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Photon mass limits from fast radio bursts

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We dedicate this paper to the memory of Lev Okun, an expert on photon mass

ABSTRACT

The frequency-dependent time delays in fast radio bursts (FRBs) can be used to constrain the photon mass, if the FRB redshifts are known, but the similarity between the frequency dependences of dispersion due to plasma effects and a photon mass complicates the derivation of a limit on m_γ. The dispersion measure (DM) of FRB 150418 is known to $\sim 0.1\%$, and there is a claim to have measured its redshift with an accuracy of $\sim 2\%$, but the strength of the constraint on m_γ is limited by uncertainties in the modelling of the host galaxy and the Milky Way, as well as possible inhomogeneities in the intergalactic medium (IGM). Allowing for these uncertainties, the recent data on FRB 150418 indicate that $m_\gamma \lesssim 1.8 \times 10^{-14}$ eV c^{-2} (3.2×10^{-50} kg), if FRB 150418 indeed has a redshift $z = 0.492$ as initially reported. In the future, the different redshift dependences of the plasma and photon mass contributions to DM can be used to improve the sensitivity to m_γ if more FRB redshifts are measured. For a fixed fractional uncertainty in the extra-galactic contribution to the DM of an FRB, one with a lower redshift would provide greater sensitivity to m_γ.

When setting an upper limit on the photon mass, the Particle Data Group (PDG) [1] cites the outcome of modelling the solar system magnetic field: first at 1 AU, $m_\gamma < 5.6 \times 10^{-17}$ eV c^{-2} ($= 10^{-52}$ kg) [2,3], and later at 40 AU, $m_\gamma < 8.4 \times 10^{-19}$ eV c^{-2} ($= 1.5 \times 10^{-54}$ kg) [2]. However, the laboratory upper limit is four orders of magnitude larger [4]; for reviews see [5,6]. In [6], the authors state the concern that "*Quoted photon-mass limits have at times been overly optimistic in the strengths of their characterizations. This is perhaps due to the temptation to assert too strongly something one 'knows' to be true*". This concern was mainly addressed to the galactic magnetic field model limits [7], but it should be borne in mind also when assessing the solar system limits.

Indeed, the estimates on the deviations from Ampère's law in the solar wind [2,3] are not based simply on *in situ* measurements. For example: (i) the magnetic field is assumed to be exactly, always and everywhere a Parker spiral; (ii) the accuracy of particle data measurements from, *e.g.*, Pioneer or Voyager, has not been discussed; (iii) there is no error analysis, nor data presentation, instead; (iv) there is extensive use of a *reductio ad absurdum* approach based on earlier results of other authors, which are often devoted to other issues than establishing a basis for an extremely difficult measurement of a mass that is many orders of magnitude lower than that of an electron or a neutrino.

In order to check these estimates of the solar wind at 1 AU, a more experimental approach has been pursued via a thorough analysis of Cluster data [8], leading to a mass upper limit lying between 1.4×10^{-49} and 3.4×10^{-51} kg, according to the estimated potential. The difference between the results of this conservative approach and previous estimates, as well as the need for astrophysical modelling, motivates the development of additional methods for constraining the photon mass.

The time structures of electromagnetic emissions from astrophysical sources at cosmological distances have been used to constrain other aspects of photon/electromagnetic wave propagation,

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such a possible Lorentz-violating energy/frequency dependence of the velocity of light *in vacuo* [9–13], and the possibility of dispersion in photon velocities of fixed energy/frequency, as suggested by some models of quantum gravity and space–time foam [14,15]. Similarly, the gravitational waves recently observed by Advanced LIGO from the source GW150914 have been used to constrain aspects of graviton/gravitational wave propagation, including an upper limit on the graviton mass: $m_g < 1.2 \times 10^{-22}$ eV c^{-2} ($= 2.1 \times 10^{-58}$ kg) [16,17] and limits on Lorentz violation [18,19], and the possible observation by Fermi of an associated γ-ray pulse [20] suggests that light and gravitational waves have the same velocities to within 10^{-17} [18,21].

The time structures of electromagnetic emissions from astrophysical sources at cosmological distances can also be used to derive an upper limit on the photon mass, m_γ. Since the effect of the photon mass on the velocity of light is enhanced at low frequency ν (energy E): $\Delta v \propto -m_\gamma^2 c^4/h^2\nu^2$ ($-m_\gamma^2 c^4/E^2$), measurements of time structures at low frequency or energy are particularly sensitive to m_γ. For this reason, measurements of short time structures in radio emissions from sources at cosmological distances are especially powerful for constraining m_γ. This is to be contrasted with probes of Lorentz violation, for instance, where measurements of high-energy photons such as γ rays are at a premium. This is why probes of the photon mass using gamma-ray bursters (GRBs) [22] and active galactic nuclei (AGNs) have not been competitive in constraining m_γ. As we mention later, a stronger limit can be obtained by using the apparent coincidence of a radio afterglow with a GRB, but this is also not competitive with the sensitivity offered by fast radio bursts (FRBs).

FRBs are potentially very interesting because their radio signals have well-measured time delays that exhibit the $1/\nu^2$ dependence expected for both the free electron density along the line of sight and mass effects on photon propagation. Until recently, the drawback was that no FRB had had its redshift measured, though there was considerable evidence that they occurred at cosmological distances. This has now changed with FRB 150418 [23], which has been reported to have occurred in a galaxy with a well-measured redshift $z = 0.492 \pm 0.008$. The identification of its host galaxy has been questioned, and the alternative possibility of a coincidence with an AGN flare has been raised [24], though the likelihood of this is currently an open question [25]. In the following we assume the host galaxy identification made in [23], and also discuss more generally how non-galactic FRBs could be used to constrain photon propagation.

The frequency-dependent time lag of FRB 150418 between the arrivals of pulses with $\nu_1 = 1.2$ GHz and $\nu_2 = 1.5$ GHz is $\Delta t_{12}^{\rm FRB} \approx 0.8$ s, and was used in [23] to extract very accurately the dispersion measure (DM), which is given in the absence of a photon mass by the integrated column density of free electrons along the propagation path of a radio signal, $\int n_e dl$. The delay of an electromagnetic wave with frequency ν propagating through a plasma with an electron density n_e, relative to a signal in a vacuum, makes the following frequency-dependent contribution to the time delay [26,27]

$$\Delta t_{\rm DM} = \int \frac{dl}{c}\frac{\nu_p^2}{2\nu^2} = 415\left(\frac{\nu}{1\ {\rm GHz}}\right)^{-2}\frac{\rm DM}{10^5\ {\rm pc\,cm^{-3}}}\ {\rm s}, \qquad (1)$$

where $\nu_p = (n_e e^2/\pi m_e)^{1/2} = 8.98 \cdot 10^3 n_e^{1/2}$ Hz (cgs units). As is discussed in [23], plasma effects with DM = 776.2(5) cm^{-3} pc could be responsible for the entire $\Delta t_{12}^{\rm FRB}$ that was measured.[1]

There are contributions to the DM of this extragalactic object from the free electron density in the host galaxy, estimated to be ~ 37 cm^{-3} pc, from the Milky Way and its halo, estimated to be 219 cm^{-3} pc, and the intergalactic medium (IGM). Subtracting the other contributions, the IGM contribution to the DM was estimated to be $\simeq 520$ cm^{-3} pc, with uncertainties ~ 38 cm^{-3} pc from the modelling of the Milky Way using NE2001 [28][2] and ~ 100 cm^{-3} pc from inhomogeneities in the IGM. The DM$_{\rm IGM}$ contribution to the dispersion delay (1) for a source at red shift z can be expressed in terms of the density fraction $\Omega_{\rm IGM}$ of ionized baryons [26]:

$$\mathrm{DM_{IGM}} = \frac{3cH_0\Omega_{\rm IGM}}{8\pi G m_p} H_e(z), \qquad (2)$$

where H_0 is the present Hubble expansion rate, G is the Newton constant, m_p is the proton mass, and the factor

$$H_e(z) \equiv \int_0^z \frac{(1+z')dz'}{\sqrt{\Omega_\Lambda + (1+z')^3\Omega_m}}, \qquad (3)$$

takes proper account of the time stretching in (1) and evolution of the free-electron density due to the cosmological expansion [26,27,10,30]. The relation (2) was used in [23] to estimate the density of ionized baryons in the IGM: $\Omega_{\rm IGM}^{\rm FRB} = 0.049 \pm 0.013$, assuming that the helium fraction in the IGM has the cosmological value of 24%. We also assume that the present cosmological constant density fraction $\Omega_\Lambda = 0.714$ and the present matter density fraction $\Omega_m = 0.286$, and set the reduced Hubble expansion rate, $h_0 \equiv H_0/(100\ {\rm km\,s^{-1}\,Mpc^{-1}}) = 0.69$ [31]. This measurement of $\Omega_{\rm IGM}$ is quite compatible with the density expected within standard ΛCDM cosmology [31]: $\Omega_{\rm IGM}^{\Lambda\rm CDM} = 0.041 \pm 0.002$.

The measurement of $\Delta t_{12}^{\rm FRB}$ can also be used to constrain the photon mass. For this purpose, we note that the difference in distance covered by two particles emitted by an object at a red shift z with velocity difference Δu is

$$\Delta L = H_0^{-1}\int_0^z \frac{\Delta u dz'}{\sqrt{\Omega_\Lambda + (1+z')^3\Omega_m}}. \qquad (4)$$

In case of the cosmological propagation of two massive photons with energies $E_2 > E_1$ the velocity difference is

$$\Delta u_{m_\gamma} = \frac{m_\gamma^2}{2(1+z)^2}\left(\frac{1}{E_1^2} - \frac{1}{E_2^2}\right), \qquad (5)$$

where the red shifts of the photon energies are taken into account and we use units: $\hbar = c = k = 1$. Thus, difference in arrival times of two photons of different energies from a remote cosmological object due to a non-zero photon mass can be parametrized as follows:

$$\Delta t_{\rm lag} = \frac{m_\gamma^2}{2H_0}\cdot F(E_1,E_2)\cdot H_\gamma(z) + \Delta t_{\rm DM} + b_{\rm sf}(1+z), \qquad (6)$$

where $F(E_1,E_2) \equiv \left(\frac{1}{E_1^2} - \frac{1}{E_2^2}\right)$,

$$H_\gamma(z) \equiv \int_0^z \frac{dz'}{(1+z')^2\sqrt{\Omega_\Lambda + (1+z')^3\Omega_m}}, \qquad (7)$$

[1] In [23] a different method has been used to obtain the DM value. However, for this letter it is enough to compare the arrival times of these two frequencies, which reproduces quite accurately the result of [23].

[2] For limitations of NE2001, see [29].