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Spectral Monitoring of Mrk 421 during 2004

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Daily monitoring of Mrk 421 in the X-ray and TeV bands during the first half of 2004 showed rapid flaring events above an elevated base flux level, culminating from March to May 2004 at an average flux level matching the highest detected flux state in 2001. Here we summarise the daily X-ray spectral variability observed with the RXTE-PCA instrument. We also explore the X-ray and TeV gamma-ray connection from near simultaneous data obtained using the Whipple 10m Čerenkov imaging telescope.

1. Introduction

Mrk 421 is the archetype and closest known TeV blazar (z = 0.031), first detected at TeV γ-ray energies by the Whipple 10m telescope in 1992 [1]. Blazars typically reside in large elliptical galaxies and are characterised by rapid variability at γ-ray energies, providing evidence of relativistic jet beaming along the line of sight [2]. Blazar surveys show a continuous sequence in Spectral Energy Distributions (SEDs) with TeV blazars at the high energy, low luminosity end [3]. In the SSC model the first broadband peak in the SED (from UV to soft X-ray) is attributed to synchrotron radiation, and the second peak at GeV energies from inverse-Compton emission. Detailed studies of the X-ray spectrum over a broad energy range from 0.1-25 keV detected by the satellite missions $BeppoSAX$, $ASCA$, $RXTE$, and XMM find the synchrotron peak shifted to higher energies (0.5-2 keV) during high flux levels [4]. Mrk 421 displays strong variability in the X-ray and γ-ray TeV bands on nearly all time-scales of hours to years with particularly strong flaring states detected by multiwavelength campaigns in 1995, 1998, 2001, and recently in 2004 [5]. Błażejowski et al. (2005) present a temporal analysis and correlation study of Whipple 10m γ-ray observations and near simultaneous $RXTE$ X-ray observations from December 2003 to May 2004. This paper provides an extended analysis of the same data by resolving the X-ray spectrum on day time-scales and providing integral flux and hardness ratios for the TeV γ-ray data.

2. X-ray Observations and Data Analysis

The NASA X-ray satellite $RXTE$ was launched in 1995, and is still in operation. The Proportional Counter Array (RXTE-PCA) instrument on board covers a nominal energy range of 2-60 keV and consists of 5 PCU detectors. During the 2004 campaign only PCU0 and PCU2 were operational. The daily "snap-shot" observations range from 0.6-16 ksec with a mean of 2.2 ksec. We followed the standard procedure for data reduction using FTOOLS 5.3 by filtering the data into Good Time Intervals and extracting a spectrum for individual observations. Using the latest background models and calibration tools simulated background spectra and response matrices were created with PCABACKEST and PCARSP. For the high-state flux level during 12-23 April 2004 the spectra were fit over 28 bins from 4-15 keV. All other spectra were rebinned by a factor of three due to low significances (4-6σ), resulting in nine bins covering 4-15 keV. Three fit models were tested: a simple power law, power law with an exponential cut-off, and a log-parabolic model. All fits included the fixed galactic column density $N_H = 1.61 \cdot 10^{20}$ cm^{-2} accounting for absorption from interstellar gas. Figure 1 shows the distribution of reduced χ^2 goodness of fits for all observations to a power law and log-parabolic model. It is clear a power law is not applicable to the data. The fits to an exponential cut-off give a marginally worse mean reduced χ^2 of 0.98 compared to 0.87 for a log-parabolic model. Due to the limited energy coverage of 4-15 keV the calculated break energy in the exponential cut-off is unrealistically pushed to energies beyond the fit range ($E_c > 15$ keV) [4]. We therefore proceed with the log-parabolic fit described by

$$F(E) = K(E/E_1)^{-(a+b\cdot Log_{10}(E/E_1))}$$

with E_1 set at 1 keV, giving three parameters: normalisation $K(E/E_1)$, index a, and curvature term b [4]. The peak flux in the log-parabolic curve (synchrotron peak) is given as $\nu_p F(\nu_p) = 1.6 \cdot 10^{-9} \cdot K \cdot E_1^2 \cdot 10^{(2-a)^2/4b}$ in erg cm^{-2} s^{-1} and the peak energy as $E_p = E_1 \cdot 10^{(2-a)/2b}$ in keV.

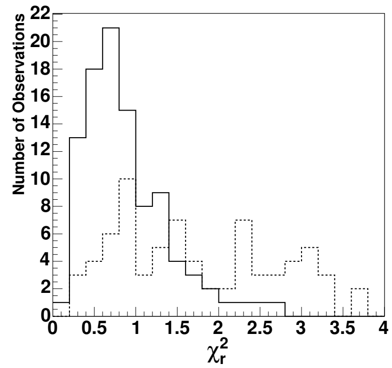

Figure 1. Reduced χ^2 for power law fits (dashed) and log-parabolic fits (solid) to all RXTE-PCA spectra.

3. TeV γ-ray Observations and Data Analysis

The Whipple 10m telescope is located on Mt. Hopkins, Arizona, USA at an elevation of 2312 m and is presently operating with the 379 pixel, 2.6° field of view camera in place since 1999. Monitoring Mrk 421 for high-state variability is a high priority; from November 2003 to May 2004 over 250 source $Tracking$ observations were carried out, each with a duration of 28 minutes. From this data set 141 runs met the criteria of zenith angle $< 28°$ and relative throughput > 0.7 [6]. Monte Carlo simulations of 10^6 γ-ray primary air showers with an energy distribution of $E^{-2.5}$ from 100 GeV to 50 TeV were generated with the GrISU package applying the 2004 telescope configuration for detection and analysis. The energy "threshold", defined as the position of the peak in the detected differential energy spectrum, is 250 GeV at trigger level, and 400 GeV for events passing background rejection cuts described below.

A combination of techniques from Whipple 10m, HEGRA CT1, and H. E. S. S. data analysis are used here to derive integral flux values. After image cleaning, second moment and angle parameterisation, and trigger level cuts, γ/hadron "extended" cuts on $length$ and $width$ parameters were calculated from γ-ray simulations for a 90% cut efficiency nearly independent of energy [7]. Due to the small field of view shower images at the edge of the camera are truncated. A cut on $distance$ of $< 0.9°$ reduces this effect. The energy of each event is estimated using the method for HEGRA CT1 data described in [8]. The $size$ parameter was scaled according to the throughput of each observation relative to a clear off field at 20° zenith angle, providing a gain correction for nights with low atmospheric transparency [6]. A resolution in the shower core distance I_r of $RMS(\Delta I)$ =20% and energy resolution $RMS(\Delta E)$ of 26% for Whipple 10m simulations agree with that found for HEGRA CT1 [8]. We apply a "tracking" analysis where the background region of the $alpha$ plot was used to estimate the background in the signal region $0° < alpha < 20°$ [5]. An alternative approach is to match off fields from different observations to the $Tracking$ data based on zenith angle, throughput, and other factors. Comparing both techniques to a subset of Mrk 421 data with dedicated off field observations gives a systematic error of 6% in the estimated background number, and 10% in the integral flux value.

The integral flux is then simply the sum over the inverse effective areas calculated for each excess event, divided by the observation time. By using the "modified" effective area (collection area as a function of estimated energy) the energy resolution and biases are implicitly accounted for [7]. The individual event effective areas are found by linear interpolation between logarithmic energy bins. The lower energy limit for integral flux values has been placed at 500 GeV, above which energy the effective area is relatively flat and independent of spectral shape. A hardness ratio was set for the bands I(0.5-1 TeV)/I(1-9 TeV). Data over the April 2004 high-state flux level are resolved on nightly time-scales with exposures ranging from 0.5-2.8 hours. Data from lower flux levels are binned by 1-9 days, yielding higher statistics necessary in the high energy band.

4. Results and Conclusions

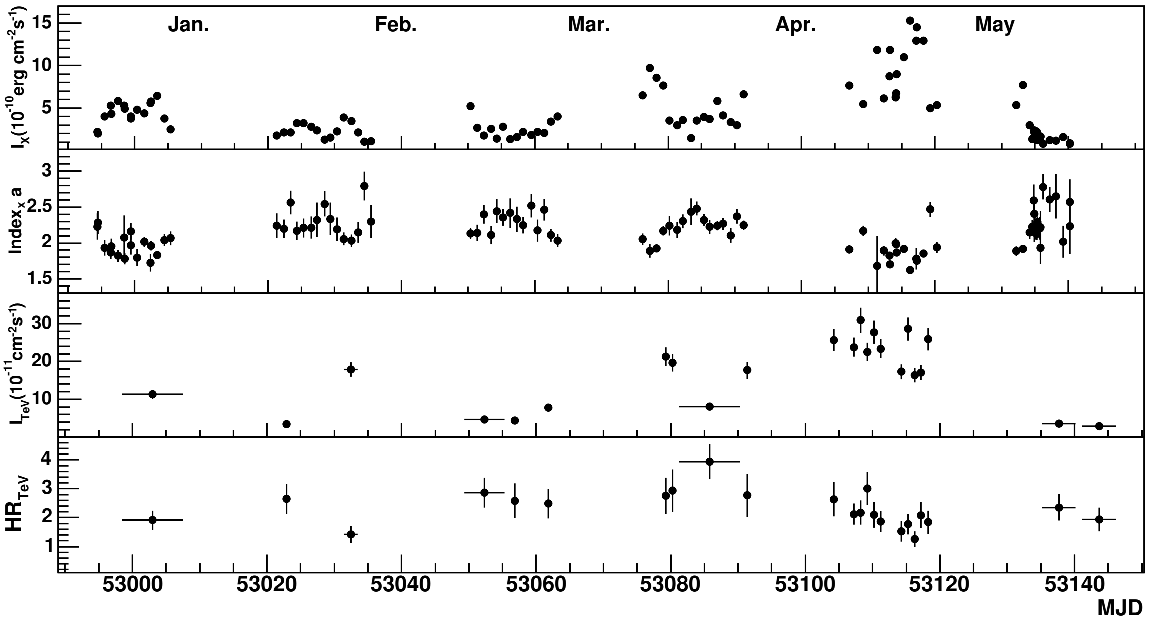

Figure 2. Long-term light curve of Mrk 421 in 2004. The upper two panels show the RXTE-PCA 4-15 keV integral flux values, and spectral index "a" from log-parabolic fits to the data. Below are Whipple 10m integral flux I(E>500 GeV) and hardness ratios I(0.5-1 TeV)/I(1-9 TeV) on nightly time-scales for the high-state phase in April 2004, and with varying exposures from 1-9 days for the lower flux states. Systematic effects are included in the Whipple 10m flux errors.

Figure 2 shows the Mrk 421 light curve from December 2003 to May 2004. The RXTE-PCA X-ray integral flux I(4-15 keV) varies from a medium flux state to the near the highest yet detected, reaching the March 2001 peak value of $\sim 15 \cdot 10^{-10}$ erg cm^{-2} s^{-1} [5]. The TeV γ-ray integral flux I(E>500 GeV) is variable over the range 0.28-2.8 $\cdot 10^{-10}$ cm^{-2} s^{-1}. The TeV γ-ray hardness ratios give an indication of spectral variability. As a reference, for the chosen intervals I(0.5-1 TeV)/I(1-9 TeV) spectra with power law indices (Γ =-2.0, -2.5, -3.0) yield hardness ratios (HR=1.1, 1.9, 3.0). The hardness ratios agree with previous results that find Γ varying from -3 to -2 during medium to high flux states [5]. Figure 3 shows the correlation of RXTE-PCA spectral index "a" to flux state. Previous X-ray spectral studies have shown rising flare events are initiated at high energies, resulting in a flatter spectrum at high flux levels [4]. Figure 4 shows the rising RXTE-PCA spectrum in a high state during April 2004. The spectral shape stays nearly constant during the first day (53114 MJD). The spectrum for the following day is steeper, with an increase in flux at lower energies. Finally, during the detected flare peak on 53116 MJD the spectrum is very flat, evident

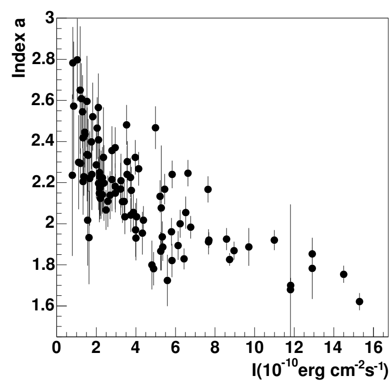

Figure 3. Correlation of RXTE-PCA spectral index "a" and integral flux over 4-15 keV.

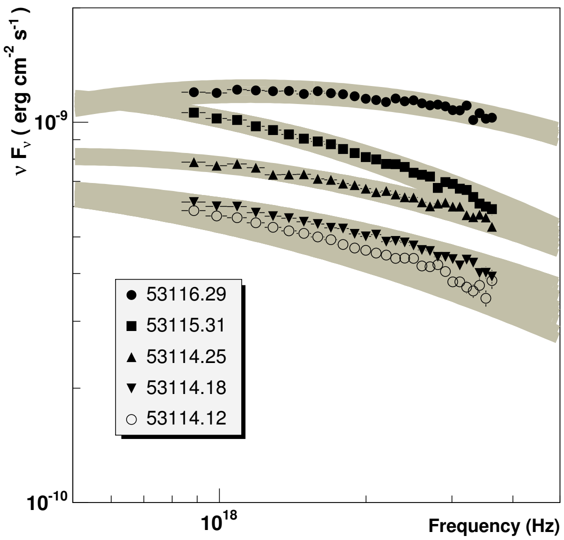

Figure 4. RXTE-PCA X-ray spectrum of Mrk 421 from 19-21 April 2004 (identified by MJD in plot). The grey shaded bands show the 1 σ statistical error region from a log-parabolic fit.

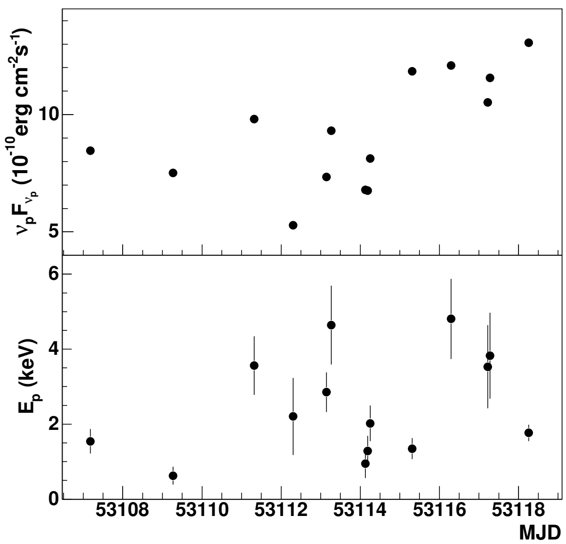

Figure 5. Light curve of Mrk 421 peak synchrotron flux and energy variability derived from log-parabolic fits to the RXTE-PCA X-ray spectrum from 12-23 April 2004.

of flaring at high energies. Due to the sparse data sampling the full evolution in the X-ray spectrum is obscured. Figure 5 shows the calculated peak flux and peak energy E_p values from the high-state X-ray spectrum during April 2004. Estimates of E_p are limited by the fit range (4-15 keV). Still, we find the synchrotron peak shifted to the highest detected energies, reaching above 2 keV. Sampling synchrotron peak variability is necessary in deriving physical limits to emission mechanisms in TeV blazars. This campaign has allowed us to sample a wide range of flux states and flaring episodes, however future continuous multi-day X-ray observations of Mrk 421 with XMM and simultaneous TeV γ-ray observations with VERITAS promise a clear view of spectral variability on hourly flaring time-scales.

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