \ , \tag{5}$$

which gives the trajectory of the charged particle above the polar cap of a rotating neutron star in MOG.

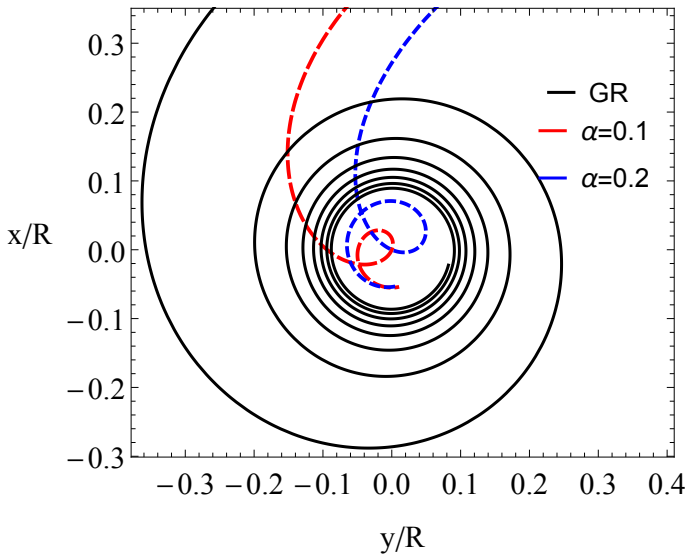


FIG. 2: Projection of charged particles' trajectory profiles above the polar cap region where magnetic field lines are open to the $x - y$ plane for the different values of MOG parameter α.

Charged particles trajectories on the polar cap region of the magnetized neutron star are illustrated in Fig. 2 for the different values of MOG parameter. One can see that with increase of the parameter α the steps of the trajectory of the particle decreases due to the decreasing of polar cap size in the presence of MOG parameter in comparison with the general relativity. It implies electromagnetic radiation beam so-called jet phenomena smooths as the increase of the parameter α.

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III. CONCLUSION

This work is devoted to investigate charged particles dynamics and their acceleration along open field lines coming from polar cap of rotating magnetized neutron stars due to accelerating electric field in frame of modified gravity. We have obtained that the velocity of the charged particle is zero at closer points in comparison with GR. It is shown that in the presence of the MOG parameter the charged particles reach their maximum energy at small distances than in general relativistic case n the presence of MOG parameter, the accelerated electrons from the surface of the star radiate at the distances closer to the surface than in general relativity and pair production process starts much earlier, because the charged particles are accelerating under two different forces: those of the accelerating electric field and the gravitational field of the central object. Also, we study charged particles trajectories on the polar cap region of the magnetized neutron star for the different values of MOG parameter. We show that with increase of the MOG parameter the steps of the trajectory of the particle decreases due to the decreasing of polar cap size in the presence of MOG parameter in comparison with the general relativity. It implies electromagnetic radiation beam so-called jet phenomena smooths as the increase of the MOG parameter.

IV. ACKNOWLEDGEMENT

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