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UPPER LIMIT FOR THE ELECTRIC CHARGE OF THE PHOTONS
FROM THE MILLISECOND PULSAR 1937+21 OBSERVATIONS

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The period τ (1.5578 ... ms) of the pulsar 1937+21 has been measured, by now, for more than 4 years by the Princeton-Arecibo group¹⁾, and it is determined with a precision of $\Delta\tau/\tau \lesssim 10^{-14}$.

In order to obtain such an astonishing result the time of arrival of the narrow spikes of radiation was corrected not only for the motion of the Earth and for the gravitational frequency-shifts, but also for the so-called dispersion, i.e. the delay due to the index of refraction created by the presence of free electrons (10^{-1} - 10^{-2} cm⁻³) in the galactic path between the source and the Earth (about 5 kpc)²⁾. The time taken by the photons to reach the Earth is then given by the following expression:

$$t = \frac{S}{c} + \frac{D}{f^2} ,$$

where S is the distance of the pulsar from the Earth, f the frequency (Hz) of the radiowave, and D (s⁻¹) is the dispersion measure. By observing the pulsar at two frequencies, $f_1 = 1.408$ GHz and $f_2 = 2.380$ GHz, it has been found that for pulsar 1937+21

$$D = (29.479 \pm 0.001) \times 10^{16} \text{ s}^{-1} .$$

This precision measurement indicates that the two photons, f_1 and f_2 , are emitted at the peak of the pulsar light curve simultaneously within

$$\Delta t = \frac{\Delta D}{f^2} = \frac{D}{f^2} \frac{\Delta D}{D} = \frac{3 \times 10^{17}}{(2 \times 10^9)^2} \frac{1}{29479} = 10^{-5.6} \text{ s} \approx 2 \text{ } \mu\text{s} ,$$

where

$$f = \frac{1}{2} (f_1 + f_2) \approx 2 \text{ GHz} .$$

The aim of this note is to show that the simultaneity, within Δt , maintained by the two photons after a travel lasting $t = S/c = 10^{11.7} \text{ s} \approx 10^4$ years, across a galactic space filled with magnetic fields of a few microgauss, indicates that the photons cannot have an electric charge larger than about 10^{-32} times that of the electron.

Though zero charge is expected for photons, an experimental zero with 32 significant decimals seems to be interesting enough to warrant notice.

To calculate this limit, we are going to use the same formalism introduced to establish an upper limit for the electric charge of the neutrinos from the 1987 supernova³).

If B (tesla) is the uniform magnetic field normal to the path of the photons of charge q (e) and energy E (GeV), the radius of curvature of the photon trajectory (in metres) is

$$r = \frac{E}{0.3Bq} .$$

The length of the arc, $r\theta$, followed by the photon is longer than the straight path, S , by

$$\delta S = r\theta - 2r \sin \frac{\theta}{2} \rightarrow S \frac{\theta^2}{24} \quad (\theta = \frac{S}{r} \ll 1) .$$

The difference in length of the trajectory of two photons of average energy $E = hf$, differing in energy by ΔE , is then

$$\frac{\Delta S}{S} = \frac{\Delta t}{t} = \frac{1}{12} \frac{(0.3BSq)^2}{E^2} \frac{\Delta E}{E} ,$$

where $t = S/c$ and Δt is the difference in the arrival time of the photons on Earth. As a conclusion:

$$\frac{q}{e} \leq \frac{12^{1/2}}{0.3} \frac{E}{BS} \left(\frac{\Delta t/t}{\Delta E/E} \right)^{1/2} = 10^{-22.8} \frac{(f/1 \text{ GHz})}{(S/1 \text{ kpc})(B/1 \text{ } \mu\text{G})} \left(\frac{\Delta t/t}{\Delta f/f} \right)^{1/2} .$$

The pulsar in question, at $19^{\text{h}}37^{\text{m}}$ right-ascension and 21° North declination is, similarly to the Sun, near the galactic plane, about 60° off the galactic centre, hence in a direction, seen from the Earth, not parallel to the spiral arm. Since the galactic magnetic fields, of a few μG , run mostly along the spiral arms, the field B normal to the photon trajectory is a fraction of the total field, say $B \approx 1 \text{ } \mu\text{G}$. With

$$f = 2 \text{ GHz} , \quad \left[\begin{array}{l} S = 5 \text{ kpc} \\ t = 10^{11.7} \text{ s} \end{array} \right. \quad \frac{\Delta f}{f} \approx \frac{1}{2} \quad \text{and} \quad \frac{\Delta t}{t} = \frac{10^{-5.6}}{10^{11.7}} = 10^{-17.3} ,$$

the above equation gives

$$\frac{g}{e} \lesssim 2 \times 10^{-32} .$$

To appreciate the significance of this limit consider, for example, the ratio R , independent of distance, between the electric and the gravitational force. For the electrons

$$R_e = \frac{e^2}{Gm_e^2} \simeq 10^{42} .$$

For a photon of zero charge, the same ratio is, of course, zero. For 2 GHz photons of charge not zero, but $\lesssim 10^{-32}e$, and energy equivalent to $hf/c^2 = 10^{-11}m_e$, the ratio is

$$R_{\text{photons}} \lesssim 1 ,$$

and hence the electric force between these photons is weaker than that due to gravitation.

Finally, it is perhaps worth noticing that the same difference Δt (2 μ s) discussed previously cannot be interpreted as a delay due to a finite mass of the photons. This is because the group velocity of the photons (from which the dispersion measure is derived) is

$$\beta_{\text{group}} = 1 - \frac{1}{2} \frac{f_p^2}{f^2} \quad (f \gg f_p) ,$$

where f_p , the plasma frequency, is equal to $9 \times 10^3 N_e^{1/2}$ Hz, N_e (cm^{-3}) being the number density of free electrons. This expression is formally equivalent to that of the relativistic velocity of a body of energy $E = hf$ and mass $m = E/\gamma$ ($\gamma \gg 1$):

$$\beta = 1 - \frac{1}{2} \frac{1}{\gamma^2} .$$

Consequently the limit of the mass is, as shown by Feinberg⁴⁾,

$$m \lesssim \frac{hf}{c^2} p \approx 10^{-16} m_e .$$

Only a precise determination of the free-electron density N_e along the whole trajectory could discriminate, within the dispersion measure, the contribution of a smaller, non-zero mass.

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