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Radio, optical and photopolarimetric observations of Markarian 421 around the great 1996-97 outburst

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Abstract. We present the results of radio, optical and photopolarimetric observations of Mkn 421 from October 1994 to June 1997. During our monitoring the object showed many flares and major outbursts over a large span of temporal scales. A large optical outburst occurred in the winter 1996-97, followed by a radio outburst with a delay of only 30-60 days. In the same period Mkn 421 increased its polarization level toward values never observed before. From our data a clear correlation between the colour index and the brightness level appears, which may be due to the thermal contribution of the host galaxy. The frequency dependence of the optical polarization cannot be due to the host galaxy dilution and, therefore, it is related to the physics of the blazar synchrotron emission and to the geometry of the source. The most natural explanation seems to be the inhomogeneous jet model, and the outburst behaviour is such as might be expected at a shock front in the jet. We discuss how the optical variability can be explained if the spectra observed during flares are superpositions of spectra arising from spatially separated sources (shocks or reconnection sites) in the jet.

Key words: galaxies: individual: Mkn 421 – BL Lacertae objects: general – galaxies: active

1. Introduction

Mkn 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, Liu et al. 1997). The surrounding envelope is a typical giant elliptical galaxy with redshift z = 0.03 (Ulrich et al. 1975).

Mkn 421 is very active at high energies, and it was the first extragalactic source discovered by the Whipple Observatory to emit TeV γ–rays (Punch et al., 1992). The spectral energy distribution (SED) shows a double-peaked feature with two maxima (see, e. g. Buckley et al. 1996). The first hump has a maximum around UV-Soft X frequencies and is generally explained as the synchrotron emission of relativistic electrons in a well-collimated jet beamed toward the observer. 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. The radiation field involved in this process can be the same synchrotron emission of the jet, in the so-called SSC model (see, e. g., Brodie et al. 1987, Makino et al. 1987, George et al. 1988, Mufson et al. 1990), otherwise the photons involved in the inverse Compton emission may come from external radiation field (see e. g., Dermer & Schlickeiser 1993). A different model explains the high power emitted at γ-rays with a cascade process beginning with photomesons production by very high–energy protons accelerated by shock waves in the jet (see, e. g., Mannheim 1993).

Mkn 421 is extensively observed at high-energies, especially in the keV and TeV regions, which are the final tails of the two components in the SED. Optical and radio observations are generally used only for a comparison with the rapid high-energy flares, and there is a lack in the analysis of its variability at larger temporal scales, although Mkn 421 is a well known variable source in the optical. For this reason we collected many optical and radio observations during the last years, with the aim of analysing variability in the low-energy part of the synchrotron component. We also obtained photopolarimetric observations since the polarization of synchrotron radiation gives important informations on the source properties.

In this paper we present radio, optical and photopolarimetric observations of Mkn 421 since October 1994. In Sect. 2 we describe the observations and the analysis procedure adopted. We discuss the results in Sect. 3. Conclusions will follow in Sect. 4.

2. Observations

2.1. Optical

The observations were carried out with several telescopes (see Table 1).

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Table 1. List of the instruments used

Observ.	telescope	detector	filter(s)	FOV
Crimea	1.25 m	Photopol.	UBVRI	
Torino	1.05 m	CCD	BVR	$10' \times 10'$
Tuorla	1.0 m	CCD	V	$5' \times 3'$
Perugia	0.4 m	CCD	BVRI	$5' \times 5'$

The 1.25m telescope at the Crimean Astrophysical Observatory was equipped with a Double Image Chopping UBVRI Photopolarimeter (Piirola, 1988). The instrument provides measurements of both the intensity and the polarization simultaneously in the UBVRI bands (0.36, 0.44, 0.54, 0.69, 0.83 μm respectively) by using four dichroic filters which split the light into the five spectral passbands. The passbands are close to the standard UBV(Johnson) and RI(Cousins) systems, allowing an accurate conversion of the photometric data from the instrumental to the standard system. All photometric data were calibrated using standard comparison stars (Landolt 1983a, 1983b, 1992).

The other telescopes were equipped with CCD cameras and broad band Johnson-Cousins filters. The integration times during the exposures varied from 3 to 6 min depending on the brightness of the objects and the filter used. Data reduction was performed with locally developed software packages, which operate all the standard corrections required (bias and dark subtraction, flat field correction) and the instrumental magnitudes computation.

Mkn 421 is in the centre of a bright host galaxy, in addition, a nearby galaxy in the N-E direction from the source is well visible. 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 data analysed in this paper were obtained using an aperture diameter of 10 arcsec centered in the nucleus of Mkn 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 (FOV), which are able to saturate the frame and, sometimes, to cover the BL Lac object. Because of these bright stars and the small FOV of the Tuorla and Perugia CCD cameras, we could not have Mkn 421 and comparison stars in the same image. Therefore, we observed Mkn 421 with these instruments only on photometric nights, jumping between the object and the Landolt comparison stars. The photometric images obtained at the Torino Astronomical Observatory were large enough to include the three reference stars calibrated by Villata et al. (1998).

The comparison among the data acquired with different telescopes in the same night is fully satisfying, and no significant colour effect was found.

In Fig. 1 we report the light curve in the UBVRI filters collecting the data obtained with the above mentioned instruments during the monitoring campaign, from November 1994 to June 1997 (JD 2449676-2450606). The more sampled light curves are those obtained with the V and R filters (255 and 236 observations respectively). Optical variations are synchronous in all the observed broad bands, but the amplitudes are generally enhanced toward higher frequencies.

During 1995 and the first half of 1996 (from JD 2449676 to 2450233), Mkn 421 showed small amplitude variations and a modulation with a time-scale of some months. In the winter 1996-1997 a large outburst occurred (see Fig. 2), with the observed maximum of about V$\simeq$12.0 (JD 24500403, 14 November 1996 UT), one of the highest values of brightness reported in the historical light curve. It can be considered ended in March 1997, when the source faded to V$\simeq$13.1 (JD 2450525), although this is not the fainter state observed in Mkn 421. From our data it is impossible to estimate the beginning of the outburst, nevertheless visual estimates reported by the Variable Star Network (VSNET; http://www.kusastro.kyoto-u.ac.jp/vsnet/) show that it probably started around the end of October 1996, only a few weeks before our first detection. Therefore the outburst time scale was $\simeq 5$ months.

The light curve shows many flares superimposed to the overall trend. Very interesting is a flare that occurred around JD 2450158 (15 March 1996, see Fig. 3), with a temporal scale of a few days and a V amplitude of half a magnitude. Although the maximum is reported as only one photometric point, it is the average of eighteen observations and therefore it is reliable. Many other flares have similar time-scales but smaller amplitudes. In any case, we have never observed rapid flares with temporal scales less than a day (however, we have not obtained well sampled intranight observations).

In Fig. 4 we report the colour index (U-I) as a function of the V magnitude: we observe a reddening of the spectral index when the object is fainter. The reddening is well visible with the other colour indices, too. This is a typical feature discovered in other BL Lacs that have an evident host galaxy, therefore this phenomenon is generally interpreted as due to the thermal emission of the 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.

2.2. Polarimetry

The polarimetric study of Mkn 421 has a long history. First polarimetry of this source was made in 1973 by Ulrich et al. (1975) and Hagen-Thorn & Semenova (1974). Successively, many works were made by various groups of observers from the ultraviolet to near infrared regions (see, e.g., Mead et al. 1990, Takalo 1991, Takalo et al. 1992, Takalo & Sillanpää 1993). The object showed moderate polarization varying from about 1% to 7% (Takalo, 1991), with the position angle of polarization varying in the range 40° – 50°. Frequency dependent polarization (FDP) was found increasing toward the short wavelengths, while the wavelength dependence of position angle (FDPA) was not so definite. The data on circular polarization are very rare and controversial: no circular polarization was found in May 1976 (Maza et al., 1978), but small circular polarization was detected in one night in January 1992 (Takalo & Sillanpää, 1993).

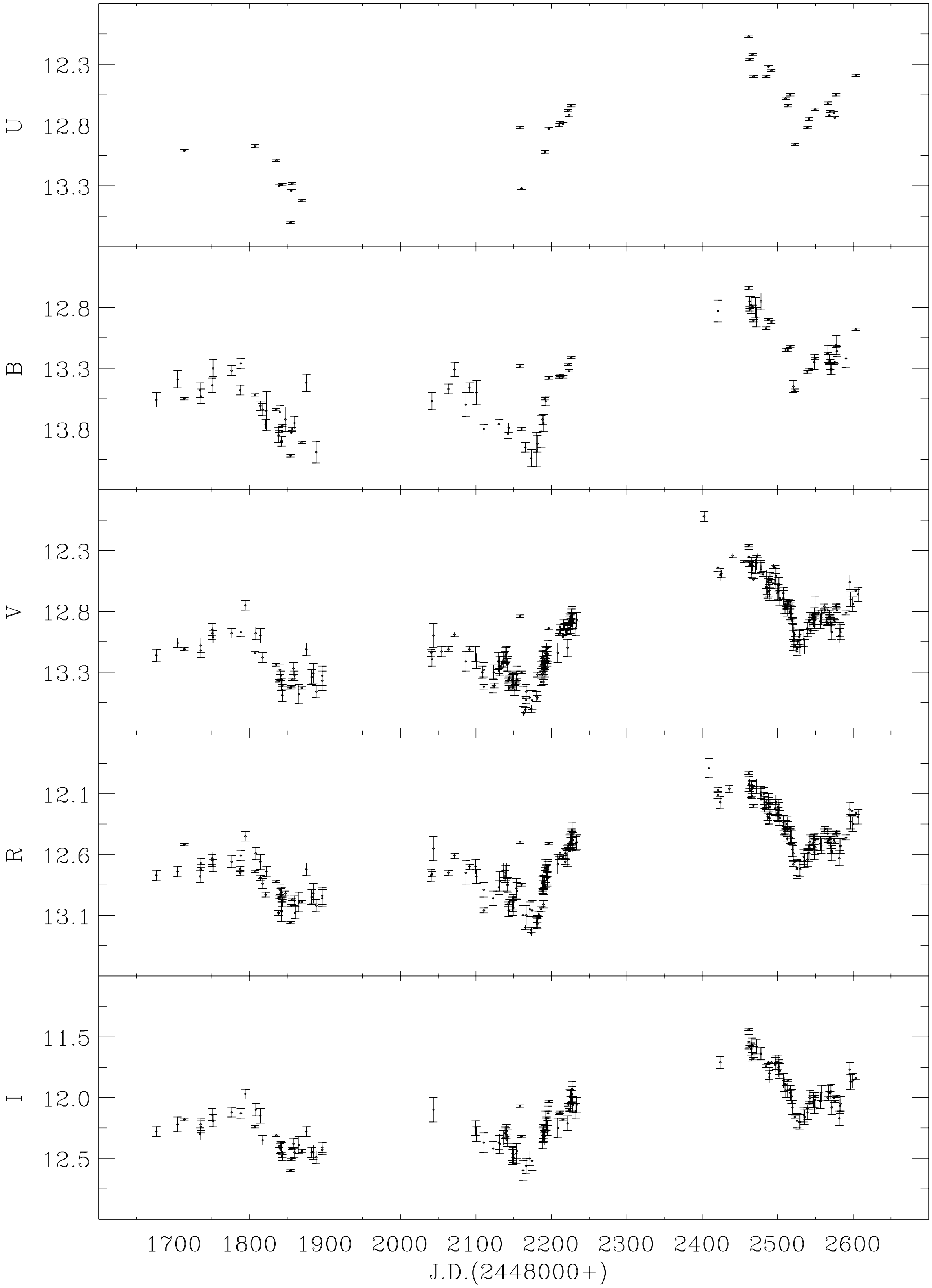

Fig. 1. UBVRI light curves of Mkn 421

Our photopolarimetric observations of Mkn 421 were carried out at the Crimean Astrophysical Observatory. All polarimetric data were corrected for instrumental polarization, calculated from the measurements of standard stars with low and high polarization.

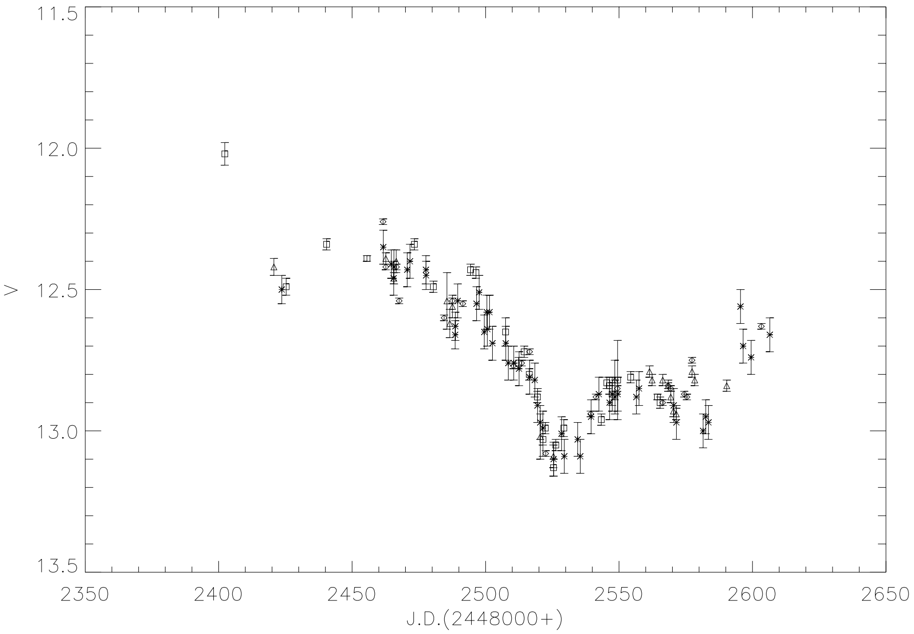

Fig. 2. V light curves of Mkn 421 during the large outburst observed in autumn-winter 1996-97. Observations are obtained at Tuorla (box), Torino (triangle), Crimea (diamond) and Perugia (star).

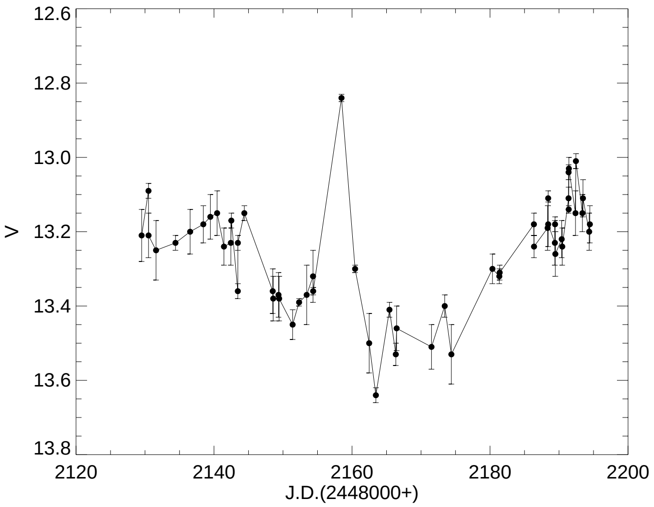

Fig. 3. V light curves of Mkn 421 during early 1996

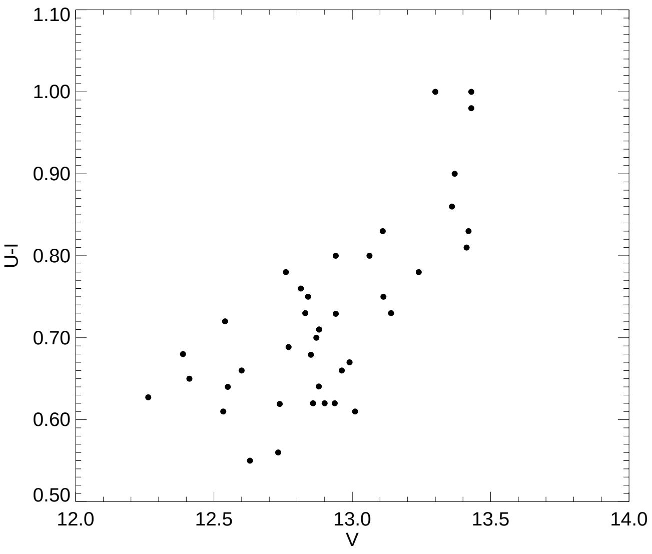

Fig. 4. Behaviour of the (U-I) colour index vs V magnitude

The general behaviour was very similar in all wavebands. The results in the V band, since 1995, are shown in Fig. 5, where we can note that most of the time the degree of polarization varied between 0% and 5%. During the 1997 outburst the degree of polarization rose up to $\simeq$ 14% and there was clear correlation between the variations of polarization degree and the brightness of Mkn 421. No such high polarization was detected before ($P_U = 16.3\%, P_B = 15.1\%, P_V = 13.8\%, P_R = 12.5\%, P_I = 11.9\%$ on JD 2450466.6).

An historical analysis of the polarization angle (PA) is reported by Efimov et al. (1998). Mkn 421 showed a rotation of the position angle of about 90° from May to October 1995. However, such rapid jumps of position angle of polarization were observed also in 1974-1980 (Hagen-Thorn et al.,1983), in April 1985 and in January 1990 (Valtaoja et al., 1991).

The comparison of the V light curve with the observed polarization shows that the enhancement of the linear polarization is strictly related to the great outburst, but the polarization decays faster than the source brightness. The polarization angle do not seem to be affected by the optical outburst.

There are also evidences for changes in the polarization with frequency (FDP) in this object, while no definite FDPA was seen. Some FDP, selected from our observations, are shown in Fig. 6.

2.3. Radio observations

Our radio observations were carried out with the Metsähovi 13.7 meter radiotelescope using 22 and 37 GHz receivers. These

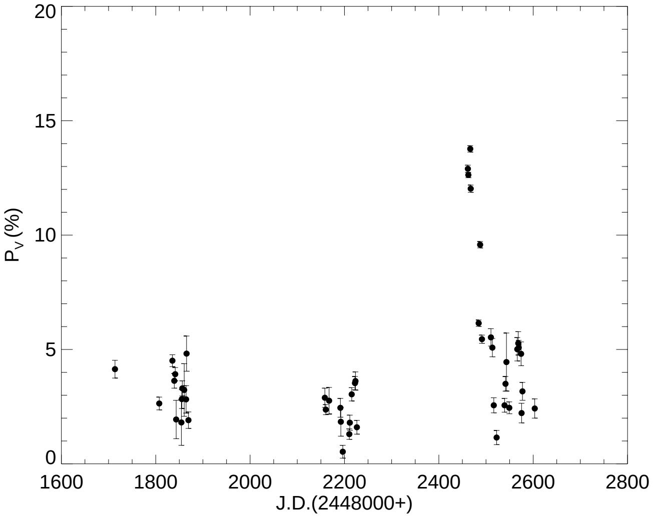

Fig. 5. V linear polarization of Mkn 421

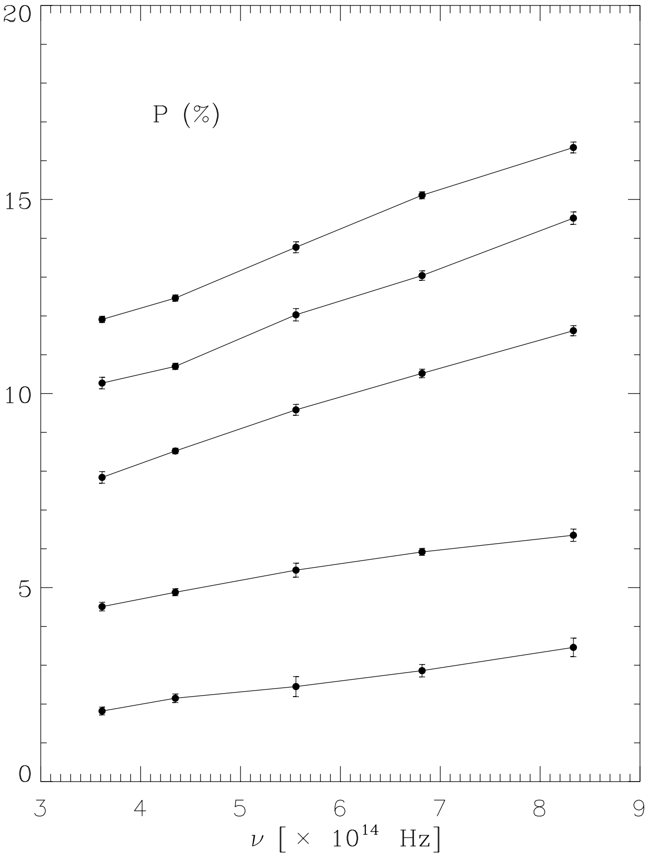

Fig. 6. FDP examples

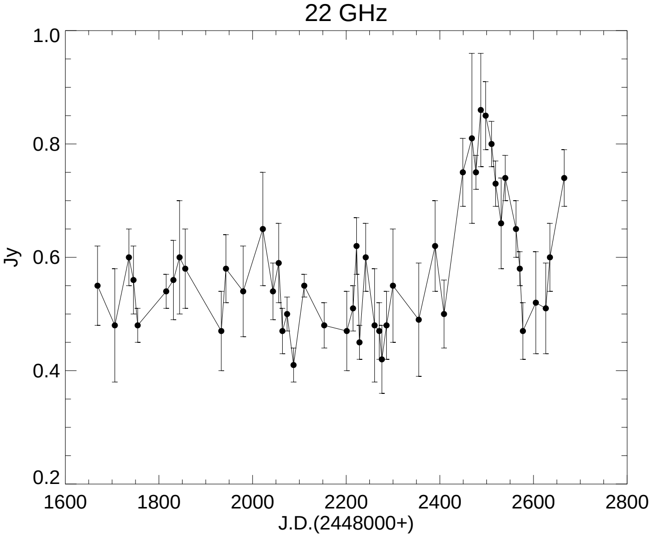

Fig. 7. 22 GHz flux curve (in Jy) of Mkn 421

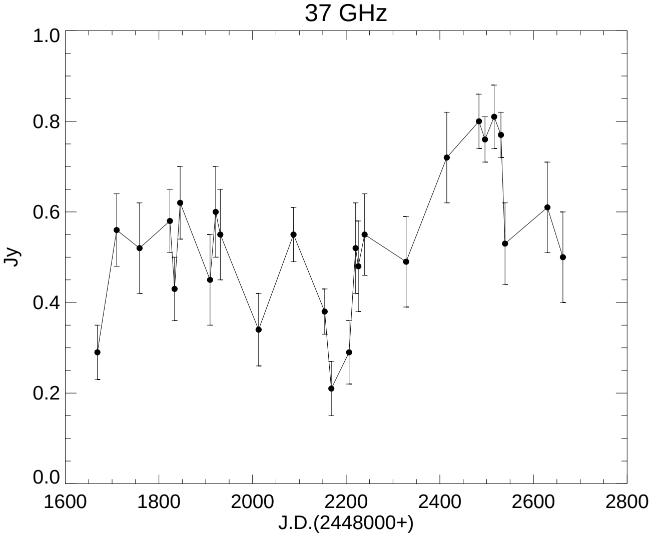

Fig. 8. 37 GHz flux curve (in Jy) of Mkn 421

observations are part of an ongoing quasar monitoring program running at Metsähovi since 1981.

The 22 GHz and 37 GHz light curves of Mkn 421 are reported in Figs. 7-8, where we can see an enhancement of the radio emission peaking around January-February 1997. We have to remember that this is a very rare phenomenon in Mk421 which is normally a very stable and weak radio source. Very interesting is the fact that the radio outburst has a delay of only a few months with respect to the optical outburst, and they have the same temporal scale. Therefore, they are probably correlated.

3. Results and discussion

3.1. Spectral index variations

We have seen that there is a reddening of the colour indices when the source becomes fainter. We can generally relate this effect to the host galaxy contribution to the total light, nevertheless it could be an intrinsic characteristic of the emission mechanism and, for this reason, we have performed a further analysis. We have 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 UBVRI data were grouped daily (since we have never seen intra–night variations), corrected for the interstellar reddening,

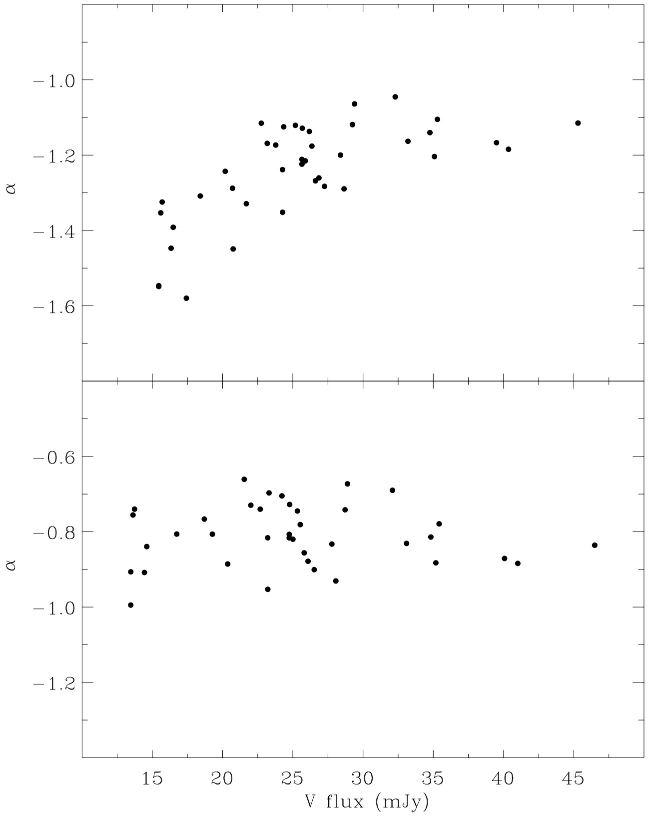

Fig. 9. Spectral slope vs V flux with only the interstellar correction (top), and with the host galaxy subtraction (bottom)

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 $E_{(B-V)} = 0.031$ (Lockman & Savage 1995). From $E_{(B-V)}$ we have evaluated the UBVRI extinction coefficients with the formula of Cardelli et al. (1989) assuming R_V=3.1 (Rieke and Lebofsky, 1985).

The spectral slopes with only the interstellar correction are plotted in Fig. 9 with respect to the V flux (top panel) and we can note that the slope is steeper when the flux is lower.

We considered the host galaxy component due to a typical elliptical galaxy assuming as free parameters its V magnitude and the colour indices (U-B), (B-V), (V-R) and (V-I). The UBVRI fluxes of each night (corrected by the host galaxy contribute) were interpolated with a power law distribution $F_\nu \propto \nu^{-\alpha}$ and the corresponding slopes compared. We found that the best fit is obtained considering a host galaxy with V=15.0, (U-B)=0.6, (B-V)=1.0, (V-R)=0.6 and (V-I)=1.4. The power–law distribution (see Fig. 9, low panel) has a mean spectral slope α=0.85±0.07. This value of α can be considered typical of the X–ray selected BL Lac objects (see Pian et al., 1994) and the colour indices are in agreement with the typical colour indices of elliptical galaxies (see, e. g., Arimoto & Yoshi, 1987).

The brightness distribution of the underlying galaxy of Mkn 421 has been studied by multiaperture photometry (see, e.g., Kinman 1978, Mufson et al. 1980, Makino et al. 1987, Kikucki & Mikami 1987) and direct imaging (Hickson et al. 1982). These studies show that the typical V magnitude of the galaxy with an aperture of 10 arcsec is ≃14.8, in substantial agreement with our estimate.

In conclusion, our data show that the optical spectral index (α) variations can be easily explained as the host galaxy contribution to the total light. However, this cannot exclude that an intrinsic variability of the spectral slope could be present, but it must have a small amplitude.

3.2. Frequency dependent polarization

Polarization observations at different wavelengths together with flux measurements offer valuable information in trying to understand the behaviour of BL Lacs. Polarization is important when the synchrotron emission hides the effects of possible other components in the spectrum, especially the host galaxy and the accretion disk emissions. Besides, polarization gives information about the magnetic field structure in the source.

Fig. 6 shows the presence of a strong frequency dependent polarization (FDP) in Mkn 421. This is a common phenomenon in BL Lacs (see, e. g., Valtaoja et al. 1991), but the synchrotron radiation produced by an homogeneous plasma causes frequency independent polarization. For this reason many mechanisms have been proposed in order to explain the observed FDP. The most important is the dilution by the thermal, unpolarized light of the host galaxy, that decreases the degree of polarization toward longer wavelengths. Dilution can also be caused by the hotter thermal radiation emitted by the accretion disk around the central black hole (Malkan & Sargent 1982, Smith et al. 1986). In this case the observed degree of polarization should decrease toward shorter wavelengths. In Mkn 421 the degree of polarization decreases toward longer wavelengths and, then, FDP cannot be strictly related to accretion disk dilution.

Fig. 10 (top panel) shows the behaviour of the FDP slope with respect to the magnitude and we can note that the slope is greater when the source is brighter. We have then scaled the linear polarization levels taking into account the host galaxy, with the following transformation:

$$P_{true} = P_{obs}[1 - 10^{0.4(m_{tot}-m_{gal})}]^{-1}$$

where P_{true} is the true polarization level, P_{obs} is the observed polarization, m_{tot} the total magnitude and m_{gal} the galaxy magnitude derived in Sect. 3.1. Then we have computed the FDP slopes and the new values are reported in Fig. 10 (bottom panel). We see that dilution by host galaxy emission can explain the FDP only when the source is faint. Moreover we note again that the FDP is greater when the source is brighter. For this reason an intrinsic source of FDP is needed.

The intrinsic FDP in BL Lacs may be explained either considering two different emitting regions, in the so–called two component models (see, e. g., Smith et al. 1986, Brindle et al. 1986, Ballard et al. 1990), or by a single component if we consider an inhomogeneous jet model (Bjornsson 1985). Although both the models are controversial and more observations are re-

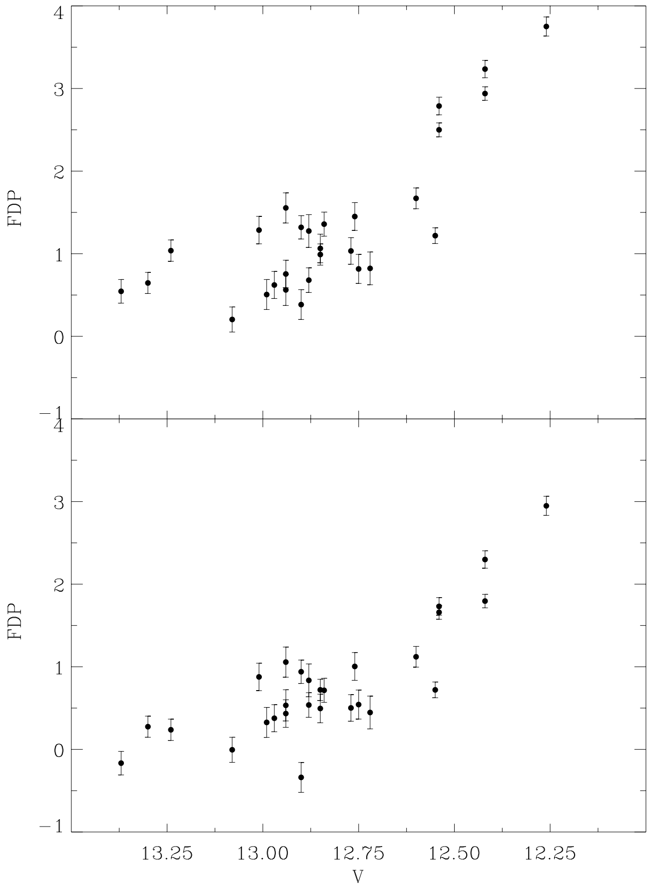

Fig. 10. FDP slope vs V magnitude without correction (top), and with the host galaxy subtraction (bottom)

quired, we can note that they can explain the FDP observed in Mkn 421.

3.3. Optical-radio comparison

A visual comparison between polarimetric, optical and radio light curves around the outburst is reported in Fig. 11. Although we have missed the beginning of the optical outburst, this comparison suggests that the radio emission has a lag respect to the optical. If we consider the decline we can estimate a temporal lag of almost 1-2 months, the same is true if we consider the optical maximum and the radio peak. The polarization flare is obviously related to the optical and radio outburst but we have missed the beginning and, therefore, we cannot have a quantitative comparison of the events. We can only argue that the polarization flare seems to decay faster than the optical and radio ones.

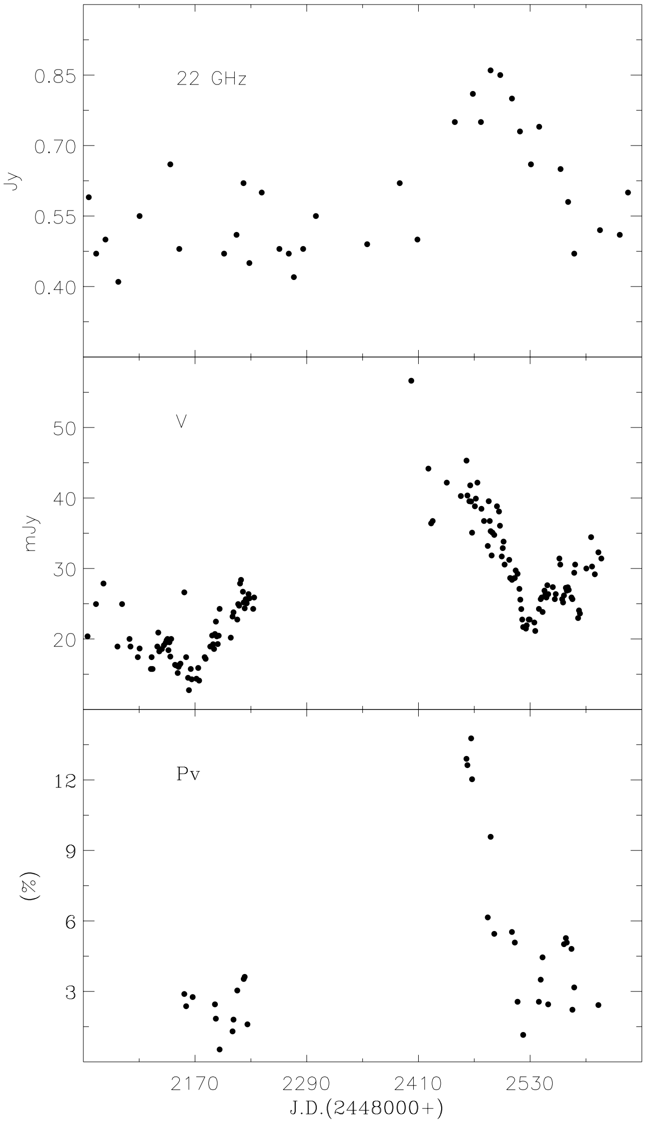

Fig. 11. Radio (22 GHz) and optical (V) flux curves, and optical polarization around the great 96-97 outburst

We have analysed the correlation between the optical and radio behaviour on the 1996-97 outburst of Mkn 421 using the discrete correlation function and the modified mean deviation method. The discrete correlation function (DCF) is analogous to the classical correlation function (which requires evenly sampled data) except that it can work with unevenly sampled data (see Edelson & Krolik 1988). The value of T_{lag} for which DCF has the maximum is the best estimate of the lag. The optical–22 GHz cross correlation function is shown in Fig. 12. The figure shows a peak at $\simeq$ 45 days. Fig. 13 reports the optical–37 GHz cross correlation function, with a peak at $\simeq$ 30 days.

Another method used in this study is a modification of the mean variance method (MMD) introduced by Hufnagel & Bregman (1992) and recently performed by Edelson et al. (1995). The value of T_{lag} for which MMD has the minimum is the best estimate of the lag. Fig. 14 shows the result for the optical-22 GHz and the lag is confirmed. The minimum is around $\simeq$ 60 days, but the curve is quite broad and a range between 30 an 60 days is reasonable. The optical-37 GHz comparison is reported in Fig. 15, and in this case the lag is of 20-30 days.

The 37 GHz radio data have a poor sampling and a low S/N ratio, then it is impossible to find a clear correlation between 22 and 37 GHz.

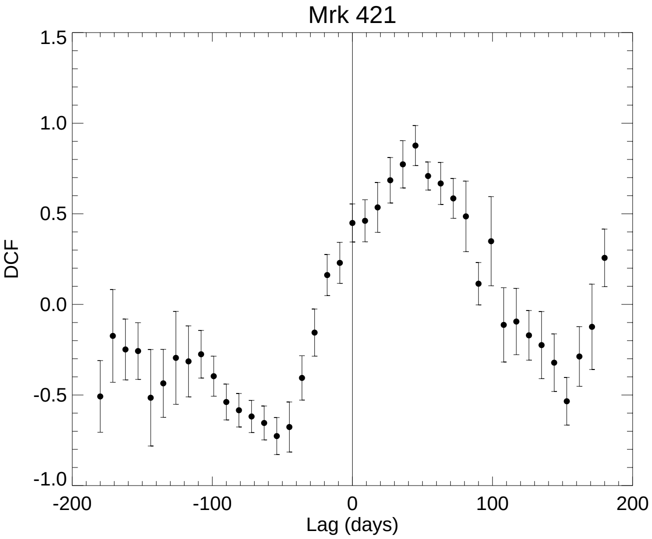

Fig. 12. Optical-22 GHz cross correlation, ΔT_{lag}=9 days

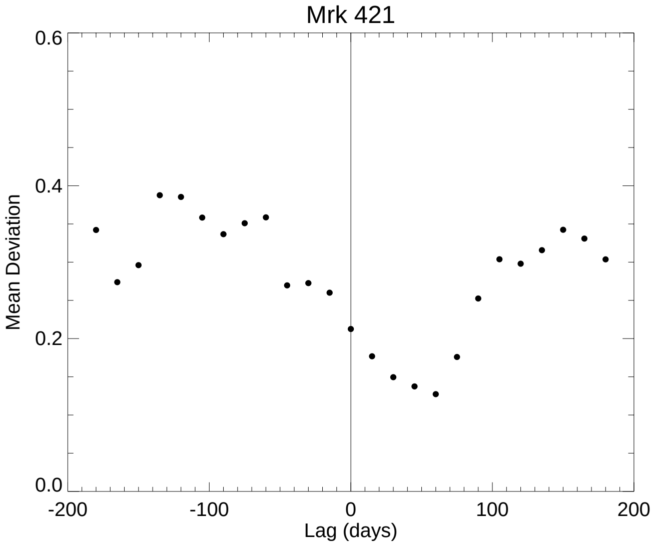

Fig. 14. Optical-22 GHz mean dispersion, ΔT_{lag}=15 days

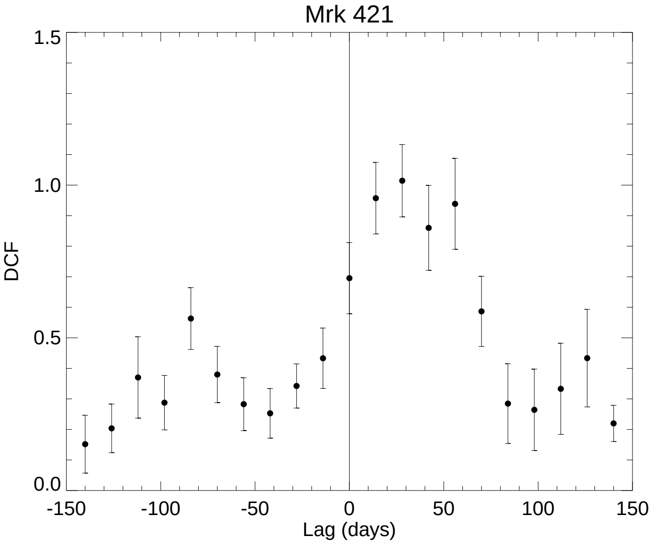

Fig. 13. Optical-37 GHz cross correlation, ΔT_{lag}=14 days

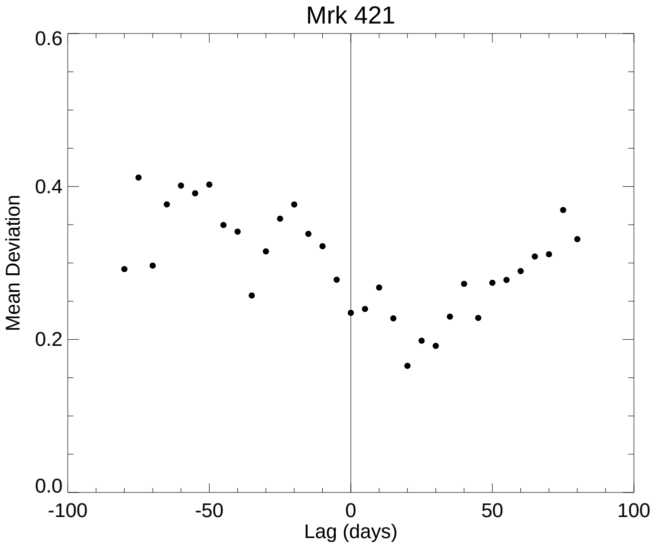

Fig. 15. Optical-37 GHz mean dispersion, ΔT_{lag}=5 days

3.4. Where does the outburst originate?

The origin of the radio flux can be explained by the shock-in-jet-models discussed, e. g., in Marscher & Gear (1985), Hughes et al. (1989), Valtaoja et al. (1992). According to these models, the radio outbursts are caused by shocks in the relativistic jets, and an enhancement of the polarization level is expected.

It is usually expected that there should be little correlation between the optical and radio behaviour in BL Lacs. This is partly due to the fact that the optical variations typically occur more rapidly than the radio variations and, therefore, this was taken as support for the idea that the optical emission is generated in a much smaller volume than the radio emission. In some inhomogeneous synchrotron source models for blazars, however, the radio and optical emission may be strictly correlated. For some combinations of the jet geometry and particle outflow acceleration, the radio and optical emission could come from the same region, in the outer part of the jet (Ghisellini et al., 1985). For a different choice of the jet geometry and particle flow, the optical emission could come from the inner part of the jet while the radio emission is produced in the outer regions.

Many attempts to search for correlations between the optical and radio emissions in BL Lacs yielded no clear indication of a connection between the emission at the two frequencies, while different radio frequencies are well correlated, with a time delay of the emission at longer wavelengths with respect to the shorter ones (see, e.g., Hufnagel & Bregman 1992). However, other authors confirmed the correlation between some optical and radio flux variations and suggested that sometimes the optical variations precede the radio outbursts (see, e.g., Valtaoja et al. 1987, Tornikoski et al. 1994b). The radio delays can be easily explained by source opacity arguments, and one might even expect radio and optical variations to be simultaneous above the frequency where the source turns transparent (for an example see Tornikoski et al. 1994a).

Although our radio data on Mkn 421 are affected by large uncertainty, the statistical analysis we performed shows quite clearly the optical-radio correlation for the great 1996-97 outburst, with the radio emission which lags of 30-60 days respect to the optical emission. The lag is shorter than the outburst temporal scale ($\simeq$5 months), therefore the radio and optical emissions probably came from the same physical region, such as might be expected at a shock front in the jet.

Moreover, recent comparisons of the optical and VLBI polarization position angles for BL Lacs appear to confirm that the optical and radio emissions are sometimes linked (Gabuzda & Sitko 1994, Gabuzda et al. 1996). This observed correspondence could be explained in a natural way if the optical polarization of BL Lac objects is associated with the formation and emergence of new VLBI components. One natural possibility is that the optical polarization originates in compact, highly energetic shocks as they form and emerge from the core (Gabuzda et al. 1996). Since the distance traveled behind the shock front by a relativistic electron before suffering radiative losses would depend on energy, the thickness of the emission region would decrease with increasing frequency. This would naturally produce the optical/radio lag and account for its being shorter than the variability time–scales. However, shock fronts alone cannot solve all the problems with the relativistic jet model, since spectral variability would still be expected. Celotti, Maraschi & Treves (1991) computed simulated light curves that would be expected in the inhomogeneous jet model, approximating the propagation of a shock wave in the jet by a schematic perturbation of given size and amplitude moving at constant speed. They predicted strong spectral variability only above the spectral break and a substantial stability below. If we consider that for Mkn 421 the spectral break is placed in the X–ray region, we can argue that the observed lack of spectral variability in the optical region is therefore in agreement with this model.

Very high resolution VLBI maps of Mkn 421 show an unresolved core and outer components that exhibit apparent superluminal motion along the jet without significant change of position angle (Zhang & Baath 1990, 1991). VLBI observations therefore can be used to study a new component emerging from the core during an outburst and to study its behaviour on its way out. Recent observations (13 March 1997) made with the NRAO VLBA at the frequency of 15 GHz seem to confirm the presence of a new component after the 96/97 outburst (Kellermann et al. 1998).

3.5. Comparison between our data and high-energy flares

Mkn 421 is a well-known variable source in the TeV and X-ray spectral bands. Whipple observations show that the mean γ-ray emission has gradually decreased from 1995 to 1997 (Mc Enery et al. 1997). Some well definite rapid flares are superimposed to this trend, with typical time scales of only a few hours or days. On February 1, 1997, for example, the γ-ray emission increased by a factor of 5.5 above the average flux with a duration less than a day. The most impressive variation occurred in May 7, 1996, when the flux increased by a factor of 5 in 2.5 hours and Mkn 421 became the most intense source of TeV γ-rays ever observed (Mc Enery et al. 1997). This flare was followed by another less pronounced γ-ray flare only a few days after (May 15, 1996).

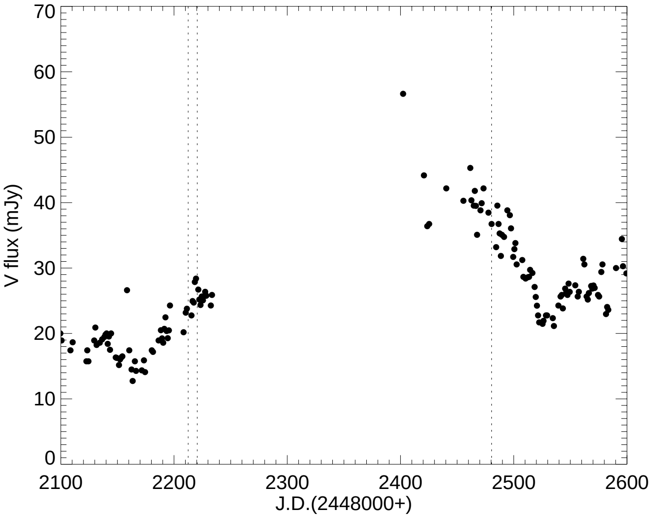

Fig. 16. Optical V flux around the outburst and the dates of the X-ray/TeV flares: May 7, 1996, May 15, 1996 and February 1, 1997

Similar to the TeV γ-ray variability, also the X–ray behaviour of Mkn 421 can be described as composed of a series of rapid flares (Schubnell 1997). Up to date, many evidences are available that show how rapid TeV and X-ray flares are strictly correlated, and this fact find a natural explanation if the same non–thermal electrons are responsible for the two emission components, with the γ–rays produced by Inverse Compton Scattering (see, e.g. Macomb et al. 1995).

Optical data taken in the same period of the X-ray/TeV flares generally did not show an increase in the optical flux (Schubnell 1997, Fiorucci et al. 1997) or show a correlation with high-energy flares but a less pronounced variation of only one or two tenths of magnitude (Buckley et al. 1996, Weekes et al. 1996).

In Fig. 16 are indicated with vertical lines the dates of the high-energy flares superposed to the optical flux. Our data substantially confirm that in the period of X-ray/TeV flares the optical flux is marginally influenced by the high-energy events. On the other hand, the optical outburst follows the May 1996 flares by almost 5 months, and the February 1997 flare happens during the decline of the outburst.

At present, there are not clear evidences that can link the long term optical and radio variation with the rapid TeV flares observed in the same period. The different temporal scales of the low-energy and high-energy events suggest that the variations arose from two distinct, spatially separated sources.

In synchrotron emission, photons are produced with energies scaled by the magnetic field intensity:

$$\nu_s \simeq \frac{4}{3}\gamma^2 \left(\frac{eB}{2\pi mc}\right) \tag{1}$$

and the electron cooling time is inversely proportional to the square of the magnetic field:

$$t_s = \frac{6\pi mc^2}{\sigma_T c\gamma B^2} \tag{2}$$

If we assume that both the maximum Lorentz factor of electrons (γ) and the magnetic field intensity (B) decrease with distance along the jet, then the spectra produced closer to the central engine are expected to be shifted to higher frequencies than the spectra produced in the more distant regions. With this assumption the high-frequency synchrotron flares are produced by electrons having a faster cooling time and so they are more rapid than the low-energy flares.

For this reason we suggest that Mkn 421 variability can be explained with the superposition of spectra arising from at least two spatially separated sources, one which is relatively long-lived (weeks, months) and is placed in the outer parts of the jet, another which is short-lived (hours/days) and is closer to the central engine. Probably both sources represent dissipative ”events” (shocks/reconnection sites) propagating along the jet at relativistic speeds, but the effects in the spectral energy distribution are different since different are the emission regions.

This effect can explain why Mkn 421 show a much higher amplitude of variability in X-ray and TeV bands than at lower energies within respective spectral components (Sikora et al. 1998): if the rapid flare is produced close to the central engine then it will be probably observed to have high amplitudes only in the high energy tails of the synchrotron and Compton components, and it will have negligible contribution at lower frequencies. On the other hand, if the long flare is produced in the outer regions of the jet then it will be probably observed to have high amplitudes only in the low energy tails of the synchrotron and Compton components.

4. Conclusions

This paper reports on the results of a radio, optical and photopolarimetric monitoring campaign on Mkn 421. The data quality, sampling, and total duration were sufficient to measure temporal correlations between optical and radio wave bands, with the optical emission that precedes the radio emission of almost 1-2 months. The most important result is the observation of a large increase of emission both at optical and radio wavelengths, with time–scales of almost 5 months, significatively longer than the lag measured between wave bands. The outburst was strictly correlated to a large increase of linear polarization. Moreover the optical polarization is higher at shorter wavelengths.

These results have important implications for theoretical models that want to explain optical and radio variability of BL Lac objects. The most natural explanation seems to be the multi-component model or its natural extension, the inhomogeneous jet model. The observation that the optical emission leads the radio one by less than the variability time–scale argues for a flattened geometry, such as might be expected at a shock front in the jet. We discussed how the variability can be explained if the spectra observed during flares are superpositions of spectra arising from spatially separated sources (shocks or reconnection sites) in the jet. In this contest the large optical-radio outbursts are generated by relatively long-lived sources placed in the outer parts of the jet, while rapid keV and TeV flares are produced closer to the central engine.

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