Constraints on the photon charge based on observations of extragalactic sources

V.V. Kobychev^{1,*}, S.B. Popov^{2,3**}. ¹Institute for Nuclear Research of Ukrainian NAS, ²University of Padova, ³Sternberg Astronomical Institute.

Using modern high-resolution observations of extragalactic compact radio sources we obtain an estimate of the upper bound on a photon electric charge at the level $e_{\gamma} \leq 3 \cdot 10^{-33}$ of elementary charge (assuming the photon charge to be energy independent). This is three orders of magnitude better than the limit obtained with radio pulsar timing. Also we set a limit on a photon charge in the gamma-ray band (energies about 0.1 MeV). In future the estimate made for extragalactic sources can be significantly improved.

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* kobychev@kinr.kiev.ua, ** polar@sai.msu.ru

1 Introduction

The most restrictive up-to-date upper limit on an electric charge of photons was obtained from the timing of millisecond radio pulsars. Radio impulses are smeared due to a dispersion of charged photons moving through the interstellar magnetic field (Cocconi, 1988; the result was later refined by Raffelt, 1994):

$$e_{\gamma}/e < 5 \cdot 10^{-30}$$
.

A little bit weaker constraint on a photon charge was discussed by Cocconi (1992) with a different approach based on an angular spread of photons propagating from distant extragalactic sources. This spread arises due to a deviation of a photon having a hypothetic small charge in a magnetic field. An estimate of $e_{\gamma}/e < 10^{-27.7} \approx 2 \cdot 10^{-28}$ has been obtained with this method from an examination of a photon trajectory in the magnetic field of our Galaxy ($B \sim 10^{-6}$ G, path length $l \sim 10$ kpc). This restriction can be significantly improved by an increasing of the path length (i.e. it is necessary to study the effect in extragalactic fields) and, additionally, by extending the bandwidth (the limit of Cocconi (1992) is based on observations in a quite narrow bandwidth ~ 2 MHz).

Another constraint has been obtained recently by a study of properties of cosmic microwave background. An existence of a small photon charge would result in charge asymmetry of the Universe and would contribute to the observed CMB anisotropy. The quantitative consideration (Caprini *et al.*, 2003) leads to a very strong upper limit of $e_{\gamma}/e < 10^{-38}$, but it is valid only in the case of non-anticorrelated charge asymmetries produced by different types of particles, and, more important, if photons have charges of only one sign. These assumptions make this limit model-dependent¹.

We note, that the best laboratory limit $e_{\gamma}/e < 8.5 \cdot 10^{-17}$ (Semertzidis *et al.*, 2003) is significantly worse than the astrophysical restrictions.

¹See also an earlier paper by Sivaram (1994) where the author discusses a limit based on the cosmic microwave background radiation.

2 Calculations and estimates

Recent observations show that magnetic fields in many galactic clusters are as large as few microgauss with a characteristic autocorrelation length of few kpc (see a review of Carilli and Taylor (2002) and references therein). If a photon exhibits small but finite electric charge (and all photons have the same sign of the charge) then photons with different energies moving through intracluster magnetic field would follow different trajectories. It would result in an increase of an angular size of a source (of course the same but smaller effect should exist for intercluster fields). Also in observations at two different frequencies centers of images would be shifted relative to each other ², simultaneously emitted photons of different energies would reach an observer at different moments. If photons have different signs of the charge (but the same absolute values) then images would be smeared even for monoenergetic radiation; however, the position of the image center should not depend on photons energy in this case.

Let an ultrarelativistic particle (a photon) with an electric charge e_{γ} and a momentum $p = h\nu/c$ move through a magnetic field with a component B_Y orthogonal to the momentum. Its trajectory will have a curvature radius equal to $cp/(e_{\gamma}B_Y)$. One can see that a deviation will be more significant for low-energy radio photons, and, besides, the angular resolution of radio observations (with the VLBI technique) is much better than in other parts of electromagnetic spectrum – it can be as small as 10^{-5} arcseconds. Thus, one should expect that the best restriction on a photon charge will be obtained in the radio frequency range. But taking into account that the origin of the effective charge of photon can be related to violation of Lorentz-invariance we will discuss the upper limit on a photon charge in a wide range of energies.

A photon travelling along an arc with a radius of r_H after passing a distance dl turns by an angle dl/r_H (in radians). So the source at a distance l_{\star} from a detector will be observed shifted by an angle

$$\varphi_X = \int_0^{l_\star} \frac{dl}{r_H(l)} = \frac{e_\gamma}{h} \int_0^{l_\star} \frac{B_Y(l)dl}{\nu(l)}.$$
(1)

along the X-axis orthogonal to the line of sight (Z axis).

A dependence of a frequency on l appears for cosmological distances due to a redshift: $\nu(z) = (1+z)\nu_0$.

²We assume the angles of deviation to be small throughout this article.

Two photons with different energies diverge by an angle (if the photon charge is not energy dependent):

$$\Delta \varphi = \varphi_1 - \varphi_2 = \frac{e_\gamma}{h} \int_0^{l_\star} B_Y \left(\frac{1}{\nu_1} - \frac{1}{\nu_2}\right) dl.$$
⁽²⁾

Thus, observation of a source with an angular diameter $\Delta \varphi$ in a band $\Delta \nu$ (with $\Delta \nu \ll \nu$) leads to a constraint on a photon charge:

$$e_{\gamma}/e \lesssim \frac{\Delta\varphi h}{e} \left(\int_0^{l_{\star}} \frac{B_Y \Delta\nu dl}{\nu^2} \right)^{-1}.$$
 (3)

On the other hand, when observations are performed in two well separated frequency ranges ($\nu_1 \ll \nu_2$) one can use an approximation $\Delta \nu / \nu^2 \approx 1 / \nu_1$, and

$$e_{\gamma}/e \lesssim \frac{\Delta \varphi h}{e} \left(\int_{0}^{l_{\star}} \frac{B_{Y} dl}{\nu_{1}} \right)^{-1}.$$
 (4)

Here $\Delta \varphi$ should be considered as an angular distance between two images in two different bands. The integrals in the equations (3) and (4) can be estimated from an observational data on the Faraday rotation of polarization plane of the radio wave propagating in magnetized plasma. This quantity is expressed in terms of rotation measure (RM) defined as the angle of polarization rotation divided by the wave length squared. For a completely ionized medium we have (Clark *et al.*, 2001):

$$RM = 8.12 \times 10^5 \int_0^{l_\star} n_e B_Z dl.$$
 (5)

The distance is given in Mpc, n_e in cm⁻³, B_Z is the longitudinal projection of magnetic field (in microgausses). In the case of isotropic distribution of the field, the longitudinal projection under the integral can be changed by a projection on any other axis, for instance by B_Y . Assuming this further we will omit the projection index of B.

The redshift dependence is neglected in the equations above. In the case of z being not negligible, the formulae should be rewritten in the terms of the redshift rather than the distance. Beside this, the cosmological effects should be taken into account.

The element of integration may be expressed as:

$$dl = -\frac{c}{H_0}(1+z)^{-3/2}dz$$

(this equation is related to the flat Universe without the "dark energy" contribution; taking this contribution into account would make the limit more restrictive). $B(z) = B_0(1+z)^2$, $\nu(z) = \nu_0(1+z)$ (Ryu *et al.*, 1998).

Then the Eq. (3) is transformed to:

$$e_{\gamma}/e < \frac{\Delta\varphi h}{e} \left(\int_{0}^{z_{\star}} \frac{\Delta\nu_{0}(1+z)}{\nu_{0}^{2}(1+z)^{2}} B_{0}(1+z)^{2} \frac{c}{H_{0}}(1+z)^{-3/2} dz \right)^{-1} = \frac{\Delta\varphi h}{e} \frac{H_{0}\nu_{0}^{2}}{cB_{0}\Delta\nu_{0}} \cdot \frac{1}{2(\sqrt{1+z_{\star}}-1)}.$$
(6)

For $z_{\star} \ll 1$ the last fraction in the Eq. (7) tends to $1/z_{\star}$.

In the case of extragalactic sources usually it is difficult (or impossible) to obtain a good estimate of the magnetic field on the line of sight. Here for illustrative purposes we derive a limit on a photon electric charge using modern estimates of large scale extragalactic magnetic fields. Considering the effect of large scale magnetic field (with the scale larger than the size of a galactic cluster) one can use the estimation made by Kronberg (1994) for the upper limit on the "cosmologically aligned" magnetic field: $B_0 < 10^{-11} \text{ G}$ (these data are obtained from the upper bound of 5 rad/m² on any systematical growth of RM with distance for z = 2.5), as well as the upper limit of $B_0 < 10^{-9}$ G for changing field with the correlation length of ~ 1 Mpc. Widrow (2002) gives the upper limit on the uniform component of the cosmological field of $B_0 < 6 \cdot 10^{-12} \text{ G} (n_e/10^{-5} \text{ cm}^{-3})^{-1}$. This limit agrees with the quoted above estimation by Kronberg. Different investigations (see the up-to-date review in Widrow, 2002) indicate that the real rotation measure cannot be less than the given upper limit by 2-3 orders of magnitude. So we can conservatively take $B_0 > 6 \cdot 10^{-15}$ G as the lower limit for the "noncompensated" cosmological field.

Let us use real observations to estimate an effect of such low magnetic fields. As part of the VSOP (VLBI Space Observatory program) Lobanov et al. (2001) observed the quasar PKS 2215+020 at $\nu_0 = 1.6$ GHz in a bandwidth $\Delta \nu_0 = 32$ MHz. The angular resolution was about 1 mas. The redshift of the source is $z_{\star} = 3.57$ that corresponds to the distance $l_{\star} \approx$ 4700 Mpc. Substituting these quantities into Eq. (6) and assuming $B_0 =$ $6\cdot10^{-15}$ G, $H_0=70~{\rm km/s/Mpc}{=}2.3\cdot10^{-18}$ 1/s, we get the limit on a photon charge:

$$e_{\gamma}/e \lesssim 6 \cdot 10^{-29}$$
.

It is only an order of magnitude worse than the restriction of Raffelt (1994). However, we use here only a very conservative upper limit on the uniform component of extragalactic magnetic field. As another example let us consider an improvement of this limit (with the same frequencies and angular resolution) if the source is observed through a typical cluster (relatively close to us, $z \ll 1$). Neglecting the cosmological effects the integral in (3) is transformed to $(\Delta \nu / \nu^2) \int B dl$. With an estimate of its value as $Bl = 1\mu \text{ G} \cdot \text{Mpc}$ (the product of typical values of intracluster field and the size of the central part of cluster) we obtain:

$$e_{\gamma}/e < \frac{\Delta \varphi h}{e} \frac{\nu^2}{Bl \Delta \nu} = 2 \cdot 10^{-33}.$$

Thus, observation of a source through relatively high intracluster fields (which are, besides, known with better accuracy than the fields outside clusters) allows to improve significantly the limit on an electric charge of photon in spite of the shorter pass length in the field.

3 Specific example

In the example presented below a cluster of galaxies (which works as a "scattering screen") has $z \ll 1$ and the influence of an intercluster field is neglected. When z is low, the dependence of frequency on distance in Eqs. (3) an (4) can be neglected. Owing to this the limit on a photon charge can be expressed directly in terms of the observable rotation measure by excluding the distribution of magnetic field end electron density along the photon trajectory:

$$e_{\gamma}/e \lesssim 3.2 \cdot 10^{-19} \frac{\Delta \varphi h}{e} f(\nu)^{-1} \frac{812h_{70}^{1/2}}{RM},$$
(7)

where $f(\nu) = \Delta \nu / \nu^2$ or $1/\nu_1$ if the frequencies are close or distant correspondingly. We use Eq. (5) and express an electron density as $n_e = 10^{-3} h_{70}^{1/2} 1/\text{cm}^3$ (Clarke *et al.*, 2001)³.

When observations are performed in separated frequencies $(\nu_1 \ll \nu_2)$ this formula can be rewritten as:

$$e_{\gamma}/e = 1.8 \cdot 10^{-32} h_{70}^{1/2} \left(\frac{\Delta \varphi}{0.001''}\right) \left(\frac{\nu_1}{1 \text{ GHz}}\right) \left(\frac{RM}{1 \text{ rad/m}^2}\right)^{-1}.$$
 (8)

Let us consider the compact source 3C84 in the galaxy NGC1275 that is situated close to the center of the cluster Abell 426 (the Perseus cluster, z = 0.0183). This source was observed by Scott *et al.* (2004). These authors made a survey of 102 active galactic nuclei at 5 GHz with the VSOP facility (the VLBI network with the space antenna HALCA). Among six components of 3C84 the smallest one has a diameter (at FWHM) 0.8 mas. Taking into account 10% precision cited in that paper we conservatively assume the angular diameter to be 0.9 mas. The central frequency and the band width are 4.8 GHz and 32 MHz correspondingly.

The rotation measure for 3C84 was measured by Rusk (1988):

$$RM = +76 \operatorname{rad/m}^2$$
.

In addition it is worth noting that the Perseus cluster is a source of polarized dispersed radio emission at 350 MHz (Brentjens, de Bruyn, 2003) with

³Note that the normalized Hubble constant h_{70} is always used with a lower index, whereas the Planck constant h is written without an index.

 $RM \sim 25$ -90 rad/m² (including the cluster outskirts). Taking all together we can safely assume that at least a rotation measure $\sim 25 \text{ rad/m}^2$ is acquired not in the central regions with high electron density but in the outer regions of the cluster. According to Churazov *et al.* (2003) n_e outside the central sphere with a radius ~ 0.3 Mpc is small ($\lesssim 10^{-3} \text{ cm}^{-3}$) and weakly depends on the distance from the cluster center.

At first let us discuss the case of two signs of a photon charge. In this case the smearing of a point source appears even in observations in a narrow band, so we can use Eq. (8). Substituting $\nu_1 = 4.8$ GHz, RM = 25 rad/m², $n_e = 10^{-3} \ 1/\text{cm}^3$, $\Delta \varphi = 0.9$ mas, we obtain a limit on the absolute value of a photon charge:

$$e_{\gamma}/e \lesssim 3 \cdot 10^{-33}$$

For photons with the one sign of charge, the widening appears due to different energies of the particles, i.e. it depends on the bandwidth ($\Delta \nu = 32$ MHz in our case), and the effect is smaller. Using Eq. (7) and $f(\nu) = \Delta \nu / \nu^2$ we have:

$$e_{\gamma}/e \lesssim 4 \cdot 10^{-31}$$

4 Discussion

Different methods to derive limits on a photon charge are possible. They may be related to different technique as well as to observations in different spectral ranges.

A strong constraint can be obtained from the VLBI observations of close pairs of sources in several frequencies. In this case the angular distance between the sources can be measured as accurately as tens of μ as (Bartel, 2003). Observations of two sources with different redshifts in several frequencies (like the ones carried out by Rioja, Porcas, 2003) can give important upper limits.

Cocconi (1992) had also obtained some constraints (quite weak) from data on an angular dispersion in optical and X-ray ranges: $e_{\gamma}/e < 10^{-25.4}$. He considered the dispersion in magnetic fields of the Galaxy. The usage of modern data on extragalactic fields can provide a significantly improved limit.

Study of gamma-ray bursts with known redshifts (these data were not available at the time of publication of Cocconi, 1988, 1992 and Raffelt, 1994) cannot provide limits comparable with those obtained from the pulsar timing and from angular deflection of radio sources. However, the possible energy dependency of a photon charge (as mentioned above) gives a good occasion to discuss charge limits in a wide energy range.

Taking into account that the dispersion for gamma quanta in the interstellar medium is negligible, the time delay is written as (Barbiellini, Cocconi, 1987):

$$\Delta t = \frac{e_{\gamma}^2 B^2 l_{\star}^3}{24 c E^2}.$$

Here the delay is calculated relative to the arrival time of the photons with energies much larger than E. If it is not the case (for example observations are made in a narrow band $\Delta E \ll E$) then the delay can be written as:

$$\Delta t = \frac{e_{\gamma}^2 B^2 l_{\star}^3}{12cE^2} \frac{\Delta E}{E}.$$

Both the formulae can be applied to photons with different signs of charge as well as to photons with the same sign.

A width of a rising edge of GRB is sometimes shorter than 1 ms (~200-250 μ s, Schaefer, Walker 1999). This quantity can be taken as an estimate

of a maximum time delay. Then for $\Delta E/E = 0.5$ we have (neglecting cosmological effects):

$$e_{\gamma}/e < 5.6 \cdot 10^{-21} \left(\frac{E}{100 \,\mathrm{keV}}\right) \left(\frac{B}{6 \cdot 10^{-15} \,\mathrm{G}}\right)^{-1} \left(\frac{\Delta t}{0.1 \,\mathrm{ms}}\right)^{1/2} \left(\frac{l_{\star}}{1000 \,\mathrm{Mpc}}\right)^{-3/2}$$

Here we normalize the magnetic field by the lower limit on the uniform component of the extracluster field without taking into account the chaotic component of the field that is not known reliably yet. As before, the restriction can be strenghtened significantly if a GRB would be observed through a cluster with known magnetic field.

5 Conclusions

Modern VLBI observations of extragalactic radio sources give the stringest limits on the photon electric charge at the level of $e_{\gamma}/e \leq 3 \cdot 10^{-33}$ (with an assumption that photons with different signs of the charge are equaly abundant, and that a photon charge does not depend on energy). These limits can be improved by the VLBI observations of close pairs of compact sources through clusters with known magnetic field as for the case of close sources the precision of angular distance measurements can be about 10 μ as. Also it is desirable to use data on several sources to improve the statistics⁴. In future, space radio telescopes will achieve much better angular resolution (Bartel, 2003; Fomalont, Reid, 2004), so precise observations of extragalactic radio sources will provide the most restrictive upper limits on the photon electric charge.

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⁴This comment was suggested by an anonymous referee

References

- M.F. Aller, H.D. Aller, P.A. Hughes, Astrophys.J., 586, 33 [astro-ph/0211265] (2003).
- [2] G. Barbiellini, G. Cocconi, Nature **329**, 21 (1987).
- [3] N. Bartel, Astronomy in Latin America, Second Meeting on Astrometry in Latin America and Third Brazilian Meeting on Fundamental Astronomy. Eds. R. Teixeira, N.V. Leister, V.A.F. Martin, and P. Benevides-Soares. ADeLA Publications Series, vol. 1, 35 [astro-ph/0303342] (2003).
- [4] M.A.Brentjens and A.G. de Bruyn, The Riddle of Cooling Flows in Galaxies and Clusters of Galaxies, Charlottesville, VA, USA. May 31 – June 4, 2003. (Eds. T.H.Reiprich, J.C.Kempner, N. Socker. Published electronically at http://www.astro.virginia.edu/coolflow/proc.php)
- [5] C. Caprini, S. Biller, P.G. Ferreira, hep-ph/0310066 (2003).
- [6] C.L. Carilli, G.B. Taylor, Ann. Rev. Astron. Astrophys., 40, 319
 [astro-ph/0110655] (2002).
- [7] T.E. Clarke, P.P. Kronberg, H. Böhringer, Astrophys. J., 547, L111 (2001).
- [8] E. Churazov, W. Forman, C. Jones, H. Böhringer, Astrophys. J., 590, 225 (2003).
- [9] G. Cocconi, Phys. Lett., **B206**, 705 (1988).
- [10] G. Cocconi, Am. J. Phys., **60**, 750 (1992).
- [11] E. Fomalont, M. Reid, astro-ph/0409611 (2004).
- [12] P.P. Kronberg, Rep. Prog. Phys., 57, 325 (1994).
- [13] A.P. Lobanov, L.I. Gurvits, S. Frey, R.T. Schilizzi, N. Kawaguchi, I.I.K. Pauliny-Toth, Astrophys. J., 547, 714 (2001).
- [14] G. Raffelt, Phys. Rev., **D50**, 7729 [hep-ph/9409461] (1994).
- [15] M.J. Rioja, R.W. Porcas, Astron. Astrophys. 355, 552
 [astro-ph/0002097] (2000).

- [16] R.E. Rusk, Ph.D. Thesis, University of Toronto (1988); cited accroding to: Aller et al. 2003.
- [17] D. Ryu, H. Kang, P.L. Biermann, Astron. Astrophys., 335, 19 (1998).
- [18] B.E. Schaefer, K.C. Walker, Astrophys. J., **511**, L89 (1999).
- [19] W.K. Scott, E.B. Fomalont et al., astro-ph/0407041. Accepted by Ap. J. Supp. (2004).
- [20] Y.K. Semertzidis, G.T. Danby, D.M. Lazarus, Phys. Rev. D, 67, 017701 (2003).
- [21] C. Sivaram, Am. J. Phys., **63**, 1473 (1994).
- [22] L.M. Widrow, Rev. of Mod. Phys., 74, 775 [astro-ph/0207240] (2002).