Effect of Scalar Photon Interaction in a Magnetized Media

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Introduction

Usually scalar (ϕ) photon (γ) interaction through dim-5 operators originates in many theories beyond standard model of particle physics. Scalar photon interaction turns vacuum into a birefringent and dichoric one [1] and as a result, when a plane polarized light passes through such a medium, its plane of polarization rotates, making the vacuum optically active. The main motivation behind the studies of these theories, is to estimate the magnitude of the dimensionful coupling constant that is present in the interaction term of the Lagrangian/Hamiltonian. In this note, we propose a novel way to do the same from the observed polarization spectra of compact astrophysical objects like White Dwarves (WD) and Neutron Stars(NS). Dim-5 photon scalar coupling as such is responsible for, energy ω dependent optical activty and production of circular or elliptic polarization from plane polarized light. However, in the stellar environment of compact stars, the energy ω of nonthermal photons (γ) are emitted via curvature radiation (*that is plane polarized too*). The energy ω of the produced γ at any point depends on the distance of that point from the surface of the compact star. Therefore, though the radiation for different ω would originate at different points in space but their detection point, as observed, would remain the same. Therefore an energy dependent path difference gets automatically introduced to the nonthermal radiation spectra of such objects. For an extremely cold and compact star the later contribution can be estiamted. Hence one can analyse the polarimetric data (i.e stokes I, Q, U, V) for such objects to find signatures of dim-5, ϕFF coupling. In this note we have also evaluated the polarization angle Ψ and the ellipticity angle χ , that the propagating beam of light generates at different ω, upon propagation through a distance z. Interestingly enough, while performing the analysis we find the existence of identical values of (Ψ) and (χ) for multiple values of (ω), when the distance travelled by the beam is the same. The details of these issues are discussed later.

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Equations of Motion.

The action for coupled scalar photon interaction in flat four dimensional space-time is given by:

$$S = \int d^4x[\frac{1}{2}(\partial_\mu\phi)(\partial^\mu\phi) -\frac{1}{4}g_{\phi\gamma\gamma}\phi F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}] \tag{1}$$

. Where ϕ is the scalar field, $g_{\phi\gamma\gamma}$ is the coupling constant for scalar photon system, $F_{\mu\nu}$ is the EM field tensor that can be decomposed as $F^{\mu\nu} = \bar{F}^{\mu\nu} + f^{\mu\nu}$, where $\bar{F}^{\mu\nu}$ is the background field and $f^{\mu\nu}$ is the fluctuation with magnitude same as ϕ. By applying variational principle the equations of motion for electromagnetic field and scalar field and retaining terms those are linear in fluctuations one can derive the equations of motion. Further more introducing two new variables $\psi = f^{\nu\lambda}\bar{F}_{\nu\lambda}$ and $\tilde{\psi} = f_{\mu\nu}\tilde{F}^{\mu\nu}$ and after going to momentum space, we can write the equations of motion (assuming only $\bar{F}^{12} \neq 0$) in matrix form:

$$\begin{pmatrix} k^2 & 0 & 0 \\ 0 & k^2-\Omega & 0 \\ 0 & 0 & k^2+\Omega \end{pmatrix} \begin{pmatrix} \tilde{\psi} \\ \frac{\Phi+\psi}{\sqrt{2}} \\ \frac{\Phi-\psi}{\sqrt{2}} \end{pmatrix} = 0 \tag{2}$$

Here we have used a shorthand notation $g_{\gamma\gamma\phi}\mathcal{B}sin\Theta\omega = \Omega$ for simplicity. In order to

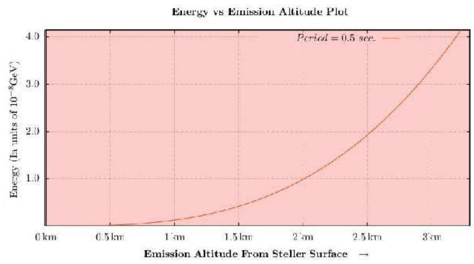

FIG. 1: Plot Of Emission altitude versus energy of emitted synchrotron radiation, for a relatively cold compact star(WD) with dipolar magnetic field stregth $\sim 10^{13}$, Gauss and period 0.5 sec.

evaluate the polarimetric variables (Stokes parameters), one can construct the coherency matrix by taking different correlations of the vector potentials or the fields [2]. Various optical parameters of interest like polarization, ellipticity and degree of polarization of a given light beam, can be found out from the values of the Stokes parameters, constructed from the components of the coherency matrix. The Stokes parameters are:

$$\begin{aligned} \mathrm{I} &= <\psi^*\psi> + <\tilde{\psi}^*\tilde{\psi}>, \\ \mathrm{Q} &= <\psi^*\psi> - <\tilde{\psi}^*\tilde{\psi}>, \\ \mathrm{U} &= 2\mathrm{Re} <\psi^*\tilde{\psi}>, \\ \mathrm{V} &= 2\,\mathrm{Im} <\psi^*\tilde{\psi}>. \end{aligned} \quad (3)$$

Astrophysical Implications: Compact as-

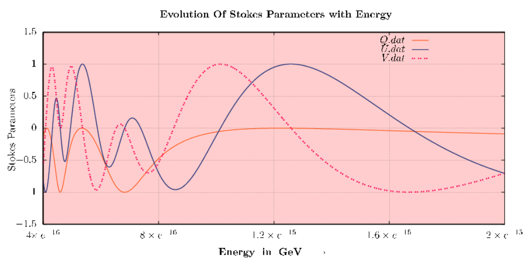

FIG. 2: Plots for Stokes parameters, Q (orange line), U (blue line) and V (dotted line) versus ω for $g_{\gamma\gamma\phi} = 10^{-11} GeV^{-1}$ and $\mathcal{B} = 4.41 \times 10^{13}$ Gauss.

trophysical objects like WD pulsar, or NS pulsar are associated with very strong dipole magnetic field. The rotating magnetic dipole induces an electric field of magnitude $E_{||} \simeq \frac{1}{8\sqrt{3}} (\Omega R)^{\frac{5}{2}} eB_s$ in the corotating magnetosphere of the compact object. Where eB_s is the surface magnetic field, Ω and R are the angular velocity and radius of the compact star. It is possible to estimate the Lorentz factor Γ form $E_{||}$ [5]. Charged particles with Lorentz factor Γ, emit curvature photon with energy $\omega = \frac{3\Gamma^3}{2R_c}$,where R_c is the radius of curvature of the field lines [3, 4]. We have plotted emission altitude vs energy in [1] for a compact star of radius 10 km and period 0.5 second and $B_s \sim 10^{13}$Gauss (see [5], for further details). Our numerical estimates show that, the ω reaches $\sim 10^{-8}$GeV pretty close to the surface (within 2 km height) of the star; and increases as one moves further away. We have evaluated and plotted the stokes parameters Q, U and V for ω around 10^{-15}GeV, in [2] (for details see [5]) . The plot shows how an initially plane polarized light develops, linear to circular to elliptic polarization for changes in ω. Numerical estimates of ellipticity angle (χ), and the polarization angle defined by [2] $\tan 2\chi = \frac{\mathrm{V}}{\sqrt{\mathrm{Q}^2+\mathrm{U}^2}}$, and $\tan 2\Psi = \frac{\mathrm{U}}{\mathrm{Q}}$ shows that both (χ) and Ψ are multiple valued functions of ω. To conclude, ϕFF is capable of generating circular polarizatin from plane polarized curvature radiation. If it's detected, then one can initiate further studies to find out the magnitude of the coupling constant.

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