TESTS OF THE EINSTEIN EQUIVALENCE PRINCIPLE USING TeV BLAZARS

JUN-JIE WEI\textsuperscript{1}, JIE-SHUANG WANG\textsuperscript{2}, HE GAO\textsuperscript{3}, AND XUE-FENG WU\textsuperscript{1,4}

\textsuperscript{1} Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing 210008, China; jjwei@pmo.ac.cn, xfwu@pmo.ac.cn
\textsuperscript{2} School of Astronomy and Space Science, Nanjing University, Nanjing 210093, China
\textsuperscript{3} Department of Astronomy, Beijing Normal University, Beijing 100875, China
\textsuperscript{4} Joint Center for Particle, Nuclear Physics and Cosmology, Nanjing University-Purple Mountain Observatory, Nanjing 210008, China

Received 2016 January 13; accepted 2016 January 16; published 2016 February 1

ABSTRACT

The observed time delays between different energy bands from TeV blazars provide a new, interesting way of testing the Einstein Equivalence Principle (EEP). If the whole time delay is assumed to be dominated by the gravitational field of the Milky Way, the conservative upper limit on the EEP can be estimated. Here, we show that the strict limits on the differences of the parameterized post-Newtonian parameter $\gamma$ values are $\gamma_{\text{TeV}} - \gamma_{\text{keV}} < 3.86 \times 10^{-3}$ for Mrk 421 and $\gamma_{\text{TeV}} - \gamma_{\text{keV}} < 4.43 \times 10^{-3}$ for Mrk 501, while expanding the scope of the tested EEP energy range out to the TeV–keV range for the first time. With the small time lag from the 0.2–0.8 TeV and >0.8 TeV light curves of PKS 2155-304, a much more severe constraint on $\gamma$ differences of $\sim 10^{-6}$ can be achieved, although the energy difference is of the order of $\sim$TeV. Furthermore, we can combine these limits on the energy dependence of $\gamma$ with the bound on the absolute $\gamma$ value $\gamma - 1 \sim 0.3\%$ from light deflection measurements at the optical (eV) bands, and conclude that this absolute bound on $\gamma$ can be extended from optical to TeV energies.

Key words: BL Lacertae objects; general – gravitation

1. INTRODUCTION

The Einstein Equivalence Principle (EEP), which is one of the major pillars of general relativity and other metric theories of gravity, says that the trajectories of freely falling, uncharged test bodies are independent of their internal compositions and structures. The possible violations of EEP would have a significant impact on people’s understanding of nature; it is therefore important to sequentially improve the verification of its accuracy.

The validity of the EEP and general relativity in a post-Newtonian context can be characterized by limits on the numerical coefficients of the parameterized post-Newtonian (PPN) parameters, such as the parameter $\gamma$. Here, $\gamma$ is defined as how much space curvature is produced by unit rest mass (see Will 2006, 2014 for a recent review). More specifically, one can test the accuracy of EEP and general relativity by measuring the absolute value of $\gamma$ (e.g., Froschel et al. 1997; Bertotti et al. 2003; Lambert & Le Poncin-Lafitte 2009, 2011), as well as constraining the differences of $\gamma$ values for different types of massless (or negligible rest-mass) neutral particles, or for the same type of particle with different energies (e.g., Krauss & Tremaine 1988; Longo 1988; Gao et al. 2015; Wei et al. 2015), since general relativity predicts $\gamma \equiv 1$ and all gravity theories incorporating the EEP also predict $\gamma_1 = \gamma_2 \equiv \gamma$, where the subscripts correspond to two different test particles.

Determinations of the absolute $\gamma$ values have reached high precision from light deflection and time delay measurements. The light deflection measurements from the very long baseline radio interferometry yielded $\gamma - 1 = (-0.8 \pm 1.2) \times 10^{-4}$ (Lambert & Le Poncin-Lafitte 2009, 2011). Through the time delay measurements of a radar signal from the Cassini spacecraft, Bertotti et al. (2003) obtained an accurate determination of $\gamma - 1 = (2.1 \pm 2.3) \times 10^{-5}$. These results are in good agreement with the prediction of general relativity.\footnote{Note that some other gravitational theories besides general relativity also predict $\gamma \equiv 1$ (Will 1993).}

On the other hand, some astronomical sources have been used to test the EEP by comparing the $\gamma$ values for different test particles in a few instances, including the following representative cases. Krauss & Tremaine (1988) and Longo (1988) proposed that the observed time delay of the neutrinos and photons from supernova 1987A provides a new test of the EEP; they presented an upper limit on $\gamma$ differences of 0.34% for neutrinos and photons, and a more severe limit of $1.6 \times 10^{-6}$ for neutrinos ranging in energy from 7.5 to 40 MeV. Gao et al. (2015) used the time delays between correlated photons from gamma-ray bursts (GRBs) to constrain the accuracy of the EEP and found that the differences of the $\gamma$ values for photons over the MeV–GeV or eV–MeV range is as low as $\sim 10^{-7}$, improving the limits from supernova 1987A by at least one order of magnitude. Wei et al. (2015) proved that fast radio bursts (FRBs) of extragalactic origin can serve as an ideal testbed to probe the EEP and set the most stringent limit on $\gamma$ differences up to now, yielding $\sim 10^{-8}$, by analyzing the arrival time delay of FRB photons of different frequencies, which is at least 10–100 times tighter than the constraints from supernova 1987A and GRBs.

It is well known that blazars are an extreme subclass of active galactic nuclei, which can be further divided into flat-spectrum radio quasars if they have strong emission lines and BL Lacertae objects if they have weak or no emission lines (e.g., Ulrich et al. 1997). Blazars are characterized by broadband non-thermal emission extending from radio up to high-energy and very high energy (VHE) gamma-rays, and a display of violent variability on different timescales from minutes to years (e.g., Wagner & Witzel 1995). The broadband radiation is produced by a relativistic jet pointed along the line

\footnote{Note that some other gravitational theories besides general relativity also predict $\gamma \equiv 1$ (Will 1993).}
of sight (e.g., Begelman et al. 1984; Urry & Padovani 1995). Because of their fast flux variability, cosmological distances, and VHE photons in the TeV range, TeV blazars have been deemed as an effective way to probe the effect of Lorentz invariance violation (LIV; e.g., Biller et al. 1999; Aharonian et al. 2008; MAGIC Collaboration et al. 2008; H.E.S.S. Collaboration et al. 2011). Here, we suggest that TeV blazars can also provide a good astrophysical laboratory to constrain the EEP, which can further extend for the first time the scope of the tested energy range out to TeV energies.

It is worth pointing out that testing the EEP with both GRBs and TeV blazars is of great fundamental interest. GRBs can be detected out to very high redshifts (z ~ 8.2), but with very few high-energy (E > GeV) photons. On the contrary, TeV blazars can be well observed by ground-based detectors with large statistics of photons above a few tens of TeV. However, since high-energy photons would be absorbed by extragalactic background light, TeV observations are limited to sources with low redshifts. Hence, GRBs and TeV blazars are mutually complementary in constraining the EEP, and they enable us to test different redshift and energy ranges. In this work, we first try to test the accuracy of the EEP using TeV blazars. The rest of this Letter is arranged as follows. In Section 2, we briefly describe the method of testing the EEP. The constraints on the EEP from TeV blazars are shown in Section 3. Finally, we summarize our conclusions in Section 4.

2. METHOD DESCRIPTION

The observed time delays between different energy bands from the cosmological sources have been used to set bounds on the EEP. In principle, the observed time delay (∆t_{obs}, Gao et al. 2015; Wei et al. 2015)

\[ \Delta t_{\text{obs}} = \Delta t_{\text{int}} + \Delta t_{\text{LIV}} + \Delta t_{\text{spe}} + \Delta t_{\text{DM}} + \Delta t_{\text{gra}} \]  

has contributions from the intrinsic time lag (∆t_{int}), the LIV-induced time delay (∆t_{LIV}), the possible time delay due to the non-zero mass of photons in special relativity (∆t_{spe}), the underlying time delay arisen from the dispersion by the line-of-sight free electron content (∆t_{DM}), and the travel time delay (∆t_{gra}) between energy bands E1 and E2, caused by an external gravitational potential U(r), respectively. Among these terms,

\[ \Delta t_{\text{gra}} = \gamma - \frac{\gamma_2}{c^2} \int_{r_o}^{\infty} U(r) dr \]  

is the relevant one to probe the EEP. Here, γ is the PPN parameter, r_o and r_e represent locations of Earth and source. For high-energy photons, such as the gamma-ray signals considered here, ∆t_{DM} is absolutely negligible. In addition, considering that both ∆t_{LIV} and ∆t_{spe} are also negligible for the analysis of this work, and assuming ∆t_{int} > 0, one can derive

\[ \Delta t_{\text{obs}} > \frac{\gamma_1 - \gamma_2}{c^2} \int_{r_o}^{\infty} U(r) dr. \]  

We refer the reader to Gao et al. (2015) for more details.

Generally, U(r) should have three components, i.e.,

\[ U(r) = U_{\text{MW}}(r) + U_{\text{IG}}(r) + U_{\text{gas}}(r), \]

including the gravitational potentials of the Milky Way, intergalactic background, and host galaxy of the cosmological source, respectively. Although the potential models of U_{IG}(r) and U_{gas}(r) are hard to know, it is plausible to assume that the effect of these two components is much greater than if we just consider the potential of the Milky Way U_{MW}(r). Adopting the Keplerian potential for the Milky Way, it would be reasonable to have

\[ \gamma_1 - \gamma_2 < \Delta t_{\text{obs}} \left( \frac{GM_{\text{MW}}}{c^3} \right)^{-1} \ln^{-1} \left( \frac{d}{b} \right) \]  

where \( M_{\text{MW}} \sim 6 \times 10^{11} M_\odot \) is the total mass of the Milky Way (McMillan 2011; Kasli et al. 2012), b represents the impact parameter of the rays, and d denotes the distance from the Earth to the source.

3. TESTS ON THE EEP FROM TeV BLAZARS

As we know, mankind’s view of nature would be greatly affected if the EEP is violated. Thus, it is important to constantly test the validity of the EEP with all kinds of alternative astronomical sources. We continue to search for such sources and propose that TeV blazars are a new, interesting tool for constraining the EEP, while extending the tested EEP energy range out to TeV energies (more on this below). As examples, we use three famous TeV blazars (Mrk 421, Mrk 501, and PKS 2155-304) to constrain the EEP accuracy.

3.1. Mrk 421

Markarian 421 (Mrk 421; z = 0.031) is the first extragalactic TeV blazar to be detected at gammaray energy E > 500 GeV (Punch et al. 1992), with coordinates (J2000) R.A. = 1°04′19″, decl. = 38°11′44″. Using the High Altitude Gamma Ray (HAGAR) telescope array, Shukla et al. (2012) observed Mrk 421 in its high state of flux activity during 2010 February 13–19 and also detected a very bright flare above 0.25 TeV. They investigated the correlation between light curves of different energies with the cross-correlation function and found that a VHE gamma-ray (>0.25 TeV) flux reaches peak with a 1.3 days lag compared with the peak time of the X-ray (1.5–12 keV) flare. With the measured time delay ∆t_{obs} = 1.3 days and location information, we thus obtain EEP constraint from Equation (4) for Mrk 421

\[ \gamma_{\text{TeV}} - \gamma_{\text{keV}} < 3.86 \times 10^{-3}. \]  

3.2. Mrk 501

The TeV blazar Markarian 501 (Mrk 501) is a nearby, bright X-ray-emitting source at z = 0.034, also well known to emit VHE (E > 100 GeV) gamma-ray photons (Quinn et al. 1996), with coordinates (J2000) R.A. = 16°52′52″, decl. = 39°45′36″. Furniss et al. (2015) reported on the multiwavelength observational campaign of Mrk 501 between 2013 April 1 and August 10, including the first display of hard X-ray variability with Swift and NuSTAR. The discrete correlation function was applied to study the cross-correlations between different energy bands. A time lag of 0 ± 1.5 days was measured between the VHE observations (>0.2 TeV) and the 0.3–3 keV Swift/XRT band. To be conservative, we adopt the largest value of 1.5 days as the time delay ∆t_{obs} between these two energy bands. With the above information of Mrk

---

6 The location information of TeV blazars are available in the TeGeV Catalog at http://www.asdc.asi.it/TEGRACAT/.
501, a severe limit on the EEP from Equation (4) is
\[ \gamma_{\text{TeV}} - \gamma_{\text{keV}} < 4.43 \times 10^{-3}. \] (6)

3.3. PKS 2155-304

The source PKS 2155-304 is one of the brightest TeV blazars and located at \( z = 0.117 \), almost four times more distant than Mrk 421 and Mrk 501. It was discovered at the radio bands as part of the Parkes survey (Shimmins & Bolton 1974), and identified as a BL Lacertae object by Hewitt & Burbidge (1980), with coordinates (J2000) R.A. = 2P58m52.6, decl. = -30°13′18″. The observation of the VHE flare of PKS 2155-304 on 2006 July 28 by the High Energy Stereoscopic System (H.E.S.S) provides the current best limit on LIV derived from the observation of blazars (H.E.S.S. Collaboration et al. 2011). Aharonian et al. (2008) determined the time delay from two light curves in different energies using the modified cross correlation function. In order to keep good photon statistics in the two energy bands, while optimizing the energy gap between the two bands to 1.0 TeV, the dispersion per energy can be transformed to the measured time delay \( \Delta t_{\text{obs}} = 73 \) s. From Equation (4), we can tighten the constraint on the EEP to
\[ [\gamma(0.2 \text{ TeV} - 0.8 \text{ TeV}) - \gamma(>0.8 \text{ TeV})] < 2.18 \times 10^{-6} \] (7)
for PKS 2155-304, which is as good as the results on supernova 1987A from Longo (1988).

4. SUMMARY AND DISCUSSION

The accuracy of the EEP at the post-Newtonian level can be tested through the relative differential variations of the PPN parameters, such as the parameter \( \gamma \). Inspired by the work of Gao et al. (2015), we continue to search for other alternative astronomical sources that are suitable for testing the EEP accuracy. In this work, we propose that TeV blazars can serve as a new good candidate for this purpose. Furthermore, GRBs and TeV blazars are complementary to each other in constraining the EEP since they are observed in different energy and redshift ranges and with different levels of variability.

Using the observed time delay \( \Delta t \sim 1.5 \) days for the light curves with energy bands of keV to TeV and an assumption that the time delay is dominated by the gravitational potential of the Milky Way, we place robust limits on \( \gamma \) differences for the two TeV blazars, i.e., \( \gamma_{\text{TeV}} - \gamma_{\text{keV}} < 3.86 \times 10^{-3} \) for Mrk 421 and \( \gamma_{\text{TeV}} - \gamma_{\text{keV}} < 4.43 \times 10^{-3} \) for Mrk 501. On the basis of the time delay from two light curves between 0.2 and 0.8 TeV and >0.8 TeV bands, we can tighten the limit on \( \gamma \) differences to \( [\gamma(0.2 \text{ TeV} - 0.8 \text{ TeV}) - \gamma(>0.8 \text{ TeV})] < 2.18 \times 10^{-6} \) for PKS 2155-304, but the energy difference is of the order of ~TeV. It should be underlined that these upper limits are based on very conservative estimates of the observed time delay and the total gravitational potential. The inclusion of contributions from the neglected components in the observed time delay (see Equation (1)) could improve these limits to some degree. In addition, if we have a better understanding of the host galaxy and the intergalactic gravitational potential, and these two effects are taken into consideration, our constraint results would significantly improve by orders of magnitude.

In the past, tests of the EEP through the differences of the \( \gamma \) parameter have been made of emissions from supernova 1987A (Krauss & Tremaine 1988; Longo 1988), GRBs (Sivaram 1999; Gao et al. 2015), and FRBs (Wei et al. 2015). In particular, the observation of FRBs not only provided the most stringent limits on the accuracy of the EEP, showing that the EEP is obeyed to the level of \( 10^{-8} \), but also extended the EEP tested energy range down to the radio band (Wei et al. 2015). Also, Gao et al. (2015) extended the tested energy range up to the MeV–GeV and eV–MeV ranges with the help of high-energy photons from GRBs, although the capability of GRBs for testing the EEP (~\( 10^{-7} \)) was not so strong as that of FRBs. In the present Letter, we prove that TeV blazars are a new support tool for probing the EEP in different energy and redshift ranges, and we derive the upper limits of \( 10^{-7} \) for light curves over the TeV–keV range and of \( 10^{-6} \) for light curves over an energy range between 0.2 and 0.8 TeV and above 0.8 TeV. Although our constraints on the EEP accuracy are not as tight as previous results of GRBs or FRBs, the tested energy range can be further extended out to the TeV–keV range by using the measured time delays of TeV blazars.

As mentioned above, the most precise limits on the absolute \( \gamma \) value of photons yield an agreement with a general relativity of \( \gamma - 1 \sim 10^{-5} \), which is from radio photons (Bertotti et al. 2003). And the light deflection measurements using the Hipparcos optical astrometry satellite have reached \( \gamma_{\text{keV}} - 1 \sim 0.3\% \) (Froeschle et al. 1997). On the other hand, by constraining the differences of \( \gamma \) values between various energies, Gao et al. (2015) found that the absolute \( \gamma \) values of MeV or GeV photons differ from that of optical (eV) photons by \( <10^{-7} \), and our results show that the absolute \( \gamma \) values of TeV photons differ from that of keV photons by \( <10^{-3} \). Combining these results, we can predict that the limits on the absolute \( \gamma \) values of TeV photons should also be consistent with general relativity to the same level of \( \sim 0.3\% \), i.e., \( \gamma_{\text{TeV}} - 1 \sim 0.3\% \). We therefore conclude that this absolute bound on \( \gamma \) can be extended from the optical to the TeV range, and the value of \( \gamma \) is identical for photons between optical and TeV to within approximately \( 10^{-3} \).

We are grateful to the anonymous referee for useful suggestions, which led to an improvement in the presentation of our manuscript. We also acknowledge Houdun Zeng for helpful communications. This work is partially supported by the National Basic Research Program (“973” Program) of China (grant Nos. 2014CB845800 and 2013CB834900), the National Natural Science Foundation of China (grant Nos. 11322328, 11433009, and 11543005), the National Natural Science Foundation of China (grant Nos. 11322328, 11433009, and 11543005), the Youth Innovation Promotion Association (2011231), and the Strategic Priority Research Program “The Emergence of Cosmological Structures” (grant No. XDB09000000) of the Chinese Academy of Sciences.

REFERENCES

Aharonian, F., Akhperjanian, A. G., Barres de Almeida, U., et al. 2008, PhRvL, 101, 170402
Begelman, M. C., Blandford, R. D., & Rees, M. J. 1984, RvMP, 56, 255
Berti, B., Iess, L., & Tortora, P. 2003, Natur, 425, 374
Biller, S. D., Breslin, A. C., Buckley, J., et al. 1999, PhRvL, 83, 2108
Froeschle, M., Mignard, F., & Arenou, F. 1997, in Proc. of ESA Symposium, Vol. 402, Hipparcos - Venice ’97 (Venice: ESA), 49
Furniss, A., Noda, K., Boggs, S., et al. 2015, ApJ, 812, 65
Gao, H., Wu, X.-F., & Mészáros, P. 2015, ApJ, 810, 121
H.E.S.S. Collaboration, Abramowski, A., Acero, F., et al. 2011, APh, 34, 738
Hewitt, A., & Burbidge, G. 1980, ApJS, 43, 57
Kafle, P. R., Sharma, S., Lewis, G. F., & Bland-Hawthorn, J. 2012, ApJ, 761, 98
Krauss, L. M., & Tremaine, S. 1988, PhRvL, 60, 176
Lambert, S. B., & Le Poncin-Lafitte, C. 2009, A&A, 499, 331
Lambert, S. B., & Le Poncin-Lafitte, C. 2011, A&A, 529, A70
Longo, M. J. 1988, PhRvL, 60, 173
MAGIC Collaboration, Albert, J., Aliu, E., et al. 2008, PhLB, 668, 253
McMillan, P. J. 2011, MNRAS, 414, 2446
Punch, M., Akerlof, C. W., Cawley, M. F., et al. 1992, Natur, 358, 477
Quinn, J., Akerlof, C. W., Biller, S., et al. 1996, ApJL, 456, L83
Shimmins, A. J., & Bolton, J. G. 1974, AuJPA, 32, 1
Shukla, A., Chitrnis, V. R., Vijnwanath, P. R., et al. 2012, A&A, 541, A140
Sivaram, C. 1999, BASI, 27, 627
Ulrich, M.-H., Maraschi, L., & Urry, C. M. 1997, ARA&A, 35, 445
Urry, C. M., & Padovani, P. 1995, PASP, 107, 803
Wagner, S. J., & Witzel, A. 1995, ARA&A, 33, 163
Wei, J.-J., Gao, H., Wu, X.-F., & Mészáros, P. 2015, PhRvL, 115, 261101
Will, C. M. 1995, in Theory and Experiment in Gravitational Physics, ed. M. W. Clifford (Cambridge: Cambridge Univ. Press), 396
Will, C. M. 2006, LRR, 9, 3
Will, C. M. 2014, LRR, 17, 4