The Concept of the Massive Photon and its Astrophysical Implications

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Abstract

We discuss the concept of the massive photon with its possible implications in astrophysics. We use the term "mass equivalent" instead of relativistic or effective mass. We also analyzed modified Planck's law and estimated (mean mass/rest mass) ratio in connection to the temperature of blackbody radiation of the massive photons. This ratio diverges at high temperatures and approaches unity at low temperatures.The "mass equivalent" for the CMB radiation was estimated to be equal to 0.0468% of the total mass of the Universe. We have discussed importance of the Breit-Wheeler process of particle – antiparticle production in the early Universe. We have evaluated the upper limit of the rest mass of the photon using gravitational and cosmological redshifts. A correlation was found between estimated masses of the photon and the lowest/highest frequencies of the spectral bands used for estimation of the mass.

Keywords: *the rest mass of the photon, optical dispersion in vacuum; modified Planck's law, gravitational and cosmological red shifts, linear regression*

1. Introduction

The question of whether photons have non-zero rest mass has been a subject of debates for many years. Being out of mainstream physical studies,this hypothesis is, nevertheless, of great interest in physics and astrophysics, and may have serious implications for field theories and cosmology as well as the theory of radiation transfer and physics of active astrophysical sources. The most rigorous mathematical foundation for findings pertaining to the massive photon hypothesis is the Proca equation (Poenaru et al., 2006, Tu et al., 2004), which can be reduced to the Klein-Gordon equation - the quantized version of the energy-momentum relation (also relativistic dispersion equation). Making use of these equations one can obtain an expression for optical dispersion in vacuum – frequency - dependent speed of light in free space. This term appears in the modified Planck's law (Torres-Hernanadez J., 1985), time dispersion (or frequency - dependent electromagnetic signal time arrival formula) and can be used to estimate relative speed of light variations at different frequencies from astrophysical sources (Biller S.D., 1999, Shaefer, 1999). In the last paragraphs we estimate the mass of the photon by making use of uncertainties in gravitational and cosmological redshifts and show the correlation between the rest mass of the photon and the lowest/highest frequencies of spectral bands used for estimation of the mass. (Breit G., 1934)

2. Energy-momentum relation

This relation is also known as the relativistic dispersion equation and is written in the form $E^2 = (pc)^2 + (\mu_\gamma c^2)^2$. Here E is the energy of a particle with the rest (invariant) mass μ_γ moving with the speed v, c is the invariant speed of light (included in Lorentz transformations) and $\vec{p} = \frac{E\vec{v}}{c^2}$ is its momentum. If we write $E = h\nu$, where h is the Plank constant ($h = 6.626x10^{-34}Js$), then we can derive the formula for the optical dispersion in vacuum (or "inherent dispersion" relation):

$$v = c\sqrt{1 - \frac{\nu_0^2}{\nu^2}} \tag{1}$$

Here $\nu_0 = \frac{\mu_\gamma c^2}{h}$ "rest frequency" (not to be understood literally). For $\nu_0 \ll \nu$ (1) can be reduced to $v = csqrt\left(1 - \frac{\nu_0 2}{2\nu^2}\right)$. These results be derived from the Proca equation (Tu et al., 2004).

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Table 1. Mass ratio vs. parameter b

b	0.01	0.1	1	5	10	20	70
$\frac{m}{m_\gamma}$	270.32	17.067	3.048	1.360	1.166	1.079	1.021

3. The mass equivalent

The relation (1) can be obtained from the formula for the "relativistic mass" (m) of the photon $m = \frac{m_\nu}{\sqrt{1-\frac{v^2}{c^2}}}$ the term that was a subject of multiple criticism by different authors (see Okun, 1989, Taylor E.F., 1992). We can rewrite this formula as follows $m = \frac{c}{\sqrt{1-\frac{m_\gamma^2}{m^2}}}$. It makes visible the fact that the invariant mass is zero if $v = c$. In the meantime, its "relativistic mass" (m) could be an arbitrary number. Although the double limit (when v approaches c and $_\gamma$ approaches zero) leads to the mathematical uncertainty $\frac{0}{0}$, the physical limit of the "relativistic mass" still does exist and equals to $m = \frac{h\nu}{c^2}$. The ratio on the right side has a dimension of mass and will be interpreted as "mass equivalent".

4. The photon mean mass equivalent for Planck spectrum

The mean energy of photons in Planck spectrum is $\langle\varepsilon\rangle \approx 2.701\,kT$ (R., 1978). Thus, the mean mass (equivalent) of the photon is $m = \frac{2.701kT}{c^2} = 4.148 \times 10^{-40} Tkg$. If we take $T = 10000K$ for a typical A-star, we obtain $\langle m\rangle = 4.148 \times 10^{-36} kg$. Comparing it with the mass of the electron $m_e = 9.109 \times 10^{-31}$ kg we see that the mean mass equivalent of the photon from A- stars is approximately $10^{-5} - 10^{-4}$ times lighter. Photons become heavier with increase in temperature. For CMB radiation $\langle m\rangle = 1.132 \times 10^{-39} kg$.

5. Modified Planck's law (MPL)

The blackbody radiation of massive photons can be derived from the partition function and for the spectral energy density takes the form (Torres-Hernanadez J., 1985):

$$\rho(\nu, \mu_\gamma, T) = \rho_0(\nu, T)\sqrt{1 - (\frac{m_\gamma c^2}{h\nu})^2}\,; \quad \rho(\nu, T) = \frac{8\pi h\nu^3}{c^3}\frac{1}{e^{h\nu}kT - 1}, \tag{2}$$

where $\rho_0(\nu, T)$ is the standard Planck,s law (PL). Graph of MPL is shown on Fig. 1. and is compared with PL for two different temperatures.

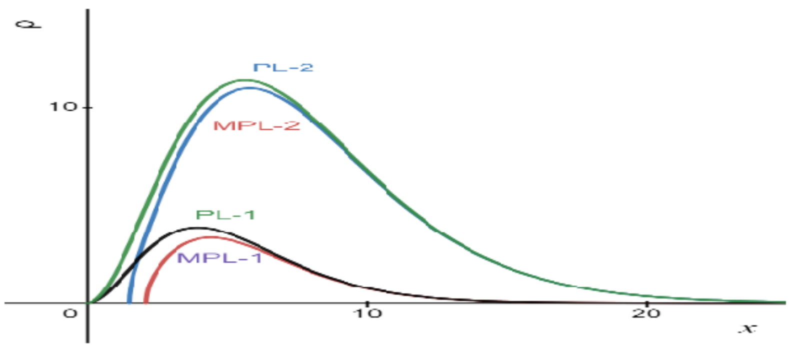

Figure 1. Modified (MPL) and regular (PL) Planck's laws.

The function 2 was used to calculate the mass ratio $\frac{\langle m\rangle}{\mu_\gamma}$ for different values of the parameter $b = \frac{m_\gamma c^2}{kT}$.

For high temperatures ($m_\gamma c^2 \ll kT$) $b \ll 1$ and MPL approaches PL, and the mass ratio tends to infinity. For low temperatures ($kT \ll m_\gamma c^2$) $b \gg 1$ and $m_\gamma \rightarrow < m >$. We can say that the upper limit of the invariant mass of the photon does not exceed the mean mass equivalent of the photon of the modified Planck spectrum. These calculations will be shown in more detail in a separate paper.

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6. The mass equivalent of the CMB radiation

CMB radiation is considered to be an example of the perfect blackbody radiation with temperature $T = 2.728\,K$. With its energy density $u = 4.17367 \times 10^{-14} J/m^3$ and the density of the mass equivalent $\rho = \frac{u}{c^2} = 4.6374 \times 10^{-30} kg/m^3$ in the volume of the Universe within the Standard Cosmological Model $V = 3.568 \times 10^{80} m^3$ (based on measured cosmological parameters, Bennet, 2013, Hinshaw G., et al, 2013, NASA/WMAP & Science team, 2011, Planck Collaboration et al., 2021) the mass of the CMB radiation is $M_C MB = \rho V = 1.655 \times 10^{51} kg$ or 4.6842×10^{-4} of the total mass of the Universe with the energy density (in mass units) $9.9 \times 10^{-27} kg/m^3$.

7. Breit-Wheeler process of particle-antiparticle pair production

As it may seem from the above, the mass of the photon tends to infinity with increase in temperature. However, the increased radiation density will result in $e^- e^+$ pair production from collisions of two photons (Breit G., 1934), which may prevent their mass growth. This (BW) process is found to have a very low probability $\sim 10^{-7} - 10^{-4}$ (Ribeyre & et al., 2016) with the cross section $\sim r_e^2, r_e \sim 2.8179 \times 10^{-15} m$ -classical electron radius. It was confirmed experimentally (Adam et al., 2021) when about 200 GeV energy level was achieved. The equivalent temperature for this energy is $\sim (10^{14} - 10^{15})\,K$, typical for and soon after the electroweak epoch of the Universe. How massive photons with finite Compton wavelengths may affect duration of the pre-combination epoch of the Universe is a question that, as far as we know, has not been discussed yet.

8. Gravitational redshift corrected for the optical dispersion in vacuum

The optical dispersion in vacuum discussed above results in additional redshift in spectra of astrophysical objects. Indeed, the gravitational redshift in the standard scenario is defined as

$$\frac{\Delta\nu}{\nu'} = \frac{r_g}{2r} \quad \Delta\nu = \nu - \nu' \quad (\nu > \nu') \tag{3}$$

where ν is the emitted frequency, ν' - observed frequency, r_g - gravitational radius, r is the distance from the center of gravity at which the redshift is measured. This equation can be rewritten in the following way, if we account for the optical dispersion effect in vacuum:

$$z = \frac{\Delta\nu'}{\nu'} = \frac{r_y}{2r}(1 + \frac{\nu_0^2}{\nu^2}) \tag{4}$$

This relationship shows that the gravitational redshift becomes more reddish with decrease in frequency and remains close to standard values when the frequency increases. If we denote ν" an observed frequency of radiation in the modified gravitational shift scenario and put $z^{'} = \frac{\delta\nu^{''}}{\nu"} = \frac{\nu' - \nu"}{\nu"}$, then the difference $\Delta z = z' - z$ can be interpreted in terms of uncertainties in measured redshifts. Using the existing accuracy of measurements $\sim 10^{-9} - 10^{-5}$ (Mueller H., 2010) one can find the upper limit of the mass of the photon by applying formula $\mu_\gamma = 7.362 \times 10^{-51} \nu \times \sqrt{\frac{\delta z}{z}}$ if δz and z are known. For the pulsar PSR J0348+0432 z=0.2226 (Xian-Feng & Huan-Yu, 2014). If $\Delta z = 7.5 \times 10^{-5}$ and $\nu = 10^1 5 Hz$, then $m_\gamma \sim 1.305 \times 10^{-39} kg$.

9. Modified cosmological redshift

Similar conclusions are true for the cosmological redshift as well. In non-relativistic standard scenario $V \ll c, z = \frac{V}{c}$, V is the recession velocity of a galaxy. If we denote $z' = \frac{V}{v}$, ν is the frequency-dependent speed of light, then $z{=}z(1{+}\frac{\nu_0^2}{2\nu^2})$ – modified redshift with optical dispersion in vacuum. Decrease in frequency makes redshift more reddish. Decrease in frequency makes redshift more reddish. If we assign the difference $\Delta z = z' - z$ to uncertainties in measured redshifts $\sim 10^{-4}$ (Rosseli & et al., 2022), then we find for the upper limit of the rest mass of the photon: $m_\gamma \leq \frac{h}{c^2} sqrt \frac{2}{z} \times 10^{-2} \times \nu$. For the galaxy Mrk 421 with the spectral band at $\nu = 10^{15}$ Hz, $\mu_\gamma \leq 5.933 \times 10^{-37}$ kg against the published one $2.1 \times 10^(-31)$ kg in γ-band with $\nu \sim 10^{26}$ Hz (Biller S.D., 1999, Shaefer, 1999). One can notice that both redshift-based estimates of the photon mass are linked to a frequency like many others.

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10. The correlation "Estimated mass of the photon vs frequency"

The mass of the photon in the Proca equation is a constant. But estimates of its upper limit can depend on the radiating energy generation mechanisms and its interactions with matter in space as well as experimental and observational factors. We have analyzed published data on estimates on upper limits of the mass of the photon (see Shaefer, 1999, Tu et al., 2004) and multiple refewrences therein) and have found the correlation between the mass (in grams) and the lowest/highest requency (in Hz) in specific spectral bands picked to evaluate the upperr limit of the mass in logarithmic scale $x = log(\nu), y = log(m_\gamma)$.The line of the best fit based on 29 points was found in the case of lowest frequency with the coefficient $R \approx 0.7709$ (for highest and midpoint frequencies $R \approx 0.513$ and 0.524, correspondingly). The linear regression is described by the equation $y = 0.59632x - 46.596$ and shown on Fig. 2. The standard deviation of differences between published and our recalculated mass logarithms $\sigma = 2.034$. Two examples are Mrk 421 galaxy with $m_\gamma \sim 1.061 \times 10^{-31}$ g against $2.1 \times 10^{(} - 28)$ g published and Gamma Ray Burst GRB 930131 with $m_\gamma \sim 1.073 \times 10^{-37}$ g against 7.4×10^{38} g (frequency 7.2×10^{18} Hz, Shaefer, 1999).

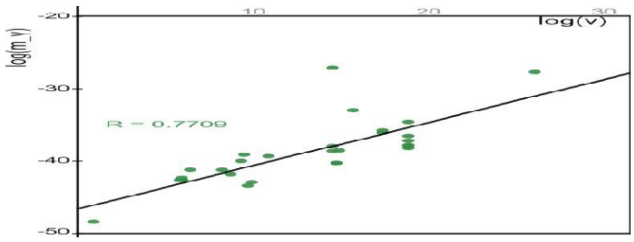

Figure 2. Estimated mass of the photon vs. frequency.

A few values of the mass associated with specific frequencies have been included in the statistics as well. The main conclusion is that the lower is the frequency used for measurements the lower is the estimated mass of the photon. These results will be discussed in more detail in a separate publication.

11. Conclusions

The hypothesis about the non-zero mass of the photon was discussed in connection with some astrophysical implications. We coin the term "mass equivalent" instead of traditionally used relativistic/effective mass. It is shown that the rest (invariant) mass of the photon can not exceed the mean value of the mass equivalent for Planck photons. The mean mass equivalent of the photon is proportional to the temperature of a blackbody radiation. The mass of the CMB radiation was found to be equal to 0.0468% of the total mass of the Universe. Corrections to the gravitational and cosmological redshifts, caused by the frequency - dependent speed of light, show that both redshifts are more reddish compared with their standard scenarios. A statistical study of published data shows that the lower is the frequency of radiation used to estimate the mass of the photon the lower is the value of the obtained mass.

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