

Limits to Quantum Gravity Effects from Observations of TeV Flares in Active Galaxies

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Abstract

Data from a TeV γ -ray flare associated with Markarian 421 has been used to place bounds on the possible energy-dependence of the speed of light in the context of an effective quantum gravitational energy scale (Biller et al., 1998). The limits derived indicate this energy scale to be in excess of 6×10^{16} GeV for at least one approach to quantum gravity in the context of D-brane string theory. To the best of our knowledge, this constitutes the first convincing limit on such phenomena in this energy regime.

It has recently been pointed out that many quantum gravity scenarios may result in an observable time dispersion for high energy radiation originating at large distances from the Earth (Amelino-Camelia *et al*, 1998; Garay 1998; Gambini, Rodolfo and Pullin, 1998) This would result from an effective energy-dependence to the velocity of light in vacuum owing to propagation through a gravitational medium containing quantum fluctuations on distance scales near the Planck length, $L_P \simeq 10^{-33}$ cm, with timescales on the order of $1/E_P$, where E_P is the Planck Mass ($\simeq 10^{19}$ GeV). In particular, it has been indicated that different approaches to quantum gravity lead to a similar description of the first-order effects of such a time dispersion:

$$\Delta t \simeq \xi \frac{E}{E_{QG}} \frac{L}{c} \quad (1)$$

where Δt is the time delay relative to the standard, energy-independent speed of light, c ; ξ is a model-dependent factor of order 1; E is the energy of the observed radiation; E_{QG} is the assumed energy scale for quantum gravitational effects which can couple to electromagnetic radiation; and L is the distance over which the radiation has propagated. While E_{QG} is generally assumed to be on the order of E_P , recent work within the context of string theory suggests that the onset of noticeable quantum gravitational effects may correspond to a characteristic energy scale smaller than the Planck mass and perhaps as low as 10^{16} GeV (Witten, 1996). Thus, any experimental probe of such scales or higher would be of great interest.

In a recent paper (Amelino-Camelia *et al*, 1998) it was suggested that γ -ray bursts (GRBs) could provide a natural way to test such predictions owing to the short duration, high energies and the

apparent cosmological origin of at least some of these bursts. However, stringent and robust limits to E_{QG} can already be set based instead on the rapidly rising TeV flares seen to occur in active galaxies.

The most rapid flare observed thus far was seen from Markarian 421 on 15 May 1996 (Gaidos *et al.*, 1996). This data is shown in figure 1, where the excess rate of γ -ray selected events above a threshold of 350 GeV is binned in intervals of 280 seconds duration, as it appeared in the original publication of this observation. To avoid confusion (and potential bias), we will retain this same binning throughout the current analysis. The doubling time of the flare is less than 15 minutes, although variability is apparent on the scale of the binning at the 99% confidence level. Because of the rapidly falling energy spectrum, the γ -ray data is dominated by events near the triggering threshold. Thus, the peak of the flare is almost entirely defined by events with γ -ray energies less than 1 TeV, as shown at the top of figure 2 where the average background level is ~ 12 events per bin. The lower plot in figure 2 shows the same distribution for events with γ -ray energies in excess of 2 TeV, where ~ 1 of the 7 events is expected to be background.

It is worth noting that the bin containing the largest number of higher energy events out of the 36 intervals shown in figure 1, is the same 280 s interval which contains the largest number of lower energy events. The absence of events in either of the immediately adjacent bins therefore suggests that no such lag is present on scales greater than that of the binning. To explicitly quantify this, we first note that the excess of low energy events above the average background level can be used to define a probability density function (PDF), binned in time. This may then be used to compute the relative likelihood for the observed distribution of higher energy events (depicted in the bottom half of figure 2) to be drawn from an identical distribution which is shifted in time with respect to the lower energy events. The PDF must be suitably normalized over those bins which allow such a mapping owing to the ‘‘edges’’ of the 28 minute, uninterrupted data run. The quantity $-2\log(L_r)$, where L_r is the relevant likelihood ratio, is approximately distributed as a χ^2 distribution with 1 degree of freedom (Wilks, 1938), and may therefore be used to determine confidence levels. For the hypothesis of higher energy emission leading the lower energy emission by one 280 s interval, the resulting value of $-2\log(L_r)$ is 5.8, whereas a value of 4.7 is obtained for the case of higher energy emission lagging the lower energy emission. Hence, at the greater than 95% confidence level (verified by Monte Carlo sampling of the time distributions), emission above 2 TeV appears to keep in step with emission below 1 TeV for variability timescales less than 280 seconds. A caveat to this analysis is that it is possible to conceive of a scenario in which high and low energy emission are emitted at slightly different times at the source in just such a way as to compensate for time delays in the propagation of the radiation due to quantum gravity effects. However, we regard this scenario as being overly conspiratorial in nature and note that future studies of sources at different redshifts will resolve this issue beyond doubt.

The redshift of Markarian 421 is 0.031, which translates to 1.1×10^{16} light-seconds for an assumed Hubble constant of 85 km/s/Mpc. From equation 1, our results then lead to a lower bound on E_{QG}/ξ of 4×10^{16} GeV. Recent calculations in the context of D-brane theory (Ellis, Mavromatos and Nanopoulos, 1999) indicate a value of $\xi \sim 3/2$, leading to a bound of $E_{QG} > 6 \times 10^{16}$ GeV for this model. On the other hand, calculations in the context of loop gravity (Gambini, Rodolfo and Pullin, 1998) lead to a value of ξ as large as 4, suggesting an energy scale in excess of 1.6×10^{17} GeV.

We note that an earlier limit on the energy-dependence of the speed of light, which would be more restrictive than that given here, had been derived from the possible ultra-high-energy detection of anomalous pulsed emission from Her X-1 in 1986 (Haines *et al.*, 1990). However, more recent analyses and the lack of further such detections suggests that the interpretation of that observation as a statistical fluctuation is not an unreasonable one (Biller, 1992). We therefore believe that the limits presented in this paper represent the most credible and stringent bounds thus far obtained.

The next generation of proposed ground-based instruments, such as VERITAS and HESS, will

feature multi-telescope systems with much improved sensitivity, energy coverage and resolution, along with the ability to track candidate sources of flares more continuously using dedicated telescopes. This will allow for both a more detailed study of the time structure of currently known TeV sources and the prospect of discovering and studying more distant objects. It is therefore reasonable to expect to probe E_{QG} to even higher energies in the near future from further studies of TeV flares. The distinctive dependence of the shortest observable variability timescale on both energy and source distance for quantum gravitational dispersion should allow source-specific effects to be distinguished. Thus, future TeV studies could conceivably provide convincing evidence for quantum gravity, particularly if the resulting time-dispersion effects are associated with characteristic energy scales less than the Planck mass.

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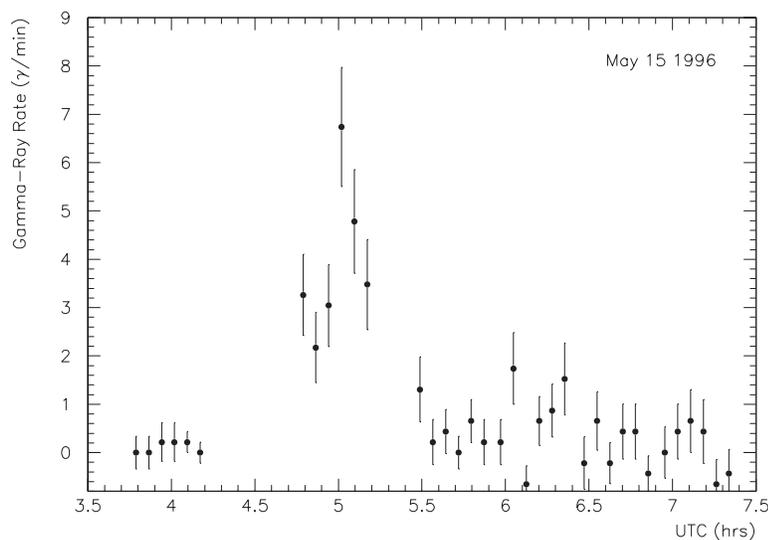


Figure 1: TeV γ -ray flare from Markarian 421 observed on 15 May 1996 by the Whipple γ -ray observatory. The rate of excess γ -ray selected events is binned in intervals of 280 seconds. (taken from reference Gaidos *et al.*, 1996)

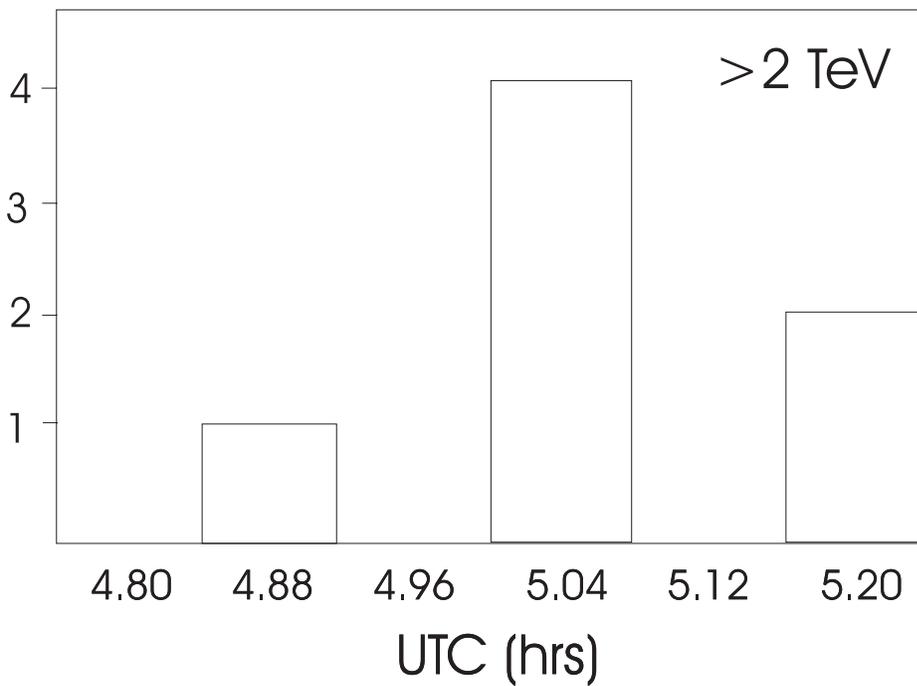
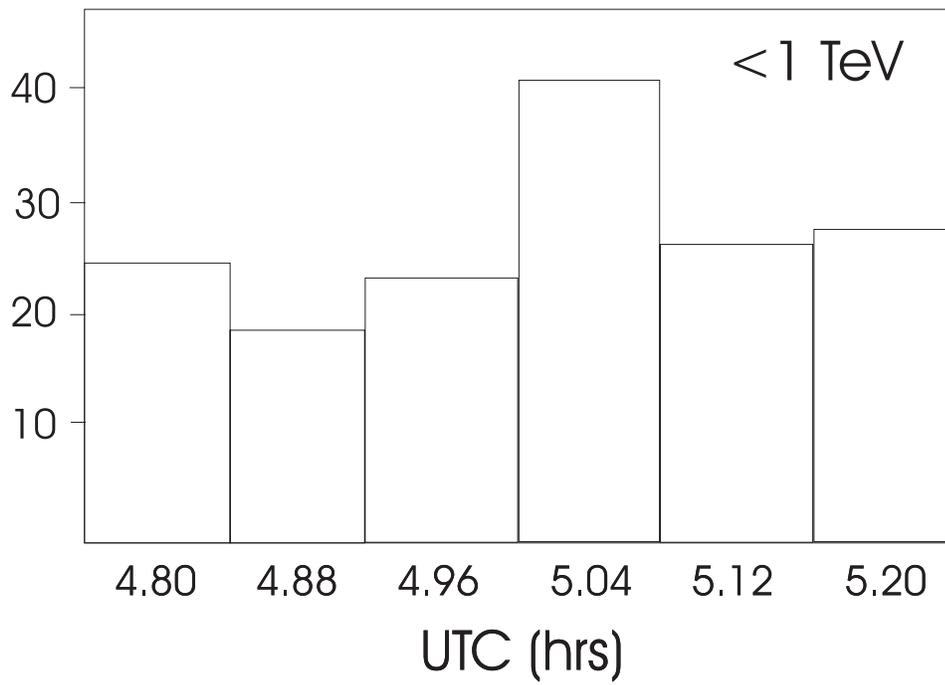


Figure 2: Total number of γ -ray selected events occurring in each 280 second interval near the peak of the 15 May 1996 flare from Markarian 421. The top plot consists of events with γ -ray energies less than 1 TeV, whereas the bottom plot is for energies greater than 2 TeV. (taken from Biller *et al*, 1998)