Limits on C and P violation in gravitation from SN 1987A data

L. D. Almeida, G. E. A. Matsas, and A. A. Natale
Instituto de Física Teórica, Universidade Estadual Paulista, 01405 Rua Pamplona 145, São Paulo, São Paulo, Brazil
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We show that the analyses of Longo and Krauss and Tremaine which determine limits on the equivalence principle from SN 1987A data, can be used to constrain the existence of C and P violation in gravitation.

Recently Longo[1] and Krauss and Tremaine,[2] using data from supernova 1987A, were able to fix new precise limits to the equivalence principle. Basically they used the difference between the arrival time of neutrinos and photons. It was concluded that neutrinos and photons see the same gravitationally induced time delay to about 0.2%. This idea can be used to verify a possible nonconservation of discrete symmetries (C, P, and T) in the gravitational interaction. The possibility of nonconservation of these symmetries in gravitation was investigated in some works[3-6] before the appearance of SN 1987A, in which generalizations of the gravitational potential violating C, P, or T were supposed to exist.

Let us introduce the potential

$$U_{CPT}(\mathbf{r})=\frac{GM}{r}\left[A_1\boldsymbol{\sigma}\cdot\hat{\mathbf{r}}+A_2\boldsymbol{\sigma}\cdot\frac{\mathbf{v}}{c}+A_3\hat{\mathbf{r}}\cdot\left[\frac{\mathbf{v}}{c}\times\boldsymbol{\sigma}\right]\right], \tag{1}$$

where A_1, A_2, and A_3 are dimensionless constants and are supposed to be much smaller than unity. M is the source mass and $\boldsymbol{\sigma}$ ($\mathbf{v}$) is the particle spin (velocity). The first term in (1) was proposed originally by Leitner and Okubo[3] and violates P and T conservation, the second term violates P and C conservation and the last one violates C and T. Note that the potential as a whole conserves the CPT symmetry and violates the weak equivalence principle (yielding different potentials for particles of different spin). We stress also that other families of potentials with, say $1/r^n$ dependence are possible,[5,6] although we used $n=1$ following Ref. 3 because these terms produce long-range predominant effects. Leitner and Okubo[3] determined an upper limit to A_1 by studying the hyperfine splitting of the ground state ($^1S_{1/2}$) of the hydrogen atom and found that $A_1 \le 10^{-11}$. On the other hand, as far as we know there is no upper limit to A_2 yet. As first noticed by Hari Dass[6] a better determination of A_2 and A_3 must involve relativistic particles ($v \approx c$).

In this work we use the light and neutrinos trajectories bending effect produced by the galactic gravitational field to fix an upper limit to A_2 [the last term of Eq. (1) obviously vanishes]. Using (1) we write the total potential as

$$U(\mathbf{r})=U_0(r)(1+A_1\boldsymbol{\sigma}\cdot\hat{\mathbf{r}}+A_2\boldsymbol{\sigma}\cdot\mathbf{v}), \tag{2}$$

where $U_0(r)=M/r$ and we have set $c=G=1$.

A sketch of the situation is shown in Fig. 1. Using the Schwarzschild line element in isotropic coordinates[7] we can calculate the time spent by a massless particle to reach Earth:

$$\Delta t \simeq \int_{-x_S}^{x_E}[1-2U_0(R)]dx, \quad R=\sqrt{x^2+b^2}, \tag{3}$$

where M is the mass of the Galaxy and $r=R(1+M/2R)^2$. The integration line in (3) is approximated by the straight line (Fig. 1) because the deflection angle between the former and the geodesic is of order 10^{-3} rad. Another approximation used in (3) was that, following Eddington and Robertson,[7,8] we have set $M/R \ll 1$ ($<10^{-6}$ in our case). If we suppose U_{CPT} as a perturbation on U_0 then it is natural to expect that (3) will be modified to

$$\Delta t \simeq \int_{-x_S}^{x_E}[1-2U(R)]dx. \tag{4}$$

This procedure resembles parametrized-post-Newtonian (PPN) formalism where new parameters are introduced on the original potential. Since $U(R)$ has spin terms then by (4), Δt for photons and neutrinos will be different. It was measured that the SN 1987A photons arrived between 5 h earlier and 3 h later than the neutrinos.[1] To be conservative, we will adopt Longo's estimate[1] and choose $|\Delta T|=|\Delta t_\nu-\Delta t_\gamma|\le 6$ h. Introducing (2) into (4) we get

$$|\Delta T| \simeq 2M|\sigma_\nu-\sigma_\gamma| \times\left|\int_{-x_S}^{x_E}\left[A_1\frac{x}{x^2+b^2}+A_2\frac{1}{\sqrt{x^2+b^2}}\right]dx\right|. \tag{5}$$

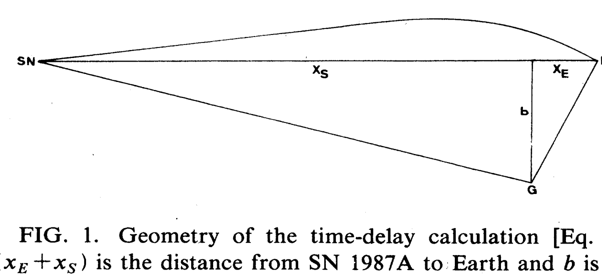

FIG. 1. Geometry of the time-delay calculation [Eq. (3)] (x_E+x_S) is the distance from SN 1987A to Earth and b is the impact parameter of photons and neutrinos.

Assuming the Galaxy mass $M = 6\times 10^{11}\ M_{\odot} = 8.8\times 10^{16}$ cm, $x_S = 50$ kpc, $b = 12$ kpc, and $x_E/b \ll 1$ we obtain

$$|\sigma_\nu - \sigma_\gamma||1.5A_1 - 2.1A_2| \le 3.6\times 10^{-3}\ . \tag{6}$$

Note that σ_γ depends on the polarization chosen for the photons, but will not modify the order of magnitude. It is worthwhile mentioning that the numerical agreement between the limit of Eq. (6) and the limits (2b) of Ref. 1 and (3) of Ref. 2 is not a coincidence, and the relation between these can be seen if we assume γ of Ref. 2 equal to 1 and interpret $U(\mathbf{r})$ as our generalized potential (2). Then our spin variables play the role of the PPN parameter γ of Refs. 1 and 2. If we saturate (6) setting $A_2 = 0$ we get $|A_1| \le 10^{-3}$ which is worse than Leitner and Okubo's estimate.[3] Setting $A_1 = 0$ (or $< 10^{-11}$) on the other hand, we obtain $|A_2| \le 10^{-3}$ which is a new constraint on A_2.

On the basis of SN 1987A data, the bending of the light and neutrinos trajectories leads to an estimate for C and P symmetry breaking in gravitation. We used the potential (1) because it is expected to produce the predominant long-range effect. This potential yields a result consistent with the observed difference time $|\Delta T| \le 6$ h if $|A_2| \le 10^{-3}$ (Ref. 9).

Note added. It has been suggested that studies of time differences for the two light polarization states from a pulsar have the possibility of producing better limits for the violation of C, P, or T symmetries in gravitation. For this study it would be necessary to know the gravitational potential the light (or radio) signal from the pulsar travel through, and to have a good temporal resolution of the light (or radio) peaks. We are currently studying this possibility.

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[9] Note that if neutrinos have a small mass m it is possible to use (3) yet because its time delay would suffer a very small increment of order $m^2(x_E + x_S)/2E^2 \sim 30$ sec (E is the neutrinos' energy), see, for example, E. W. Kolb, A. J. Stebbins, and M. S. Turner, Phys. Rev. D **35**, 3598 (1987); **36**, 3820 (1987).