Robust Limits on Photon Mass from Statistical Samples of Extragalactic Radio Pulsars

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Abstract. The photon zero-mass hypothesis has been investigated for a long time using the frequency-dependent time delays of radio emissions from astrophysical sources. However, the search for a rest mass of the photon has been hindered by the similarity between the frequency-dependent dispersions due to the plasma and nonzero photon mass effects. Considering the contributions to the observed dispersion measure from both the plasma and nonzero photon mass effects, and assuming the dispersion induced by the plasma effect is an unknown constant, we obtain a robust limit on the photon mass by directly fitting a combination of the dispersion measures of radio sources. Using the observed dispersion measures from two statistical samples of extragalactic pulsars, here we show that at the 68% confidence level, the constraints on the photon mass can be as low as $m_\gamma \leq 1.51 \times 10^{-48}$ kg $\approx 8.47 \times 10^{-13}$ eV/c$^2$ for the sample of 22 radio pulsars in the Large Magellanic Cloud and $m_\gamma \leq 1.58 \times 10^{-48}$ kg $\approx 8.86 \times 10^{-13}$ eV/c$^2$ for the other sample of 5 radio pulsars in the Small Magellanic Cloud, which are comparable with that obtained by a single extragalactic pulsar. Furthermore, the statistical approach presented here can also be used when more fast radio bursts with known redshifts are detected in the future.

Keywords: radio pulsars, intergalactic media

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1 Introduction

A basic assumption of Maxwell’s electromagnetism as well as Einstein’s special relativity is the constant speed $c$, in a vacuum, of all electromagnetic radiation. That is, the photon is expected to be massless. One of the most enduring efforts on testing the correctness of this assumption has therefore been the search for a rest mass of the photon. However, it is impossible to prove experimentally that the photon rest mass is strictly zero, the best experimentally strategy can hope to do is to set ever tighter upper limits on it and push the verification of the photon zero-mass hypothesis as far as possible. Based on the uncertainty principle, when using the age of the universe ($\sim 10^{10}$ yr), the ultimate upper limit on the photon mass is estimated to be $m_\gamma \approx \hbar / T c^2 \approx 10^{-69}$ kg \cite{1, 2}. Although such an infinitesimal upper limit would be extremely difficult to place, there are several possible visible effects associated with a nonzero photon rest mass. These effects have been employed to set upper bounds on the photon mass via different terrestrial and astronomical approaches \cite{1–6}.

To date, the methods for constraining the photon mass include measurement of the frequency dependence in the velocity of light \cite{7–15}, tests of Coulomb’s inverse square law \cite{16}, tests of Ampère’s law \cite{17}, gravitational deflection of electromagnetic radiation \cite{3, 18}, Jupiter’s magnetic field \cite{19}, mechanical stability of the magnetized gas in galaxies \cite{20}, torsion Cavendish balance \cite{21–24}, magnetohydrodynamic phenomena of the solar wind \cite{25–27}, black hole bombs \cite{28}, pulsar spindown \cite{29}, and so on. Among these methods, the most direct and model-independent one is to measure the frequency dependence in the speed of light. In this paper, we will revisit the photon mass limits from the velocity dispersion of electromagnetic waves of astronomical sources.

If the photon mass is nonzero ($m_\gamma \neq 0$), the energy of the photon can be written as

$$E = h\nu = \sqrt{p^2 c^2 + m_\gamma^2 c^4}. \quad (1.1)$$

The dispersion relation between the group velocity of photon $v$ and frequency $\nu$ is

$$v = \frac{\partial E}{\partial p} = c\sqrt{1 - \frac{m_\gamma^2 c^4}{E^2}} \approx c \left(1 - \frac{1}{2} \frac{m_\gamma^2 c^4}{\hbar^2 \nu^2} \right), \quad (1.2)$$
where the last derivation holds when \( m_\gamma \ll h\nu/c^2 \simeq 7 \times 10^{-42} \left( \frac{\nu}{\text{GHz}} \right) \text{ kg}. \) It is obvious from Equation (1.2) that lower frequency photons would propagate slower than higher frequency ones in a vacuum. The arrival-time differences of photons with different energies originating from the same source can therefore be used to constrain the photon mass. Moreover, it is easy to understand that measurements of short time structures at lower frequencies from distant astronomical sources are especially powerful for constraining the photon mass. The current best limits on the photon mass through the dispersion of light have been made using the radio emissions from fast radio bursts (FRBs: \( m_\gamma \leq 3.9 \times 10^{-50} \text{ kg} \)) \cite{10–12} and pulsars in the Large and Small Magellanic Clouds (LMC and SMC respectively; \( m_\gamma \leq 2.3 \times 10^{-48} \text{ kg} \)) \cite{14}. Recently, Ref. \cite{15} extended previous studies to FRBs where the redshift is not available, and they constructed a Bayesian formula to measure the photon mass with a catalog of FRBs.

However, it is well known that radio signals propagating through a plasma would arrive with a frequency-dependent dispersion in time of the \( \nu^{-2} \) behavior. This is the frequency dependence expected from the plasma effect, but a similar dispersion \( \propto m_\gamma^2/\nu^2 \) (see Equation 1.2) could also arise from a nonzero photon mass. In other words, the dispersion method used for testing the photon mass is hindered by the similar frequency-dependent dispersions from the plasma and photon mass. In order to identify an effect as radical as a massive photon, statistical and possible systematic uncertainties must be minimized. One cannot rely on a single source, for which it would be impossible to distinguish the dispersions induced by the plasma effect and the nonzero photon mass effect. For this reason, we develop a statistical method through which an average dispersion measure caused by the plasma effect can be extracted and a combined constraint on the photon rest mass can be obtained as well, by fitting a combination of the dispersion measures of astronomical sources.

In this work, we gather the observed dispersion measures from two samples of radio pulsars in the LMC and SMC to constrain the photon mass. The paper is organized as follows. In Section 2, we give an overview of the theoretical analysis framework. The resulting constraints on the photon mass are presented in Section 3. Our conclusions are summarized in Section 4.

2 Theoretical Framework

As described above, the pulse arrival time delay at a given frequency \( \nu \) follows the \( \nu^{-2} \) law. In this work, we suppose that the frequency-dependent delay can be attributed to two causes: (i) the plasma effect via the dispersion process from the line-of-sight free electron content, and (ii) the nonzero photon mass (if it exits).

2.1 Dispersion from the plasma effect

Due to the dispersive nature of plasma, lower frequency radio waves pass through the line-of-sight free electrons slower than higher frequency ones \cite{30}. The arrival time delay (\( \Delta t_{\text{DM}} \)) between two pulses with different frequencies (\( \nu_l < \nu_h \)), which induced by the plasma effect, is expressed as

\[
\Delta t_{\text{DM}} = \int \frac{d\nu^2}{c} \left( \frac{\nu_l^{-2}}{2} - \frac{\nu_h^{-2}}{2} \right)
= \frac{e^2}{8\pi^2 m_e e_0 c} \left( \nu_l^{-2} - \nu_h^{-2} \right) \text{DM}_\text{astro},
\]

where \( \nu_p = (n_e e^2/4\pi^2 m_e e_0)^{1/2} \) is the plasma frequency, \( n_e \) is the number density of electrons, \( e \) and \( m_e \) are the charge and mass of the electron, and \( e_0 \) is the permittivity of vacuum.

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[2.1]
dispersion measure (\(\text{DM}_{\text{astro}}\)) is defined as the integral of the electron number density along the propagation path from the source to the observer, \(\text{DM}_{\text{astro}} \equiv \int n_e dl\).

For a Magellanic Cloud pulsar, the \(\text{DM}_{\text{astro}}\) has contributions from the electron density in our Galaxy (\(\text{DM}_{\text{Gal}}\)), the Magellanic Cloud (\(\text{DM}_{\text{MC}}\)), and the intergalactic medium between the two galaxies (\(\text{DM}_{\text{IGM}}\)). In fact, since each galaxy has an extended circum-galaxy medium, there might not be a clear separation between the two. In any case, all these complications do not enter the problem we are treating since only \(\text{DM}_{\text{astro}}\) is relevant. We will present in Section 2.3 how \(\text{DM}_{\text{astro}}\) is treated in a maximum likelihood estimation.

2.2 Dispersion from a nonzero photon mass

With Equation (1.2), it is evident that two photons with different frequencies originating from the same source would arrive on Earth at different times. The arrival time difference due to a nonzero photon mass is given by

\[
\Delta t_{m,\gamma} = \frac{L m_{\gamma}^2 c^3}{2 h^2} \left( \nu_l^{-2} - \nu_h^{-2} \right),
\]

where \(L\) is the distance of the source.

2.3 Analysis method

In our analysis, the observed time delay (\(\Delta t_{\text{obs}}\)) between correlated photons should consist of two terms

\[
\Delta t_{\text{obs}} = \Delta t_{\text{DM}} + \Delta t_{m,\gamma}.
\]

These two terms have the same frequency dependence, which are consistent with the observational fact that the observed time delay \(\Delta t_{\text{obs}} \propto \nu^{-2}\). Note that the observed dispersion measure (\(\text{DM}_{\text{obs}}\)) is directly derived from the fitting of the \(\nu^{-2}\) behavior of the observed time delay. That is, both the line-of-sight free electron content and a massive photon determine the same \(\text{DM}_{\text{obs}}\), i.e.,

\[
\text{DM}_{\text{obs}} = \text{DM}_{\text{astro}} + \text{DM}_{\gamma},
\]

where \(\text{DM}_{\text{astro}}\) is the dispersion due to the plasma effect and \(\text{DM}_{\gamma}\) denotes the “effective dispersion measure” induced by a nonzero photon mass, defined by [15]

\[
\text{DM}_{\gamma} \equiv \frac{4 \pi^2 m_e \epsilon_0 c^4}{h^2 e^2} L m_{\gamma}^2.
\]

Statistically, a combined constraint on the photon mass \(m_{\gamma}\) can be obtained by combining results of several measurements of the dispersion measure into an overall result. That is, for a set of extragalactic radio pulsars, the photon mass \(m_{\gamma}\) can be constrained by maximizing the joint likelihood function

\[
\mathcal{L} = \prod_i \frac{1}{\sqrt{2\pi \left( \sigma_{\text{DM}_{\text{obs},i}}^2 + \sigma_{\text{DM}_{\text{astro},i}}^2 \right)}} \times \exp \left[ -\frac{(\text{DM}_{\text{obs},i} - \text{DM}_{\text{astro},i} - \text{DM}_{\gamma})^2}{2 \left( \sigma_{\text{DM}_{\text{obs},i}}^2 + \sigma_{\text{DM}_{\text{astro},i}}^2 \right)} \right],
\]

where \(i\) is the corresponding serial number of each pulsar, \(\sigma_{\text{DM}_{\text{obs}}}\) and \(\sigma_{\text{DM}_{\text{astro}}}\) are respectively the uncertainty of \(\text{DM}_{\text{obs}}\) and the uncertainty of \(\text{DM}_{\text{astro}}\).
Generally, given a model for the distribution of free electrons in our Galaxy, the Magellanic Cloud and the intergalactic medium between the two galaxies, we can estimate the contributions of \( \text{DM}_{\text{Gal}} \), \( \text{DM}_{\text{MC}} \) and \( \text{DM}_{\text{IGM}} \) to the \( \text{DM}_{\text{astro}} \). However, the knowledge about the electron distributions is poor, and the current electron-density model relies on many particular theoretical parameters [31]. It is obviously that the estimation of \( \text{DM}_{\text{astro}} \) is model-dependent and its uncertainty \( \sigma_{\text{DM}_{\text{astro}}} \) is large. For simplicity, we will adopt an average dispersion measure \( \langle \text{DM}_{\text{astro}} \rangle \) and use it uniformly for every radio pulsar in the same Magellanic Cloud. To account for possible electron-density model inaccuracy, we will adopt the additional free parameter \( \eta \) to relate the uncertainty \( \sigma_{\text{DM}_{\text{astro}}} \) to the observed dispersion measure \( \text{DM}_{\text{obs}} \), according to \( \sigma_{\text{DM}_{\text{astro}}} \equiv \eta \text{DM}_{\text{astro}} \simeq \eta \text{DM}_{\text{obs}} \) (where \( \text{DM}_{\gamma} \ll \text{DM}_{\text{astro}} \)). The Particle Data Group suggests the currently adopted upper limit of photon mass is \( m_{\gamma} \leq 1.5 \times 10^{-54} \text{ kg} \) [32]. With such a limit, \( \text{DM}_{\gamma} \) can be estimated as \( \sim 10^{-11} \text{ pc cm}^{-3} \) at a distance of 50 kpc (see Equation (2.5)), which is obviously far less than the value of \( \text{DM}_{\text{astro}} \). Thus, it is reasonable to assume \( \text{DM}_{\gamma} \ll \text{DM}_{\text{astro}} \). With these treatments above, the likelihood function becomes

\[
\mathcal{L} = \prod_i \frac{1}{\sqrt{2\pi} \left( \sigma^2_{\text{DM}_{\text{obs},i}} + \eta^2 \text{DM}^2_{\text{obs},i} \right)} \exp \left[ -\frac{\left( \text{DM}_{\text{obs},i} - \langle \text{DM}_{\text{astro}} \rangle - \text{DM}_{\gamma} \right)^2}{2 \left( \sigma^2_{\text{DM}_{\text{obs},i}} + \eta^2 \text{DM}^2_{\text{obs},i} \right)} \right].
\]

(2.7)

We will use the likelihood in Equation (2.7) to simultaneously constrain the photon mass \( m_{\gamma} \) and the parameters \( \langle \text{DM}_{\text{astro}} \rangle \) and \( \eta \).

### 3 Constraints on Photon Mass

Up to now, the 29 known extragalactic pulsars are all in the Magellanic Clouds. Only 27 of these have known dispersion measures, with one pulsar in each of the LMC and SMC being detected at high energies and having no radio counterpart. Of these 27 radio pulsars, 22 in the LMC and 5 in the SMC. Their observed dispersion measures \( \text{DM}_{\text{obs}} \) are listed in Table 1 along with their location information (including the right ascension coordinate and the declination coordinate). The distances of the LMC and SMC are 49.7 and 59.7 kpc, respectively. Since these extragalactic pulsars appear to be usually located in the more central regions of each Magellanic Cloud [33], we adopt the distance of the corresponding Cloud as the distance of each pulsar which lies in it.

For each sample of radio pulsars in the LMC and SMC, we use the Python Markov Chain Monte Carlo (MCMC) module, EMCEE [42], to explore the posterior distributions of parameters \( \langle m_{\gamma} \rangle \), \( \langle \text{DM}_{\text{astro}} \rangle \), and \( \eta \). We choose uniform priors on the parameters, such that \( 10^{-69} \text{ kg} < m_{\gamma} < 10^{-42} \), \( 0.0 \text{ pc cm}^{-3} < \text{DM}_{\text{astro}} < 300 \), and \( 0.0 \text{ cm}^{-3} < \eta < 1.0 \).

### 3.1 Limit from a sample of radio pulsars in the LMC

In Figure 1, we show the marginalized posterior probability densities of \( m_{\gamma} \), \( \langle \text{DM}_{\text{astro}} \rangle \), and \( \eta \) for the combination of 22 radio pulsars in the LMC. One can see from this plot that at the

\[ \text{The lower end is adopted because it corresponds to the ultimate upper limit estimated by the uncertainty principle, while the upper end is adopted because beyond which the approximation in Equation (1.2) breaks down.} \]
Table 1. Radio pulsars in the Magellanic Clouds

| Name      | Cloud | J2000 R.A. (°) | Decl. (°) | DM_{obs} (pc cm^{-3}) | Refs. |
|-----------|-------|---------------|----------|------------------------|-------|
| J0045–7042 SMC | 11.357 | -70.702 | 70 ± 3 | [33]                  |
| J0045–7319 SMC | 11.397 | -73.317 | 105.4 ± 7 | [34, 35]          |
| J0111–7131 SMC | 17.870 | -71.530 | 76 ± 3 | [33]                  |
| J0113–7220 SMC | 18.296 | -72.342 | 125.49 ± 3 | [36]             |
| J0131–7310 SMC | 22.869 | -73.169 | 205.2 ± 7 | [33]                  |
| J0449–7031 LMC | 72.274 | -70.525 | 65.83 ± 7 | [33]                  |
| J0451–67 LMC | 72.958 | -67.300 | 45 ± 1 | [33]                  |
| J0455–6951 LMC | 73.948 | -69.860 | 94.89 ± 14 | [34, 36]         |
| J0456–69 LMC | 74.125 | -69.167 | 91 ± 1 | [37]                  |
| J0457–69 LMC | 74.258 | -69.767 | 97 ± 2 | [37]                  |
| J0458–67 LMC | 74.746 | -67.717 | 126.45 ± 7 | [33]                  |
| J0502–6617 LMC | 79.945 | -69.540 | 119.4 ± 5 | [33]                  |
| J0519–6932 LMC | 80.433 | -68.583 | 136 ± 4 | [37]                  |
| J0521–68 LMC | 80.596 | -68.784 | 126.2 ± 3 | [36, 38]          |
| J0529–6652 LMC | 83.248 | -66.660 | 69.3 ± 18 | [33]                  |
| J0532–6639 LMC | 83.017 | -69.767 | 124 ± 1 | [37]                  |
| J0534–6703 LMC | 83.651 | -67.064 | 94.7 ± 12 | [33]                  |
| J0535–66 LMC | 83.917 | -66.867 | 75 ± 1 | [37]                  |
| J0536–6935 LMC | 83.750 | -69.583 | 93.7 ± 4 | [33, 36]             |
| J0537–69 LMC | 84.429 | -69.350 | 273 ± 1 | [37]                  |
| J0540–6919 LMC | 85.047 | -69.332 | 146.5 ± 2 | [39, 40]          |
| J0542–68 LMC | 85.646 | -68.267 | 114 ± 5 | [37]                  |
| J0543–6851 LMC | 85.970 | -68.857 | 131 ± 4 | [33]                  |
| J0555–7056 LMC | 88.758 | -70.946 | 73.4 ± 16 | [33]                  |

*http://www.atnf.csiro.au/research/pulsar/psrcat [41]*

95% confidence level, the central values and the corresponding uncertainties of the parameters are $m_\gamma = (1.09^{+1.47}_{-1.02}) \times 10^{-48}$ kg, $\langle DM_{\text{astro}} \rangle = 68.88^{+25.13}_{-58.78}$ pc cm$^{-3}$, and $\eta = 0.36^{+0.12}_{-0.09}$, respectively. Note that the derived parameters and their error bars are based on their respective marginalized distributions: the central values correspond to the 50th percentile in the marginalized distributions, while their error bars correspond to the 50th–2.5th and 97.5th–50th percentiles of the marginalized distributions. Figure 2 shows the marginalized accumulative posterior probability distribution on $m_\gamma$. The 68% and 95% confidence-level upper limits on $m_\gamma$ are

$$m_\gamma \leq 1.51 \times 10^{-48}\text{kg} \approx 8.47 \times 10^{-13}\text{eV}/c^2$$ (3.1)

and

$$m_\gamma \leq 2.42 \times 10^{-48}\text{kg} \approx 1.36 \times 10^{-12}\text{eV}/c^2$$, (3.2)

respectively. These 68% and 95% confidence-level limits are comparable with that obtained by a single LMC pulsar [14].

3.2 Limit from a sample of radio pulsars in the SMC

The marginalized posterior probability distributions for the combination of 5 radio pulsars in the SMC are presented in Figure 3. Similarly, we find that the 95% confidence level constraints on the parameters are $m_\gamma = (1.17^{+1.44}_{-1.10}) \times 10^{-48}$ kg, $\langle DM_{\text{astro}} \rangle = 66.53^{+50.17}_{-58.78}$ pc.
Figure 1. 1D marginalized probability distributions and 2D regions corresponding to the photon mass $m_\gamma$ and the parameters $\langle \text{DM}_\text{astro} \rangle$ and $\eta$, using the combination of 22 radio pulsars in the LMC. The vertical solid lines represent the central values, and the vertical dashed lines enclose the 95% credible region.

Figure 2. The cumulative posterior probability distribution on $m_\gamma$ from the sample of radio pulsars in the LMC. The excluded values of $m_\gamma$ at 68% and 95% CLs are displayed with shaded areas.

$cm^{-3}$, and $\eta = 0.43^{+0.36}_{-0.21}$, respectively. We also display the accumulative posterior probability distribution of $m_\gamma$ in Figure 4, which implies

$$m_\gamma \leq 1.58 \times 10^{-48} \text{kg} \simeq 8.86 \times 10^{-13} \text{eV}/c^2$$

(3.3)

and

$$m_\gamma \leq 2.43 \times 10^{-48} \text{kg} \simeq 1.36 \times 10^{-12} \text{eV}/c^2$$,

(3.4)

at the 68% and 95% confidence levels, respectively. This 95% confidence-level limit is also as good as the previous result that only used a single SMC pulsar [14].
Figure 3. Same as Figure 1, except now using the combination of 5 radio pulsars in the SMC.

Figure 4. Same as Figure 2, but now for the sample of radio pulsars in the SMC.

4 Summary and Discussion

The frequency-dependent time delays of radio emissions from astrophysical sources have been used to constrain the rest mass of the photon with high accuracy. However, the plasma and nonzero photon mass effects on photon propagation would cause the similar frequency-dependent dispersions. The key issue in the idea of searching for frequency-dependent delays, therefore, is distinguishing the dispersions induced by the plasma effect and the nonzero photon mass effect. Here we develop a statistical method based on the global fitting of observed dispersion measures $DM_{\text{obs}}$ of radio sources to constrain the photon mass, and an unknown constant is assumed to be the average dispersion measure $\langle DM_{\text{astro}} \rangle$ arisen from the plasma effect for every radio source. This is the first approach which can give a combined constraint on the photon mass.

Using the observed dispersion measures from two samples of extragalactic pulsars, we
place robust limits on the photon mass at the 68% (95%) confidence level, i.e., \( m_{\gamma} \leq 1.51 \times 10^{-48} \) kg \( (m_{\gamma} \leq 2.42 \times 10^{-48} \) kg) for the sample of 22 radio pulsars in the LMC and \( m_{\gamma} \leq 1.58 \times 10^{-48} \) kg \( (m_{\gamma} \leq 2.43 \times 10^{-48} \) kg) for the other sample of 5 radio pulsars in the SMC. Compared with previous limits from a single pulsar in each of the LMC and SMC [14], our 95% confidence-level constraints from statistical samples are equally good.

Although our limits on the photon mass are two orders of magnitude worse than the current best limit from a single FRB [10–12], there is merit to the results. First, thanks to our improved statistical technique and the adoption of a more complete data set, our constraints are much more statistically robust than previous results. Second, the analysis of the dispersion measure \( DM_{\text{astro}} \) from the plasma effect performed here is important for studying the frequency dependence of the speed of light to constrain the photon mass, since it impacts the reliability of the resulting constraints on \( m_{\gamma} \). Compared with previous works [10–12, 15], which estimated \( DM_{\text{astro}} \) based on the given model for the distribution of free electrons in the Galaxy, the Magellanic Clouds, and the intergalactic medium, our present analysis is independent of the electron-density model. Furthermore, although extragalactic pulsars are discussed in this work, the approach presented here can also be used for other radio sources, such as future FRBs with more known redshifts.

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