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Testing Einstein's Equivalence Principle with multi-band Very Long Baseline Array measurements of AGN core shifts

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ABSTRACT

The Einstein Equivalence Principle (EEP) can be tested with deflection of light in gravitational field. In this paper, we consider the apparent shifts of active galactic nuclei (AGN) core positions are due to violations of EEP. We use data from multi-wavelength Very Long Baseline Array (VLBA) measurements and the gravitational field from our Milky Way Galaxy to put constraints on the parameterized post-Newtonian (PPN) parameter γ, and the differences of γ for photons over a frequency range of 8.11 to 15.37 GHz are within 2.30×10^{-6}, while for 1.41 to 15.37 GHz photons are within 5.75×10^{-7}, considering AGN jet properties. These results provide stringent constraints of EEP over a much wider frequency range than previous analysis.

1. Introduction

The Einstein Equivalence Principle (EEP), with its statement of all uncharged test particles in vacuum following identical trajectories independent of particles' compositions and structures, serves as one of the most fundamental basics of modern gravitational physics. For microscale test particle, e.g., photons and neutrinos, a parameterized post-Newtonian (PPN) formalism, with 10 PPN parameters (Will, 1993), can be adopted to test the validity of EEP. Each metric theory of gravity, including Einstein's theory of general relativity, has its own set of PPN parameter values (Will, 2006, 2014). Thus by comparing the measured and predicted values of PPN parameters, or PPN parameter values of different types of particles, one can put constraints on the accuracy of the EEP assumption.

Of these PPN parameters γ has been tested extensively. This parameter characterizes the space curvature induced by gravity (e.g. see Misner et al., 1973 and Will, 1993). General relativity predicts $\gamma = 1$, while other theories may give rise to other γ values (Will, 1993). By observing the deflection of light in the vicinity of the Sun with very-long baseline interferometry (VLBI) in radio band, Lambert and Le Poncin-Lafitte (2009, 2011) put a limit of $|\gamma - 1| \leqslant (0.8 \pm 1.2) \times 10^{-4}$, while Bertotti et al. (2003) yielded $|\gamma - 1| \leqslant (2.1 \pm 2.3) \times 10^{-5}$ from Doppler tracking of Cassini spacecraft.

Besides, as long as EEP stands, the PPN parameters of two different zero-charge test particles (denoted as 1 and 2) γ_1 and γ_2 should be the same, that is, $\gamma_1 = \gamma_2 \equiv \gamma$. Several works have been done with Shapiro time delays between different types of zero-charge particles, or same type of particles with different energies (Shapiro, 1964), and very stringent constraints have been achieved. For example, Krauss and Tremaine (1988) and Longo (1988) compared the arrival time of eV photons and MeV neutrinos from Supernova 1987A, yielding a result of $|\gamma_\gamma - \gamma_\nu| \leqslant 3.4 \times 10^{-3}$, while Gao et al. (2015) and Wei et al. (2015) got $|\gamma_{\mathrm{GeV}} - \gamma_{\mathrm{MeV}}| \leqslant 2 \times 10^{-8}$ as well as $|\gamma_{1.23\mathrm{GHz}} - \gamma_{1.45\mathrm{GHz}}| \leqslant 4.36 \times 10^{-9}$ for GRB 090510 and FRB 100704, respectively, considering the gravitational field of the Milky Way. And more recently Wei et al. (2016) compared the arrival time of sub-TeV and ∼TeV photons from blazar PKS 2155-304, yielding $|\gamma_{0.2-0.8\mathrm{TeV}} - \gamma_{>0.8\mathrm{TeV}}|$ with an order of 10^{-6}, while Tingay and Kaplan (2016) got $|\gamma_{1.2\mathrm{GHz}} - \gamma_{1.5\mathrm{GHz}}| \leqslant 1 - 2 \times 10^{-9}$ with FRB 150418. Besides, Luo et al. (2016) further reduced $|\gamma_{1.23\mathrm{GHz}} - \gamma_{1.45\mathrm{GHz}}|$ by 4 orders of magnitudes by taking the gravitational field of Laniakea, the supercluster of galaxies in which the Milky Way resides into consideration.

However, it is also important to test EEP with different methods other than time delays. In this paper, we will test the differences of PPN parameter γ between different radio frequencies with VLBA data of active galactic nucleus (AGN) jets. By considering the AGN core shift effects as results from gravitational deflections, a stringent limit can be deduced. In Section 2 of this paper, the basic

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methods and data are described. In Section 3, our results without and with corrections of synchrotron self-absorption effect in AGN jets are presented. In Section 4, these results are summarized and discussed.

2. Method of constraining EEP with VLBA AGN observations

Active galactic nuclei are accreting supermassive black holes dwelling deep in the cores of galaxies, with relativistic jets pointing to opposite directions. VLBI observations have measured AGN jets with accuracy of milliarcsecond (mas) or higher. In such radio images, AGN cores, or the most compact bright feature corresponding to the surface with optical depth $\tau \approx 1$ near the apparent base of the relativistic jets, can be identified. With multi-band observations, a trend of "core shift" effect is clearly shown (e.g., see Kovalev et al., 2008; Sokolovsky et al., 2011). Generally speaking, the core shift effect can be explained as the change of $\tau \approx 1$ surface in different frequencies, as shown in purely synchrotron self-absorbed conical jet in equipartition model (Blandford and Königl, 1979). However, if we consider such a phenomenon purely or partially as the result of gravitational deflection at different frequencies ν due to non-constant γ_ν, constraining EEP with a different approach other than Shapiro delay can be obtained.

In the PPN formalism, the deflection angle of light θ in the vicinity of a massive object with a mass M can be described as (Will, 1993)

$$\theta \approx \frac{1}{2}(1+\gamma)\frac{4GM}{bc^2}\frac{(1+\cos\phi)}{2}\,, \tag{1}$$

where γ is the PPN parameter to be tested, G the Newtonian gravitational constant, c the vacuum speed of light, b the impact parameter, and ϕ the elongation angle between the source body and the deflecting body. Historically, Eddington applied Eq. (1) to confirm the deflection of starlight predicted by general relativity during a solar eclipse, although the accuracy then was as low as 30 percent (Kennefick, 2009), while later on Lambert and Le Poncin-Lafitte (2009, 2011) also put the most stringent constraints on the EEP from VLBI measurements through this method.

In order to compare the γ value deviations of different photons with different frequencies (energies), here we consider two photons with frequencies ν_1 and ν_2. Thus, the upper limit of difference between γ_1 and γ_2 can be written as

$$\Delta\gamma = |\gamma_1 - \gamma_2| \approx \frac{\Delta\theta bc^2}{GM(1+\cos\phi)}\,, \tag{2}$$

where $\Delta\theta = |\theta_1 - \theta_2|$ is the difference between deflection angles of these two photons. It can be seen that a smaller $\Delta\theta$, smaller b and larger M can give rise to a better result.

In this work, we adopt the Milky Way Galaxy as our deflecting body. Here the elongation angle ϕ can be calculated as

$$\cos\phi = \sin\delta_S \sin\delta_G + \cos\delta_S \cos\delta_G \cos(\beta_S - \beta_G)\,. \tag{3}$$

And the impact parameter b should be

$$b = r_G\left[1 - (\sin\delta_S \sin\delta_G + \cos\delta_S\cos\delta_G\cos(\beta_S - \beta_G))^2\right]^{1/2}\,, \tag{4}$$

where $r_G \approx 8.3$ kpc is the distance of the Galactic Center (GC) to our solar system, $\beta_S = \mathrm{RA}_S$ and $\delta_S = \mathrm{Dec}_S$ (J2000) the equatorial coordinates of the source, and $\beta_G = \mathrm{RA}_G = 17^{\mathrm{h}}45\mathrm{m}40^{\mathrm{s}.04}$ and $\delta_S = \mathrm{Dec}_S = -29°00'28''.1$ (J2000) the equatorial coordinates of the GC (Gillessen et al., 2009). And we adopt $M_{MW} \approx 6\times10^{11} M_{Sun}$ as the mass of the Milky Way (McMillan, 2011; Kafle et al., 2012). Although the Milky Way has a non-spherical shape, and within the Galaxy a more complicated form of light deflection from various mass elements should be applied in order to get an accurate constraint (e.g. see Schneider et al., 2006), Eq. (1) still yields an approximation within 1 order of magnitude to the real value, since most mass in the Milky Way exists in extended halo, thus similar mass $\sim 0.5M_{MW}$ (and gravity) can be found at either side of the Solar System.

Taking the Milky Way rather than the Sun as our gravitational source to deflect the light from extragalactic sources such as AGNs has two advantages. For one thing, a structure as vast as a whole galaxy can influence a much larger area than a single star. That is, a source farther away from the GC (with a larger ϕ) can also feel the gravity from the Milky Way. Besides, as shown in Eq. (1), the typical deflection angle in the vicinity of the Sun is $\theta \approx 1.7505''$ (Hawking, 1979), while for the Milky Way Galaxy with a typical impact parameter $b \approx 5$ kpc, a smaller θ can be expected. Besides, the exact epoch of each VLBI observation is not well described in literatures, which can bring significant uncertainties to the position of the Sun. Thus in this paper only the gravity from the Milky Way is considered.

Other astrophysical processes may also bring out AGN core shifts in different radio bands. Other than the synchrotron self-absorbed conical jet model, which can be well fitted by the function $r_{c,\nu} = a + b\nu^{-1}$ (where $r_{c,\nu}$ is the core shift related to a reference jet component other than core, ν the observed frequency, a and b free parameters, see Lobanov, 1998), photons with non-zero rest mass moving through a gravitational field can also give rise to different deflection angles at different bands (Lowenthal, 1973). By measuring the deflection of $\nu = 3$ GHz radio emission by the Sun, an upper limit of photon rest mass $m_\gamma \leqslant 7\times10^{-40}$ g has been obtained (Lowenthal, 1973). However, currently the upper limit of photon mass adopted by the Particle Data Group is $m_\gamma \leqslant 1.783\times10^{-51}$ g (Olive et al., 2014). With such a limit, the difference between the expected deflection angle and the deflection angle for zero-mass photon should not exceed the order of 10^{-47} arcsec, which is far beyond the resolution of VLBI techniques. Thus in our analysis we neglect the effect of non-zero photon mass.

Also AGNs may have "intrinsic" core shifts, that is, radiations of different frequencies arise from different components around the supermassive black hole. A notable example is J1526-1351, with a second flat-spectrum core situated ∼100 mas south of the radio peak, which may be explained as an additional bright components farther along the jet (Mantovani et al., 2002a, 2002b). Fortunately for most radio-loud AGNs, especially the AGN samples in Sokolovsky et al. (2011), this is not the case. In this work, we assume all AGN core emissions come from the apparent bases of jets.

3. EEP constraints with AGN core shift

Sokolovsky et al. (2011) performed VLBA core shift measurements for 20 AGNs at 9 frequencies from 1.41 to 15.37 GHz. And the shift related to 15.37 GHz core for each source at every frequency, as well as the AGN coordinates in J2000 are presented. We take these data as our samples for EEP analysis. First we take the assumption that such shifts are purely induced by differences in γ_ν, and our constraints with Eq. (2) are presented in Table 1. Here the first column shows the names of each AGN, while the upper limits of $\Delta\gamma$ between radio photons with different frequencies are listed in other columns.

It can be seen from Table 1 that since generally speaking the lower the frequency, the more significant the core shift related to 15.37 GHz core can be observed (see Table 4 of Sokolovsky et al., 2011), a systematic trend of $\Delta\gamma$ is shown. $\Delta\gamma$ between lower radio frequencies and 15.37 GHz are no-