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LIMITS ON AN ENERGY DEPENDENCE OF THE SPEED OF LIGHT FROM A FLARE OF THE ACTIVE GALAXY PKS 2155-304

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Abstract. The study of time-lags in light curves with Wavelet methods or Cross-correlation functions for distant astrophysical sources like active galaxies, as a function of energy, may lead to a detection of Lorentz symmetry breaking or effects due to Quantum Gravity in extra-dimension models. In this paper a search for such timelags during the H.E.S.S. observations of the exceptional Very High Energy flare of the active galaxy PKS 2155-304 on 28 July in 2006 is presented. Since no significant time-lag value was found on the minute level, the 95% Confidence Limit on the Quantum Gravity scale is set to $0.5 - 0.7\ 10^{18} GeV$, considering only a linear term in the standard photon dispersion relation.

Introduction

A Quantum Gravity theory provides a unified picture based on the Quantum Mechanics and the General Relativity, thus leading to a common description of the four fundamental forces. The Quantum Gravity effects in the framework of the String Theory (Ellis et al. 2000) where the gravitation is considered as a gauge interaction, are resulting from a graviton-like exchange in a background classical space-time. In most of the String Theory models implying large extra-dimensions these effects would take place at the Planck scale, thus leading to no 'spontaneous' Lorentz Symmetry breaking, as it may happen in models with 'foamy' structure of the quantum space-time (Amelino-Camelia et al. 1998, Ellis et al. 2000) or in models based on the General Relativity with Loop Quantum Gravity (Gambini & Pullin 1999, Alfaro et al. 2002) which postulates discrete (cellular) space-time in the Planckian regime. As a result, one may expect a spontaneous violation of the Lorentz Symmetry at high energies to be the generic signature of Quantum Gravity.

1 Extra-dimension models and Quantum Gravity

In models developed by (Ellis et al. 2002), photons propagate in vacuum which may exhibit a non-trivial refractive index due to its foamy structure on a characteristic scale approaching the Planck length or equivalently Plank energy ($E_{\mathrm{P}} = 1.22 \times 10^{19}$ GeV). This implies a light group velocity increasing as a function of energy of the subluminal photon, in contrary to the dispersion effects in any field theoretical vacuum or plasma. In general, the Quantum Gravity scale is supposed to be close to Planck energy and the standard photon dispersion relation in second order in energy can be written as:

$$c' = c\ \left(1 \pm \xi \frac{E}{E_{\mathrm{P}}} \pm \zeta^2 \frac{E^2}{E_{\mathrm{P}}^2}\right). \tag{1.1}$$

As suggested by (Amelino-Camelia et al. 1998) the tiny effects can add up to measurable time delays for photons from cosmological sources. Simultaneously-emitted photons of energies E_1 and E_2 which travel over a distance L will arrive at the observer with a time delay $\Delta t = t_1 - t_2$ per energy difference $\Delta E = E_1 - E_2$:

$$\frac{\Delta t}{\Delta E} = \frac{L}{\Delta E}\ \left(\frac{1}{c_1'} - \frac{1}{c_2'}\right) \approx \mp \xi \frac{L}{E_{\mathrm{P}} c} \quad \text{for} \quad \Delta E \ll E_{\mathrm{P}}, \tag{1.2}$$

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when conserving only the linear term in the development. Here, the cosmological expansion of the universe is neglected.

The energy dispersion is best observed in sources that show a fast flux variability, are at cosmological distances and are observed over a wide energy range. Therefore in the past, Gamma Ray Bursts and Very High Energy (VHE) flares of active galaxies have been the primary targets of these "time-of-flight" studies, which provide the least model dependent test of Lorentz symmetry. A caveat of time-of-flight measurements is that dispersion might be introduced due intrinsic source effects, which could cancel out or enhance the dispersion due to modifications to the speed of light. The most solid results on the Quantum Gravity scale of the order of $10^{16} GeV$ are provided by GRB observations with different redshifts as they take into account the possible time lags originating from source effects, resulting in limits of $\xi < 1300$ (Ellis et al. 2006, Bolmont et al. 2008). Before this study, the dispersion measurements for active galaxies exist only for two sources, Mkn 421 and Mkn 501. Both are located at a similar redshift of ∼0.03. For Mkn 421 no energy-dependent time delay was found during a VHE flare in 1996 by the Whipple collaboration (Biller et al. 1999). For Mkn 501 an indication of higher energy photons lagging the lower energy ones was reported during a VHE flare in 2005 by the MAGIC collaboration (Albert et al. 2007).

2 Analysis of the PKS2155-304 flare and results on Quantum Gravity

In the present study, photon time delays were searched for during the VHE flare of the active galaxy PKS 2155-304 observed by the High Energy Stereoscopic System (H.E.S.S.) on July 28 in 2006. PKS 2155-304 is located at a redshift of z = 0.116 , equivalent to a distance of 490 Mpc (for a Hubble constant of 71 km s^{-1} Mpc^{-1}). The light curve shows fast variability (∼ 200 s) and covers an energy range of a few TeV with no significant spectral variability (Aharonian et al. 2007). Together with the unprecedented photon statistics (∼ 10000 photons) at these energies, this flare provides a perfect testbed. The data presented here were analyzed using the standard H.E.S.S. analysis, described in detail in (Aharonian et al. 2006). Time delays between light curves of different energies were studied in order to quantify a possible energy dispersion.

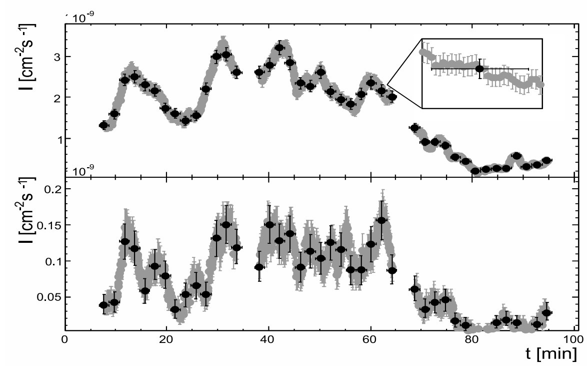

Fig. 1. Black points show the integral flux VHE light curves measured on July 28 from PKS 2155-304 by H.E.S.S. between 200-800 GeV (upper panel) and >800 GeV (lower panel), binned in two-minute time intervals. The zero time point is set to MJD 53944.02. Gray points show the oversampled light curve, meaning that the original time bins were subsequently shifted by five seconds. The inlay in the upper panel illustrates this in a zoom, where the horizontal error bar shows the two minute time duration from the original light curve.

The spectral time properties of the PKS2155-304 flare were investigated with 2 methods: Continuous Wavelet Transform (CWT) (Mallat 1998) and Modified Cross-Correlation Function (MCCF) (Li et al. 2004, Edelson & Krolik 1998). Both analyses of the light curves were done in similar two energy domains as shown in Fig. 1. To evaluate precisely the position of the sharp transitions, referred below as extrema, the CWT method was used as it is widely applied in the time lag studies of the GRB light curves 6, 7. This method relies on very different aspects of the light curves from those studied later by MCCF and provides independent crosschecks of the systematic errors. As in analyses described in (Ellis et al. 2003), the search for extrema (maxima and minima) in the light curves was done with a Mexican Hat wavelet function. The LastWave package (Bacri 2004) used in this analysis provides, for each light curve considered, a list of extrema candidates with their positions and first and second derivative. The extrema were later associated in pairs between the light curves in the two energy ranges following an algorithm based on the Lipschitz coefficient as in (Mallat 1998, Ellis et al. 2003) which characterizes the regularity of each extremum. Since tiny quantum gravity effects are to be probed, the value of the time bin-width of 60 seconds was found to be optimal as the statistics is concerned, for this study. Light curves have been constructed in the two energy bands (between 0.21 to 0.25 TeV and above 0.6 TeV) from the photon-tagged sample used in the MCCF analysis, resulting in a mean energy difference of 0.92 TeV. To evaluate the time-lag error, photon lists were generated from the real data using a parametric bootstrap model, obtained from a polynomial spline fit to the light curves in time bins of one minute and a fit of the energy distribution of the events in the real data. Samples composed of hundreds of Monte Carlo experiments were analyzed and the values of the error were found to range between 30 and 36 seconds with mean values of the reconstructed smearing different by at most 15 s. The results from error calibration have also shown that there is no major systematic bias on the mean time lag estimation induced by the method in use.

The mean time lag for two pairs of extrema identified with CWT method was found to be 27 seconds. After correction for the systematic shift deduced with the error calibration procedure, we set a 95% confidence limit to 100 s TeV^{-1} on a possible time lag.

The MCCF analysis (Li et al. 2004, Edelson & Krolik 1998), applied to oversampled light curves was used to cross-check the results obtained with CWT. To optimize the energy gap between two energy bands, while keeping good event statistics in both, the correlation analysis was performed on the light curve between 200 and 800 GeV and above 800 GeV (see Fig. 1). The mean difference of the photon energies between the two bands is 1.0 TeV. In order to measure the time delay, the central peak of the MCCF distribution was fitted by a Gaussian function plus a first-degree polynomial, resulting in a maximum at $\tau_{\mathrm{peak}} = 20$ s. The error of the measured time lag is determined by propagating the flux errors via simulations. Simulated light curves were generated for each energy band, by varying the flux points of the original oversampled light curve within its measurement errors, taking into account the correlations between bins. It was found that the Cross Correlation Peak Distribution (CCPD) has an RMS of 28 s and for 21% of the simulations the time delay is negative. Therefore the measured time delay of 20 s is considered to be not significant. The response of the MCCF to dispersion in energy was determined by injecting artificial dispersion into the H.E.S.S. data and measuring its effect on the CCPD.

A 95% confidence upper limit on a linear dispersion of 73 s TeV^{-1} was found. The accuracy of the MCCF method was also verified with the bootstrap simulation Monte Carlo and the CCPD of these simulations confirmed the previously measured error on the time delay. Artificially introduced dispersion was always recovered within the expected accuracy.

The impact of other possible systematic effects has also been investigated: selection of gamma-like events, choice of the energy domain or varying binning in the light curves changing the results at most by 0.5σ. For the wavelet method, various cuts on the CWT parameters have been applied and lead to negligible changes in the extrema identification and pair association. The probability of accidental associations in pairs has been evaluated to be $< 1\%$ with dedicated Monte Carlo simulations of random spikes in the light curve.

The measured limits are the most constraining limits from time-of-flight measurements to date: $\xi < 24.2$ (or ξ^{-1} E$_p > 5.0 \times 10^{17}$ GeV) from CWT and $\xi < 17.6$ (or ξ^{-1} E$_p > 6.9 \times 10^{17}$ GeV) from MCCF for the linear dispersion term, a slightly better result due to a larger lever arm in energy.

Conclusions

The results from PKS2155-304 flare on July 2006 are complementary to those from Mrk501 2005 flare observation by MAGIC, where a significant positive time-lag was detected with statistics lower by an order of magnitude. It should be underlined that in case of PKS2155-304 flare the analyses of variability of the light curves were performed with two orthogonal approaches and with a very robust estimation of the time-lag error. The measured time-lag of the order of few minutes with Mrk 501 would imply values above 10 minutes for PKS2155-304 redshift, if the Quantum Gravity interpretation was maintained.

In future, the large lever arm in energy of the GLAST mission will open a new era in this domain. As for the proposed Cherenkov Telescope Array (CTA), the population studies of the active galaxy data with redshift, will provide competitive results on Lorentz Symmetry breaking independently of the source induced effects.

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