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Optical, Gamma-Ray and X-Ray Monitoring of Markarian 421 in the 2005-2006 Season

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Abstract. We report on intensive multiwavelength observations of the blazar Mrk 421 with the Whipple 10m telescope and supporting observations across the electromagnetic spectrum. The observations resulted in a data set with excellent temporal and spectral coverage. This campaign is unique in the high level of gamma-ray coverage obtained given the dedication of the Whipple 10m telescope to this blazar monitoring program. Our observations also include a large number of optical observations made with the FLWO 1.2m telescope. Lightcurves, correlation functions and spectral energy distribution (SED) will be presented. We discuss the implications of these observations for various leptonic emission mod-

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els by comparing the SED to synchrotron-self-Compton and external Compton models.

1. The Whipple 10m Gamma-Ray Telescope

The Whipple 10m Gamma-ray telescope (Kildea et al. 2007) at the Whipple Observatory on Mount Hopkins, Arizona, has been operated as an imaging atmospheric Cherenkov telescope since 1982 and was used to discover the first Galactic (Weekes et al. 1989) and extra-Galactic (Punch et al. 1992) sources of TeV gamma-rays.

With the advent of VERITAS (Weekes et al. 2002), the telescope was dedicated solely to the monitoring of TeV blazars and gamma-ray burst follow-ups. Since then, the five Northern Hemisphere blazars that had already been detected by the telescope, Markarian 421, H 1426+428, Markarian 501, 1ES 1959+650 and 1ES 2344+514, were selected for monitoring routinely whenever they are visible. For the first time, long-term and well-sampled TeV lightcurves of these objects have been provided.

Mrk 421 at a redshift of $z = 0.031$, is one of the brightest VHE sources and was the first VHE gamma-ray source to be discovered with ground-based telescopes (Punch et al. 1992). Like most blazars, it shows two broad-band peaks in its spectral energy distribution (Sambruna et al. 1996). Given the high level of both gamma-ray and X-ray emission, this source has been a favorite target for multiwavelength studies. For this paper, we focus on Mrk 421 and discuss significant new optical measurements that significantly broaden our view of the multiwavelength variability of this source.

2. Multiwavelength Observations

A total of 18 telescopes participlated in the Blazar Monitoring Program. A list of telescopes, broken down by waveband, is provided in Table 1.

Table 1. The participated telescopes in the Blazar Monitoring Program.

Spectral Band	Telescopes
VHE Gamma-rays	Whipple 10 m telescope (>400 GeV), Mt Hopkins, Arizona
X-rays	RXTE (All Sky Monitor(2-10 keV) and Proportional Counter Array (3-25 keV)
Optical (R, V, B)	SAO 48-inch telescope, Mt Hopkins, Arizona
	Boltwood, Ontario, Canada
	Antipodal Transrent Observatory, Arizona & India
	Bordeaus, France
	0.6m Bell Observatory
	Coyote Hill observatory
	Sbadell
	Tenagra 32-inch telescope
	Tuorla, Finland
	Perugia, Italy
	WIYN, Kitt Peak, Arizona
Infrared (H, J, K)	PAIRTEL, Mt Hopkins, Arizona
Radio	UMRAO, Michigan (4.8 GHz, 8 GHz, 14.5 GHz)
	Metsähovi, Finland (37 GHz)
	RATAN, Russia (0.99-21.7 GHz)

Table 2 provides the coordinates and redshifts of the 5 observed blazars along with their observation exposures with 10m telescope.

Table 2. The 5 blazars observed in the Balzar Monitoring Porgram.

AGN	R.A.	Dec.	z	Exposure (hrs) in 2005-2006 season
Markarian 421	11 04 27.3	38 12 32	0.031	168
H 1426+428	14 28 32.7	42 40 20	0.129	60
Markarian 501	16 53 52.2	39 45 36	0.033	31
1ES 1959+650	19 59 59.9	65 08 55	0.048	110
1ES 2344+514	23 47 04.8	51 42 18	0.044	55

Figure 1 shows the lightcurves obtained for 5 out of 10 wavebands monitored. The data set shows excellent optical, X-ray, and TeV coverage and strong variablility in most wavebands. With such a complete set of data, measurements of correlation function and spectral energy distribution (SED) provide constraints on the emission models.

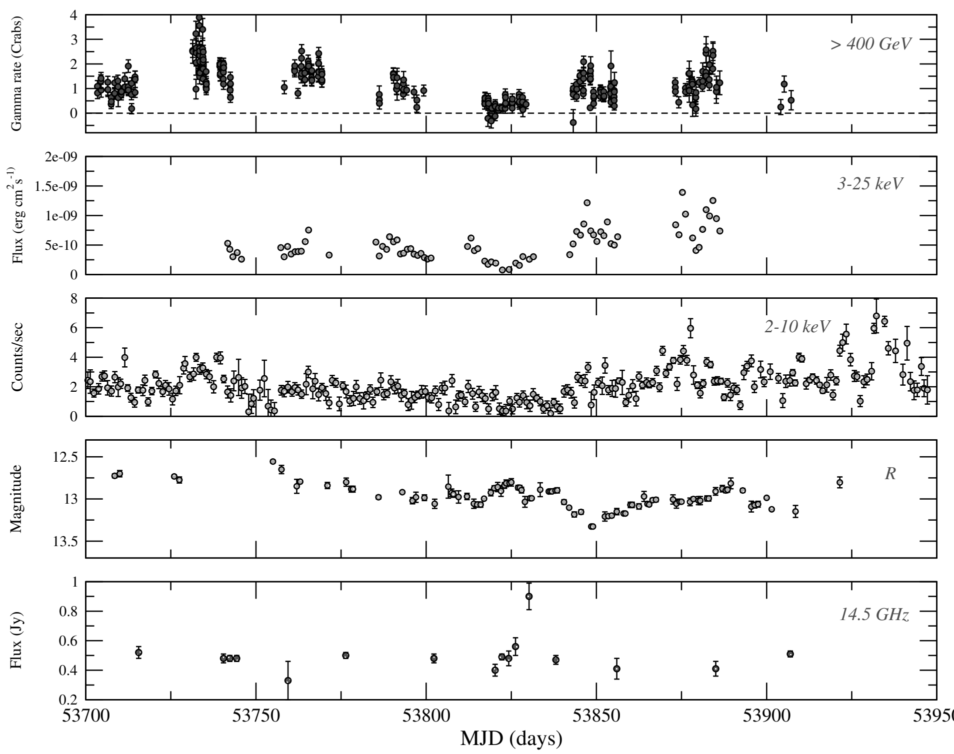

Figure 1. Multiwavelength lightcurves in the 2005-2006 season.

3. Discrete Correlation Function (DCF)

We searched for correlations between fluxes using the DCF (Edelson & Krolik 1988).

Figure 2 shows clearly that there is no correlation at zero lag between optical and gamma-ray fluxes. While there is some evidence for a second bump at a lag of $\sim$ 7-10 days (optical leading gamma-ray), this feature is found to be statistically insignificant when accounting for trials. Monte Carlo methods for determining the significance of the delayed correlation using synthetic lightcurves give a chance probability of $\sim 30\%$ assuming a prior lag distribution of ~ 10 days. It is interesting to note, however, that the gamma-optical lag appeared in two independent data sets, with about the same delay.

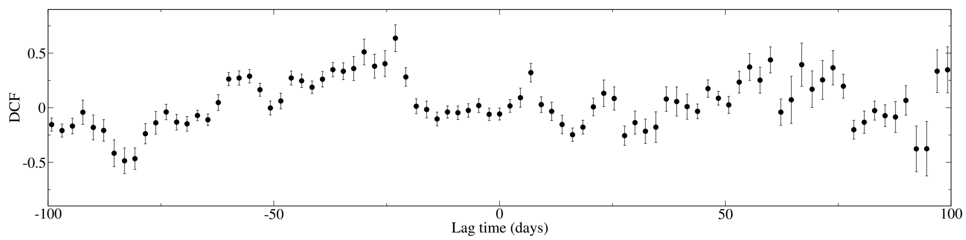

Figure 2. DCF for optical and gamma-ray fluxes.

Figure 3 shows a signigificant correlation between X-ray and gamma-ray fluxes at zero lag. The chance probability is less than 1%.

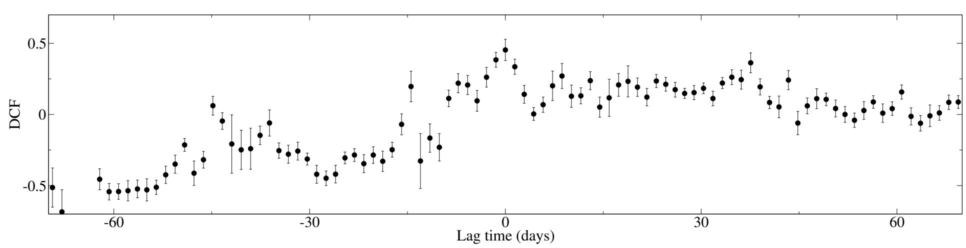

Figure 3. DCF for X-ray and gamma-ray fluxes.

4. Spectral Energy Distribution (SED)

Figure 4 shows the SED for MJD 53763 when the gamma-ray was in a high state. The TeV spectrum was obtained using the forward-folding method described in Rebillot et al.

We compare our results to a simple one-zone SSC model and an external Compton (EC) model, making an ad-hoc assumption of Comptonization of a one micron emission-component reflected back into the jet. We use the prescription of Inoue & Takahara to self-consistently determine the break energy and maximum energy of the electron spectrum using a simple model of diffusive shock acceleration. First, we note that the lightcurves of Mrk 421 in this compaign as well as in previous studies show roughly symmetric flares with comparable rise and fall times. By fitting the measured optical and X-ray structure functions to those generated from simulated lightcurves (composed of a random sequence of triangular flares) we derive a characteristic risetime of approximately 0.6 days in the X-ray variability, and between 10 and 20 days in the optical. This is in

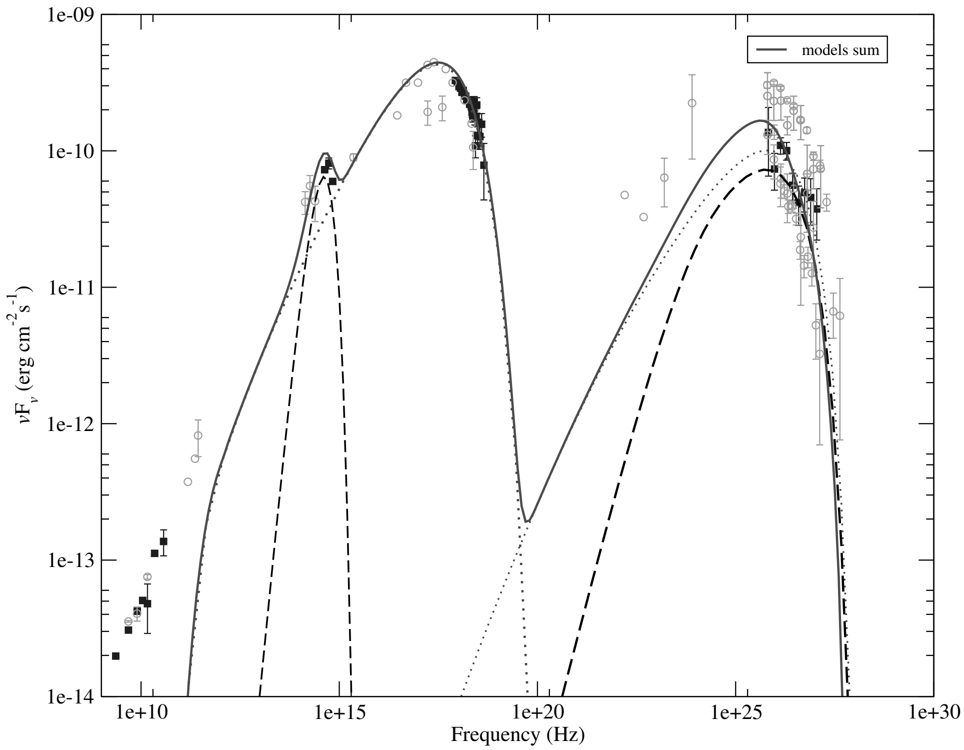

Figure 4. The filled square shows simultaneous radio, optical, X-ray and TeV SED of Mrk 421, together with archival data shows in circle. The dotted lines are SSC model fitting results and the dashed lines are the EC model fitting results. The solid line is the sum of both SSC and EC models.

general agreement with the difference in cooling times for the electron populations generating the optical and X-ray synchrotron emission, where we expect: $\tau_{\rm cool,opt} = \sqrt{\frac{\omega_X}{\omega_{\rm opt}}}\tau_{\rm cool,x} \approx \sqrt{1000} \times 0.6\,{\rm days} = 19\,{\rm days}$. However, we find it difficult to obtain a good fit to the rather hard power-law TeV emission. For this fit we require extreme values for the Doppler factor, and find some resulting inconsistencies in the parameters for shock acceleration. As in previous studies (Krawczynski et al. 2001; Rebillot et al. 2006), we find it necessary to use a high Doppler factor of $\delta = 200$, a magnetic field of 0.12 Gauss and a very small emission region of about 20 gravitational radii. We also require a very hard electron spectrum ($\sim E^{-1.7}$) contrary to the predictions for shock acceleration. The acceleration efficiency must also be quite low, with the mean-free-path for scattering ∼100 times the Bohm limit and a shock velocity of $0.02c$, resulting in very few shock crossings. If these extreme parameters are correct, it calls into question the viability of diffusive acceleration and may suggest a new acceleration mechanism such as the Poynting jet model described in Krawczynski (2006). While there are too many free parameters to find a unique solution, or to draw definitive conclusions, we also see that an EC component is not excluded. While the data do not demand an EC component, the additional cooling may be present and can reduce the maximum energy for shock acceleration, somewhat mitigating the aforementioned problems. Increasing the cooling further quickly results in a Compton-castrophe, overproducing the observed gamma-ray emission. For Mrk 501 Ghisellini et al. used external seed photons from a slow jet component to reproduce the TeV emission with lower Doppler factors. However, when we attempt to fit our data set in this way, we find that we can no longer fit the detailed shape of the declining X-ray and TeV spectrum.

5. Conclusion

The first year of the blazar monitoring program with the Whipple 10m telescope was very successful. We obtained an intensive multiwavelength observation of Mrk 421 in the 2005-2006 season.

The second season of the blazar monitoring program is well underway and even more instruments are participating in the campaign. The VERITAS array is now up with 10 times more sensitivity than Whipple, and the results from Whipple are being used to trigger VERITAS AGN observations.

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