The photon time delay in magnetized vacuum magnetosphere

A.W. Romero Jorge[†,‡], E. Rodríguez Quertz[‡], A. Pérez Martínez[‡]
aromero98@estudiantes.fisica.uh.cu, elizabeth@icimaf.cu, aurora@icimaf.cu
[†]Facultad de Física, Universidad de la Habana. [‡]ICIMAF

Introduction

• The aim of our study is to explore propagation of photons in a neutron star magnetosphere (described by magnetized vacuum).The dispersion equation is modified due to the magnetized photon self-energy in the transparency region ($0 < \omega < 2m_e$).
• the problem of light propagation in electron-positron vacuum in the presence of a magnetic field (B) is similar to the dispersion of light in an anisotropic medium, where the external field axis sets the anisotropic direction. Therefore, the photon dispersion relation is corrected by adding the polarization tensor.
• We are here interested in a photon time delay process occurring in the vicinity of the source, and unrelated with the photon interaction with matter

Details

• We use natural units: $\hbar = c = 1$
• $k^2 = k_\perp^2 - \omega^2$, photon four-momentum
• ω, frequency of the photon
• $\kappa^{(i)}$, eigenvalues of the polarization tensor
• $B_c = \dfrac{m_e^2}{e^2} = 4.41 \times 10^{13} G$, Schwinger critical field
• $m_e = 0.511$ MeV, electron mass
• Three modes of propagation: one longitudinal mode $i = 1$, that is not physical and two transverse ones $i = 2, 3$. The threshold of pair creation of second and third modes are $\omega = 2m_e$ and $\omega = m_e + \sqrt{m_e^2 + 2eB}$, respectively [2].

Contributions

• The photon time delay was calculated starting from a simple model of the magnetic field configuration in the neutron star magnetosphere
• We found that differences between the photon time delay of γ-radiation $\lesssim 1\ MeV$ is of the order of nanosecond. This difference might be due to the fact that more energetic photons interact stronger with virtual electron-positron pairs, being closer to the threshold ($\omega = 2m_e$)
• A relevant result of our work is that, contrary to the traditional time delay of photons in the interstellar medium, in the present quantum electrodynamical process the more energetic photons are delayed with respect to the lower energetic ones.

A Future Direction

• Compare our results for the photon time delay with observational data
• An interesting application could be the estimation of the distance of radiation source taking advantage of the different time delays of photons with different frequencies.

References

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Propagation of photons in a magnetized vacuum

Radiative corrections modify the photon dispersion relation, by including the photon self-energy in presence of magnetic field. The modified dispersion equations are

$$k^2 = \kappa^{(i)}(\omega, k_\parallel = 0, k_\perp, b = B/B_c),\ \ i = 2, 3 \tag{1}$$

We consider photon propagation perpendicular to the magnetic field ($\vec{k} \perp \vec{B}$). we consider only the second mode i = 2, which is more relevant in the region of transparency, since it does not depend on the magnetic field.
For a large range of frequencies, the solution of the dispersion equation corresponds to relatively small deviations from the light-cone, $k^2 \ll eB$, except for values of $\omega^2 - k_\parallel^2$ extremely close to the vacuum threshold for pair creation [2] . In this case, we can write the photon self-energy eigenvalues as polynomials in k^2, $\kappa_i = \sum_{l=0}^{\infty} \chi_{il}(\omega, B)(k^2)^l$, where the functions $\chi(\omega, B)$ are calculate in [3] . If we truncate the first four terms of the power series, for $j = 3$ we obtain a cubic equation in k^2, we solve it with the aid of hypergeometric functions [4] The dispersion equation and the photon phase velocity takes the form

$$k_\perp^2 - \omega^2 = -\sum_{j_2,\ldots,j_n=0}^{\infty} \frac{(-1)^{j_1} j_1!}{(j_0+1)! j_2! \ldots j_n!} \frac{\chi_{i0}^{j_0+1} \chi_{i2}^{j_2} \ldots \chi_{in}^{j_n}}{(\chi_{i1} - 1)^{j_1+1}} \tag{2}$$

where $j_0 = j_2 + 2j_3 + \ldots + (n-1)j_n$, $j_1 = 2j_2 + 3j_3 + \ldots + nj_n$,

$$v_{ph}(\omega, B) = \frac{\omega}{k_\perp} = \left(1 - \frac{k^2}{\omega^2}\right)^{-1/2} \tag{3}$$

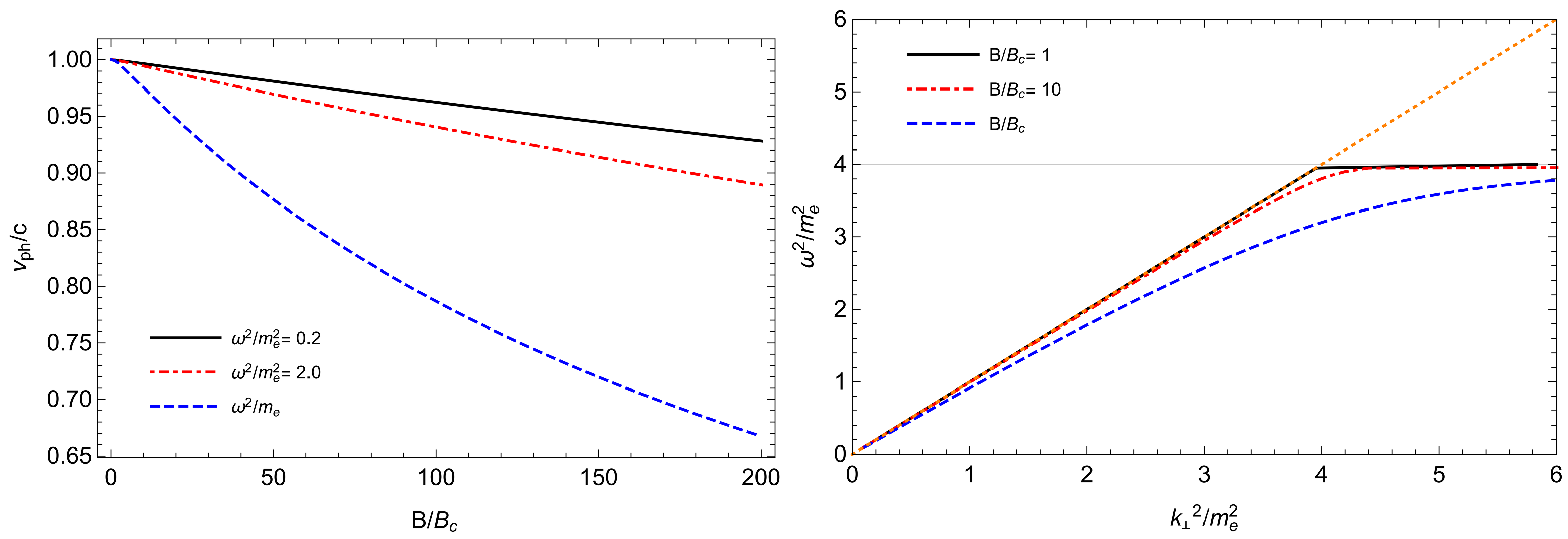

Figure 1: Left: Phase velocity in function of the magnetic field for different frequencies **Right:**Dispersion relation for selected values of the magnetic field strength

Photon time delay in magnetosphere. Results

To calculate the photons time delay when crossing the magnetosphere (magnetized vacuum), for different energies, we consider a magnetic dipole configuration [5]:

$$B(r) = B_0 \left(\frac{r_0}{r}\right)^3, \tag{4}$$

where B_0 and r_0 are, respectively, the surface magnetic field and radius of the neutron star.
We can compute the time delay of the radiation crossing the magnetosphere of the pulsars given by the expression

$$\tau = \int_{r_o}^{r} \frac{dr}{v_{ph}(\omega, B(r))}. \tag{5}$$

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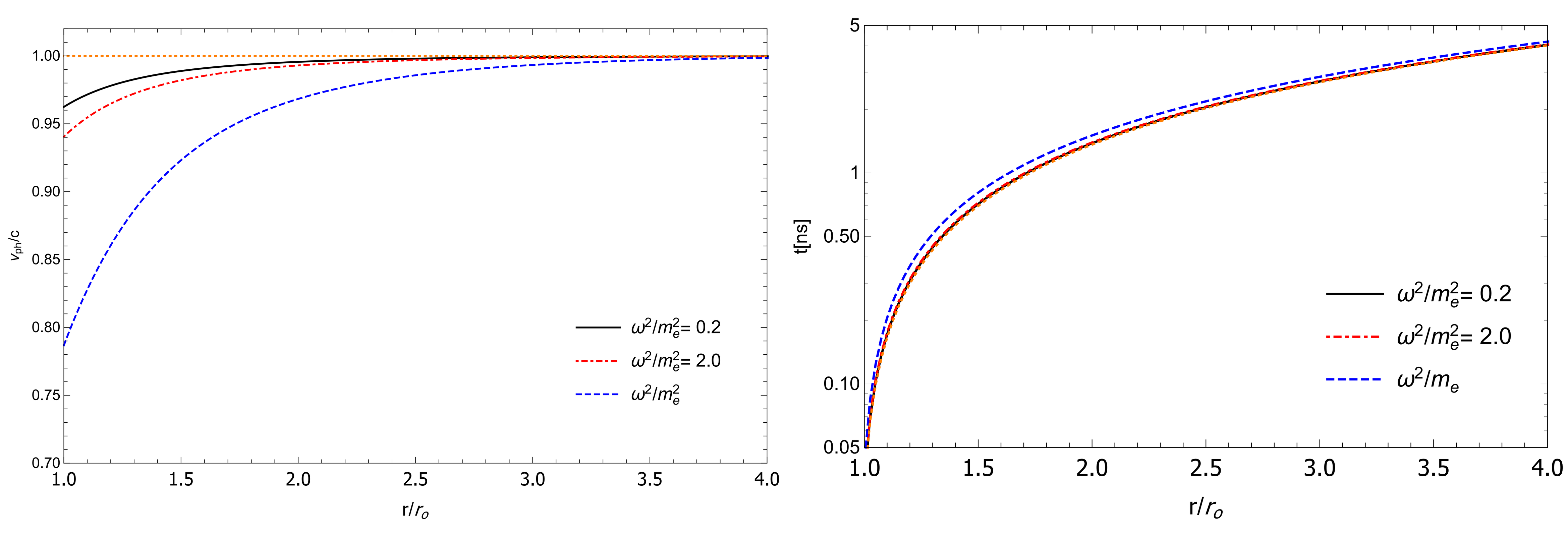

Figure 2: Left: Phase velocity as a function of the distance traveled by the photons for different frequencies ($B_0 = 100B_c$) **Right:**Time delay of photons for fixed values of frequencies ($B_0 = 100B_c$)