Bound on the Photon Charge from the Phase Coherence of Extragalactic Radiation

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If the photon possessed a nonzero charge, then electromagnetic waves traveling along different paths would acquire Aharonov-Bohm phase differences. The fact that such an effect has not hindered interferometric astronomy places a bound on the photon charge estimated to be at the $10^{-32}e$ level if all photons have the same charge and $10^{-46}e$ if different photons can carry different charges.

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In 2006, the Particle Data Group [1] listed only four bounds on the photon charge, compared with 15 on the photon mass. The photon's electrical neutrality and its masslessness are both quite important to our understanding of electrodynamics. We would therefore like to have the best bounds possible for both these quantities, yet it seems that significantly more work has gone into constraining the photon's mass. In some sense, this is not surprising, since a nonzero photon mass is much easier to accommodate theoretically. However, a significant improvement over the currently quoted bounds on the photon charge is possible, if quantum interference effects are considered.

There are some crucial differences between a photon mass and a photon charge. A photon mass parameter has meaning even at the classical level, where it determines the gap in the dispersion relation. A photon charge, on the other hard, is intrinsically quantum mechanical in nature. The charge of a propagating wave is crucially tied to the decomposition of that wave as a collection of quantized photons. Moreover, while there are at least three viable dynamical models for giving mass to an Abelian gauge field (Proca, Higgs, and Stueckelberg), it is much more difficult to construct a consistent model of charged gauge bosons. The only straightforward way to make gauge fields charged is to use a non-Abelian gauge group, but this requires the existence of a nontrivial multiplet of vector bosons. Related to this is the fact that electric charge is observed to be quantized in units of the proton charge e (in a way that mass is not); yet the present limits on the photon charge are already many orders of magnitude smaller than e.

The absence of a complete theory describing charged photons can complicate the task of placing bounds on any such putative charge. It is possible to place bounds on the photon mass using dynamical stability conditions [2] and observations of magnetohydrodynamic waves [3], as well as tests with static fields [4]. These tests are possible because we can interpret the results of our observations in the context of a well-defined theory—although there may be unexpected model dependences in the conclusions [5]. Without any equivalent theory describing the photon charge, we must rely on rather different techniques. For example, while positing the existence of a photon charge does tell us things about how photon propagation must be affected, it does not tell us anything about how static electromagnetic fields will be modified.

Any bound placed on the photon charge is going to be subject to some level of uncertainty, but some measurements are more robust that others. A very simple-minded experiment involves observing the change in a photon's energy between a source and detector placed at different voltages. Other measurements involve the deflection of photons by magnetic fields [6–8] and the associated time delays [9,10]. The best trustworthy bound derived by these methods is at the $4 \times 10^{-31}e$ level [8]. (A previously quoted better bound in [9] is considered to have been in error.) Moreover, the bounds are actually 2 orders of magnitude better if both positively and negatively charged photons are assumed to exist.

Indirect searches for the effects of a photon charge are also possible. Measurements of the anisotropy of the cosmic microwave background (CMB) can be used to place somewhat model-dependent bounds on the photon charge [11,12]. If there are no cancellations between different species, and a nonzero photon charge disturbed the overall charge neutrality of the early universe, there would be signatures in the CMB. With these assumptions, a limit can be placed on the photon charge at the $10^{-35}e$ level.

We shall suggest a more subtle direct test, which is fundamentally quantum mechanical and based on the Aharonov-Bohm effect. Charged particles moving along different paths through a magnetic field pick up different phases, and the observed coherence of photons from distant astrophysical sources will allow us to place bounds on this effect and hence on the photon charge. Other sensitive interferometric techniques, such as intensity interferometry, might also be useful for setting bounds.

The bounds we shall place are based on observations of photons that have traversed cosmological distances. These photons can be very precise probes of novel phenomena in electrodynamics, the immense distances over which they travel magnifying miniscule effects. A tiny change in how electromagnetic waves propagate can, after millions of parsecs, give rise to a readily observable effect. The strategy of observing radiation from very distant sources has already been used to place extremely stringent bounds on photon birefringence [13–15] and dispersion [16].

Our bounds should not depend in any crucial way on the intricate details of the charged photon dynamics. We shall assume only that there exists an effective Lagrangian governing the propagation of a single photon, and that the coupling of the photon to the external electromagnetic field takes the form $L_I = -\frac{q}{c} v_\mu A^\mu_{\text{ext}}$. The photon's charge is q, and $v^\mu = (c, c\hat{v})$ is its four-velocity. This Lagrangian is essentially unique, once we specify that there must be a potential energy term $-qA^0$ and demand conventional Lorentz transformation properties. The equation of motion derived from L_I is the Lorentz force law.

From L_I, we can calculate the additional phase that a charged photon picks up as it travels, relative to a conventional uncharged photon. In the eikonal approximation, in which the photon's deflection from a straight line path is neglected, the phase is

$$\phi = \frac{1}{\hbar} \int_0^t d\tau \mathcal{L}_I, \tag{1}$$

where we have taken the time interval of the photon's flight to range from 0 to t. Neglecting the contribution of the electrostatic potential and taking the total distance traveled to be L, the phase is

$$\phi = \frac{q}{\hbar c} \int_0^L d\vec{\ell} \cdot \vec{A}_{\text{ext}}. \tag{2}$$

What we can observe is the phase difference between photons arriving at different points. In practice, this is done all the time, and it is the basis of astrophysical interferometry. We consider two telescopes, separated by a baseline d. They collect data from a source lying approximately in the plane perpendicular to the baseline. The observed phase difference due to a possible photon charge is equal to the difference between two phases ϕ_1 and ϕ_2 of the form (2). Neglecting a miniscule contribution proportional to the integral of $\vec{A}_{\text{ext}}$ along the baseline, the phase difference is $\Delta\phi = \Phi q/\hbar c$, where Φ is the magnetic flux threading between the two lines of sight. This is the standard Aharonov-Bohm phase difference, and it is independent of the photon energy.

To estimate the flux integral, we must know something about the relevant magnetic fields. For randomly oriented fields, with typical magnitude B and correlation length λ_C, the flux Φ depends on $Bd\sqrt{\lambda_C L}$. To get an idea of the accompanying numerical constant, we assume that the line of sight passes though L/λ_C magnetic field domains, each of equal size. In each domain, the field is randomly oriented along one of six cardinal directions. One third of the domains contribute to the total flux, behaving like a random walk. The mean distance from the origin in this walk after $L/3\lambda_C$ steps is $\sqrt{2L/3\pi\lambda_C}$, and with an extra factor of $\frac{1}{2}$ corresponding to the triangular geometry of the threaded region, the total flux is

$$\Phi \approx \sqrt{\frac{L\lambda_C}{6\pi}} dB. \tag{3}$$

An Aharonov-Bohm phase could upset interferometric measurements. In order for interferometry to be possible, photons arriving at different telescopes must have definite phase relations. A $\Delta\phi$ of order 1 would destroy this necessary relation. (While there are phase uncertainties in real measurements due to uncertainties in telescope positions, these have very different characteristics and can be distinguished from an Aharonov-Bohm phase. Position uncertainties lead to phase differences that are proportional to the photon frequency, and they have a predictable dependence on the direction of observation, whereas the Aharonov-Bohm phase is frequency independent and varies randomly with different pointing directions. Telescopes are calibrated by observing reference sources, but as long as these are relatively nearby, the bounds will not be significantly affected, since the Aharonov-Bohm phase is related to the distance; there is no problem with this for the telescope arrangement discussed below [17].) So our ability to study objects at a distance L with interferometers of baseline d limits the photon charge to be smaller than

$$\frac{|q|}{e} < \sqrt{\frac{6\pi}{L\lambda_C}} \frac{\hbar c}{deB}. \tag{4}$$

It is worthwhile to contrast this bound with the one that can be derived from measurements of photon deflection by a magnetic field. That bound also depends on the transverse magnetic field along the line of sight. For a constant field B and line of sight L, with photons of energy E and energy spread ΔE, the bound is formulated in terms of the angular deviation $\Delta\theta$ of the different-energy photons as

$$\frac{|q|}{e} < \frac{2E^2\Delta\theta}{ceBL\Delta E}. \tag{5}$$

(If astrophysical field configurations are used, BL would again be replaced by something of order $B\sqrt{L\lambda_C}$.) It is also possible, when using photons of single energy in the laboratory, to use a time-dependent magnetic field and then look for a corresponding time-dependent angular deviation. In either case, the deflection decreases linearly with the photon energy, since higher-energy photons possess more momentum and are thus less deflected by the energy-independent Lorentz force. The Aharonov-Bohm phase is independent of energy, although it is still most advantageous to work with low-energy photons, because their phases can be determined most accurately. The Aharonov-Bohm phase $\Delta\phi$ also depends unavoidably on $\hbar$, while the bound (5) can evidently be written in an $\hbar$-independent form. There is therefore no intrinsic relationship between the bounds obtained by the two different methods, and it should be no surprise if the experimental bounds available via the two methods differ by orders of magnitude.

The greatest uncertainty in our photon charge bounds will come simply from a limited understanding of extragalactic magnetic fields. The best bounds on extragalactic fields come from observations of the Faraday rotation of photons moving through putatively magnetized plasmas [18–20]. The precise bounds one may derive from the Faraday observations depend on the assumptions one makes about the large scale structure of the field and particularly on λ_C. A bound of $B \lesssim 10^{-8}$ G is reasonable, while cosmic ray and high-energy photon data from the source Centaurus A suggest that 10^{-8} G may also be a lower bound for the magnetic field strength in the relative vicinity of our Galaxy [21].

To be conservative, we shall assume a rather lower value of the extragalactic magnetic field. Cosmic ray data suggest that $B\sqrt{\lambda_C}$ may be at the 10^{-10} G Mpc$^{1/2}$ level [22], although this still depends on assumptions about the distribution of ultra-high-energy cosmic ray sources. A possible higher density of sources would yield a higher value of the field.

$B\sqrt{\lambda_C}$ is an essentially universal (if somewhat uncertain) quantity, but the parameters d and L that enter into (4) are experimental variables. The longest baseline d available is that of the Very Long Baseline Interferometry Space Observatory Program (VSOP) satellite experiment, for which $d > 3 \times 10^9$ cm. Using radio telescopes on Earth in combination with one on the Highly Advanced Laboratory for Communications and Astronomy satellite, VSOP imaged active galactic nuclei out to redshifts $z > 3$ [17]. For objects this distant, the effects of cosmological expansion could not be ignored in any precise treatment. However, for obtaining conservative order-of-magnitude bounds on q, this level of precision is not overly important. Excellent bounds on the photon charge can be derived merely from taking $L \sim 1$ G pc, which is roughly half an order of magnitude smaller than the Hubble distance and corresponds to a redshift less than 1.

Taking $B\sqrt{\lambda_C} = 10^{-10}$ G M pc$^{1/2}$, $d = 3 \times 10^9$ cm, and $L = 1$ G pc, we find our bound on the photon charge to be

$$\frac{|q|}{e} \lesssim 10^{-32}, \tag{6}$$

which is an improvement over all previous direct bounds that do not consider photons with multiple opposing charges. There is even a small improvement relative to the erroneously stated bound from [9].

As previously mentioned, it has also been suggested that there may exist photons with positive and negative (or positive, negative, and zero) charges. If this is the case, the CMB bounds would not apply, since the photon gas filling the early universe would be charge neutral. The coherence of observed photons places bounds on this possibility as well. However, there are additional uncertainties if particles with different charges can interfere (and no pairs of like-polarized photons have ever been observed not to interfere). Although the phase difference for two particles of equal charge is always gauge invariant, for particles with different charges it is not. Therefore, the gauge in this scenario must be specified. It is no surprise that gauge invariance is destroyed, since interference between dissimilarly charged particles violates local charge conservation and charge superselection. The gauge fixing condition should arise naturally in the full theory describing this phenomenon, just as the Lorenz gauge condition $\partial^\mu A_\mu = 0$ arises if we introduce a Proca mass term. Yet without a complete theory, the precise form of the gauge condition is unknown.

Nevertheless, it is possible to place an order of magnitude bound on the charge, provided the large scale structure of $\vec{A}$ is not modified. In a magnetic field domain, the typical vector potential is $B\lambda_C/2$. Conservatively assuming that the potential falls back to zero at the edge of the domain, the net contribution to the phase for a photon of charge q is $\phi = \sqrt{\frac{L}{6\pi}} \frac{\lambda_C^{3/2} qB}{\hbar c}$, with the same factor of $\sqrt{2L/3\pi\lambda_C}$ as before. The phase difference for photons of charges q and $-q$ is twice this, even if the photons traverse exactly the same path. Because of this, the bounds are improved by a factor of $\mathcal{O}(d/\lambda_C)$. λ_C is more difficult to determine than $B^2\lambda_C$, but choosing a relatively conservative value of 100 kpc gives an improvement of $\mathcal{O}(10^{-14})$, or a bound of

$$\frac{|q|}{e} \lesssim 10^{-46} \tag{7}$$

if multiple charges are possible. This is a major improvement over previous bounds.

Moreover, the bounds (6) and (7) may still be relatively conservative. They assumed what might be too low a value for the extragalactic magnetic field and a length scale L corresponding to a relatively modest redshift. Perhaps most importantly, the bound assumes that only a phase decoherence $\Delta\phi \sim 1$ is ruled out by the availability of interferometric data. However, we feel that this level of conservatism is warranted, given the uncertainties in quantities such as $B\sqrt{\lambda_C}$.

Significant improvements in these kinds of bounds on the photon charge are possible, but only up to a certain point. A better understanding of magnetism on extragalactic scales will provide more secure (but not necessarily numerically tighter) bounds on q. More careful analyses, taking into account the expansion of the universe, could also extend the reach in L, but since the dependence on L is only as $L^{-1/2}$, the gain to be had in this area is not great. Tighter limits on the experimentally observed phase deviation $\Delta\phi$ would give proportionately tighter bounds on the charge. The largest improvements in the single charge case might come from using longer baselines. In principle, a baseline of 2 AU could be possible for certain types of interferometric measurements, and a baseline this long would improve the bound on q by 4 orders of magnitude.

The photons observed by the VSOP experiment had frequencies of 1.6, 5, and 22 GHz. This places the energies of the photons from which our bound on q was derived in the 6–90 μeV range at the time of their absorption. We might expect, based on Lorentz invariance and charge conservation, that the photon charge should be independent of energy, as is the charge of other particles; however, more exotic possibilities cannot be ruled out.

A critic might object that the Aharonov-Bohm-type phase should not contribute to the ordinary, essentially classical, phase that we observe in radio waves. In this view, the novel phase would represent some kind of intrinsically quantum effect, one which could be observed only if a single photon whose wave packet had been split were recombined and then observed (as opposed to observing distinct but coherent photons at different locations). The corresponding interference effects would have to operate entirely separately from the usual interference of electromagnetic waves. Without a viable theory of charged photons, we cannot definitively reject such a hypothesis; we do, however, note that it violates the usual correspondence principle relationship that connects photons with classical waves, in which the classical and photon phases are one and the same.

We have presented improved bounds on the magnitude of the photon charge, derived from quantum interference considerations. Charged photons, like other charged particles, could acquire Aharonov-Bohm phases, yet no evidence for these phases has been seen in interferometry experiments. Using emissions from distant astrophysical sources—which are particularly useful for constraining small deviations from conventional electrodynamics—the fraction of the fundamental charge present on a radio-frequency photon has been bounded at the 10^{-32} or 10^{-46} levels, depending on whether all photons carry the same charges and provided the large scale structure of the vector potential is unmodified.

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