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Monitoring of 3C 66A during an extended outburst. I. The light curves*

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Abstract. — We present results from a two year intensive monitoring of BL Lac object 3C 66A (PKS 0219+428). This object was observed in outburst during these two years. It reached the brightest ever observed magnitude on V=13.59 (1.2.1995) and on K=10.59 (15.2.1994). The optical and infrared light curves are characterised by randomly distributed fast flares, lasting a few days and well defined outbursts lasting a week or two. On top of these flares we can occasionally see small amplitude microvariability. No clear correlation can be found between the spectral behaviour and the occurrence of these flares. In the radio bands 3C 66A was quite faint and very stable compared to the optical variations. The light curves will be presented with preliminary analysis and discussions on the possible causes for the observed variations.

Key words: BL Lacertae objects: general; 3C 66A — radio continuum: galaxies

1. Introduction

Most of the optical quasar and blazar monitoring programs so far have been using a single telescope, like the Florida (Webb et al. 1988), Hamburg (Schramm et al. 1994), and Tuorla (Sillanpää et al. 1991; Takalo et al. 1992b) groups. Because of weather conditions, manpower requirements and the decisions of the time allocation

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committees the sampling in these monitoring programs has been very random. During the last few years a number of automated telescopes have entered this field, such as the RoboScope at Indiana University in the U.S.A. (Turner et al. 1994) and the Perugia Observatory (Tosti et al. 1996) in Italy. But even with their help the sampling will still not be continuous enough without a truly global campaign. There has also been several worldwide multifrequency monitoring campaigns organized to observe one or a few objects (e.g. Edelson et al. 1995). But usually these campaigns have lasted, at most, about two weeks. So they can only provide a brief snapshot of the object's behaviour (e.g. Gear et al. 1986; Brown et al. 1989). These snapshots will thus give information only on short term variability and spectral behaviour. Only a few of these campaigns have been able to provide detailed enough long term optical light curves (e.g Wagner et al. 1993, 1996) in order to compare them with the excellent radio light curves (Aller et al. 1994; Teräsranta et al. 1992) of these objects and to really make detailed models for the quasar and blazar emission processes.

Blazars are among the most violent and most energetic objects in the Universe. This class of objects consists of two kind of objects, BL Lacs and high polarization quasars (HPQ). The difference between these two classes is that in HPQ's we observe strong emission lines, but in BL Lac's not. BL Lacs are believed to be the centers of (mostly) elliptical galaxies (e.g. Stickel et al. 1993), and show violent variability at all observed frequencies on time scales from minutes to years (e.g. Takalo 1994; Wagner & Witzel 1995). The only energy producing machine that can create the observed emission is an accreting supermassive black hole in the center of this host galaxy (e.g. Begelman et al. 1984). Another defining characteristic for blazars is high and variable polarization (Angel & Stockman 1980). The emission is mostly synchrotron radiation that is being beamed towards us (e.g. Ballard et al. 1990; Bregman 1990). Most of the emission is believed to be originating in a jet, coming from the central black hole, that is pointing almost directly towards us (e.g. Teräsranta & Valtaoja 1994).

The observed variability has been explained (especially in the radio frequencies) with randomly occurring, radiatively decaying shocks in this jet (e.g. Marscher & Gear 1985). Other models for the observed variations in the optical include flares in the (possible) accretion disk around the central black hole (e.g. Wallinger et al. 1992), a lighthouse model (e.g. Camenzind & Krockenberger 1992) and microlensing (e.g. Stickel & Kühr 1988). In general microlensing can explain variability on longer time scales as compared to the other models, which can all explain variability on time scales down to a day.

BL Lac object 3C 66A was selected for the OJ-94 project (Takalo et al. 1994a) as a comparison object for OJ 287 because of its brightness and location in the sky (it could be observed when OJ 287 is unobservable). Also it has previously shown totally different variability behaviour than OJ 287. The variability amplitude observed in it has been 2 magnitudes. This amplitude is typical for a BL Lac object in long term light curves. In the infrared monitoring we had not observed any nightly variability (Takalo et al. 1992a). Based on these observations, we were hoping to use its observations as a means of minimizing or at least understanding instrumental effects in our nightly monitoring observations of OJ 287. However, the 3C 66A observations turned out to be very interesting in their own right. Also they cannot be used for the intended calibration purposes due to the large variations displayed by 3C 66A.

Here we will first discuss the historical behaviour of 3C 66A. Then describe the observations during the OJ-94 project and the resulting light curves. This will be followed by our preliminary analysis and discussion.

2. History of 3C 66A

Blazar 3C 66A was optically identified by Wills & Wills (1974) as a 15.2 magnitude blue stellar object, located 6.5′ from the powerful radio galaxy 3C 66B. The redshift of the BL Lac object is not well determined. The most quoted value is z=0.444 (Miller et al. 1978; Lanzetta et al. 1993). Butcher et al. (1976) found it to be located near the apparent center of a rich cluster of galaxies whose redshift they estimate to be z=0.37(+0.07, −0.03). The BL Lac object itself is a point source, with no indication of the underlying host galaxy. VLA radio maps show a point source with small extensions towards south (Price et al. 1993).

BL Lac object 3C 66A has shown large amplitude variability in X-rays, some of which seem to be simultaneous with optical variations (Maccagni et al. 1987). Its combiled multifrequency spectra (Giommi et al. 1995) looks very similar to other blazar spectra. The optical polarization for this object has been usually around 15 percent, with the position angle being at a preferred orientation of 50−60 degrees. (e.g. Takalo et al. 1991). In recent years the polarization has been close to 30 percent, with the same position angle orientation (e.g. Efimov & Shakhovskoy 1994; Takalo et al. 1994).

Previously there has been little systematic monitoring observations of this BL Lac object. The Florida group (Pica et al. 1980), the Hamburg group (Schramm et al. 1994), the Chinese group (Xie et al. 1994 and references therein) and the group at Tuorla observatory (Sillanpää et al. 1991; Takalo et al. 1992b) had included it in their monitoring programs. Note also that these groups observed partly in different optical bands. The earliest published observations of 3C 66A date back to the early 1970's. All the previous observations have been more or less sporadic, with very uneven sampling and with only a few observations per year. Figure 1 shows the historical B-band light curve of 3C 66A, with our new data included. Note the much higher brightness observed during this campaign. The average magnitudes have previously been 15.5 in B and 15.0 in V.

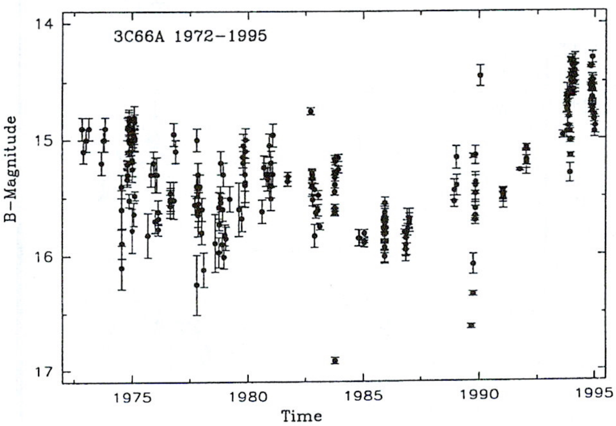

Fig. 1. The historical B-band light curve of 3C 66A, including the data taken during this project. See the text for the references for the historical light curve. Notice the increased magnitude during the latest observations

The historical light curve is based on data taken from the following references: Barbieri et al. (1982), Brindle et al. (1986), Corso et al. (1986, 1988), Folsom et al. (1976), Miller & McGimsey (1978), Holmes et al. (1984), Maccagni et al. (1987), Mead et al. (1990), Moles et al. (1985), Pica et al. (1980), Sillanpää et al. (1991), Sitko et al. (1985), Smith et al. (1987), Takalo (1991), Takalo et al. (1992b, 1994), Valtaoja et al. (1991), Worral et al. (1986), and Xie et al. (1987, 1988a,b, 1990-1992), Wills & Wills (1974).

As can be seen from Fig. 1., the object has not been very active. Only a few small outbursts have been observed (e.g. Barbieri et al. 1982; Folsom et al. 1976). Miller & McGimsey (1978) state that in the Harvard plate collection measurements the variability amplitude for this blazar has been ΔB=2.0 magnitudes, which is typical for BL Lac objects. Sillanpää et al. (1991) saw a 1.4 magnitude flare during October 1985. The historical light curve shows no systematic trends. The variations seem to be random in timescales from months to years. The mean amplitude of variations seems to be about 1.5 magnitudes in timescales of years. Maccagni et al. (1987) saw half a magnitude decrease in the brightness in two months, this decrease was accompanied with small amplitude (30%) events occuring in timescales of about one week. Similar results have been seen by the Hamburg group (Schramm et al. 1994). No clear evidence for intraday variability has been observed (e.g. Folsom et al. 1976; Miller & McGimsey 1978; Takalo et al. 1992a; Xie et al. 1992). Carini & Miller (1991) have reported on variations as fast as 0.09±0.02 mag/hr, which they claim to suggest a characteristic time scale for the variations in 3C 66A of 12 hours.

3. Observations

The observations presented in this article were taken during the OJ-94 project, between fall 1993 and spring 1995. The primary target in the project is blazar OJ 287. This project was awarded time as an international time project (ITP) on the Canary Island telescopes for a half year period starting fall 1993. An ITP-project receives 5% of the observing time on all the Canary Island telescopes. Besides the optical and infrared monitoring we observed 3C 66A spectroscopically during the ITP-time, results from which will be presented elsewhere. In order to achieve much better time resolution during the ITP, we organized a large international network of observatories to monitor both OJ 287 and 3C 66A. Currently there are 15 observatories with over 50 astronomers involved in the project. This is by far the largest monitoring program ever organized for blazar research (Takalo et al. 1994a). The bulk of the observations were taken by Boltwood and the automatic telescopes in Indiana and Perugia. These three observatories have provided us with almost daily observations in the V-band. The longest gap in the optical data (except for the solar conjunction) is one week (Pursimo & Lehto 1996). All other observatories have observed less frequently, but in some cases with much better time resolution. We have tried several times during the project to coordinate, with varying success, the observations between different observatories in order to get long continuous light curves and simultaneous observations in different wavelengths. During the ITP time a two week intensive monitoring campaign was organized for January 1994. Unfortunately weather conditions were very bad on the Canary Islands for the second week of this campaign, so it was not totally succesful.

The observations were performed as for the OJ 287 observations (see Sillanpää et al. 1994 for details). 3C 66A was observed whenever OJ 287 (the primary target in the OJ-94 project) was not observable. Whenever long nightly monitoring was performed, emphasis was given for the V-band since it is the most commonly used filter and thus available in most observatories. Also, the V-band is very well calibrated, unlike the R-band, where there exists several different filter systems. However, it is quite easy to calibrate these different R-band filter systems to give consistent results. The telescopes and instruments used are listed in Table 1.

We also received many visual estimates from "The Astronomer Organization" in England. These estimates complement the other observations, agreeing very well with the V-band light curve. The error estimate for these visual

Table 1. The observatories and instruments used in the monitoring. Photom=Photometric and Photop=Photopolarimetric observations

Telescope/Observatory	size	Instr.	Filters
Jakobus Kapteyn Telescope	1 m	CCD	*UBVRI*
Nordic Optical Telescope	2.5 m	CCD	*VRI*
		Photop	UBVRI
RoboScope	60 cm	CCD	*V*
Boltwood	17 cm	CCD	*VRI*
Heidelberg	70cm	CCD	R
Lowell Observatory	106 cm	CCD	*BVRI*
Capilla Peak Observatory	61 cm	CCD	*BVRI*
San Pedro Martir	2.1 m	CCD	*V*
Crimean Observatory	1.25 m	Photop	*UBVRI*
Tuorla Observatory	1.03 m	CCD	*V*
IAC-80 telescope	82 cm	CCD	*BVRI*
Calar Alto	1.2/2.2 m	CCD	*UBVRI*
Perugia Observatory	40 cm	CCD	*BVRI*
Torino Observatory	1.05 m	CCD	*B, R*
Carlos Sanchez telescope	1.5 m	Photom	*JHK*
Michigan Radio Telescope	26 m	Cont.	14 GHz
Metsähovi Radio Telescope	13.8 m	Cont.	22,37 GHz

estimates is 0.2 magnitudes. All observers in the project were responsible for the reduction of their own observations. All CCD observations were reduced using standard IRAF, MIDAS or VISAT reduction routines, or using systems developed for specific telescopes such as RoboScope (Honeycutt 1992; Honeycutt & Turner 1992), Perugia Observatory (Fiorucci & Tosti 1996), Boltwood observatory (Boltwood 1994) and Torino Obserytory where the Robin procedure locally developed by L. Lanteri is used (Villata et al. 1996). The CCD observations taken within the ITP-time were reduced at IAC and Tuorla. The photopolarimetric observations were reduced using reduction routines developed for the instruments in question (see e.g. Takalo et al. 1992b). The results from the polarization observations will be presented in another article (Efimov et al. in preparation).

For the photometric calibration sequence we used the stars first measured by Craine (1977). We have used the calibration by Craine (1977) and have also remeasured the calibration stars (Takalo et al. 1994b; Fiorucci & Tosti 1996; Villata et al. 1996; Gonzáles-Pérez et al. in preparation), and used the new values especially in *R* and *I* bands. Different observers have used different calibration stars, depending on their CCD-cameras image scale. Almost everyone has stars B and C (Craine 1977) in the CCD field, so they are the primary calibration stars. Since they have send to the archive the magnitude differences the use of different calibration stars does not cause problems. For the reduction of the infrared observations see Takalo et al. (1992a) and references therein for a detailed description.

We have only a few radio observations on this BL Lac object, taken with the Michigan and Metsähovi radio telescopes. The observations techniques and data reductions have been explained in Aller et al. (1994) and Teräsranta et al. (1992). It is not usually included in the radio monitoring programs at Metsähovi or Michigan radio telescopes due to the confusion created by the nearby radiogalaxy 3C 66B. This powerful radiogalaxy enters the beam at 4.8 and 8 GHz bands in Michigan telescope.

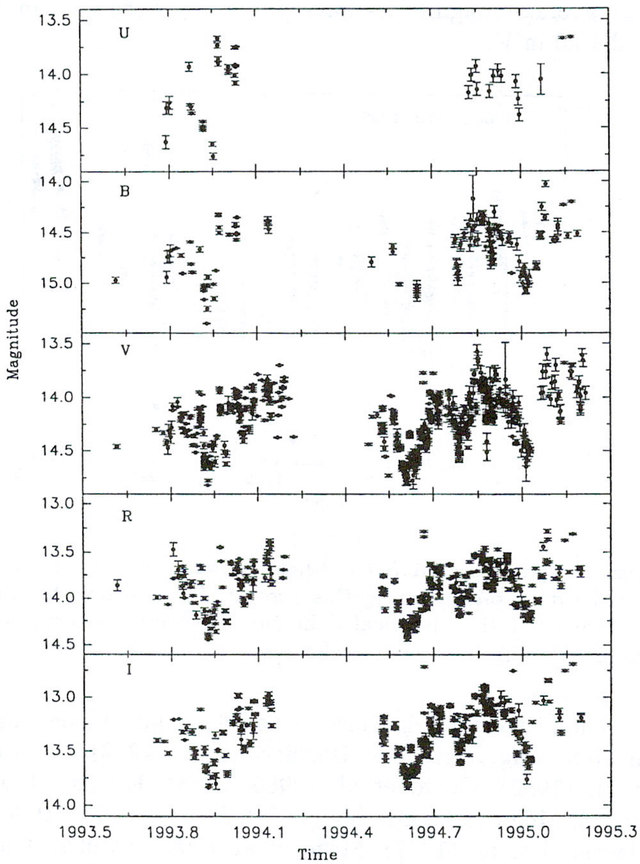

Fig. 2. The observed optical light curves

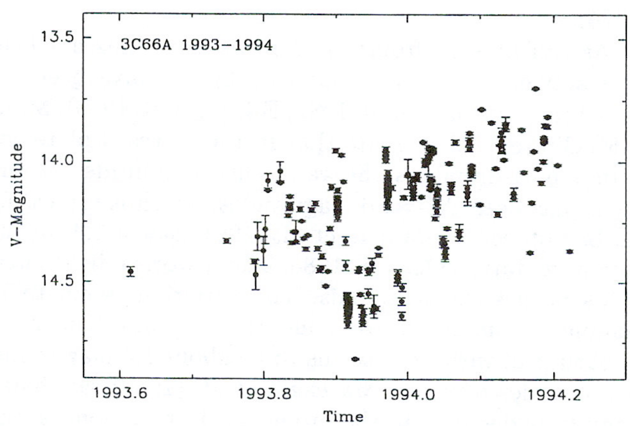

Fig. 3. The light curve in *V*-band observed during winter 1993-1994

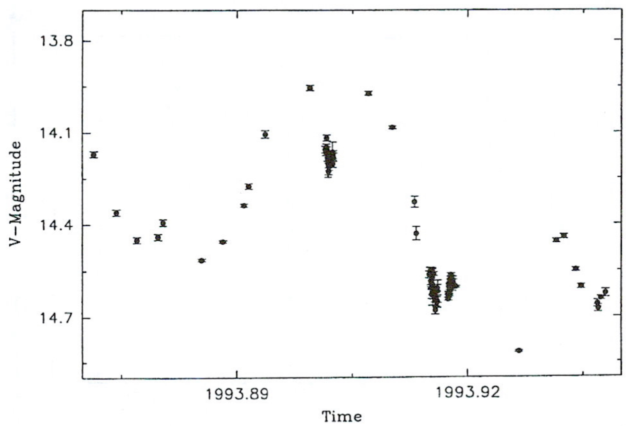

Fig. 4. Example of an outburst observed during 1993-1994 observing season

All the reduced observations are collected at Tuorla observatory in an archive. This archive contains over 2500 data points on 3C 66A (Pursimo & Lehto 1996). One major concern in this kind of campaign is the question of calibrating the different observers data together. In our campaign this is taken care of by the archiving system. Most of the observers send us only magnitude differences between the object and calibration stars, and also the diferences between different calibration stars. So we can easily then compare in several ways the observations and to use the same calibration star magnitudes for all observations (see Pursimo & Lehto 1996). No large systematic differences has been detected between the observations by different observers. Our archived data constitute by far the best ever obtained light curves of this object. The data is available on request from Tuorla observatory.

4. Results and discussion

The optical light curves since fall 1993 are displayed in Fig. 2. In the U-band and B-band the light curve does not have very good time resolution. Our temporal coverage is the best in the V-band. Almost similar coverage is also available in R and I-bands. The light curves complement each other, since in some instances we have observations in one band, but not on the others. We get a extremely good light curve coverage by combining the results from all wavelengths. In all the light curves 3C 66A is seen in outburst (cf. Fig. 1), with the mean magnitude over one magnitude above the long term average.

The behaviour of 3C 66A is very similar in all these bands and can be characterized by randomly distributed outbursts on top of a slow increase in the observed average magnitudes. The average magnitude increased by 0.5 magnitudes in the V-band during our first observing season, and by 0.8 magnitudes during the second observing season. Preliminary analysis on the V-band light curve did not show any periodic variations (Lehto 1994). At the start of the second observing season the brightness had decreased back to the level of the start of the first season. Again the average brightness inreased during the observations, now by 0.8 magnitudes in V. It reached the brightest ever recorded magnitude at V=13.59 on February 1st 1995. The magnitude increase was comparable at the other wavelengths. The total variability amplitude observed during the project has been 1.4 magnitudes in V.

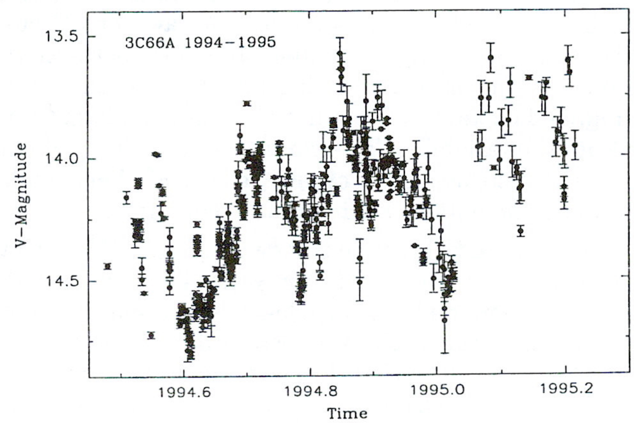

Fig. 5. The light curve in V-band observed during winter 1994-1995

Next we will describe the behaviour in more detail, concentrating on the V-band. The behaviour is very similar in all the other bands, but the coverage is best in V. Note especially the observations taken during winter 1993-1994 (Fig. 3) in which there are 3 very fast flares, with amplitudes up to 0.8 magnitudes. The time scale for these flares is of the order of days. Similar fast flares have been observed earlier in other blazars (e.g. Takalo et al. 1994c; Wagner & Witzel 1995). Due to the gaps in the light curve we may have missed some of the flares during this observing season. There are also a couple of quite well defined outbursts that last about one week. An example of such an outburst is shown in Fig. 4. Notice the symmetric double peak structure in the outburst. This kind of flares seem to be typical both in 3C 66A and OJ 287.

During the observations taken in winter 1994-1995 (Fig. 5) the behaviour seems to be less random. We see four well defined outbursts, which last from a few days to about two weeks. The first two of these outbursts are very fast. The decline from the second of these outbursts is very well sampled, showing an almost linear decline of 0.8 magnitudes to a broad minimum (Fig. 6). From this minimum the brightness increased in a month to a new outburst, lasting one month. Following a narrow minimum we have another larger outburst lasting two months. This outburst shows quite large flickering on top of the overall behaviour. Towards the end of the observations there are indications in the light curve that the behaviour is again becoming more chaotic. Unfortunately the sampling is getting poorer at this time.

Structure function analysis (Simonetti et al. 1985; Hufnagel & Bregman 1992) on the V-band data indicates that the overall behaviour of 3C 66A was very similar during both observing seasons (Fig. 7). The "spectral" slope calculated in this analysis gives α=1.0, indicating that the variability can be characterized by shot-noise type behaviour. The structure function analysis indicates a characteristic variability time scale of 145 days for 3C 66A. This time scale is approximately the time between the deep minimums observed during 1994-95 and can be seen in Fig. 5. The analysis does not show any minimum time scale for the variability. This could be due to the randomly occurring microvariability events (see below). Very similar results can be obtained using the R-band data.

The infrared light curve is shown in Fig. 8. The overall behaviour in these infrared observations is similar to the optical, but here we have much less observations. Again we have measured the brightest ever recorded infrared magnitude (K=10.59±0.06 on February 15th 1995) for this BL Lac object. (see Takalo et al. 1992a for previous observations). Unfortunately we do not have any infrared data taken during the brightest optical measurements. During fall 1993 small intranight variability was observed in the infrared bands (de Diego et al. 1996).

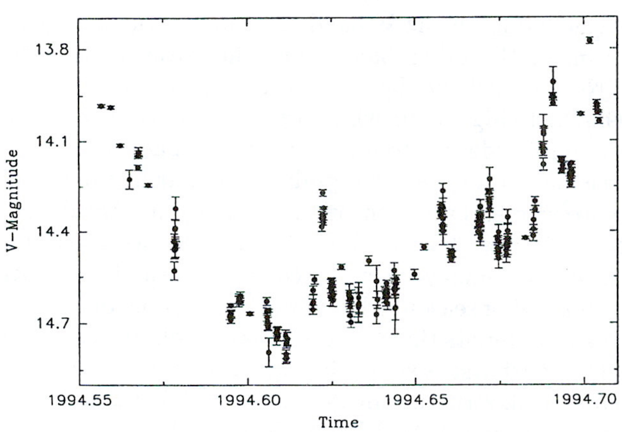

Fig. 6. The very fast outburst observed in late 1994

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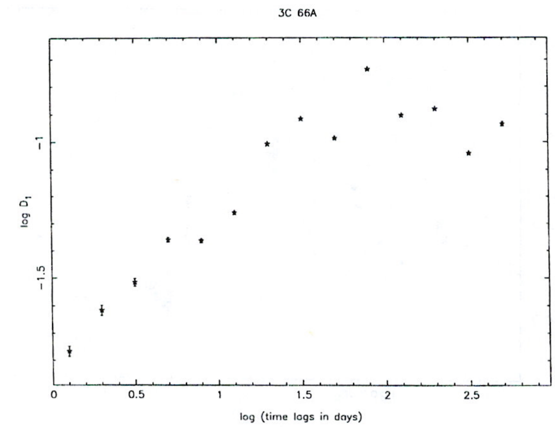

Fig. 7. The structure function results, showing the similarity of the light curves observed during the two observing seasons

In radio bands 3C 66A was very stable (Fig. 9), compared to the optical and infrared behaviour. The temporal coverage is not as good as in the optical, but anyway no indication of flaring activity can be observed. There is a small trend indicating that the flux has been slowly increasing during the observing period.

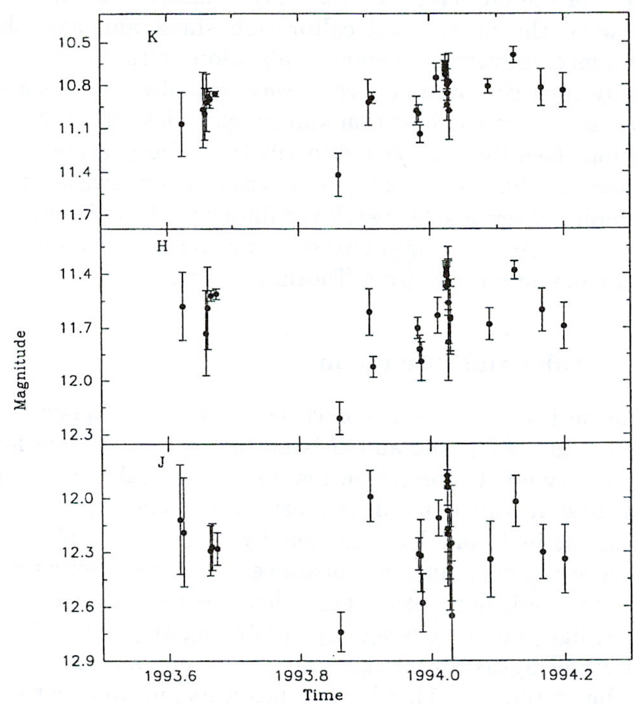

Fig. 8. The infrared light curves of 3C 66A

Several times during this project we have monitored 3C 66A for several hours during a night, in order to search for microvariability. An example of such microvariability is shown Fig. 10. We observed a 0.2 magnitude decline in the brightness in 6 hours. This is the clearest detection of

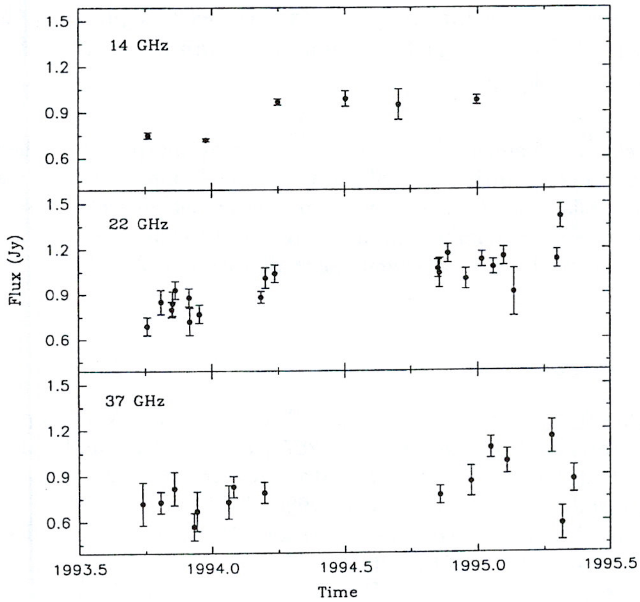

Fig. 9. The radio light curves of 3C 66A

microvariability in our monitoring, but not the only one. On the other hand we do not see microvariability during *all* our nightly monitorings. Previously there have been several attempts to search for microvariability in this object, with mixed results. Some observers have not seen any clear evidence of it (e.g. Miller & McGimsey 1978; Takalo et al. 1992a; Xie et al. 1992), while others have a clear detection of microvariability (Carini & Miller 1991; de Diego et al. 1996). This clearly shows that the microvariability in 3C 66A (and perhaps in all blazars) is a randomly occuring event (see Gonzáles-Pérez & Kidger 1996). Possible causes for the microvariability include flares on the accretion disk (Wallinger et al. 1992), instabilities in the inner accretion disk (Wiita et al. 1992) and shocks entering turbulent regions in the jet (Marscher et al. 1992). Crude analysis has shown that brightness and occurrence of microvariability may not be related. This indicates that the mechanisms for different time scale variations are not connected. This could mean that the flares and outbursts are caused by shocks in the jet (e.g. Marscher & Gear 1985) and the microvariability (perhaps) by instabilities in the accretion disk.

During the observations there are several nights with simultaneous or quasisimultaneous observations in all optical bands ($UBVRI$) and in a couple of nights also with the infrared bands (JHK). Most of the simultaneous optical observations were taken with the photopolarimeter at the Crimean observatory. We have used these observations to calculate a spectrum for 3C 66A, and have modelled this with a power-law ($f_\nu = k\nu^{-\alpha}$). The average spectral index α is 1.6, using only the optical bands. The calculation of the spectral index by using both optical and infrared observations (from V to K) gives an average index of $\alpha = 1.0$. This spectral index is consistent with the previous measurements by Takalo et al. (1992a) and Massaro et al. (1995). Our measurements indicate that there is a break in the spectrum of this object between in infrared and optical bands. This result agrees very well with the one by Worrall et al. (1984), who observed a curvature in the spectrum. In Fig. 11. we show examples of the spectra, taken at different flux levels. There are no large variations in the spectra during these observations. We do not find any correlation between the optical spectral index and the brightness in the V-band. This means that all the optical and infrared emission produced in 3C 66A have the same origin, relativistic electrons moving in the jet (e.g. Begelman et al. 1984; Brown et al. 1989). The observed variability would be caused by enhanced electron number density, maybe due to shocks in the jet. These shocks can be produced by increased (clumpy) accretion or magnetic instabilities in the jet (e.g. Wiita et al. 1992).

Our multifrequency monitoring data on 3C 66A can also be used to study another longstanding question. Although the 'formal' definition of a BL Lac object includes strong variability at all observing frequencies, it has become clear that a large fraction, perhaps the majority, of BL Lac objects are not very variable in the radio regime (see Valtaoja 1994 for a recent review). 3C 66A belongs to this class of BL Lac objects, exhibiting strong optical-infrared variability but hardly any radio variations. This may be compared to the behavior of our main project target OJ 287, which is very variable both in optical and radio (Takalo et al. 1994a).

For both 3C 66A and OJ 287 the observed total amplitude of variations Δf_ν depends on the observing frequency approximately as ν^{-1} in the optical-infrared regime, indicating that the same variability mechanism is operating in both sources. In the case of OJ 287 the amplitude of variations continues to grow all the way to the radio regime, and the variations appear to be simultaneous at least part of the time. Since the radio variations in OJ 287 are known to be produced in shocks, these optical variations must also be synchrotron radiation from the same shocks (e.g. Tornikoski et al. 1994). For 3C 66A, however, the radio variations are small and do not appear to be correlated with optical-infrared variations. Thus, some mechanism which prohibits the optical-infrared variations from reaching down to the radio regime must be operating in 3C 66A and, presumably, the other BL Lacs without strong radio variations.

5. Conclusions

We have presented the best ever observed light curves of BL Lac object 3C 66A. These light curves show almost continuous variability. This is the first time that such frequent variability has been observed in this object. Such a

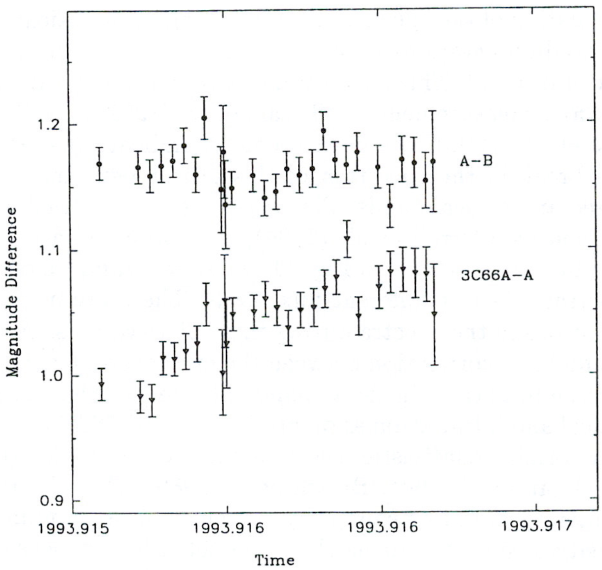

Fig. 10. Example of the observed microvariability in 3C 66A

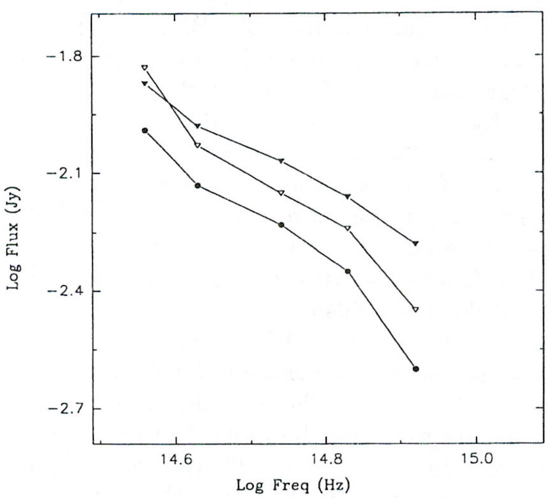

Fig. 11. Example of the observed spectra of 3C66A

behaviour will stress the current blazar models to their limits, when trying to explain these observations with them. Furher analysis of this data (in progress) will address at least the following questions raised by the light curves:
1. What is the cause(s) of the continuous variability?
2. Are there one or more components in play? Like the jet with shocks and/or the accretion disk with flares on it?
3. Why is the radio behaviour so different from the optical and infrared?

We have also clearly shown that previous monitoring observations have provided an incomplete picture of the blazar variability characteristics. In the future only large, multifrequency international campaigns can produce the needed observations for further understanding of these fascinating objects.

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