Using plasma physics to weigh the photon

This content has been downloaded from IOPscience. Please scroll down to see the full text.
(http://iopscience.iop.org/0741-3335/49/12B/S40)

View the table of contents for this issue, or go to the journal homepage for more

Download details:

IP Address: 128.118.29.73
This content was downloaded on 28/12/2014 at 15:54

Please note that terms and conditions apply.
Using plasma physics to weigh the photon

D D Ryutov
Lawrence Livermore National Laboratory, Livermore, CA 94551, USA
E-mail: ryutov1@llnl.gov
Received 6 July 2007
Published 19 November 2007
Online at stacks.iop.org/PPCF/49/B429

Abstract
The currently accepted value for the upper bound for the photon mass, \( m_{\text{ph}} \), is 22 orders of magnitude less than the electron mass. As the mass \( m_{\text{ph}} \) is so incredibly small, it has essentially no effect on atomic and nuclear physics; and it is very difficult to improve this estimate by laboratory experiments. However, even a very small mass may have a significant effect on astrophysical phenomena occurring on a scale exceeding the photon Compton length \( \lambda \) (where \( \lambda > 3 \text{ Mkm} \) for the currently accepted mass). A set of magnetohydrodynamic equations (assuming a finite photon mass) are used to analyze properties of the solar wind at Pluto’s orbit. This yields an improved (reduced) by a factor of 70 estimate of the photon mass. Possible opportunities and challenges for the further reduction of the upper limit for \( m_{\text{ph}} \) based on the properties of larger-scale astrophysical objects are discussed.

1. Introduction
Contrary to sometimes professed views, the finiteness of the photon mass is compatible with Einstein’s relativity theory. The quantum description of a finite-mass spin-one particle was developed by Proca [1]; for a modern exposition see, e.g., Landau and Lifshitz [2]. The appropriately modified Maxwell equations can be found in textbooks, including Jackson’s text [3]. A general discussion of the earlier work on the massive photon has been presented in an excellent review paper by Goldhaber and Nieto [4]; later developments have been discussed in reviews [5–8].

The currently accepted value for the upper bound of the photon mass [9] is impressively low,

\[
m_{\text{ph}} < 10^{-22} m_e \approx 10^{-49} \text{ g},
\]

where \( m_e \) is the electron mass. Certainly, so low a photon mass would not have any impact on, say, atomic physics. As the mass (even if finite) is incredibly small, it is very difficult to improve estimate (1) by laboratory experiments (see the discussions in [10–12]).
One of the consequences of the finiteness of the photon mass is that the magnetic field created by a magnetic dipole would decrease not as a usual dipole, $\sim 1/r^3$, but rather in a Yukawa-like fashion, $\sim \exp(-r/\bar{\lambda})/r^3$, where $\bar{\lambda}$ is the reduced Compton length of the photon

$$\bar{\lambda} = \hbar/m_{\text{ph}}c,$$

with $\hbar$ being the Planck constant and $c$ being the speed of light. Strictly speaking, for a finite photon mass, the speed of light depends on the wavelength, as was discussed by DeBroglie [13], who suggested using this effect to evaluate the photon mass. Therefore, it would be more accurate to say that $c$ is the speed of light for very-short-wavelength photons. For the mass (1), $\bar{\lambda} \sim 3 \times 10^{11}$ cm.

Schroedinger, who was the first to notice the appearance of the exponential cut-off in the dipole field, suggested using this effect for the evaluation of $\bar{\lambda}$ (and $m_{\text{ph}}$) based on measurements of the Earth's magnetic field [14]; his estimate of $\bar{\lambda}$ was on the order of $10^4$ km. Clearly, the stronger the magnet, the more distant one can detect its magnetic field, and the better estimate for $\bar{\lambda}$ one can make. In 1975, measurements of Jupiter's magnetic field by the Pioneer-10 spacecraft allowed Davis et al to push the limit to 0.3 Mkm [15]. At larger distances, the Jovian field gets too strongly distorted by the solar wind and magnetohydrodynamic (MHD) effects become important.

At this point, the potential importance of the plasma physics becomes clear: if one wants to study astrophysical objects with large-scale magnetic fields present, one always has to deal with the question of whether these fields are produced by some distant source (say, a dipole), or whether they are produced in situ, by the currents flowing in the local plasma. For large enough distances one would always deal with the fields generated locally. This is why MHD effects have been recognized since the 1960s as playing an important role in attempts to evaluate the photon mass based on astrophysical observations (see the discussion of this issue in [4]).

Somewhat surprisingly, a complete set of MHD equations for the case of a finite photon mass has not been written until recently. It has been first derived and discussed in the author's paper [16]. Using this set and addressing the problem of the solar wind sector structure at the Earth's orbit, the author obtained the currently accepted estimate (1). One can note that the Compton length corresponding to this mass is 50 times shorter than the Earth–Sun distance (1 Astronomical Unit, AU). This is a manifestation of the role of the ambient plasma: although the magnetic field of the solar wind is certainly ‘born’ on the Sun, it is ‘sustained’ by local plasma currents. This issue is illustrated in a more quantitative fashion below, in section 3.1, where we also illustrate a ‘reductio ad absurdum’ approach used to find a lower bound on $\bar{\lambda}$.

In this paper, we use information about the properties of the solar wind at large distances from the Sun, at the orbit of Pluto, to improve our earlier estimate of equation (1) by at least a factor of 70 (section 3.2). But, before that, in section 2, for reference purposes, we present the set of MHD equations of [16] and discuss their most salient features. After that, in section 4, we consider the possibility of improving the mass estimate by looking at more distant astrophysical objects. Finally, in section 5, we discuss the main results of this paper.

It should be noted that the entire discussion in this paper as well as in the papers mentioned above is based on the Proca model of a massive photon. Should the Proca model fail for some reason, our basic equations would also fail. In particular, if the Higgs boson model of the photon suggested in [17] is valid, the Proca description would remain valid only in one of the limiting cases discussed in [17].

One more comment is in order here. Getting extraterrestrial (in the terminology of [4]) limits on the photon mass is facilitated by the large spatial scales involved. This allows one, even by a relatively crude analysis, to make substantial progress. On the other hand, terrestrial measurements can provide much higher accuracy and probe relatively minor deviations from
standard Maxwell equations. This approach may yield interesting results: in a recent paper [18] studying the propagation of ultra-low frequency waves in the space between the conducting Earth and the ionosphere, an upper bound of $m_{ph}$ as $4 \times 10^{-49}$ g was found, i.e. not far from the currently accepted value in equation (1).

2. MHD with finite photon mass

The set of MHD equations for quasi-static processes (i.e. for the processes where both the fluid velocity and the wave velocity are much less than $c$) was first written in [16]. It reads as:

$$\frac{\partial \rho}{\partial t} + \nabla (\rho v) = 0,$$

(3)

$$\rho \frac{dv}{dt} = -\nabla p + \frac{1}{c} j \times B,$$

(4)

$$\nabla \times \nabla \times B + \frac{B}{\lambda^2} = \frac{4\pi}{c} \nabla \times j,$$

(5)

$$\nabla \times E = -\frac{1}{c} \frac{\partial B}{\partial t},$$

(6)

$$E + \frac{v \times B}{c} = 0.$$  

(7)

We use the CGS system of units, with $\rho$, $p$ and $v$ being the density, pressure and velocity of the fluid, $j$ being the current density. The standard entropy equation can be added, if needed. Electromagnetic retardation effects are ignored. When writing equation (7), we neglected the plasma electrical resistivity. This is correct for the specific situations that we consider below. A more general case was analyzed in [16].

Equations (3)–(7) coincide with the standard set of MHD equations in everything except for the second term in the left-hand side of equation (5), which accounts for the finiteness of the photon mass (we prefer to work with the equivalent characteristic, the photon Compton length $\lambda$, equation (2)). The key point in deriving this set of equations is the realization that equations (3), (4) and (7) are not changed by the finiteness of the photon mass. Indeed, one could derive them in a standard way from the kinetic equations with particle collisions accounted for, and with no effect of the finite photon mass showing up—just because the mass is extremely small and does not affect the properties of the medium at inter-particle or collisional length distances. One can apply the same arguments also to higher levels of the plasma description, based on kinetic equations. Obviously, two-fluid Braginski-type equations would also work in the appropriate collisionality domain. We, however, restrict ourselves to the single-fluid MHD.

A more formal way of looking at the problem is that equations (3)–(7) are a direct corollary to the Proca Lagrangian presented, e.g., in [3].

Among the general properties of equations (3)–(7), the most important one is that, within the Proca MHD, there does not exist such an entity as a uniform magnetic field immersed in a uniform, resting, currentless plasma. Indeed, the uniform field, according to equation (5), means the presence of non-uniform current, not collinear to the uniform field. This observation shows that such simple solutions of MHD equations as linear MHD waves in a uniform system become irrelevant. The waves would exist on the background of more or less complex non-uniform equilibria, some of which have been considered in [16].
3. Solar wind with finite photon mass

3.1. Inside the Earth’s orbit

One of the great achievements of space physics is a good level of understanding of the average properties of the solar wind, based on Parker’s original model [19] (see [20,21] and references therein for more details). The observational results for the average flow follow reasonably well the model of a radially expanding plasma that stretches the magnetic field present in the vicinity of the Sun. A dipole component of the field, when pulled by the expanding plasma, causes the appearance of an almost radially directed magnetic field, with the fluxtubes carrying the magnetic flux determined by the magnetic field in the vicinity of the Sun [19]. So, it may be tempting to say that, as we see the magnetic field in the solar wind at the Earth’s orbit, the exponential factor in the Yukawa-like solution should not be too small, meaning that the photon Compton length is greater than, say, 0.05 AU (1 Astronomical Unit is $1.5 \times 10^8$ km); at this value of $\lambda$ the exponential cut-off factor $\exp(-r/\lambda)$ would already be smaller than $10^{-8}$.

To demonstrate that this approach is misleading, we consider in some detail a purely kinematic model, wherein the radial plasma flow originates at some spherical surface, and the distribution of the normal component of the magnetic field over this surface is known. To be specific, consider a dipole distribution,

$$B_r = B_0 \cos \theta,$$

where $B_0$ is some normalization field and the angle $\theta$ is a polar angle measured from the south pole; at the equator, $\theta = \pi/2$, the radial component changes sign. This part of the problem is described by equations (5) and (7), which are the same as in the standard MHD (we consider the case of perfect conductivity, which is adequate for the parameters of the solar wind). Accordingly, our arguments here do not differ from those presented by Parker [19]. The condition $\nabla \cdot B = 0$ then yields

$$B_r = (B_0 r_0^2 / r^2) \cos \theta,$$

where $r_0$ is the radius of the initial surface. We neglect for a while the effect of the Sun’s rotation. From the symmetry of the problem, it is clear that the plasma current has only azimuthal ($\phi$) component, which can be found from equation (5):

$$j_\phi = \frac{c B_0 r_0^2}{4 \pi r^3} \left( 1 + \frac{r^2}{2\lambda^2} \right) \sin \theta.$$

The magnetic field and the current distribution are illustrated in figure 1(a). Note that there is no exponential factor either in the magnetic field or in the current density. This is due to the fact that the field (9) is generated by the local currents, not by the currents in the vicinity of the Sun. The solar currents generate the initial magnetic field, and then this field is stretched by the plasma flow due to the line-tying constraint (7). The currents far from the Sun adjust themselves so as to produce the resulting magnetic field (9).

The $j \times B$ force acts in the $\theta$ direction:

$$f_\theta = \frac{j_\phi B_r}{c} = \frac{B_0^2 r_0^2 \sin \theta \cos \theta}{4 \pi r^5} \left( 1 + \frac{r^2}{2\lambda^2} \right).$$

This force pushes plasma towards the (solar) equatorial plane (i.e. to the south at the northern side and to the north at the southern side). If $\lambda$ is less than the radius $r$, the force increases significantly. By ‘cranking up’ the photon mass (i.e. by assuming that $\lambda$ becomes smaller and smaller), one finally reaches a situation where the presence of this force becomes manifestly incompatible with the observed flow pattern. This signals that the mass is actually...
Using plasma physics to weigh the photon

Figure 1. Schematic of the magnetic field and current distribution. (a) Inside the Earth’s orbit. The short arrow in the center is the rotation axis of the Sun. The dashed line represents the equatorial plane. Magnetic field lines are directed radially, with the field direction changing polarity between north and south. Dots and crosses show the direction of the azimuthal plasma current. Block arrows show the direction of the $j \times B$ force. (b) The same for the large distances from the Sun (the scale is roughly by a factor of 50 greater than in panel (a)). The magnetic field is almost purely toroidal, with direction indicated by dots and crosses. Thin lines with arrows show parts of current streamlines.

below the assumed value. This is, basically, the ‘reductio ad absurdum’ approach. It was used, in particular, in [15] when considering the Jovian magnetic field, and in [16] when deriving estimate (1). In the following section, we apply it to the solar wind at large distances from the Sun.

3.2. In the far heliosphere

The rotation of the Sun, in combination with the line-tying, causes the magnetic field lines to be wound into an Archimedes spiral, as was first suggested by Parker [19]. The azimuthal component of the magnetic field (\(B_\phi\)) becomes noticeable at Earth’s orbit and becomes dominant at distances beyond, roughly, the Mars orbit. At the orbit of Pluto, the radial component of the field is already less than 2% of the azimuthal component. As \(B_\phi\) is produced by the winding of the radial magnetic field, which has opposite polarity in the northern and southern hemispheres, \(B_\phi\) changes sign near the equatorial plane. The global picture of the magnetic field at large distances from the Sun follows well Parker’s model: see, e.g., [22, 23].

Here we again use the ‘reductio ad absurdum’ approach. Assuming that the Compton length is significantly less than 40 AU, one would find that the current density, according to equation (5), has \(r\) and \(\theta\) components, both of the same order of magnitude,

\[
 j \sim c B_\phi r / 4\pi \lambda^2. \tag{12}
\]

The \(j \times B\) force (per unit volume) can be evaluated as

\[
 f \sim B_\phi^2 r / 4\pi \lambda^2. \tag{13}
\]

The direction of this force is such as to cause plasma compression towards the equator and to decelerate the radial expansion (figure 1(b)).

The presence of this force would cause deviation from the essentially radial expansion with the constant radial velocity \(v\) if the condition \(f > \rho v^2 / r\) was satisfied. On the other hand, direct observations show that the solar wind velocity is largely radial, including a distant zone at Pluto’s orbit, and the average velocity is the same as at Earth’s orbit, 450 km s\(^{-1}\) (for
the so-called ‘slow’ wind, e.g. [24]). This means that actually the inequality $f < \rho v^2 / r$ holds, which limits $\lambda$ from below:

$$\frac{\lambda}{r} > \frac{1}{q} \sqrt{\frac{B^2}{4\pi \rho v^2}}, \quad (14)$$

where $q$ is a safety factor, accounting for the crudeness of our analysis. Taking a generous value of $q = 3$, and $r = 40$ AU (Pluto’s orbit), and using the observational values of particle density, magnetic field and solar wind velocity at Pluto’s orbit ($n = 10^{-2} \text{ cm}^{-3}$, $B = 2 \times 10^{-6} \text{ G}$, $v = 4.5 \times 10^7 \text{ cm s}^{-1}$, [25]), we find the following bound on the photon Compton length and photon mass:

$$\lambda > 2 \times 10^{13} \text{ cm; } m_{\text{ph}} < 1.5 \times 10^{-24} m_e = 1.5 \times 10^{-51} \text{ g}. \quad (15)$$

This is a suggested new estimate of the photon mass. It is improved by almost two orders of magnitude compared with the currently accepted value (1).

This limit is based on direct in situ measurements and in this regard is as reliable as the limits established in the ground-based laboratory experiments, especially given a large safety factor that we have used. No doubt it can be improved by at least a factor of a few by more detailed numerical simulations of the flow pattern that would be produced by the set of equations (3)–(7) in the case of finite photon mass.

The current density for $\lambda < r$ is much higher than it would have been in a ‘standard’ MHD (see equation (12)). One might try to use this circumstance to obtain one more constraint on $\lambda$. (Using an evaluation of the current density for constraining $\lambda$ was suggested in [26].) The relative (‘current’) velocity of electrons and ions is $u = j / en$, where $e$ is the electron charge. In our case, taking $\lambda$ as in equation (15), and the other parameters of the solar wind at Pluto’s orbit from [25], we find $u / v_T < 10^{-5}$, meaning that the effects of the anomalous resistivity would not play any significant role. One can check that the Joule dissipation is also small, and the line-tying condition holds well.

4. Using other astrophysical objects for establishing $m_{\text{ph}}$

4.1. Galactic magnetic field

A natural way to improve the estimate of the photon Compton length is to consider electromagnetic phenomena with as large spatial scales as possible. This has been recognized as early as in 1950s, when Yamaguchi [27] (referring to discussions with Thirring) suggested using the presence of the large-scale magnetic fields of astrophysical objects for this purpose. Specifically, he used the inferred presence of the magnetic fields in the Crab Nebula, taking as the length scale 1 pc. Goldhaber and Nieto [4] pointed out that the presence of the ambient conducting medium does not allow identification of the spatial scale with the Yukawa fall-off factor [4, p 293]; they mentioned that some kind of energy balance consideration should rather be given. Chibisov [28] used a force balance discussion for the case of the large magellanic cloud and, assuming that the scale of the magnetic field is of the order of the size of the cloud, 1 kpc, concluded that the photon Compton length should exceed 1 kpc. More recently [17] Chibisov’s arguments were reproduced for our Galaxy, with reference to the magnetic field of $\sim 1 \mu \text{G}$ and the average pressure of the interstellar medium being of the order of the magnetic pressure. Then such force balance considerations (cast in the form of a virial theorem) led the authors of [17] to the conclusion that $\lambda > 1 \text{ kpc}$. However, the authors of the bi-annual compendium ‘Review of particle physics’ [9, 29] have consistently rejected estimate [28], referring to the inapplicability of the virial arguments.
in the problem under consideration. Indeed, the fact that the interstellar medium is a highly structured system with very large density variations makes the use of the virial theorem difficult [30].

It has also to be remembered that, although a large amount of observational data has been collected and the presence of the large-scale galactic magnetic field seems to be established, its magnitude, spatial structure and the level of smaller-scale fluctuations are still an area of active research (see reviews [31, 32]). The most direct technique for evaluating the global field is detection of the Faraday rotation of electromagnetic radiation from pulsars. But this effect provides information only regarding the line-integrated product of the magnetic field and electron density. Therefore, its interpretation requires additional hypotheses; in particular, the correlation between the field strength and plasma density may lead to substantial bias in the estimates of the magnetic field [33].

4.2. Magnetic field in galaxy clusters

One can hope that the improvement in our understanding of the structure of the interstellar magnetic field, based on the analysis of the constantly appearing new data, will lead to resolving the uncertainties mentioned in the previous section. Then, just due to the large scale involved, significant improvements of the mass limit will become possible. In this regard, one should also remember the presence of even larger structures, where the magnetic field plays a significant role in the plasma dynamics, namely, the clusters of galaxies [34].

The scale of typical clusters is in the range of 10 Mpc, and the predicted scale of the regions of a coherent magnetic field may reach $L \sim 0.5$ Mpc [35, 36]. Making an assumption regarding the energy equipartition between the plasma and the magnetic field, one finds, in the same way as in [17, 28], that strong deviations from the present models would appear if the photon Compton length was shorter than the characteristic scale $L$. Introducing safety factor $q \sim 5$ (see section 3.2), one finds the following lower bound on $\bar{\lambda}$:

$$\bar{\lambda} \geq \frac{L}{5} \sim 100 \text{kpc}.$$ 

This conclusion, however, would be subject of the same concerns as an estimate based on the assumed properties of the galactic magnetic field (section 4.1).

4.3. Smaller-scale astrophysical objects

In the near term, there may be a better chance of improving the mass estimate by considering astrophysical objects of an intermediate scale (up to a few parsec), such as dense molecular clouds or stellar outflows. For the first group of objects there exists a large database for the magnetic field strengths and/or its geometrical structure [37]. There is also a growing understanding of the underlying dynamics, including the role of gravitation and star formation (e.g. [38]) and of the magnetic field (e.g. [39, 40]). As these objects are numerous, well defined spatially, and well characterized, one can expect to obtain a reliable limit on $m_{ph}$.

Protostellar and stellar outflows are also quite numerous, and a number of them are spatially well resolved. It is generally assumed that magnetic fields play an important role in their formation and collimation. One can obtain constraints on $m_{ph}$ by analyzing equilibria and stability of these outflows as well as suggested in [41]. Interestingly, there exist laboratory Z-pinch experiments [42] that produce structures strikingly similar to those observed on the sky, thereby supporting assumptions regarding the significant role of magnetic fields in the stellar outflows.
5. Discussion

There exists a reliable theoretical framework for assessing MHD processes in the case where the finite (Proca) photon mass is important. In the quasi-static limit (wave velocity and fluid velocity slow compared with the speed of light), a new term arises only in Ampere’s law. It leads to a substantial modification of MHD processes with spatial scales greater than the photon Compton length $\lambda$, equation (2). In order to make the effect of such a large-scale field on the dynamics of the system important, the magnetic field must be strong enough. So, to evaluate the photon mass based on the observations of a certain system, one has to have information about both the magnetic field and the plasma.

This author believes that, at present, the most reliable limit on the photon mass comes from the spacecraft measurements of the magnetic field and a plasma of the solar wind. Most notable among them are the Voyager spacecrafts. Remarkable agreement has been reached between the observed global structure of the magnetic field and theory (standard, zero-photon-mass, MHD) that takes into account two basic features of the problem: the radial plasma expansion and the rotation of the Sun. The predicted [19] average angle between the magnetic field and the direction to the Sun agrees very well with the spacecraft measurements at distances ranging from Mercury to Pluto [20]. The field strength also agrees well with the theory. These data make the solar wind a very useful object for deducing a limit on the photon mass. Assuming a finite $m_{ph}$ and comparing predictions of the modified MHD equations (3)–(7) with observations, one obtains an upper bound for $m_{ph}$. By choosing a large safety margin, one obtains an estimate as reliable as one could obtain in the laboratory. This approach has been implemented in this paper for the solar wind at large distances from the Sun. The resulting (recommended) estimate is given by equation (15).

Further improvements may come from three directions. The first is a more detailed analysis of the solar wind, with detailed numerical simulations of the flow patterns arising from the finiteness of $m_{ph}$ and comparing the results with observations. This may give rise to the improvement (reduction) of the mass estimate by a factor 5–10.

The second direction is applying an analysis of the type presented in section 3.2, to relatively compact astrophysical objects ($\sim$1 pc scale) such as dense molecular clouds in HII regions. There already exists a large amount of observational information about magnetic fields and plasma parameters in such bodies, and a general understanding of their dynamics is gradually emerging.

The third direction is analyzing the large-scale fields in galaxies and galaxy clusters. Such data can potentially lead to a dramatic improvement of the mass limit. There are, however, difficulties in making reliable predictions associated with insufficient knowledge of the underlying dynamics. The simultaneous presence of both the large-scale field with length scales exceeding $\lambda$, and of a stronger, small-scale field with length scales less than $\lambda$, may make this analysis quite difficult.

A summary of some available estimates of the photon mass is presented in table 1. The last column in this table represents a so-called ‘ultimate’ limit on the photon mass, which is imposed simply by the presence of a finite spatial scale of the Universe [4]. One sees that even the best conceivable estimates of the photon mass are still far above the ultimate limit. New ideas are needed to bridge this gap.

Acknowledgments

The author is grateful to D N Hill and E J Synakowski for their support and encouragement, and to B I Cohen, A Dimits, E B Hooper, L L LoDestro, T D Rognlien and M V Umansky.
Using plasma physics to weigh the photon

Table 1. Some of the available estimates of the photon mass.

<table>
<thead>
<tr>
<th>References</th>
<th>[15]</th>
<th>[16]</th>
<th>[18]</th>
<th>This paper [17, 28]</th>
<th>This paper [4]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Object</td>
<td>Jupiter</td>
<td>Solar wind, 1 AU</td>
<td>Ultra-low frequency waves at 40 AU</td>
<td>Solar wind Galactic cluster magnetic field</td>
<td>The Universe magnetic field</td>
</tr>
<tr>
<td>( \lambda ) (cm, lower bound)</td>
<td>( 3 \times 10^{10} )</td>
<td>( 3 \times 10^{11} )</td>
<td>( 7.5 \times 10^{11} )</td>
<td>( 2 \times 10^{13} )</td>
<td>( 3 \times 10^{23} )</td>
</tr>
<tr>
<td>( m_{ph} ) (g, upper bound)</td>
<td>( 3 \times 10^{-48} )</td>
<td>( 10^{-49} )</td>
<td>( 4 \times 10^{-49} )</td>
<td>( 1.5 \times 10^{-5} )</td>
<td>( 10^{-61} )</td>
</tr>
</tbody>
</table>

\( a \) This is the currently accepted limit.
\( b \) This is the limit suggested in this paper.
\( c \) Insufficient information is available regarding the magnetic field structure in these objects. Accordingly, these values of the photon mass are not quite reliable.
\( d \) This is actually a lower bound on the photon mass, related by the uncertainty principle to the age of the Universe.

for helpful discussions. Greatly appreciated are comments by A S Goldhaber and M M Nieto. This work was performed for the US Department of Energy by the University of California Lawrence Livermore National Laboratory under contract No W-7405-Eng-48.

References