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Observation of Markarian 421 in TeV gamma rays over a 14-year time span

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The variability of the blazar Markarian 421 in TeV gamma rays over a 14-year time period has been explored with the Whipple 10 m telescope. It is shown that the dynamic range of its flux variations is large and similar to that in X-rays. A correlation between the X-ray and TeV energy bands is observed during some bright flares and when the complete data sets are binned on long timescales. The main database consists of 878.4 h of observation with the Whipple telescope, spread over 783 nights. The peak energy response of the telescope was 400 GeV with 20% uncertainty. This is the largest database of any TeV-emitting active galactic nucleus (AGN) and hence was used to explore the variability profile of Markarian 421. The time-averaged flux from Markarian 421 over this period was 0.446 ± 0.008 Crab flux units. The flux exceeded 10 Crab flux units on three separate occasions. For the 2000–2001 season the average flux reached 1.86 Crab units, while in the 1996–1997 season the average flux was only 0.23 Crab units.

1. Introduction

Blazars are the most powerful active galactic nuclei (AGN) observed and are remarkable for their variability. Their most prominent characteristic is the relativistic jets which are aligned with the line of sight to the observer. In this preferred direction the blazar can be very bright. Although they are detectable over a wide range of frequencies, their alignment does not permit spatial resolution and makes the detection of optical spectral lines very difficult. Their broadband emission is clearly nonthermal and the nature of the progenitor particles (electrons or protons) is uncertain. In principle, there is much observational evidence which should make their understanding straightforward, but in practice there is a wealth of often contradictory observations which demonstrate that the underlying mechanisms are complex and often ambiguous. While their variability makes these AGN inherently interesting, observations (preferably simultaneous) over a long time interval at a variety of wavelengths are required to draw any firm conclusions.

The spectral energy distribution (SED) of blazars is generally represented by a double-peaked structure, with the lower-energy peak modeled by a synchrotron emission mechanism in which the synchrotron photons arise from electrons in the relativistic beam; the Compton scattering of these electrons on the low-energy photons (which may be either of synchrotron origin or external from some other mechanism) results in high-energy gamma-ray emission [1]. Generally, the former simple model (i.e., self-Compton) is preferred, but some sources appear to require external photons [2]. In another class of model, hadronic interactions are invoked to explain the higher-energy peak [3].

Markarian 421 (Mrk421) was one of 70 AGN reported in the Third EGRET Catalog of 100 MeV sources [4,5]. It was remarkable in that it was both the weakest and the closest (redshift $z = 0.031$) of these AGN. Its variability was not particularly noteworthy in the discovery gamma-ray observation. Subsequently it was determined that, unlike the other AGN in the EGRET catalog, it should be classified as a HBL (high-frequency-peaked BL Lacertae object) in which the synchrotron and Compton peaks in its spectral energy distribution were displaced some decades to higher frequency relative to the norm of EGRET-detected AGN. This made it a prime candidate for TeV emission. It was on a short list of EGRET-detected AGN selected for observation at TeV energies with the Whipple 10 m telescope [6]. It was the only one on the list which gave evidence of a signal, and the subsequent paper [7] announced the first unambiguous detection of an extragalactic source at TeV energies.

Since that time, Mrk421 has been observed every season at the Whipple Observatory. Although more than 50 AGN have now been detected at TeV energies [8], Mrk421 is still, on average, the strongest AGN source of TeV gamma rays in the northern hemisphere. Because of its proximity and high degree of variability, it was considered a good candidate for the detailed study of an AGN that was a TeV gamma-ray emitter. During the large flare in 2001, it was observed to reach a peak emission of 13 times the level of the Crab Nebula (the brightest known steady TeV source) over a four-minute integration time and to show other rapid variations [9].

Atmospheric Cherenkov telescopes are particularly useful for the study of HBLs such as Mrk421 because of their high sensitivity to rapid variations. The Whipple telescope has detected flux variability with doubling times as short as 15 min [10]; there is some correlation between emission at X-ray keV energies and gamma-ray TeV energies [11,12]. Rapid variations in TeV emission have also been observed in other AGN [13,14]. It has been shown that the energy spectrum of Mrk421 hardens with increasing intensity [9].

In this paper, we summarize intensive observations of Mrk421 with a single gamma-ray telescope over a long period. The principal telescope used in this study, the 10 m reflector and imaging camera at the Whipple Observatory, is described in Section 2. Section 3 describes the database of TeV observations taken over the 14-year epoch. Correlations with simultaneous X-ray observations are presented in Section 4. The level of variability in the TeV signal is explored in Section 5. Section 6 explores those intervals in which the TeV signal was particularly strong and the source may be said to have been flaring.

2. Whipple observations

The principal data reported here were taken at TeV energies with the Whipple 10 m atmospheric Cherenkov telescope and imaging camera over a 14-year period (December 1995–May 2009). Although observations were made both before and after this period, this time interval was chosen as it represents the best period of uniform operation and performance of the telescope.

The Whipple photomultiplier (PMT) camera evolved during this time [15]. From 2001 to 2009, the camera consisted of a hexagonal array of 379 PMTs of diameter 1.2 cm, giving a total field of view of 2.8°. Winston light cones in front of the PMTs minimized the light loss and gave a relatively uniform sensitivity across the face of the camera. The camera was triggered when the light level in at least three tubes exceeded a preset threshold. Before 2001, the camera had PMTs of 2.5 cm diameter and had a larger field of view.

The Whipple observations were supplemented by observations with the VERITAS (Very Energetic Radiation Imaging Telescope Array System) observatory, located at the basecamp of the Fred