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Long Duration Variability of Mrk 421

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Abstract: Active Galaxies such as Mrk 421 have been shown to be highly variable at all time scales. Atmospheric Cherenkov Telescopes (ACTs) have excellent instantaneous sensitivity and have observed short bright flares from Mrk 421. However, long duration variability is difficult to monitor with ACTs due to their intermittent exposure. Milagro, in contrast, monitors Mrk 421 with daily observations. While Milagro lacks the sensitivity to detect short duration flares unless they are i extremely bright, it is well suited to make long duration monitoring of the total flux of Mrk 421 on time scales from months to years. In this paper we present the long duration variability and total fluence of Mrk 421 using 6 years of data from Milagro.

Introduction

Active galactic nuclei (AGN) are among the most interesting sources of gamma-rays. At the highest energies, blazars are the most luminous class of AGN with only a single non-blazar detection, M87[1]. There are currently 13 known TeV blazars with more than half discovered in the last 3 years. The TeV emission from blazars is generally modeled as originating from a relativistic jet that is pointed in the direction of the observer. Observations of TeV blazars over the last decade by ACTs have shown variability on time scales from minutes to months. Similar, variability has been observed at other wavelengths as well. The spectral energy distribution for blazars is characterized by 2 peaks, one in the X-ray and another in the the TeV regime. The common interpretation is that the X-ray and TeV emission is due to synchrotron radiation and inverse Compton scattering from a single population of VHE electrons.

Mrk 421 is the closest TeV blazar with a red shift of 0.030. The close proximity minimizes the attenuation of TeV gamma-rays due to pair production with the inter-galactic IR radiation field. Numerous multi-wavelengths campaigns have been conducted where TeV, X-ray and longer wavelength instruments have simultaneously observed

Mrk 421 for periods from hours to weeks. These observations have established a "fairly loose" correlation between the X-ray [2] and TeV flux of these sources. However, orphan TeV flares (flares with no X-ray counterpart) have also been observed from AGN [3].

For durations longer than 2 weeks, ACT's are not well suited because they can only operate during moon-less nights so observations can only be conducted during 2 week moon-less cycles during the half of the year when the source under consideration is up at night. Extended Air Shower detectors such as Milagro however operate continuously during the day and the night and are typically not effected by weather. While the sensitivity of Milagro for short duration observations is considerable less than ACTs such as VERITAS or HESS, they are well suited to study long duration variability. The Milagro detector can also measure the long duration average fluxes of AGN and study the correlation with X-rays by combining the Milagro observations with those of the the All Sky Monitor (ASM) on board the RXTE satellite. The ASM, while less sensitive than more narrow field x-ray telescopes, has a wide field and makes frequent long duration observations of the entire sky.

In this paper, we study the long duration variability of Mrk 421 using X-ray data from the ASM[1] and TeV data from Milagro. We also study the long duration X-ray and TeV correlation.

Milagro Detector

The Milagro Detector is an air-shower array that employs a man-made pond of water instrumented with photo-multiplier tubes (PMTs) to detect Čerenkov radiation from secondary shower particles in extensive air showers. The detector is located in the Jemez Mountains near Los Alamos, New Mexico at an altitude of 2650m (750g/cm^2 of overburden). The detector consists of a rectangular reservoir measuring 80m x 60m and 7m deep instrumented with 2 layers of 8" PMTs. The top layer contains 450 PMTs distributed in an 25 x 18 grid at a depth of 1.4m and is used primarily for measurement of the arrival times of secondary shower particles. The bottom layer contains 273 PMTs on a smaller 21 x 13 grid at a depth of 6m.

Figure 1: Aerial view of the Milagro detector.

This deep layer provides a calorimetric measurement of secondary shower particles and is used to distinguish deeply penetrating muons and hadrons, common in hadron induced air showers, from electrons and γ-rays. The central pond detector is surrounded by an array of 175 'outrigger detectors'. The outriggers consist of a single PMT immersed in a 4000l water tank.

Data Analysis

The Milagro Gamma-Ray Observatory has operated continuously since July 20, 2000 with 90% on-time. In the intervening years numerous upgrades to the hardware and software have increased the sensitivity of Milagro. With our current reconstruction and analysis, Milagro obtains $12\sigma/\sqrt{yr}$ on the Crab with a median energy of roughly 12 TeV [4]. This high sensitivity is achieved by strongly weighting the highest energy events. High energy events, while few in number, have the best angular resolution and are easier to separate from

1. This work is based on data from the MIT archive at http://xte.mit.edu/

background. However, Markarian 421 has a softer spectrum than the Crab and, unlike the Crab, cuts off below 10 TeV, so the new Milagro analysis that places emphasis on the highest energy events does not markedly improve the sensitivity. Furthermore, in this analysis we are studying the long duration light curve for Mrk 421, so we wish to choose a set of cuts that that will not change over time in our archival data set. We have found that for Mrk 421, the application of only a modest gamma-hadron cut maximizes the significance and the application of no gamma-hadron cut results in 80% of the peak sensitivity and is very stable over time. We have chosen to use the no gamma-hadron cut analysis presented here and to not apply weighting.

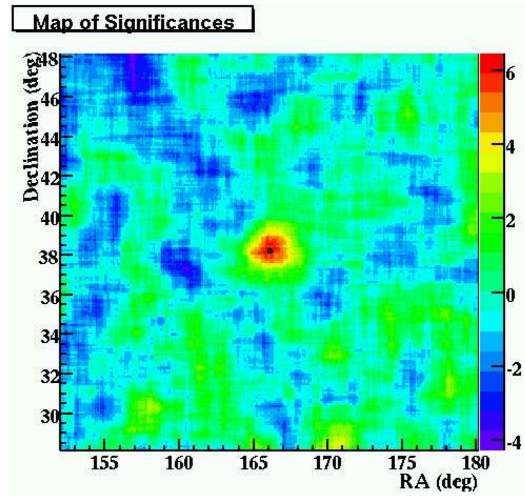

Figure 2: Significance of excess/deficit in the vicinity of Mrk 421.

Results

We measure an excess of 5.9σ at the known position of the Mrk 421 for the duration of the data set. The measured excess is 18+/-3 events/day compared with 25±4 events/day for a crab like source transiting at the declination of Mrk 421. In this analysis, the Crab is observed at 7 sigma (Note: we observe the Crab at ¿15 sigma in the weighted analysis with a gamma-hadron cut applied). The median energy for reconstructed events is 3 TeV in this analysis.

The X-ray and TeV fluxes were computed for each day in which data from both experiments were available. Approximately 70% of the TeV daily observations have associated concurrent X-ray observations and are included in the analysis. The plot below show the TeV flux plotted as a function of the X-ray flux. There is a clear correlation between X-ray and TeV measurements. For the highest x-ray flux days, the TeV flux from Mrk421 exceeds that of the Crab by a factor of 2, and during X-ray dim periods, the TeV flux is only ≈1/4 that of the Crab. Fits were made to the correlation plot assuming a linear correlation and a quadratic correlation (a quadratic correlation is predicted from self-Compton models). Both functional forms will fit with reasonable Chi-squared.

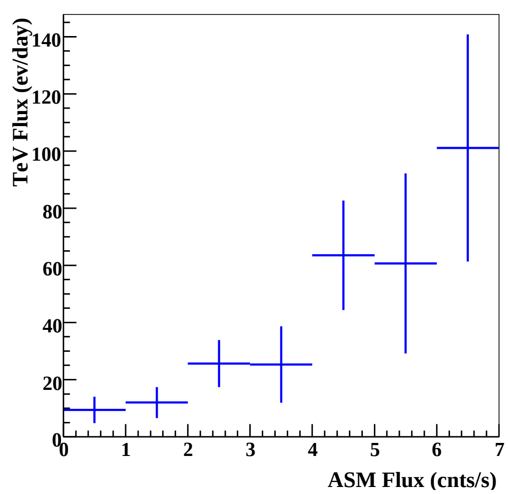

Figure 3: TeV vs X-ray flux correlation.

Figure 4 shows TeV and X-ray light curves for time scales ranging from 32 to 256 days. There is an clear correlation between the TeV and X-ray measurements for these long durations. Nearly all points of large TeV excess occur during periods of X-ray high state. One exception to this is the 2.5 Crab TeV "flare" that occurred at JD≈53530. The feature is clearest in the 64 day light curve where the largest excess for the entire 6 year observation period is observed, but the X-ray flux is measured to be in a low state. This single point has an excess that corresponds to 5σ not accounting for trials. This flare occurred during the Summer of 2005 when Imaging atmospheric telescopes were not able to observe this target, because it was not up at night.

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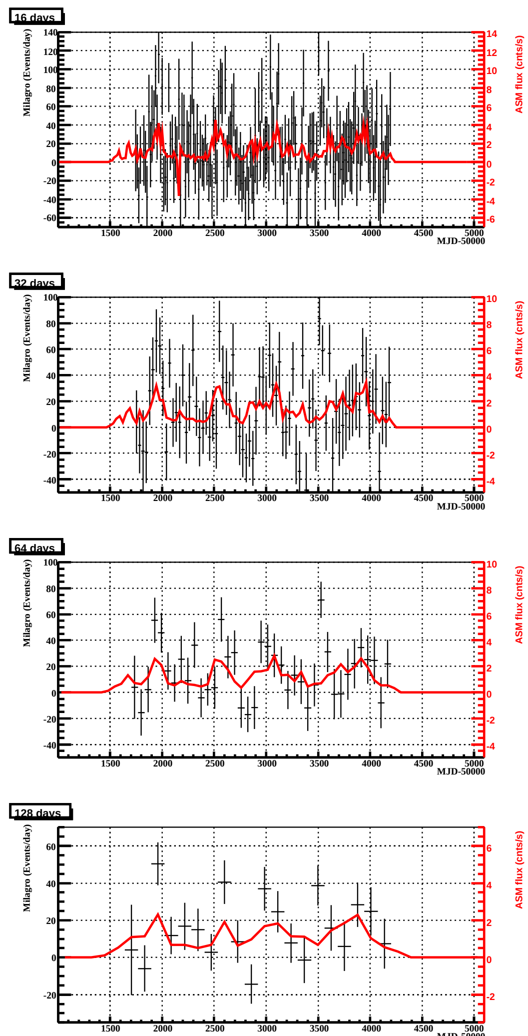

Figure 4: Markarian 421 6 year light curve. Milagro TeV measurements are shown in balck. The RXTE ASM flux is shown in Red.