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New limits on the photon mass with radio pulsars in the Magellanic clouds

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Abstract A conservative constraint on the rest mass of the photon can be estimated under the assumption that the frequency dependence of dispersion from astronomical sources is mainly contributed by the nonzero photon mass effect. Photon mass limits have been set earlier through the optical emissions of the Crab Nebula pulsar, but we demonstrate that these limits can be significantly improved with the dispersion measure (DM) measurements of radio pulsars in the Large and Small Magellanic Clouds. The combination of DM measurements of pulsars and distances of the Magellanic Clouds provides a strict upper limit on the photon mass as low as $m_\gamma \leq 2.0 \times 10^{-45}$ g, which is at least four orders of magnitude smaller than the constraint from the Crab Nebula pulsar. Although our limit is not as tight as the current best result ($\sim 10^{-47}$ g) from a fast radio burst (FRB 150418) at a cosmological distance, the cosmological origin of FRB 150418 remains under debate; and our limit can reach the same high precision of FRB 150418 when it has an extragalactic origin ($\sim 10^{-45}$ g).

Key words: pulsars: general — Magellanic Clouds — astroparticle physics

1 INTRODUCTION

The cornerstones of modern physics, such as classical Maxwellian electromagnetism and the second postulate of Einstein's theory of special relativity, have a basic assumption that all electromagnetic radiation travels in a vacuum at the constant speed c, which implies that the photon rest mass should be strictly zero. Searching for a rest mass of the photon has therefore been one of the most important efforts related to testing the validity of this assumption.

However, it is not possible to do any experiment that would firmly confirm the photon mass is exactly zero. Considering an age of the Universe of about 10^{10} years, the ultimate upper limit on the rest mass of the photon can be estimated to be $m_\gamma \approx \hbar/(\Delta t)c^2 \approx 10^{-66}$ g on the basis of the Heisenberg uncertainty principle, where $\hbar$ is the Plank constant (Tu et al. 2005). Although such an infinitesimal mass would be hard to detect, there are some possible observable effects associated with a nonzero photon mass. These effects include a frequency dependence of the velocity of light in a vacuum, deviations in the behavior of static electromagnetic fields, the existence of longitudinal electromagnetic radiation, the gravitational deflection of massive photons, and so on. All these observable effects have been studied carefully and have been applied to set upper limits on the photon mass, either through terrestrial/laboratory experiments or astrophysical observations (see Lowenthal 1973; Tu et al. 2005; Okun 2006; Goldhaber & Nieto 2010; Spavieri et al. 2011 for reviews).

The Particle Data Group (Olive & Particle Data Group 2014) suggests the currently accepted upper limit on the photon mass is $m_\gamma \leq 1.5 \times 10^{-51}$ g, almost 10^{24} times smaller than the electron mass, and this value was obtained by analyzing magnetohydrodynamic phenomena related to the solar wind at Pluto's orbit (Ryutov 2007; but see Retinò et al. 2016).

Since the photon mass is exceedingly small, there is essentially no effect on atomic and nuclear physics; and it is extremely difficult to improve this limit by laboratory experiments. However, even a very minor mass would have a significant effect on astrophysical phenomena occurring at large distances over the photon Compton wavelength. This introduces the need to develop more methods for constraining the photon mass with many kinds of alternative astrophysical observations.

In astrophysical observations, the most direct and model-independent method for determining the photon mass is to measure the frequency dependence of the velocity of light. Up to now, limits on the photon mass through the dispersion of light have been made using the electromagnetic emissions from flare stars (Lovell et al. 1964), the Crab Nebula pulsar (Warner & Nather 1969), active galactic nuclei (AGNs; Schaefer 1999), high redshift Type Ia supernovae (Schaefer 1999), gamma-ray bursts (GRBs; Schaefer 1999; Zhang et al. 2016) and fast radio bursts (FRBs; Wu et al. 2016; Bonetti et al. 2016). In particular, by analyzing the observed time delay between photons with different frequencies from FRB 150418 at a cosmological distance of $z = 0.492$ (Keane et al. 2016), Wu et al. (2016) set the most strict limit to date on the frequency dependence of the speed of light, implying a photon mass of $m_\gamma \leq 5.2 \times 10^{-47}$ g. However, the redshift determination of FRB 150418 has been questionable. Williams & Berger (2016) proposed that the so-called radio transient of FRB 150418 may come from common AGN variability and could be unrelated to the FRB itself, and so this redshift measurement may not be justified (but see Li & Zhang 2016). Although the cosmological origin of FRB 150418 is still under debate, Wu et al. (2016) also showed that even if FRB 150418 originated in our Local Group (1 Mpc), a stringent limit on the photon mass of $m_\gamma \leq 1.9 \times 10^{-45}$ g can be still obtained, which is already one order of magnitude better than the previous best result from GRB 980703 ($m_\gamma \leq 4.2 \times 10^{-44}$ g; Schaefer 1999).

We note that although a pulsar has been used to constrain the photon mass, this constraint relied on the relative arrival time delay for pulses from the Crab Nebula pulsar over the optical wavelength range of 0.35–0.55 μm, yielding a limit of only $m_\gamma \leq 5.2 \times 10^{-41}$ g (Warner & Nather 1969). Due to the fact that limits on the photon mass could be significantly improved by several orders of magnitude with radio observations of pulsars at farther distances, here we suggest that radio pulsars in the Large and Small Magellanic Clouds (LMC and SMC respectively) are also good candidates for constraining the photon mass. Compared to the prospects offered by the Crab Nebula pulsar in constraining the photon mass, radio pulsars in the LMC and SMC have two advantages. Firstly, measurements of time structures at lower frequency are particularly powerful for constraining the photon mass, and hence radio emissions from pulsars should be used for this purpose, rather than optical emissions. Secondly, the distances of the LMC and SMC (49.7 and 59.7 kpc respectively) are much more distant than that of the Crab Nebula (2 kpc). The value of the distance also plays an important role in constraining the photon mass; a larger distance leads to better constraints on the photon mass. On the other hand, unlike FRBs which are subject to uncertainties in distance, radio pulsars in the LMC and SMC have very certain distances, and the photon mass constraints from these pulsars would be more reliable than those of FRBs.

In this work, we first try to constrain the photon rest mass using radio pulsars in the LMC and SMC. The rest of the paper is organized as follows. In Section 2, we illustrate the velocity dispersion method used for our analysis. New limits on the photon mass from radio pulsars are presented in Section 3. Lastly, we summarize our conclusions in Section 4.

2 DESCRIPTION OF THE METHOD

2.1 Velocity Dispersion from a Nonzero Photon Mass

According to Einstein's special relativity, the energy of a photon with rest mass m_γ can be expressed as

$$E = h\nu = \sqrt{p^2 c^2 + m_\gamma^2 c^4} \,. \tag{1}$$

For the nonzero mass ($m_\gamma \neq 0$) case, the speed of photon υ in a vacuum is no longer a constant, but depends on the

frequency ν. The dispersion relation is given by

$$
\begin{aligned}
\upsilon &= \frac{\partial E}{\partial p} \\
&= c\sqrt{1 - \frac{m_\gamma^2 c^4}{E^2}} \\
&= c\left(1 - A\nu^{-2}\right)^{1/2} \\
&\approx c\left(1 - \frac{1}{2}A\nu^{-2}\right) ,
\end{aligned}
\tag{2}
$$

where $A = m_\gamma^2 c^4/h^2$. One can see from Equation (2) that high frequency photons propagate in a vacuum faster than low frequency photons.

Consider two photons with different frequencies (denoted by ν_h and ν_l, where $\nu_h > \nu_l$) that are emitted simultaneously from the same source at distance L. Since the lower frequency photon is slightly slower than the higher frequency one, these two photons would be received at different times by the observer, whose differences can be estimated as

$$
\begin{aligned}
\Delta t_{m_\gamma \neq 0} &= \frac{L}{\upsilon_l} - \frac{L}{\upsilon_h} \\
&\approx \frac{LA}{2c}\left(\nu_l^{-2} - \nu_h^{-2}\right) .
\end{aligned}
\tag{3}
$$

Thus, Equation (3) leads to constraints on the photon rest mass given by

$$
m_\gamma \approx hc^{-3/2}\left[\frac{2\Delta t_{m_\gamma \neq 0}}{\left(\nu_l^{-2} - \nu_h^{-2}\right)L}\right]^{1/2} .
\tag{4}
$$

2.2 Velocity Dispersion from the Plasma Effect

It is well known that pulsar radiation would be affected by free electrons in the interstellar medium (ISM) when they travel across the ISM, especially low energy radiation (e.g., radio emissions; Han et al. 2015; Xu & Han 2015). Due to the dispersive nature of plasma, or ionized parts of atoms, the velocity dispersion of photons would be related to

$$
\upsilon = c\left[1 - \left(\frac{\nu_p}{\nu}\right)^2\right]^{1/2} ,
\tag{5}
$$

where $\nu_p = (ne^2/\pi m_e)^{1/2}$ is the plasma frequency. Here n is average electron density along the line-of-sight; m_e and e are the mass and charge of the electron respectively. Equation (5) also implies that higher frequency radio photons pass through the ISM faster than lower frequency ones (see e.g., Bentum et al. 2016).

With Equation (5), we have the arrival time delay between two different frequencies caused by the ISM plasma effect, i.e.,

$$
\begin{aligned}
\Delta t &= \frac{e^2}{2\pi m_e c}\left(\nu_l^{-2} - \nu_h^{-2}\right)\int n_e \mathrm{d}l \\
&= \frac{e^2}{2\pi m_e c}\left(\nu_l^{-2} - \nu_h^{-2}\right)\mathrm{DM} ,
\end{aligned}
\tag{6}
$$

where the dispersion measure (DM) represents the integrated electron density along the line-of-sight, i.e., $\mathrm{DM} = \int n_e \mathrm{d}l$.

2.3 Methodology

Generally, the observed arrival time delay (Δt_{obs}) between different wavelengths for pulses from a pulsar is directly used to measure the DM. However, the observed time delay Δt_{obs} should be, in principle, mostly contributed by the nonzero photon mass ($m_\gamma \neq 0$) effect (if it exists) and the plasma effect. In other words, both the massive photon and the line-of-sight free electron content determine the same DM. Assuming that all of the DM measurement is dominated by the $m_\gamma \neq 0$ effect, a conservative upper limit on the photon mass can be estimated by combining Equations (3) and (6), i.e.,

$$
m_\gamma \leq \frac{he}{c^2}\left(\frac{\mathrm{DM}}{\pi m_e L}\right)^{1/2} ,
\tag{7}
$$

which can be further reduced to

$$
\begin{aligned}
m_\gamma &\leq \left(6.6 \times 10^{-45}\,\mathrm{g}\right)\left(\frac{\mathrm{DM}}{100\,\mathrm{pc\,cm^{-3}}}\right)^{1/2} \\
&\times \left(\frac{L}{10\,\mathrm{kpc}}\right)^{-1/2} .
\end{aligned}
\tag{8}
$$

3 PHOTON MASS LIMITS FROM RADIO PULSARS

The LMC and SMC are the closest galaxies to our Milky Way Galaxy and, so far, the only galaxies other than our own that have detectable pulsars. Several surveys for radio pulsars in the Magellanic Clouds have been carried out by McCulloch et al. (1983), McConnell et al. (1991), Crawford et al. (2001), Manchester et al. (2006) and Ridley et al. (2013), which discovered 21 radio pulsars in the LMC. In addition, five radio pulsars were also discovered in the SMC in these surveys (see McConnell et al. 1991; Crawford et al. 2001; Manchester et al. 2006), leading to a total of 26 radio pulsars in the Magellanic Clouds. We now examine how radio pulsars

in the Magellanic Clouds provide an excellent way of probing the photon mass by taking two typical extragalactic pulsars (PSRs J0451–67 and J0045–7042) as examples. Here we choose these two pulsars with the smallest DM values in the LMC and SMC to get the best constraints on the photon mass (see Eq. (8)).

3.1 PSR J0451–67

In a systematic survey of radio pulsars in the LMC and SMC, Manchester et al. (2006) discovered 14 pulsars using the Parkes 64 m radio telescope at 1400 MHz, 12 of which are believed to be in the Magellanic Clouds. Of these 12 radio pulsars, nine are in the LMC and three are in the SMC. In addition, they appear to be generally located in the central regions of each Magellanic Cloud.

PSR J0451–67 is one of the LMC pulsars, with a mean flux density (averaged over the pulse period) of ~ 0.05 mJy at 1400 MHz with the DM value of $\mathrm{DM} = 45 \, \mathrm{pc\,cm^{-3}}$. Using the known distance ($L = 49.7$ kpc) and DM measurement of PSR J0451–67, a strict upper limit on the photon mass from Equation (8) is $m_\gamma \leq 2.0 \times 10^{-45}$ g, which is four orders of magnitude tighter than that obtained by the Crab Nebula pulsar (Warner & Nather 1969), and is as good as the result that uses FRB 150418 when the FRB originates within our Local Group (Wu et al. 2016).

3.2 PSR J0045–7042

In this extensive survey of Manchester et al. (2006), PSR J0045–7042 was found to lie within the SMC ($L = 59.7$ kpc). It has a mean flux density of ~ 0.11 mJy at 1400 MHz, and its DM measurement is $70 \, \mathrm{pc\,cm^{-3}}$. With this information on PSR J0045–7042, we can constrain the photon mass from Equation (8) to be $m_\gamma \leq 2.3 \times 10^{-45}$ g, which is also 10^4 times better than the constraint from the Crab Nebula pulsar (Warner & Nather 1969), and is also as good as the result that regards FRB 150418 as being in our Local Group (Wu et al. 2016).

4 CONCLUSIONS

The rest mass of the photon m_γ can be effectively constrained by measuring the frequency dependence of the speed of light. Using this dispersion method, we demonstrate that radio pulsars in the Magellanic Clouds can serve as a new excellent candidate for constraining the photon mass. Assuming that the whole DM measurement of a pulsar between different radio bands is mainly due to the nonzero photon mass ($m_\gamma \neq 0$) effect and adopting the distance of the LMC or SMC, we place robust limits on the photon mass for two extragalactic pulsars: $m_\gamma \leq 2.0 \times 10^{-45}$ g for the LMC pulsar PSR J0451–67 and $m_\gamma \leq 2.3 \times 10^{-45}$ g for the SMC pulsar PSR J0045–7042. Compared with the limit from optical emissions of the Crab Nebula pulsar (Warner & Nather 1969), our constraints on m_γ with radio pulsars in the Magellanic Clouds represent an improvement of at least four orders of magnitude.

Previously, the cosmological distance ($z = 0.492$) of FRB 150418 provided the most stringent limit on the photon mass through the dispersion method, showing an upper limit of 5.2×10^{-47} g (Wu et al. 2016). However, the redshift measurement of FRB 150418 remains controversial (Williams & Berger 2016; but see Li & Zhang 2016), so the strict constraint on the photon mass from FRB 150418 may not be quite reliable. But it is encouraging that even if FRB 150418 is not cosmological, the extragalactic origin of FRB 150418 can still lead to a strict limit on the photon mass of $m_\gamma \leq 1.9 \times 10^{-45}$ g (Wu et al. 2016). Although our limits on the photon mass ($\sim 10^{-45}$ g) are not as tight as the result that relies on cosmological FRBs, our limits can reach the high precision associated with an extragalactic FRB.

It should be underlined that because our limits are based on a very conservative estimate of the DM measurement, we suppose that all of the DM is mainly contributed by the $m_\gamma \neq 0$ effect. In fact, the DM measurement should be strongly dominated by the plasma effect, with a very small contribution possibly from the $m_\gamma \neq 0$ effect. We find that if the $m_\gamma \neq 0$ effect is responsible for 10.0% of DM associated with radio pulsars, much stricter limits could be obtained, implying $m_\gamma \leq 6.3 \times 10^{-46}$ g for PSR J0451–67 and $m_\gamma \leq 7.3 \times 10^{-46}$ g for PSR J0045–7042.

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