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Multiwavelength observations of Markarian 421

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Abstract. We report results from multiwavelength observations of the BL Lac Mrk 421 during the period March 18, 2001 to April 1, 2001 with the Whipple Gamma-Ray Observatory, the Whipple Observatory's 1.2 m optical telescope, the newly completed 0.5 m Antipodal Transient Observatory (ATO) telescope, and with the RXTE PCA detector. To better sample the extremely rapid variability of Mrk421, this campaign included the highest temporal density X-ray observations possible with a nearly continuous $>$330 ks exposure with RXTE (Fossati et al., 2001). Numerous ground-based atmospheric Cherenkov and optical observations were scheduled during this period to improve longitudinal/temporal coverage. A preliminary analysis of a subset of these data are presented here. Frequent correlated hour-scale X-ray and gamma-ray flares were observed. Dramatic intra-day optical variability was also observed, although the temporal correlation is unclear.

1 Introduction

The Blazars Mrk 421 and Mrk 501 have been extensively studied in the X-ray and gamma-ray regimes. For Mrk 421, however, most of the coordinated multiwavelength observations have been of insufficient temporal density to draw definitive conclusions about temporal correlations (e.g., Buckley et al., 1999). Both Mrk 421 and Mrk 501 are X-ray selected BL Lac objects with similar properties to the other objects in their class. From radio up to the TeV gamma-ray regime the broad-band emission of these galaxies is dominated by highly variable, nonthermal radiation thought to originate from a relativistic jet pointed very nearly along the line of sight. Recent multiwavelength observations of Mrk 501 reveal almost identical trends in the high energy X-ray and VHE gamma-ray lightcurves, leaving little doubt that the two components are produced by the same population of electrons in roughly the same emission region (e.g., Catanese et al. 1997). The most natural model explains the emission as being composed of two components: synchrotron emission accounting for the radio to X-ray emission; and Comptonization of ambient or synchrotron photons to gamma-ray energies. While both Mrk 421 and Mrk 501 are considered members of the high-energy-peaked BL Lac (HBL; Padovani and Giommi, 1995) class (with the synchrotron power peaking above keV energies), Mrk 421 differs from Mrk 501 in a number of significant ways. The synchrotron power of Mrk 421 peaks in the UV to keV X-ray band, while the synchrotron spectrum of Mrk 501 extends up to the $\sim$100 keV hard X-ray band in recent observations. Mrk 421 appears to be a less extreme blazar, possibly with a lower energy cutoff to the electron spectrum (e.g., Fossati et al., 1998). Unlike Mrk 501, Mrk 421 was first discovered by EGRET as a GeV emitter and can perhaps be viewed as a transitional object between the low-energy-peaked class of BL Lac (LBLs) (that comprise a large subset of the EGRET Blazars; Thompson et al., 1995) and the other TeV blazars: Mrk 501 (Quinn, et al., 1995), 1ES2344+514 (Catanese et al., 1998), 1ES2155-304 (Chadwick et al., 1999), and 1H1426+428 (Horan et al., 2001). In the unified framework of Fossati et al. (1998) we might expect such a transitional object to have a higher level of ambient photons limiting the maximum acceleration energy and giving significant gamma-ray emission in the form of Comptonized external accretion photons in addition to self-Compton emission. Understanding the differences in the temporal behavior of these sources could be a key to testing this unified model. However, Mrk 421 is characterized by extremely rapid, sub-hour-scale X-ray and TeV variability, and almost all previous multiwavelength observations undersample the light curves making it difficult to draw conclusions from this multiwavelength data.

Over the last year, Mrk 421 entered a high state with its TeV flux frequently exceeding twice that of the Crab Nebula. Extensive observations at other wavelengths were scheduled fortuitously for precisely this period of peak activity. Here we present a preliminary subset of these results. These data

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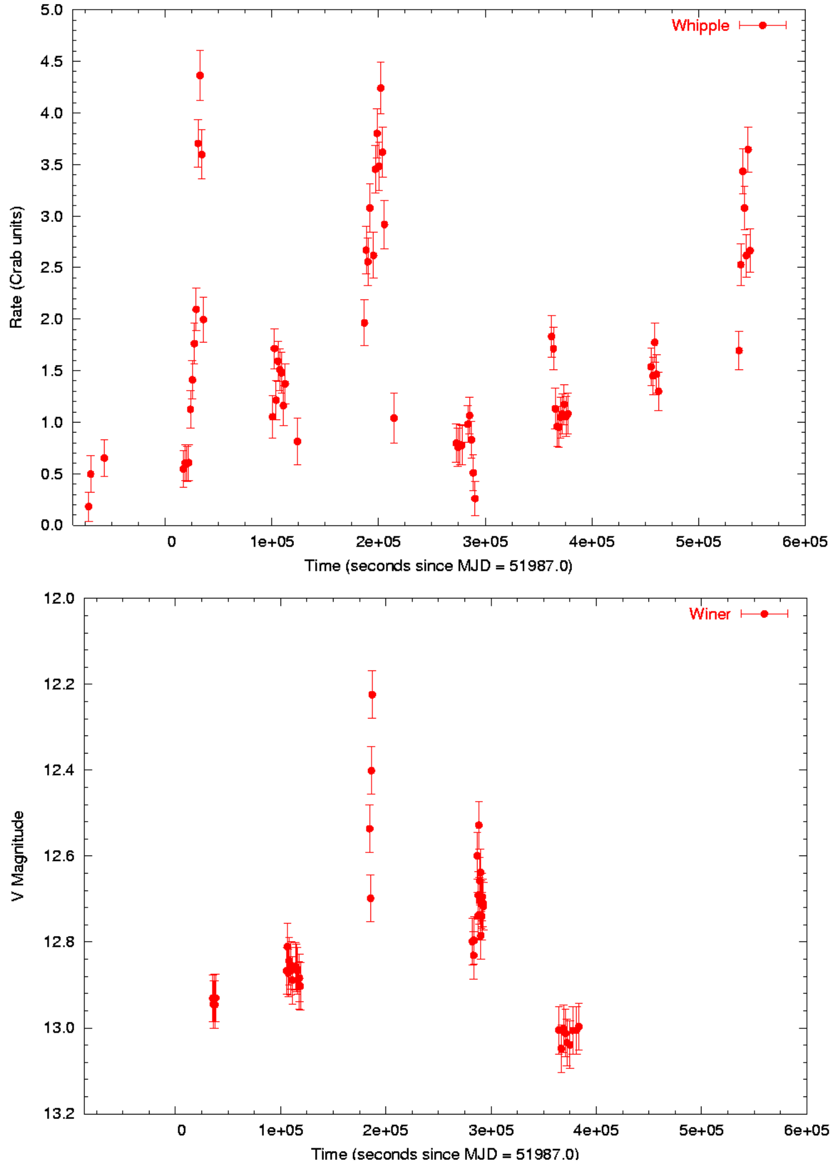

Fig. 1. *Above:* Lightcurve showing gamma-ray emission (peak energy 370 GeV) over the period March 18, 2001 to April 1, 2001. Note that 100 ksec = 10^5 sec corresponds to 28 hours (roughly a day). The data have been normalized to the zenith angle dependent Crab Nebula rate. *Below:* V-band relative photometry obtained with the ATO 0.5m telescope during the same period. No galaxy light subtraction has been performed.

will provide important new information about the emission mechanism including new constraints on the Doppler factor, magnetic field strength, geometry of the emission region and nature of the seed photon population. Interpretation of these results will be discussed in a subsequent paper (Fossati et al., 2001).

2 Mrk421 Multiwavelength Data

The multiwavelength campaign included scheduled observations with six different instruments: RXTE, the Whipple 10m telescope; the 1.2m optical telescope on Mt. Hopkins; the 0.5 m Antipodal Transient Observatory (ATO) optical telescope at Winer Observatory in Sonoita, AZ; the HEGRA atmospheric Cherenkov array; and optical telescopes in Perugia, Italy. Here we report on the Whipple data and on a part of the data collected by RXTE and by the 0.5m optical telescope during this period. Data gaps in the TeV and optical coverage will be filled by HEGRA and CAT observations, and optical data will be supplemented with data taken with the AIT telescope in Perugia Italy and with the 2m optical telescope on Mt. Saraswati in the Western Himalayas in India.

2.1 Whipple TeV gamma-ray data

The Whipple 10m telescope located on Mt. Hopkins in Amado, AZ collected data on Mrk421 over a wide range of elevations with as much overlap as possible with the RXTE instrument. To minimize data gaps, the telescope was operated in a continuous *TRACKING* mode during the majority of the time and *ON/OFF* mode for the remaining observations. We used the standard *TRACKING analysis* whereby the shower images that fail to point back to the source are used to estimate the background level. The $alpha$ ratio (the ratio of background counts in the on-source orientation interval $alpha <$

15° to the off-source interval $20^{\circ} < alpha < 65^{\circ}$) was determined using the off-source data taken during the same period. To further minimize systematic errors, random noise was added to the off-source data to mimic the on-source star field using the procedure of *software padding*.

To correct for the zenith angle dependence of the rate, we collected 50 ON/OFF data pairs taken on the Crab at various elevations since October 25, 2000 when the telescope was operating stably with the GRANITE-III camera. These data were fit with a semi-analytical interpolating function to model the zenith angle dependence of the Crab Nebula gamma-ray rate.

The interpolating function is based on the assumptions that the effective area scales as

$$A_{\rm eff} \propto \sec^2(\theta) \quad (1)$$

and that the energy threshold scales as

$$E_{\rm thr} \propto \sec^2(\theta)^2 \exp(-z/h) \quad (2)$$

The $\sec(\theta)$ term comes from simple geometry (the more distant shower max, the more the light pool spreads increasing the effective area and increasing the energy threshold). The exponential term gives another sensible free parameter based on the assumption that atmospheric absorption effects the energy threshold but not the effective area. The Crab rate $R_{\rm Crab}$ is calculated using the product of the integral Crab Nebula spectrum (Hillas et al., 1998) and the effective area,

$$R_{\rm Crab} \propto A_{\rm eff} {E_{\rm th}}^{-1.49} \quad (3)$$

A reasonable fit to the Crab data was obtained with a reduced ξ^2 value of 2.0. Contrary to previous studies of the Crab Nebula stability (e.g., Buckley et al. 1996), this season there is some indication for non-Poissonian fluctuations in the nightly Crab Nebula data rate. We therefore assign a systematic error of $\pm 1\gamma$/min to the Mrk 421 data rate, but see no strong indication of such a systematic error on shorter (intra-day) timescales. In subsequent analysis we will explore the utility of a correction for the instrument throughput factor (Holder et al., 2001).

A first-order correction for the Mrk421 rate is made by normalizing to the zenith-angle dependent Crab rate. This normalization is only sensible if the Mrk 421 spectrum is similar to that of the Crab. This assumption is reasonable given previous spectral measurements of Mrk 421 (e.g., Krennrich et al., 1999).

Total observations came to 10.3 hours of *ON/OFF* data and 37.7 hours of *TRACKING* data for a total of 48 hours of data. The most interesting night for the Whipple data was March 19 (UT) with nearly a 9-fold increase in the rate in 4.5 hours followed by a decrease in the rate nearly as fast as the increase. The shortest doubling rate was observed to be 1 hour and also occurred on March 19 (UT). The March 19 flare is significant in that it is the first flare with good enough statistics and adequate sampling to resolve nearly the entire time structure of a single outburst.

2.2 Optical Data

We present analysis of a subset of the data taken with one of the two ATO telescopes. The ATO telescopes are robotic 0.5m Ritchie-Chretien telescopes with a UVBRI filter set and back-illuminated wide-field 1024x1024 pixel CCD camera. The first (operational) telescope is located at the Winer observatory in Sonoita Arizona. A second identical telescope (currently under evaluation in Arizona) will be moved to Mt. Saraswati in northern India later this year. The two telescopes, separated by 170 degrees longitude (roughly at the *antipodes* of the earth) will be used for nearly continuous observation of interday optical variability of a number of AGNs. The newly completed 2m telescope on Mt. Saraswati was used to provide data to complement the first ATO instrument for this period.

Since the ATO telescope was only newly commissioned, we took simultaneous data with the CfA 1.2m telescope on Mt. Hopkins for cross-calibration. For the preliminary analysis presented here, we use relative photometry with a large aperture and without galaxy light subtraction. First, we compared our two data analysis programs. For this test, V-band exposures obtained with the ATO telescope were analyzed with the IRAF apphot package and with the OCAAS photometry software that is integral to the robotic ATO telescope. While the automated OCAAS software gave somewhat unreliable results, the manual OCAAS and IRAF analyses gave essentially identical results.

Simultaneous ATO and 1.2m data were then used to cross-calibrate the two instruments. To accomplish this, we performed aperture photometry with respect to a single photometric standard that consistently appeared in both the ATO and 1.2m field. Even though we might expect the relative contamination from galaxy light to differ in the two telescopes, the mean difference in the V-magnitude for these two instruments was only 0.05, and the square-root of the variance was $\sigma = 0.02$ magnitude. Statistical errors for all exposures were significantly smaller than the dominant systematic uncertainty of $\sim$0.05 magnitude. The resulting V-band light curve for a small subset of the ATO data is shown in Figure 1. To be conservative, error bars are systematic not statistical with $\sigma_{\rm systematic} = 0.05$ mag. These errors will be substantially reduced by a more careful analysis of the full data set, and a more careful characterization of the ATO telescope.

2.3 RXTE PCA data

X-ray data were obtained with the Proportional Counter Array (PCA) aboard the Rossi X-ray Timing Explorer (RXTE). RXTE observed Mrk421 continuously over the period, subject to occasional data gaps. These data will be presented in a subsequent paper (Fossati et al., 2001). We include here only a small subset of these data showing the close correlation of the TeV and X-ray (2-10 keV) lightcurves on March 19, 2001.

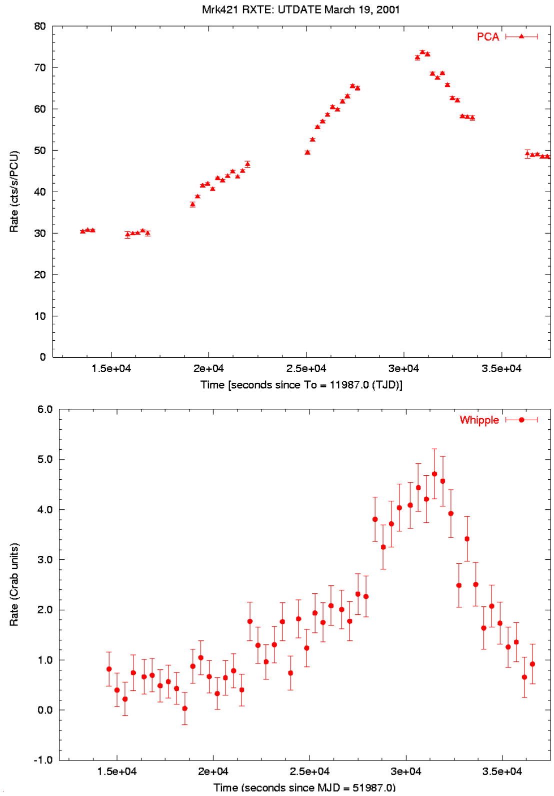

Fig. 2. Simultaneous X-ray/ gamma-ray flare observed on March 19, 2001. The 2-10 keV X-ray light curve was obtained with the PCA detector on RXTE (Fossati et al., 2001); data points are binned in 256s intervals. The $E > 300$ GeV gamma-ray data were obtained with the Whipple 10m telescope and are binned into 4 minute intervals.

3 Conclusions

The dramatic flaring of Mrk 421 and fortuitous multiwavelength observations provide invaluable new data for testing models of blazar emission. Variability timescales place limits on the cooling, acceleration and light-crossing timescales. Multiwavelength lags will provide information about the geometry of the emission region. While it is too early to draw detailed conclusions, we note that The symmetric flares at keV and TeV energies may indicate comparable acceleration times and synchrotron cooling times as predicted by diffusive shock acceleration models (e.g. Inoue and Takahara 1996). However, the short optical variability timescales are significantly shorter than the synchrotron cooling time for typical jet parameters (e.g., a 30 to 100 mGauss field, and Doppler factor $\delta \sim 10$ to 40). Analysis of soft-hard lags in the X-ray analysis and a detailed analysis of the multiwavelength spectral energy distribution will help to address these and other issues.

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