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Pulsar polarization measurements and the nonsymmetric gravitational theory

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Because of the breakdown of the Einstein equivalence principle in the nonsymmetric gravitational theory (NGT) of Moffat, orthogonally polarized electromagnetic waves can propagate at different velocities in a gravitational field. Moffat has proposed that galactic dark matter, in the form of cosmions, may act as a significant source of gravity in the NGT. We discuss how observations of the highly polarized radiation from distant pulsars could provide significant limits on the strength of the coupling of cosmions in the NGT.

I. INTRODUCTION AND SUMMARY

In the nonsymmetric gravitational theory (NGT) of Moffat [1], which is based upon a nonsymmetric metric, fermions play a key role in generating the antisymmetric part of the metric. When the theory is coupled to the laws of electromagnetism, violations of the Einstein equivalence principle (EEP) can occur which depend upon the strength of the coupling of fermions in the NGT [2–5]. In addition to violating the principle of the equality of free-fall for test bodies [known as the weak equivalence principle (WEP)], other violations of the EEP can occur. In particular, Gabriel *et al.* have shown in detail how orthogonally polarized electromagnetic waves can propagate at different velocities [4]. In this paper, we apply this result to pulsar observations and determine the limits which can be placed upon the coupling of galactic cosmions in the NGT.

The violation of the WEP for test bodies having different electromagnetic binding energies can be avoided in the NGT by carefully designing the way in which the metric couples to the electromagnetic field [3]. Nonetheless, test bodies may still fall at different rates because of the explicit coupling of the NGT to fermion number. The total fermion number of a body is expressed in terms of a parameter l, having the dimensions of length, according to

$$l^2=\sum_i f_i^2 \int n_i d^3x \,, \tag{1}$$

where n_i is the number density of the ith type of fermion with coupling constant f_i^2. Sensitive laboratory experiments which test the composition dependence of the accelerations of test bodies in a gravitational field have thus provided strong limits on f^2 for normal matter [6].

The theory could still be of interest for explaining certain astrophysical observations provided that sufficient galactic dark matter exists in the form of cosmions, weakly interacting massive particles which have been proposed to solve simultaneously the problems of missing galactic matter and missing solar neutrinos (for reviews, see Ref. [7]). Both problems may be solved provided that the cosmion has a mass of between 4 and 15 GeV and a galactic density of roughly 0.1 cm^{-3}. For a cosmion density in the Sun which is 10^{-11} of the baryon density, Moffat has proposed a cosmion coupling constant in the NGT of $f_c^2=8.75\times10^{-30}$ cm^2. Spacecraft flybys of Jupiter may limit $f_c^2<6.60\times10^{-30}$ cm^2 (Ref. [8]). However, this limit is dependent upon the core density of Jupiter and the related cosmion evaporation rate. A limit of $f_c^2<6.83\times10^{-30}$ cm^2 can be inferred from atomic-clock tests performed in the solar gravitational field [5].

From the recent results of Gabriel *et al.*, it can be shown that a tighter limit on the cosmion coupling constant may be provided by pulsar observations. These authors used a generalized form of the gravitationally modified laws of electromagnetism to investigate the coupling of the NGT to electromagnetic waves. Prior to Gabriel *et al.*, Ni investigated the coupling of gravity to electromagnetism using an alternative generalized model called the χ-g framework [9,10]. In this framework, it can be shown that for general gravitational couplings the propagation velocity of an electromagnetic wave is polarization dependent. Ni discussed how this dependence could be severely constrained by pulsar observations. The pulses emitted are generally highly polarized, where the polarization may vary significantly between primary pulses or subpulses (for a review, see Ref. [11]; a more detailed discussion can be found in Ref. [12]). Because the relative delay observed between differently polarized pulses can be as small as a millisecond, or even smaller for microstructure in individual pulses, orthogonal polarizations must travel between the pulsar and Earth at the same velocity to high accuracy. In the following, it is shown that galactic pulsars thus could limit $f_c^2 < 10^{-30}$ cm^2 and that more distant pulsars in the Magellanic Clouds could tighten this limit by at least an order of magnitude.

II. PULSAR POLARIZATION OBSERVATIONS

In an isotropic coordinate frame centered upon a static, spherically symmetric body, Gabriel *et al.* have shown that two orthogonal, linearly polarized plane electromagnetic waves can suffer a relative delay given by (to first order)

$$c\delta t = \tfrac{1}{2} \int L^2(r) \sin^2\theta ds \,, \tag{2.1}$$

where the line integral is to be evaluated along the path between emission and reception, and θ is the angle between the direction of propagation and a vector pointing away from the body. Interior and exterior to a uniform, spherical distribution of fermions, the function $L(r)$ is given by

$$L(r) = \begin{cases} l^2 R^{-3} r & \text{interior}\,, & (2.2\text{a}) \\ l^2 r^{-2} & \text{exterior}\,, & (2.2\text{b}) \end{cases}$$

where R is the radius of the distribution. Specializing to a galactic distribution of cosmions, we have $l^2 = (4\pi/3) \times R^3 f_c^2 n_c$. With the origin of our coordinate system placed at the galactic center, and using the geometry shown in Fig. (1a), Eqs. (2.1) and (2.2a) yield

$$c\delta t = \tfrac{1}{2} (l^2 R^{-3})^2 p^2 d \,, \tag{2.3}$$

where $p = x_e \sin\alpha$. The angle α is related to conventional galactic longitude λ by $\alpha = 360° - \lambda$. Solving for f_c^2, where we take the distance from the galactic center to Earth to be $x_e = 10$ kpc, and assuming a nominal cosmion density of $n_c = 0.1$ cm^{-3},

$$f_c^2 = 1.079 \times 10^{-29} (\delta t / d \sin^2\lambda)^{1/2} \text{cm}^2 \,, \tag{2.4}$$

where δt is in milliseconds and d is in kiloparsecs. This equation can be used to limit f_c^2 from pulsar polarization observations.

If we consider the well-known Crab pulsar (PSR 0531+21), for example, with galactic longitude and latitude (184.6°, −5.8°), $d = 2.2$ kpc, and take $\delta t < 1$ ms, then $f_c^2 < 9 \times 10^{-29}$ cm^2. This is a weak limit. However,

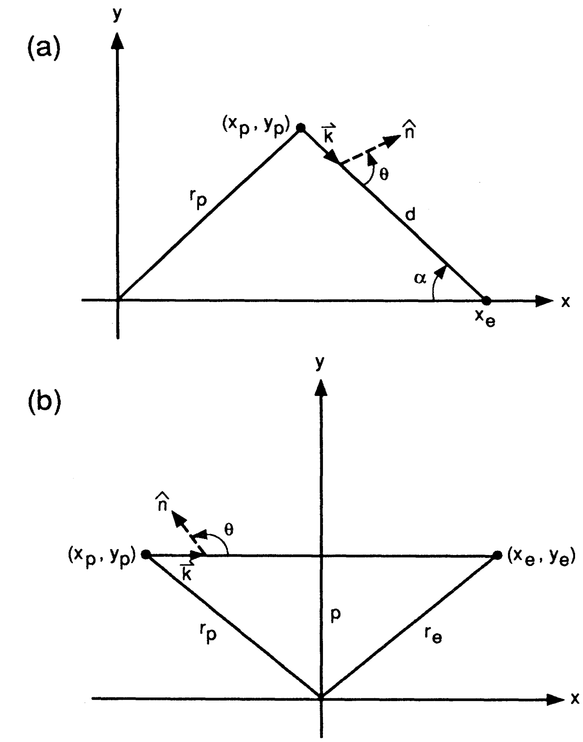

FIG. 1. (a) Convenient geometry for performing the integration of Eq. (2.1) inside a uniform, spherical distribution of galactic cosmions. The coordinate system is to be centered upon the galactic center, with the pulsar located at the point (x_p, y_p) and Earth located on the x axis at the point x_e. d is the distance between Earth and the pulsar, while r_p is the distance of the pulsar from the galactic center. θ is the angle made between the wave vector of a signal emitted by the pulsar and a unit vector $\hat{\mathbf{n}}$ directed away from the galactic center. If the coordinate system is placed in the galactic plane, then the angle θ is related to conventional galactic longitude λ by $\alpha = 360° - \lambda$. (b) Alternate geometry for performing the integration of Eq. (2.1) exterior to a uniform, spherical distribution of cosmions. The coordinate system is to be centered upon the galactic center, with Earth located at (x_e, y_e) and the pulsar located at (x_p, y_p). The ray impact parameter p denotes the distance of closest approach of the signal to the galactic center.

several pulsars are observed at distances of $d > 10$ kpc (a compilation of pulsars discovered up until 1989 March can be found in Ref. [11]). Taking $\lambda = 50°$, because a deep Arecibo survey was concentrated upon this longitude, there results $f_c^2 < 4.5 \times 10^{-30}$ cm^2, an interesting limit.

The most distant pulsars are two which have been observed in the Small and Large Magellanic Clouds (SMC and LMC), respectively (not counting the possible existence of a pulsar in the remnant of supernova 1987A in the LMC). In the above analysis, it has been assumed that the cosmions in our Galaxy are distributed in a uniform sphere about the center, whose radius is roughly 25 kpc. Because the SMC and the LMC reside outside of this sphere at distances of roughly 60 and 50 kpc, respectively, it is necessary to evaluate Eq. (2.1) using Eq.

(2.2b). In this case, it is useful to use the geometry shown in Fig. 1(b). The result is

$$c\delta t = \tfrac{1}{2} l^4 p^2 I(x_p, x_e) , \tag{2.5a}$$

$$I(x_p,x_e) = \left[\frac{x}{4p^2(p^2+x^2)^2} + \frac{x}{8p^4(p^2+x^2)} + \frac{3}{8p^5} \arctan\left(\frac{x}{p}\right) \right] \Bigg|_{x_p}^{x_e} . \tag{2.5b}$$

For signals propagating from the Magellanic Clouds, the total delay can be obtained by combining Eq. (2.5) for the delay external to the Milky Way cosmion distribution and Eq. (2.3) for the interior delay. The coordinates of each galaxy pertaining to Fig. 1 were determined from their galactic longitude and latitude, which are $(280°, -33°)_{\rm LMC}$ and $(303°, -45°)_{\rm SMC}$. For each galaxy, the results were approximately the same:

$$\delta t_{\rm tot} = \delta t_{\rm int} + \delta t_{\rm ext} , \tag{2.6a}$$

$$\delta t_{\rm int} = 2\times 10^{59} (f_c/{\rm cm})^4 \ {\rm ms} , \tag{2.6b}$$

$$\delta t_{\rm ext} = 1\times 10^{62} (f_c/{\rm cm})^4 \ {\rm ms} . \tag{2.6c}$$

Solving for f_c^2, there results the limit $f_c^2 < 10^{-31} (\delta t_{\rm tot})^{1/2}$ cm^2, a tight limit for $\delta t_{\rm tot} < 1$ ms.

III. CONCLUSIONS

We have determined that polarization measurements of distant pulsars could provide stringent limits on the strength of the coupling of cosmions in the NGT. This could have a significant impact upon the ability of the theory to explain certain observations. In the past, Moffat has proposed that the theory could account for the precession of the perihelion of Mercury for the case of a large solar quadrupole moment. However, strong evidence is mounting from recent solar oscillation measurements that the quadrupole moment is not significantly larger than the value expected from uniform rotation [13]. When this result is combined with the results of continued radar ranging to Mercury [14], no corrections to the prediction of standard general relativity are found to be necessary. Moffat has also proposed that the NGT could explain the anomalous apsidal motion seen in certain massive binaries. However, with stringent limits placed upon the coupling of the NGT to normal matter and possibly to cosmions as well, the predictions of the theory would not differ significantly from general relativity for these systems.

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