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Redshift modification of pulsars and magnetars by relativistic plasmas and vacuum polarization

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ABSTRACT

The redshifts of emissions from pulsars and magnetars consist of two components: gravitational and non-gravitational redshifts. The latter results from the electromagnetic and kinetic effects of relativistic plasmas, characterized by refractive indices and streaming velocities of the media, respectively. The vacuum polarization effect induced by strong magnetic fields can modify the refractive indices of the media, and thus leads to a modification to the redshifts. The Gordon effective metric is introduced to study the redshifts of emissions. The modification of the gravitational redshift, caused by the effects of relativistic plasmas and vacuum polarization, is obtained.

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1. Introduction

Since the first pulsar was observed by Jocelyn Bell and Anthony Hewish in 1967, people established different models to describe the dynamics of pulsars, such as the neutron star and strange star models [1–5]. Theoretically, the mass-to-radius ratios (M/R) of stars are different for the neutron star and strange star. Thus, the stellar mass-to-radius ratio can manifest the constituents of the cores of stars. According to present researches, measuring the gravitational redshifts z of spectral lines is the most straightforward method of determining the mass-to-radius ratio, which gives $M/R = (c^2/2G)[1-(1+z)^{-2}]$, where G is the gravitational constant. Up to now, people already identified some spectral lines from pulsars and magnetars and inferred the redshifts of these lines. In 2002, Cottam et al. reported the discovery of significant absorption lines in the spectra of the low-mass X-ray binary EXO 0748-676, with most of the features associated with Fe^{26} and Fe^{25} $n = 2$–3 and O^8 $n = 1$–2 transitions, all at a redshift $z = 0.35$ [6]. Identification of absorption lines was also achieved by Sanwal et al. in the isolated neutron star 1E 1207.4-5209 [7]. The lines were found to correspond to energies 0.7 and 1.4 keV, which are interpreted as the atomic transition of singly ionized helium in a strong magnetic field. The inferred redshift is 0.12–0.23. Tiengo et al. discovered a redshifted X-ray emission line centered at about 19.2 Å in the symbiotic neutron star binary 4U 1700+24 [8]. They gave two possible interpretations for this line: the Ly-α transition of O^8 at redshift $z \simeq 0.012$ or the Ne^9 triplet at redshifts $z \sim 0.4$. These observations provide an opportunity to measure the mass-to-radius ratio and hence constrain the equation of state of the superdense matter in the stellar core. However, the above spectral analyses are usually based on an assumption that the redshifts of emission lines are uniquely produced by the gravitational field. It should be noticed that the redshifts of spectral lines also include the frequency shifts caused by other effects. Mosquera Cuesta and Salim pointed out that non-linear electrodynamics effects produced by the superstrong magnetic field of pulsars can modify gravitational redshifts [9,10]. Ji et al. suggested that the electromagnetic and dynamic effects of magnetoplasma can affect redshifts of spectral lines [11]. Hence, a correct procedure to estimate the mass-to-radius ratio and the equation of state of a compact star from the gravitational redshifts demands a separation of non-gravitational redshifts from the pure gravitational ones.

It is well known that pulsars and magnetars possess extremely strong magnetic fields and are surrounded by magnetospheres consisted of relativistic electron–positron pair plasmas [12–16]. The emissions of stars first propagate through the pair plasmas, and then attain to the observers. Thus the action of the relativistic moving pair plasmas on the emissions should be taken into account. From the viewpoint of physics, a “dragging” effect of relativistic pair plasmas gives rise to a transfer of energies and momenta to photons traveling in the plasmas, and thus leads to frequency shifting of photons. The problem of frequency shifts

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of photons has been studied in the laboratory environment for a long time, when photons propagate through a relativistic charged-particle fluid [17–20]. From the viewpoint of geometry, the propagation of photons in a moving medium can be described as photons following zero-geodesic lines in a curved space–time resulted from the moving medium [21–24]. For photons, they really experience the effect of localized curved space–time which is caused by moving media. This is analogous to the case in which the action of a gravitational field on any particles can be described as particles moving in a curved space–time caused by the gravitational field. In 1923, Gordon established a fascinating analogy between moving media and gravitational fields [21,22]. He formulated the electromagnetism in moving media in terms of an effective gravitational field (an effective metric). In this case, the propagation of light in a moving medium can be described as light transmitting in a curved space–time characterized by the Gordon metric. Therefore, the Gordon effective metric, generalized to weak-dispersive media, is introduced to study the redshifts of emissions from pulsars and magnetars in this Letter. The results show that, except for the gravitational redshift, there is also the non-gravitational redshift for the emissions from pulsars and magnetars. The non-gravitational redshift depends on the four-vector velocity u_μ and the dispersion relation of moving media. Furthermore, the vacuum becomes birefringent in the super-strong magnetic field [25,26]. The vacuum polarization effect will modify the dispersion relation of the medium, and thus modify the redshifts of emissions. Therefore the modification of redshifts caused by the vacuum polarization effect is particularly considered in this Letter.

The paper is organized as follows. In Section 2, the redshifts of emissions produced at the surface of pulsars and magnetars are analyzed using the Gordon metric theory. In Section 3, the modification of the gravitational redshifts, caused by magnetized pair plasmas and vacuum polarization, is calculated in detail. Finally, some discussions and conclusions are given in Section 4.

2. Modification of the gravitational redshift

The change in the frequency of electromagnetic radiation in a gravitational field is predicted by Einstein's general relativity. The redshift is often denoted with a dimensionless variable z, defined as the fractional change of the wavelength or frequency,

$$z=\frac{\lambda_o-\lambda_e}{\lambda_e}=\frac{\nu_e-\nu_o}{\nu_o}, \tag{1}$$

where λ_e (ν_e) and λ_o (ν_o) are wavelengths (frequencies) of photons as measured by the emitter and observer respectively. Particles moving in the space–time with static metrics are governed by the localized energy conservation law $|g_{00}(r)|^{1/2}E_{\text{local}}=\text{const.}$ [27], where E_{local} is the localized energy of particles and $g_{00}(r)$ is the time–time component of the metric tensor. For photons, $|g_{00}(r)|^{1/2}\nu_{\text{local}}=\text{const.}$, so Eq. (1) can be written as

$$1+z=\frac{\nu_e}{\nu_o}=\sqrt{\frac{g_{00}(o)}{g_{00}(e)}}, \tag{2}$$

where $g_{00}(e)$ and $g_{00}(o)$ are the time–time components of the gravitational metrics at the emitter and the observer respectively. The above formula (2) indicates that the essence of gravitational redshift is the change of space–time measurement resulted from the difference of gravitational fields at the emitter and the observer. In the spherically symmetric Schwarzschild gravitational field, $g_{00}(e)=1-2GM/(c^2R)$. Thus, the gravitational redshift of the emission radiated from the stellar surface can be expressed as

$$1+z=\left[1-\frac{2GM}{c^2R}\right]^{-\frac{1}{2}}. \tag{3}$$

For a typical pulsar with the mass $M\approx 1.4M_\odot$, where $M_\odot$ is the mass of the Sun, and the radius $R\sim 10$ km, the gravitational redshift is $z\approx 0.31$.

The magnetospheres of pulsars and magnetars consist of relativistic electron–positron pairs stream outward with a relativistic velocity [12–16]. When the emissions propagate through the pair plasmas, the electromagnetic interaction between relativistic plasmas and emissions will lead to non-gravitational frequency shifts of emissions. In this Letter, Gordon effective metric is introduced to deal with the interaction between the emission and the gravitation, as well as the electromagnetic interaction between the emission and the medium. Namely, the moving media and the gravitational field are together treated as the geometry of a curved space–time, and the trajectories of photons are interpreted as null geodesics of this new space–time.

Gordon metric is deduced from Maxwell's equations in a curved space–time, which is defined as [21,22]

$$G_{\mu\nu}=g_{\mu\nu}+\left(\frac{1}{n^2}-1\right)u_\mu u_\nu, \tag{4}$$

where $g_{\mu\nu}$ is the gravitational metric which can be reduced to Minkowski metric $\eta_{\mu\nu}=\text{diag}(1,-1,-1,-1)$ when no gravity, n is the refractive index of the medium, and $u_\mu=\gamma(1,-\boldsymbol{V}/c)$ is the four-vector velocity of the medium ($\boldsymbol{V}$ is the three-dimensional velocity of medium seen by a distant static observer, with the Lorentz factor $\gamma=(1-\beta^2)^{-1/2}$, where $\beta=V/c$). It should be pointed out that Gordon metric was presented originally for the light propagating in a moving non-dispersive medium. However, the Gordon metric can be generalized to a weak-dispersive medium (see Appendix A in detail), if the susceptibility of the medium $|\chi|\ll 1$. Light traveling in a weak-dispersive medium can be described equivalently as light propagating in a curved space–time characterized by an effective metric under an external field specified by an effective potential A^μ. In such case, the kinetic momentum of a photon, $dx^\mu/d\lambda=(\omega/c,\boldsymbol{k})$, is no longer following null geodesics due to the dispersive effect of the medium, while the canonical momentum, $K^\mu=dx^\mu/d\lambda-A^\mu=(\omega/c-A^0,\boldsymbol{k}-\boldsymbol{A})$, is governed by the geodesics equation, where λ is the affine parameter along the ray, $\boldsymbol{k}$ and $\boldsymbol{A}$ are three-dimensional wave vector and effective potential respectively. Thus the Gordon metric is still valid as an effective metric in the cases of light propagating in a weak-dispersive medium, but it is required that an effective potential is added because of the dispersive effect.

The redshift of the emission contributed by the effects of the gravitational field and the moving medium around pulsars is now corrected as

$$1+\tilde{z}=\frac{\Omega_e}{\Omega_o}=\sqrt{\frac{G_{00}(o)}{G_{00}(e)}}, \tag{5}$$

where $G_{00}(e)$ and $G_{00}(o)$ denote the time–time components of Gordon metrics at the emitter and the observer respectively, Ω_e and Ω_o are the time–time components of canonical momenta of photons at the emitter and the observer respectively, called the canonical frequencies, and $\tilde{z}$ is the redshift for the canonical frequency. The above formula (5) can be further written as

$$\frac{\nu_e-\frac{cA^0}{2\pi}}{\nu_o}=1+z-\frac{cA^0}{2\pi\nu_o}=\sqrt{\frac{G_{00}(o)}{G_{00}(e)}}. \tag{6}$$

Inserting Eq. (4) into the above formula, one obtains

$$1+z\simeq\left[g_{00}(e)+\left(\frac{1}{n^2}-1\right)u_0u_0\right]^{-\frac{1}{2}}+\frac{cA^0}{2\pi\nu_o}, \tag{7}$$

where $A^0=\chi'\tilde{\omega}^2u^0/(2c^2)$, $\chi'=c(\partial\chi/\partial\tilde{\omega})$, and $\tilde{\omega}$ is the local photon frequency in the co-moving frame with the medium (see

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