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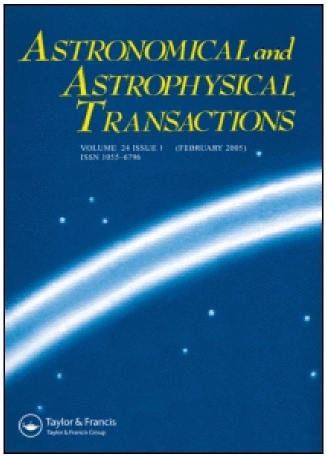

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OPTICAL BEHAVIOUR OF MARKARIAN 421 DURING HIGH-ENERGY FLARES

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In this paper we present the optical behaviour of Mrk 421 from 1992 to April, 1995. The observations were obtained at the Perugia University Observatory with the automatic imaging telescope in the BVR_cI_c broad-bands. Visual estimates done by "The Astronomer" group and the British Astronomical Association (BAA) are inclosed in the light curve to give a better temporal coverage. During our monitoring the object showed many flares and major outbursts over a large span of temporal scales. From our data there is also a clear correlation between the colour index and the brightness level, which may be due to the thermal contribution of the host galaxy. Furthermore, we found that the X and TeV flares observed in Mrk 421 during 1992–1995 are not well correlated with the more intense optical flares. These data, together with the relative stability of the spectral slope during the optical activity, suggest that the optical emission may be related to knots moving in the jet along a helical path.

KEY WORDS BL Lac objects, variability, Mrk 421

1 INTRODUCTION

Mrk 421 (B2 1101+38) is a BL Lacertae (BL Lac) object extensively observed at all wavelengths and characterized by a strong variability in the optical region (Miller, 1975). The surrounding envelope is a typical giant elliptical galaxy with redshift $z = 0.03$ (Ulrich *et al.*, 1975). It is worth noting that Mrk 421 is very active at high energies. It was the first extragalactic source discovered by the Whipple Observatory to emit TeV γ-rays (Punch *et al.*, 1992; Weekes, 1992) and, to date, only Mrk 501 has the same property (Quinn *et al.*, 1995, 1996). X and TeV flares were observed around May 16, 1994 (Kerrick, 1994; Takahashi *et al.*, 1994; Kerrick *et al.*, 1995) and, more recently, around April 25, 1995 (Takahashi *et al.*, 1995). Mrk 421 was also detected by the EGRET instrument onboard the Compton Observatory (Lin *et al.*, 1992; Michelson *et al.*, 1992) but it seems more stable in this range of energy and is considered a notable exception to the variability which has generally been associated with the other EGRET active galactic nuclei (AGN) sources. During the TeV and X flare of May, 1994 the EGRET detected only a marginal variation on the 100 MeV flux. The high emission in the TeV band, in a source that, unlike the other BL Lacs, is not very powerful at other wavelengths, is commonly explained by the proximity of this object to the Earth (Punch *et al.*, 1992). For this reason Mrk 421 is now considered an exceptional tool for the comprehension of the emission mechanism operating in BL Lac objects, and is subject to many multi-wavelength observations.

In this paper we present the optical light curve of Mrk 421 from 1992, when it was detected for the first time at TeV energies, up to April, 1995. During this time interval the source showed many flares and a major outburst in the first half of 1992. The high-energy flares are not well correlated with the more intense optical flares and we discuss the data in terms of current models of blazar emission.

2 OBSERVATIONS AND DATA REDUCTION

Mrk 421 is one of the best-observed objects included in the large sample of blazars (see Fiorucci and Tosti, 1996), observed at the Perugia University Observatory with the automatic imaging telescope (AIT) described by Tosti *et al.* (1996).

The photometric images are obtained with a CCD camera equipped with Johnson-Cousins BVR_cI_c filters. The integration times during the exposures varied from 3 to 5 min depending on the brightness of the objects. The CCD frames were corrected for bias and dark signal. Instrumental magnitudes were obtained in simulated aperture photometry using a modified version of the DAOPHOT routines (Stetson, 1987) and internal checks were done to eliminate eventual imperfections (cosmic ray traces) or to evaluate the goodness of the value of the sky mode around each star.

This source is in the centre of a bright host galaxy, in addition, it is well visible the presence of a nearby galaxy in a N–E direction from Mrk 421. The distance between the two nuclei is of about 14 arcsec (Hickson *et al.*, 1982), as a consequence the photometric reduction is related to the choice of the aperture radius. The light curves presented in this paper were obtained using an aperture radius of 7 arcsec centered in the nucleus of Mrk 421. Another major obstacle to the CCD monitoring of this source is caused by the presence of two bright stars in the field of view, which are able to saturate the frame and, sometimes, to cover the BL Lac object. Nevertheless, the small size of our CCD and the good pointing of our AIT permits us to place these two bright stars outside the field of view.

The relatively high standard deviations (with a typical value of 0.08 mag) and the large gaps in the data are due to the absence of comparison stars in the field of Mrk 421 (except for the two bright stars mentioned above) which do not allowus to carry out differential photometry. Therefore, we observed this blazar only on photometric nights using standard stars (Landolt, 1983a, b) for magnitude calibration.

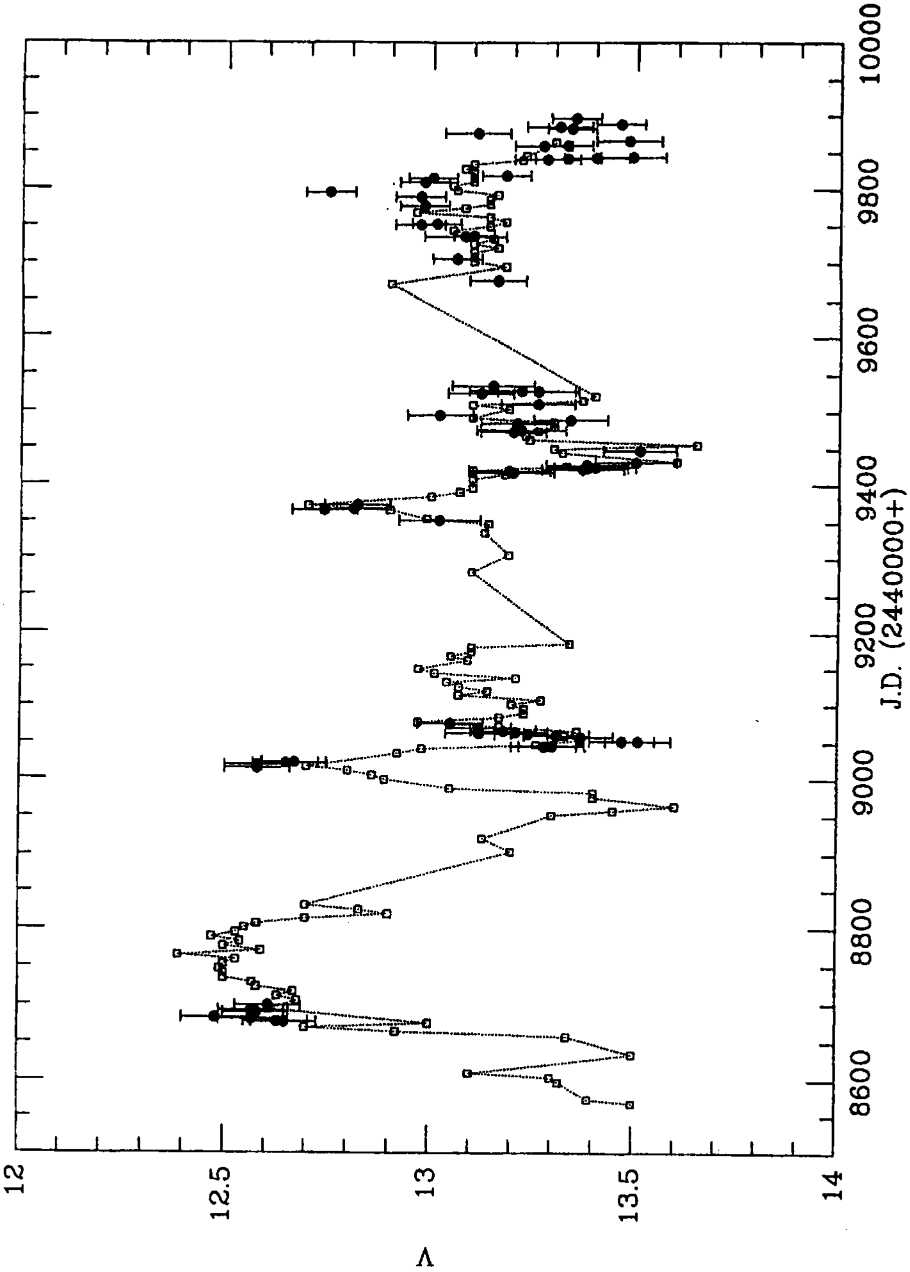

Figure 1 *V* light curve of Mrk 421 during 1992–1995.

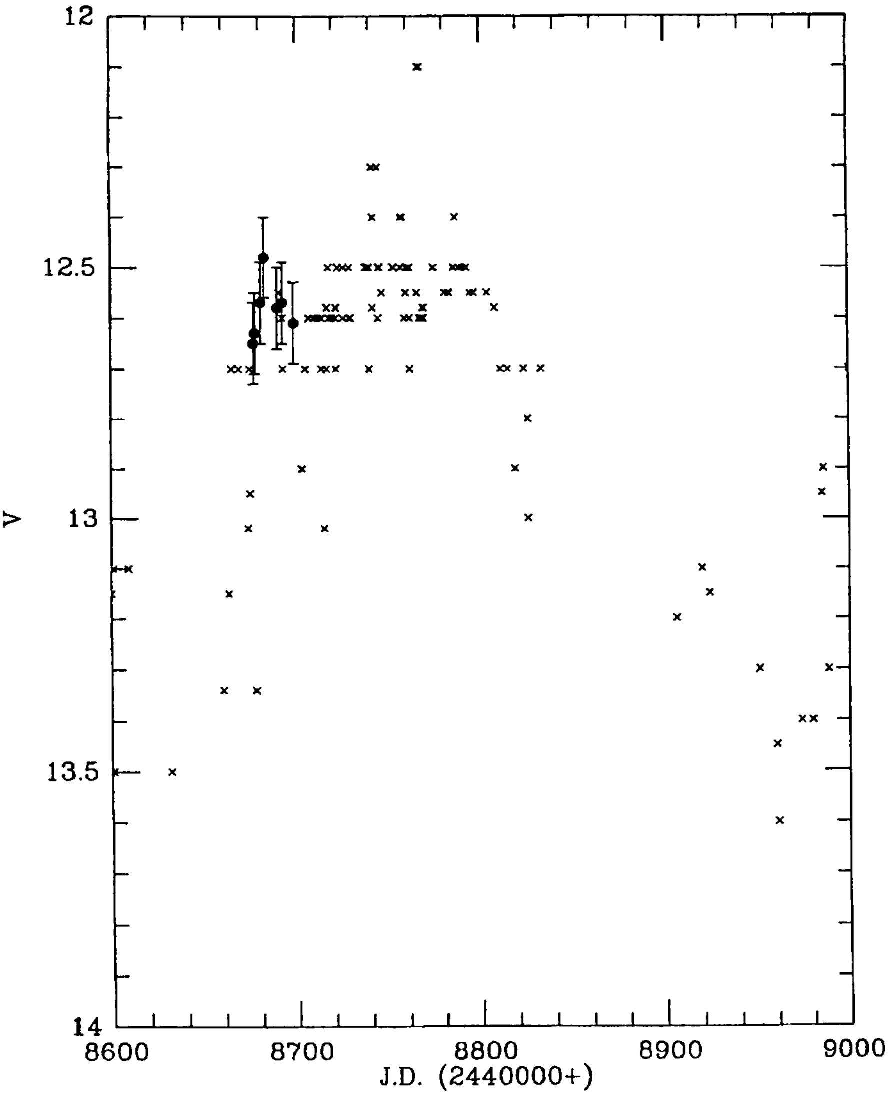

Figure 2 V light curve of Mrk 421 during the large outburst observed in 1992.

Mrk 421 has been extensively observed by The Astronomer group and BAA since 1981 and a large data base of visual estimates is available. The data are obtained by comparison of visual magnitude with a set of known stars in the field of view. These visual estimates are very useful to enlarge the temporal coverage of the light curve and the precision is enough to allow a good description of the major events. We have compared these visual estimates with the V magnitudes obtained with the CCD camera for all the nights when quasi-simultaneous data were available. Gene-

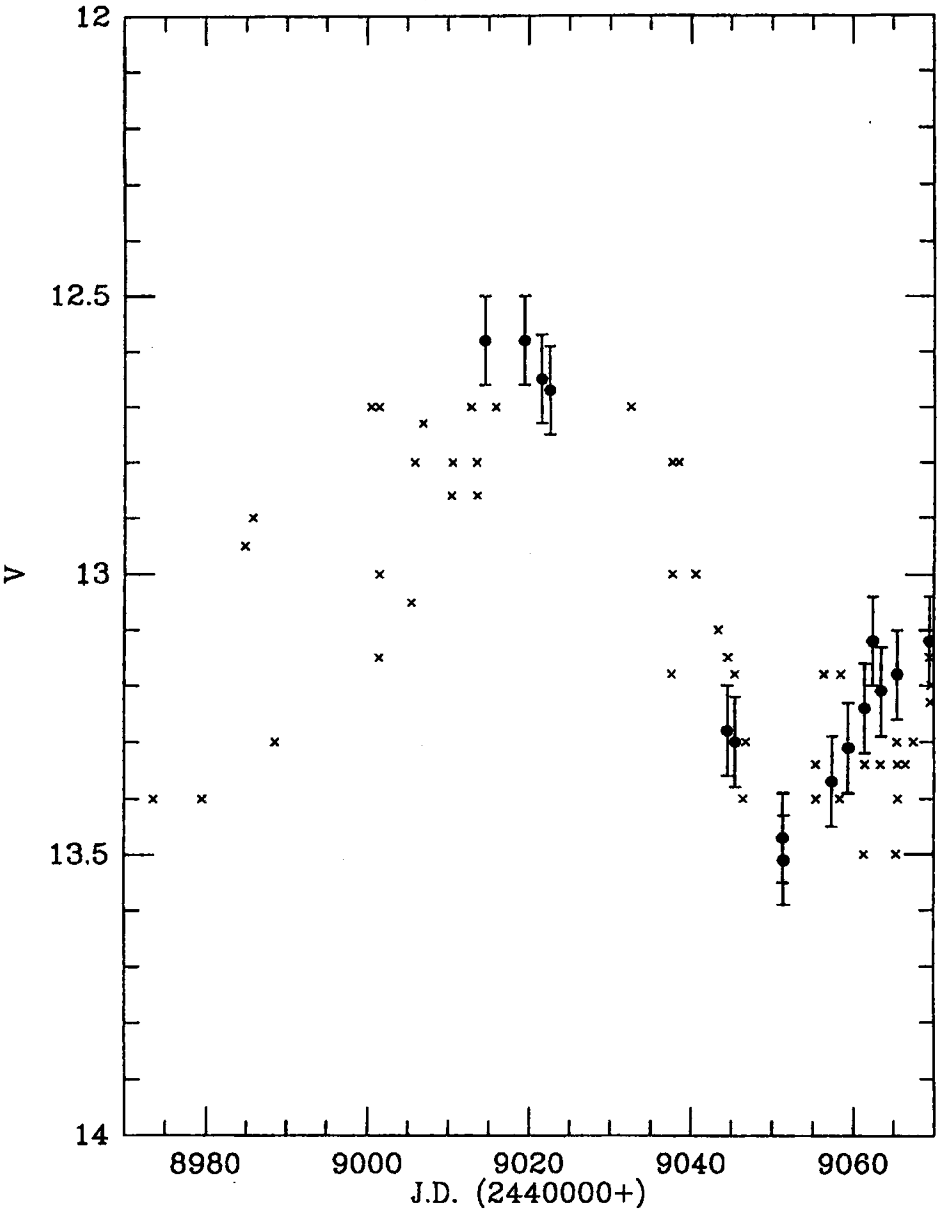

Figure 3 *V* light curve of Mrk 421 during the outburst observed in 1993.

rally, there is a good agreement for the average values and the differences between the AIT and the visual estimated data are always less then 0.3 mag, with a standard deviation of almost 0.2 mag.

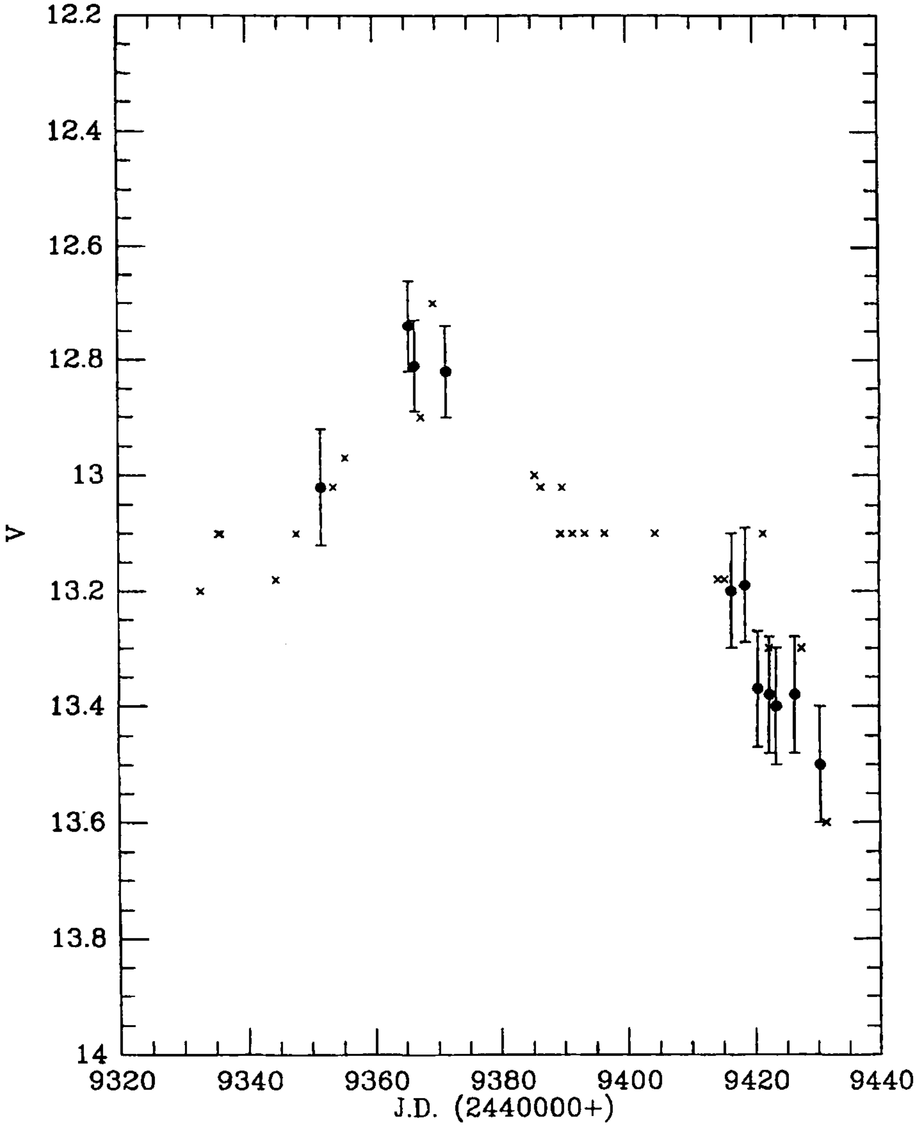

Figure 4 *V* light curve of Mrk 421 during the outburst observed in 1994.

3 RESULTS

In Figure 1 we report the light curve in the *V* filter during the monitoring campaign. Visual estimates are binned together every 6 days to have a better estimate of the overall trend and these data are connected. The magnitudes obtained with the AIT CCD camera are reported with the error bar equal to the standard deviation.

During 1992 Mrk 421 was very bright (Figure 2) because of the large outburst that started in January (Fiorucci and Tosti, 1992; Hurst, 1992) and ended in June, with a time-scale of almost 200 days. During the high brightness phase flickering with smaller time-scales was also evident, but the precision of the visual estimates is not enough to give a better understanding of the variability behaviour. During 1993 we observed a great outburst around January 30 (Figure 3) with a time-scale of a few months and characterized by a rapid rise and decay. Another outburst is evident in early 1994 (Figure 4), while in 1995 Mrk 421 was more stable.

In Figure 5 we report a typical colour index $V - I_c$ as a function of the V-magnitude: we observe a reddening of the spectral index when the object is less bright. This is a typical feature discovered in other BL Lac objects and is well interpreted as due to the thermal emission of the host galaxy (Hagen–Thorn *et al.*, 1983; Sillanpää *et al.*, 1988): when the synchrotron continuum of the AGN becomes less luminous then the spectrum of the galaxy is well observable and the colour index is redder.

To better evaluate this behaviour we decomposed the observed spectral flux distribution in terms of the host galaxy plus a typical synchrotron power law $F\nu \propto \nu^{-\alpha}$ of constant slope. To separate the two components, the BVR_cI_c data were grouped daily, corrected for the interstellar reddening, and then transformed in fluxes using the relations reported by Bessell (1979).

The correction for the galactic interstellar reddening was performed using the colour excess $E_{(B-V)}$ deduced by the relation $N_{(H)}/E_{(B-V)} = 5.2 \times 10^{21}$ (Shull and Van Steenberg, 1985), where $N_{(H)}$ is the equivalent hydrogen absorbing column density due to our Galaxy, which is equal to 1.8×10^{20} cm^{-2} in the direction of Mrk 421 (Elvis *et al.*, 1989). From $E_{(B-V)}$ we have evaluated the BVR_cI_c extinction coefficients with the formula of Cardelli *et al.* (1989) assuming $R_V = 3.1$ (Rieke and Lebofsky, 1985).

We considered the host galaxy component due to a typical giant elliptical galaxy (Arimoto and Yoshii, 1987) assuming as a free parameter its absolute visual magnitude M_V ($H_0 = 75$ Km s^{-1} Mpc^{-1} and $q_0 = 0.5$). The BVR_cI_c fluxes of each night, were interpolated with a power law distribution $F_\nu = \nu^{-\alpha}$ and the corresponding slopes compared. We found that the best fit is obtained considering a host galaxy with $M_V \simeq -20$ and a power-law distribution with mean spectral slope $\alpha = 0.60 \pm 0.08$. This value of α can be considered typical of the X-ray selected BL Lac objects (see Pian *et al.*, 1994).

4 DISCUSSION

Our data are almost coincident with the rapid flares detected by the Whipple Observatory at TeV energies and can be useful for a comparison at different wavelengths.

In general the spectral energy distribution (SED) of blazars shows a double-peaked feature with two maxima (von Montigny *et al.*, 1995). The first hump has a maximum around IR-UV frequencies and is generally explained as the synchrotron

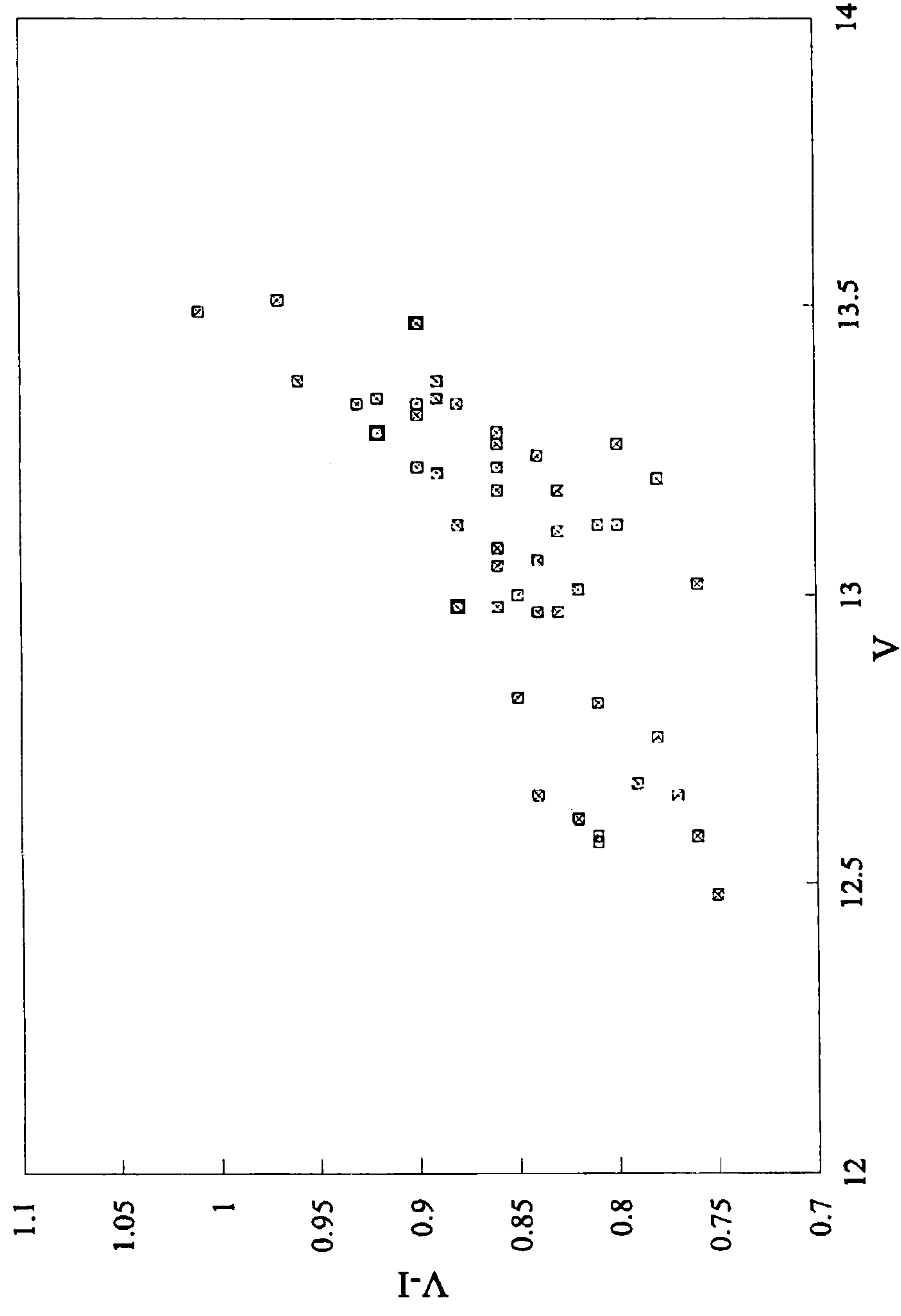

Figure 5 Colour index $V - I_c$ with respect to the V magnitude.

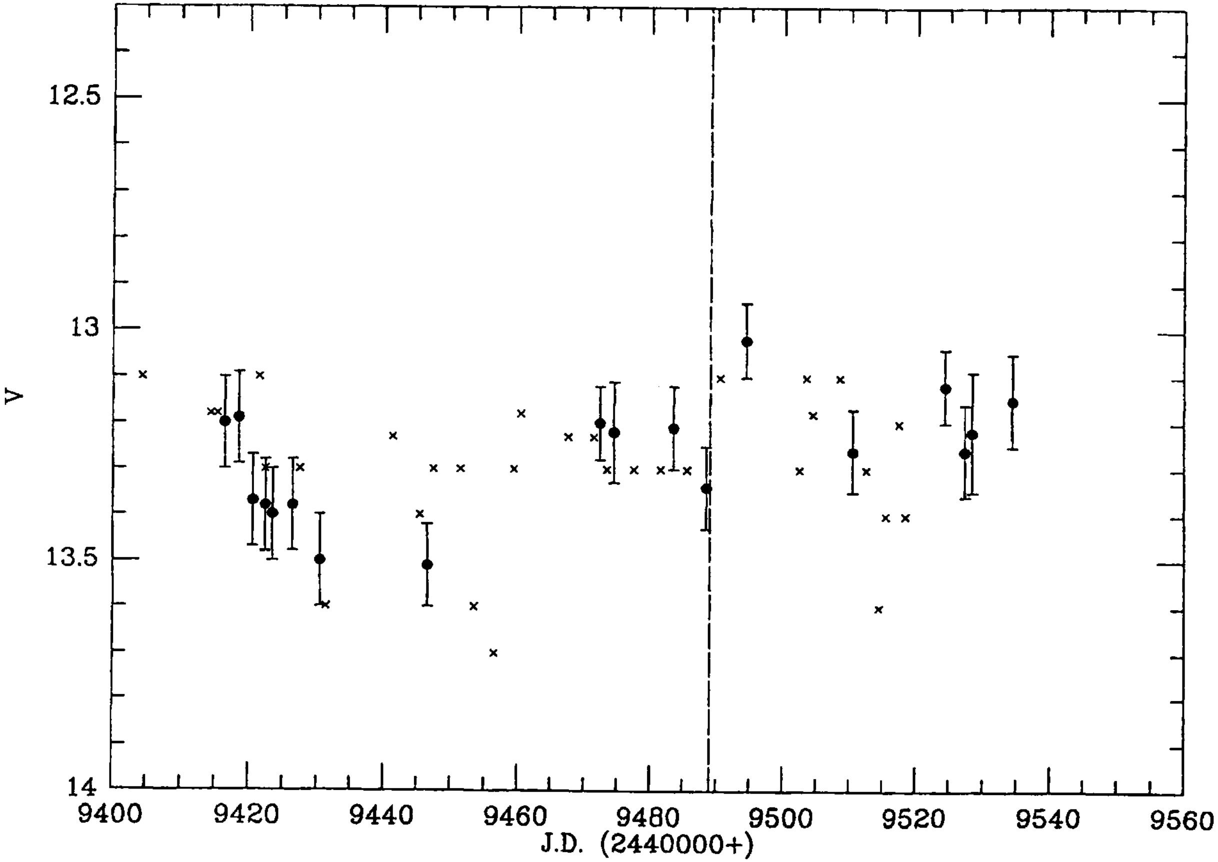

Figure 6 *V* light curve of Mrk 421 around the high-energy flare observed in 1994. The vertical dashed line indicates the date May 15, 1994 of the TeV flare observed by the Whipple Observatory.

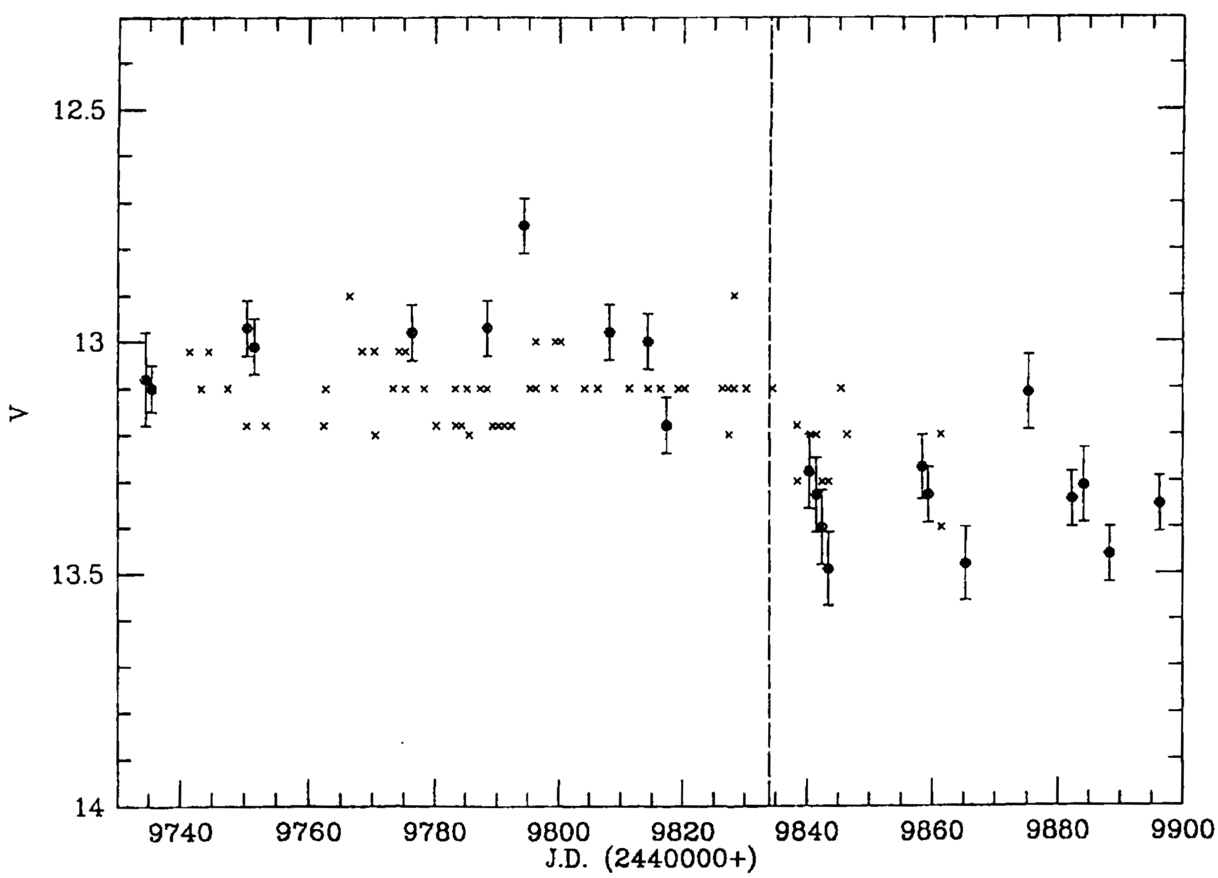

Figure 7 *V* light curve of Mrk 421 around the high-energy flare observed in 1995. The vertical dashed line indicates the date (April 15, 1995) of the hard X-ray/TeV flare observed by the Whipple Observatory and ASCA.

emission of relativistic electrons in a well-collimated jet beamed toward the observer (Blandford and Rees, 1978; Blandford and Königl, 1979; Marscher, 1980). The second hump is at γ-ray frequencies and is generally explained as the inverse Compton scattering of low-energy photons from the relativistic electrons in the jet. In the socalled synchrotron-self-Compton (SSC) effect (e.g. Königl, 1981; Ghisellini *et al.*, 1985; Ghisellini and Maraschi, 1989) the radiation field involved in this process is the same synchrotron emission of the jet. Otherwise the photons involved in the inverse Compton effect could be emitted by the accretion disk (e.g. Melia and Königl, 1989; Dermer and Schlickeiser, 1994), or by the emission of the accretion disk scattered back toward the jet by the ambient medium (e.g. Sikora *et al.*, 1994; Blandford and Levinson, 1995). A different model (e.g. Mannheim, 1993) explains the high power emitted at γ-rays with a cascade process beginning with photomeson production by very high-energy protons accelerated by shock waves in the jet.

The spectral energy distribution of Mrk 421 shows the same behaviour, with a single synchrotron component from the radio to the hard X-ray frequencies, typical of X-ray selected BL Lacs (see Giommi *et al.*, 1995), and a second component in the γ-ray region. The multi-wavelength spectrum of Mrk 421 is adequately fitted by the SSC model (Brodie *et al.*, 1987; Makino *et al.*, 1987; George *et al.*, 1988; Mufson *et al.*, 1990), but also by the model where the photons involved in the inverse Compton emission come from external radiation field (Dermer and Schlickeiser, 1994) and by the baryon-induced electromagnetic cascade model (Mannheim, 1996). For this reason multi-wavelength analysis of the variability can be useful for an understanding of the dominant mechanism on the emission processes of BL Lac objects.

Figure 6 shows the optical light curve around the observed TeV flares of May 15, 1994. We may note that during the TeV flare Mrk 421 was not particularly bright in the optical. This behaviour is consistent with the data reported by Macomb *et al.* (1995), who observed a quasi-simultaneous TeV and X-ray flare, but only a small increase in the emission recorded by EGRET at 100 MeV–GeV and no sign of activity at lower frequencies. It is worth noting that a small flare in the BVR_cI_c bands was observed a few days after the TeV and hard X-ray flare.

Figure 7 shows the optical light curve around the flare of April 15, 1995 observed by the Whipple and ASCA teams. Also in this case Mrk 421 was not particularly bright in the optical. The high-energy event was very rapid ($\simeq$ 2 days) and in the TeV it was less energetic than the flare observed in 1994. In the optical we have only one visual estimate during the same night of the TeV flare. We observed a small fade in the following 2 weeks but our light curve is not so well sampled early after the high-energy flare to exclude some optical activity as that observed on the occasion of the 1994 TeV flare.

It is worth noting that the largest optical outbursts observed in the years 1992, 1993, and 1994 do not seem to be correlated to any high-energy flares, both for the temporal distance and for the different temporal scales of variability.

The baryon-initiated cascade mechanism cannot explain easily the fact that the two flares observed at TeV energies are almost coincident with the flares observed by ASCA at hard X-ray energies whereas all the data in the optical and at other wavelengths (see Macomb *et al.*, 1995) show a substantial steady flux. The prediction of this model is that the high-energy cascade emission (the γ-ray outburst) follows the optical outburst on the very short proton photo-production cooling time-scale. In the proton-initiated cascade only target photons in the infrared to optical regime are important (Mannheim, 1996) and so we would have observed an optical outburst before the γ-ray outburst with only a short time lag. The absence of such an optical outburst in our data before the two high-energy flares strongly constrains the hadronic model.

In the model of Dermer and Schlickeiser (1993) the emission from the accretion disk is the cause of the big bump observed in the UV region in many optically violent variable (OVV) quasars. This bump is undetectable in BL Lac objects because of the strong enhancement of the synchrotron emission by the beaming effect. In this model the synchrotron and the γ-ray emissions originate in different regions of the jet. The model is then in contrast with the observed correlation between TeV and the hard X flares.

Also the model of Blandford and Levinson (1995) is in contrast with this behaviour, while both the SSC and Sikora *et al.* (1994) models are able to explain the simultaneous hard X-ray/TeV flares and the quite constant flux observed at 100 MeV. In effect, an increase in the upper cut-off energy of the relativistic electron distribution, without effecting either the magnetic field or the electron density on the jet, would cause a synchrotron flare to occur only at X-ray frequencies and, as a consequence, an inverse Compton flare at TeV energies (see George *et al.*, 1988; Macomb *et al.*, 1995). In this scenario the small optical flare observable after the hard X-ray/TeV flare of May, 1994 may be associated with the small enhancement observed by EGRET and it can be explained as the effect of the progressive cooling of high-energy electrons after the sudden energization. Nevertheless, a similar optical flare is not observable in our data after the 1995 TeV flare, but we have only a few observations and the high-energy event was extremely fast (Takahashi *et al.*, 1995).

More information could be achieved with a comparison of the major optical outbursts with the high-energy data. In the period 1992–1995 Mrk 421 has been extensively observed by EGRET and ASCA. Furthermore, since its discovery as a TeV source in 1992, it has also been monitored by the Whipple Observatory. As far as we know, high-energy data have been published only for the May, 1994 and April, 1995 flares, so it is not possible to make definitive speculations about the correlation between optical and high-energy behaviour until all the data at different wavelengths are available. Nevertheless, we can propose some preliminary ideas.

It is our suggestion that during an outburst the emission may come predominantly from a very restricted region within the inhomogeneous relativistic jet. This knot may be responsible for flares that are dominant only in particular regions of the spectrum depending on the physical parameters involved in the process. The TeV and hard X-ray flares may come from a small region with a sudden increase in the efficiency of acceleration of the highest energy electrons. In the same manner an optical flare may come from a region with a sudden increase in the local magnetic field or, near the inner regions of the jet, an increase of the electron density. Such an event will produce an enhancement of the synchrotron emission especially in that region of the spectrum where the parameters characterizing the knot give the maximum synchrotron emission, with only a marginal increase at other wavelengths.

In this context we could also explain the apparent smoothed periodicity in the optical outbursts observed from 1992 to the present, with an effect similar to the lighthouse model due to the helical motion of the emitting knot (Wagner *et al.*, 1995). We believe that in the 1992 a large knot was produced in the inner part of the jet and it was the cause of the major optical outburst. In the same period Mrk 421 was very bright in the soft X-band, as reported by ROSAT observations (Lamer *et al.*, 1996), and the Whipple Observatory detected the first TeV emission. It is worth noting that in 1992 Mrk 421 was observed at TeV energies with a factor of approximately 2 above the level observed in the period 1994, January–April; while the level on May 15, 1994 was 10 times that of the January–April flux. This is in agreement with a general differentiation between the rapid high-energy flares, produced in small regions where the electrons are considerably accelerated, and the slower variations, produced by large dishomogeneity in the jet structure. Within the framework of the lighthouse model proposed by Wagner *et al.* (1995) the knot rotates around the jet axis and there is a time dependence of the angle between the line of sight and the velocity vector of the knot. If this model is accurate, the region of production of the 1992 optical outburst may be the same as that which provoked the 1993 and 1994 outbursts.

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