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Intensive monitoring of OJ 287*,**,***,†

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Abstract. We present intensive optical, infrared, and radio monitoring observations of the BL Lac object OJ 287, taken between the years 1993-1998. Two large optical outbursts were detected at the predicted times in November 1994 and December 1995. The detection of these outbursts supports the binary black hole model for OJ 287. Optical and radio polarisation observations show large variability in the degree of polarisation and position angle, very similar to those observed during the 1983/84 outburst in OJ 287. The polarisation position angles show very similar behaviour during these observations, indicating that, at least, the magnetic field orientations in radio and optical bands are related in OJ 287. Optical and infrared light curves show continuous variability in time scales ranging from tens of minutes to years. In the radio bands we have observed some of the lowest ever measured flux levels. During the first optical outburst in November 1994 the observed radio flux was very low, but during the second optical outburst radio bands also showed high flux levels. This is a puzzling observation, which can hopefully be used for discriminating between different outburst models. On top of the large outbursts OJ 287 has displayed flaring activity in time scales from days to weeks and shorter time scale flickering.

Key words: BL Lac objects — OJ 287 — photometry

1. Introduction

During the past few years studies of long term optical light curves of blazars have indicated that several of them show periodic variations on time scales of few years (e.g. OJ 287, Sillanpää et al. 1988; Kidger et al. 1992; BL Lac, Fan et al. 1998a; ON 231, Liu et al. 1995; Tosti et al. 1998). These periodicities have been explained by a variety of models; e.g. binary black hole (Sillanpää et al. 1988; Valtonen & Lehto 1997), precessing jet (Katz 1997) and rotating helical jet (Villata et al. 1998; Villata & Raiteri 1999). Occasionally, indications of recurring time scales from a few days to weeks and months have been reported (e.g. OJ 287 9.3 days, Sillanpää 1991; 3C 66A, 65 days, Lainela et al. 1999; S5 0716+714 from one to seven days, Wagner et al. 1996). The reasons for these shorter time scale variations are still unclear (e.g. Wagner & Witzel 1995). Confirmation and understanding of all these preferred timescales will provide new tools in revealing the mystery of BL Lac objects.

Blazar OJ 287 is one of the best observed extragalactic objects. It has been observed for over 100 years, providing us a very good historical light curve (see Takalo 1994 for a review of the earlier observations). Based on the historical light curve Sillanpää et al. (1988) concluded that OJ 287 shows large optical outbursts with a period of 11.6 years (see also Kidger et al. 1992). They explained these periodic outbursts with a binary black hole model, in which the brightenings are due to enhanced inflow from the larger accretion disk into the primary black hole, caused by strong perturbations every time the secondary black hole is in proximity of the pericentre. Sillanpää et al. (1988) predicted that the next outburst would occur during the fall 1994. In order to verify this outburst the OJ-94 Project was created in 1993.

In the next section we give first a short description of the OJ-94 project. Section 3 will describe briefly the observations and data reductions, followed by the results in Sect. 4. Conclusions will be given in Sect. 5.

2. OJ-94 project

The OJ-94 project was set up at a meeting in Seili, Finland, July 1993. This meeting was attended by eight astronomers, who have later formed the key members of the project (see Takalo 1996). The plan was to apply for the International ITP-time on the Canary Island Telescopes in order to confirm the predicted optical outburst in blazar OJ 287 and to collect extensive monitoring observations. It was also decided then that in addition to OJ 287 we will include 3C 66A, AO 0235+164 and S5 0716+714 as objects to be observed. The main goal in this was to use the observations of these objects as control observations for OJ 287, in order to study and understand various instrumental effects. All these objects are BL Lac objects, with similar characteristics as OJ 287. Especially in 3C 66A we had not seen any short time scale (hours) variability in the infrared monitoring at the Carlos Sanchez Telescope (Takalo et al. 1992) and nor had it shown any large variability in optical bands (see Takalo et al. 1996). This strategy for the control objects, failed partly because all these objects showed large variability during the project observations (e.g. Takalo et al. 1996, 1998, 1999).

The first observations in the OJ-94 Project were taken during autumn 1993. We also received the ITP-time at the Canary Island Telescopes for the project for half a year, during winter 1993/94. During the ITP-time the project receives 5% of the observing time on these telescopes. Since we were interested in detailed long term light curves of these objects we asked colleagues around the world, to join us in monitoring these objects. We were very succesful in this. Today there are over 60 astronomers from 11 different countries in the project. During these last six years we have collected over 10000 data points on OJ 287, and about 7000 on 3C 66A. These data sets constitute the best ever observed optical light curves on any extragalactic objects. Besides optical observations we have also infrared and radio monitoring data, and some UV, X-ray, and gamma-ray data on OJ 287.

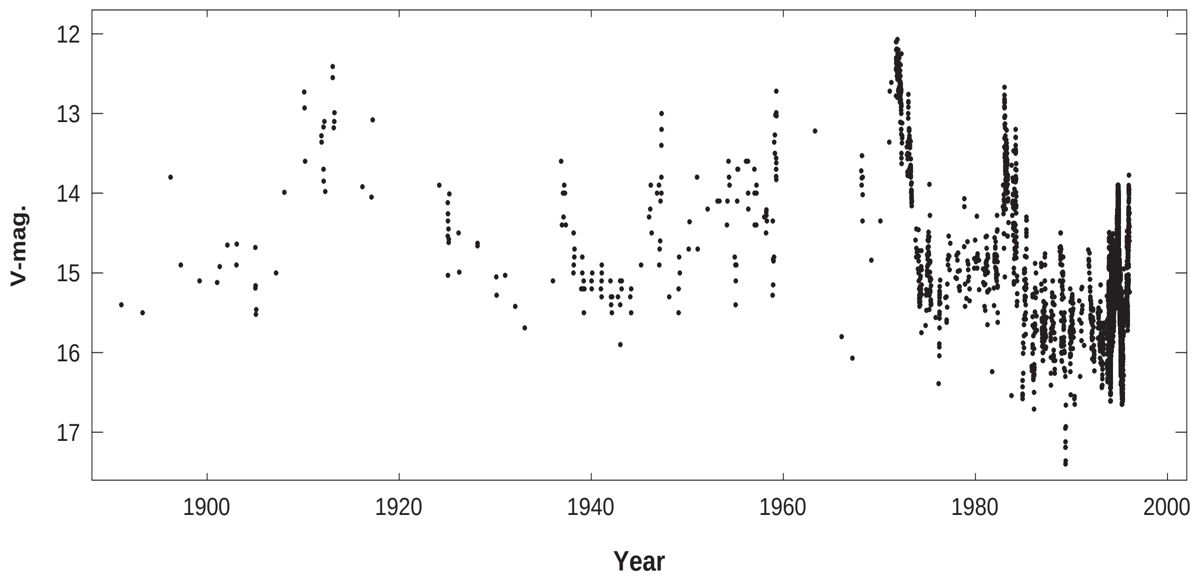

Fig. 1. The historical light curve of OJ 287 with the new data, showing the large optical outbursts with the 11.86 year period

During the project we have held yearly project meetings, in which the project observations and results have been discussed. After the meeting in Seili, meetings have been held at Orilampi, Finland (1994), Oxford, UK (1995), Girona, Spain (1996), Perugia, Italy (1997), Turku, Finland (1998), and Torino, Italy (1999). Presentations given in some of these meetings have been published in a series of books (Kidger & Takalo 1994; Takalo 1996; Tosti & Takalo 1998; Raiteri et al. 1999). These meetings have been very productive and informative in discussing the current status of the OJ-94 project and blazar monitoring campaigns as a whole. The OJ-94 Project is still in operation and will continue to the next expected outburst of OJ 287 in 2006/07; furthermore the monitoring has been extended to some other bright blazars. This project has strongly increased the collaborations between different monitoring groups. We invite other observing groups to collaborate in this project.

3. Observations

Observations presented here were collected during the OJ-94 project between autumn 1993 and spring 1998. The observatories and instruments used are listed in Table 1. Some of these instruments are automatic telescopes, like the one in Perugia (Fiorucci & Tosti 1996b) and RoboScope (Honeycutt & Turner 1992). Most of the optical observations were taken using CCD-cameras. With these cameras we performed differential photometry, comparing the brightness of OJ 287 to the stars in the same image. The calibration stars used are stars 10, 11, and 4 (Smith et al. 1985). During this program we have recalibrated the stars (e.g. Fiorucci & Tosti 1996a). The new calibrations agree quite well with the old ones. All the observers were responsible for the reduction of their own observations. The CCD observations were reduced using different reduction programs, like IRAF and MIDAS and some locally developed software (Fiorucci & Tosti 1996a; Honeycutt 1992; Villata et al. 1997; Lanteri 1999). In all cases the standard bias and flatfield corrections were performed. We have also received a large number of visual brightness estimates from the Astronomer Organization from UK. These estimates can be used for settling the brightness level of OJ 287 on those nights, when we do not have other observations of it.

All the optical polarisation observations were made using similar $UBVRI$ photopolarimeter both at Crimea and at the NOT. The instrument is a double image chopping photopolarimeter developed by Piirola (1973, 1975, 1988). With this instrument one obtains strictly simultaneous polarimetric and photometric measurements in the five ($UBVRI$) bands (see Huovelin & Piirola 1990; Piirola 1988). The light is split into the five bands using four dichroic filters, which reflect the desired spectral interval light into a photomultiplier and transmit the other wavelenghts. The effective bands produced by the dichroic mirrors are close to the standard Johnson system. Polarisation and photometric calibration stars were observed every night. Details of the instrument and observing procedures can be found from Efimov & Shakhovskoy (1998), Piirola (1988) and Takalo (1991). The data reductions were made using programs developed specifically for this instrument (Piirola 1973, 1975).

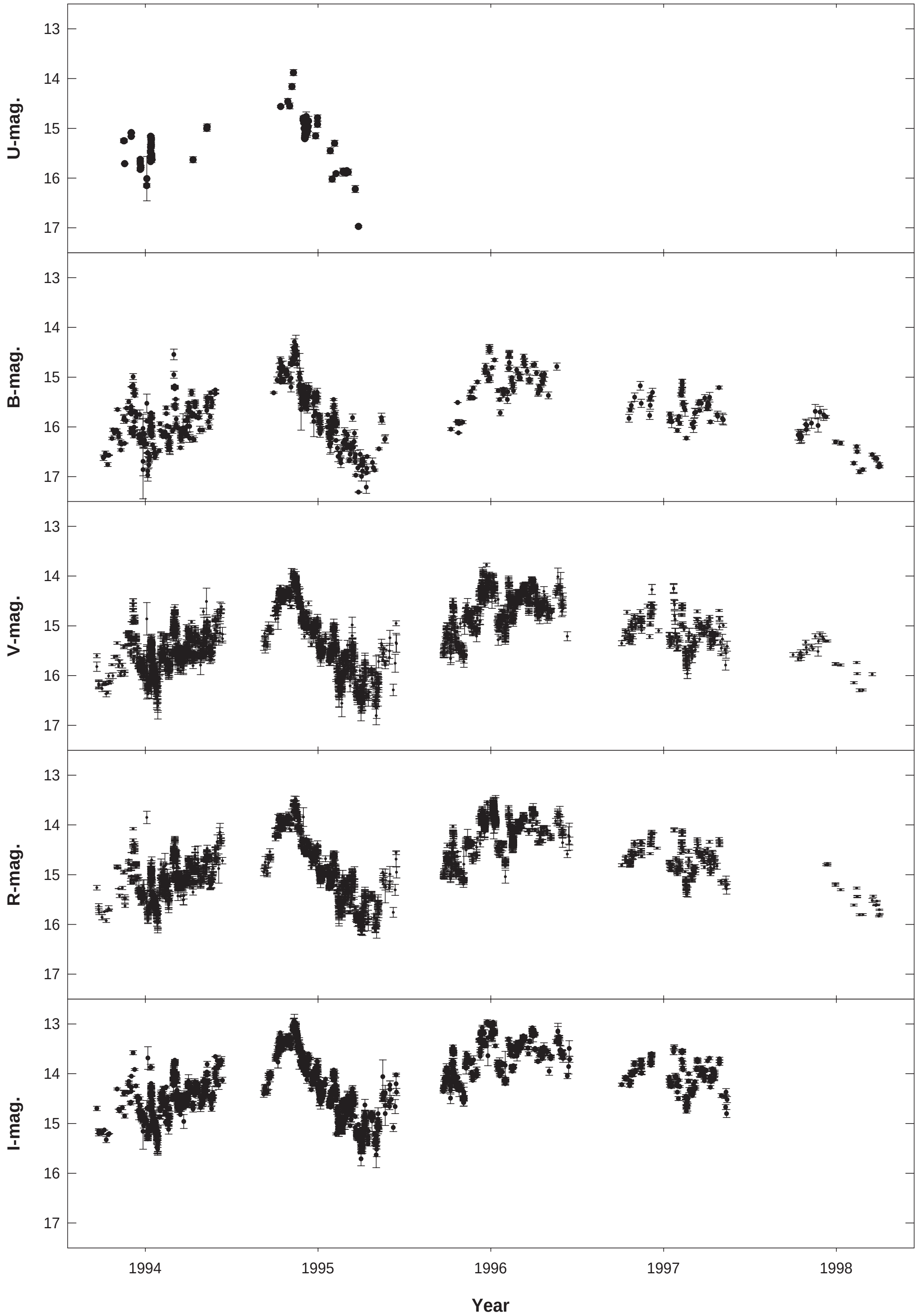

Fig. 2. The optical light curves of OJ 287 observed during the OJ-94 project

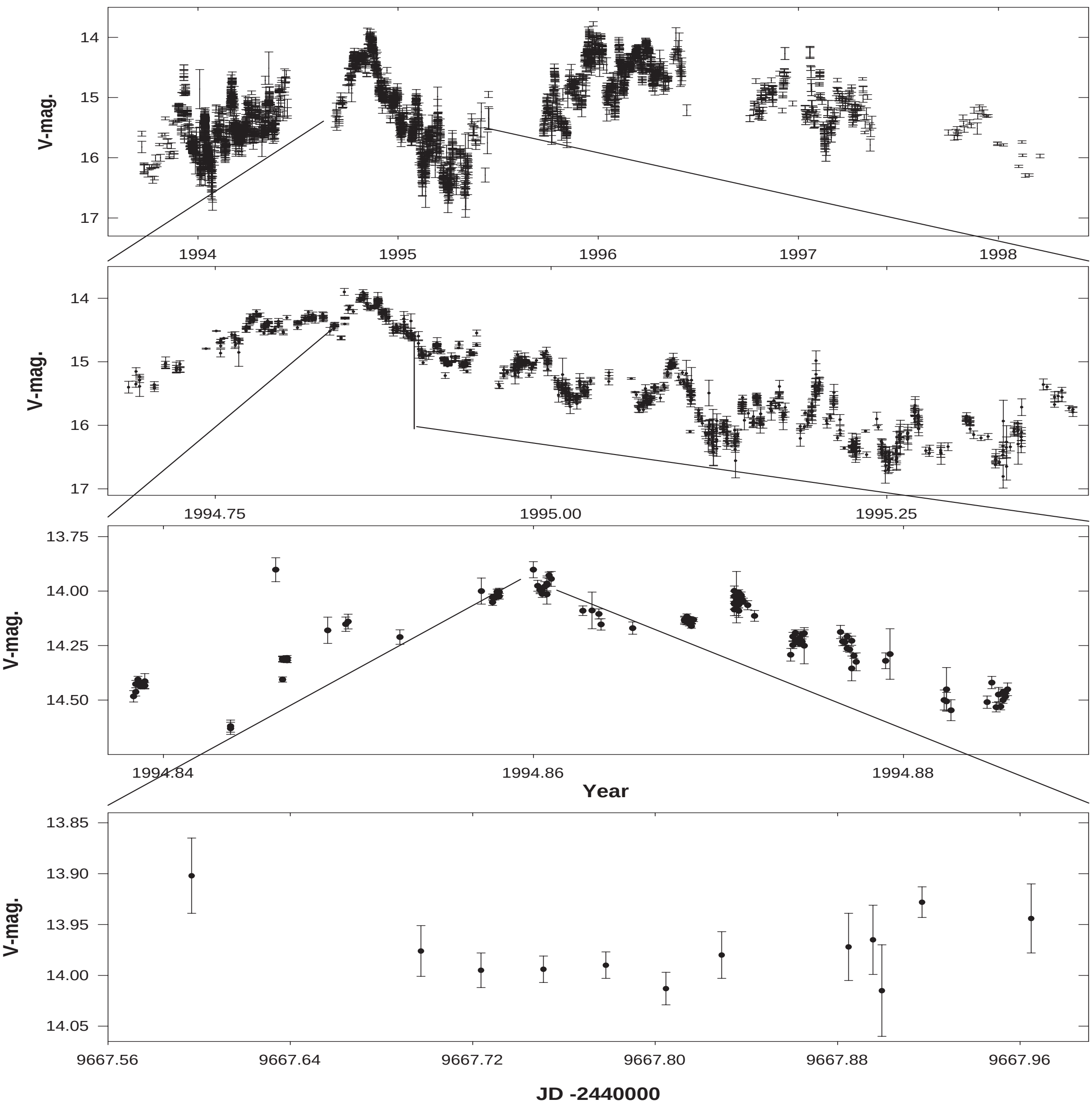

Fig. 3. Example of the observed flaring activity in different timescales

The infrared data were collected mostly at the 1.5 m Carlos Sanchez telescope on Tenerife, using a single channel CVF-photometer, with an InSb detector. The CVF permits a sequence of filters to be defined, which allows one to observe nearly simultaneously in all three (JHK) colour bands. For detailed description of the instrumentation, calibrations and data reduction see Takalo et al. (1992) and Kidger et al. (1995). Some infrared data were also obtained using UKIRT on Hawaii.

The radio data are nightly averages collected within radio monitoring programs at Michigan, Metsähovi, and SEST. The University of Michigan monitoring program started already during 1965. Currenly they observe at three frequencies, 4.8, 8 and 14.8 GHz, obtaining simultaneously both flux and polarisation measurements. Detailed description of the instrumentation and reduction procedures can be found from Aller et al. (1985). The Metsähovi data at 22 and 37 GHz are part of the long term monitoring program started in 1980. Both receivers have two feed horns with orthogonal polarization giving a mean value of the flux even if the source is polarized. The observations are standard ON-ON type and calibrated against DR 21. The data (only flux measurements) are nightly means. The observing and data reduction procedure is described in more detail in Teräsranta et al. (1998). The observations at the SEST telescope are

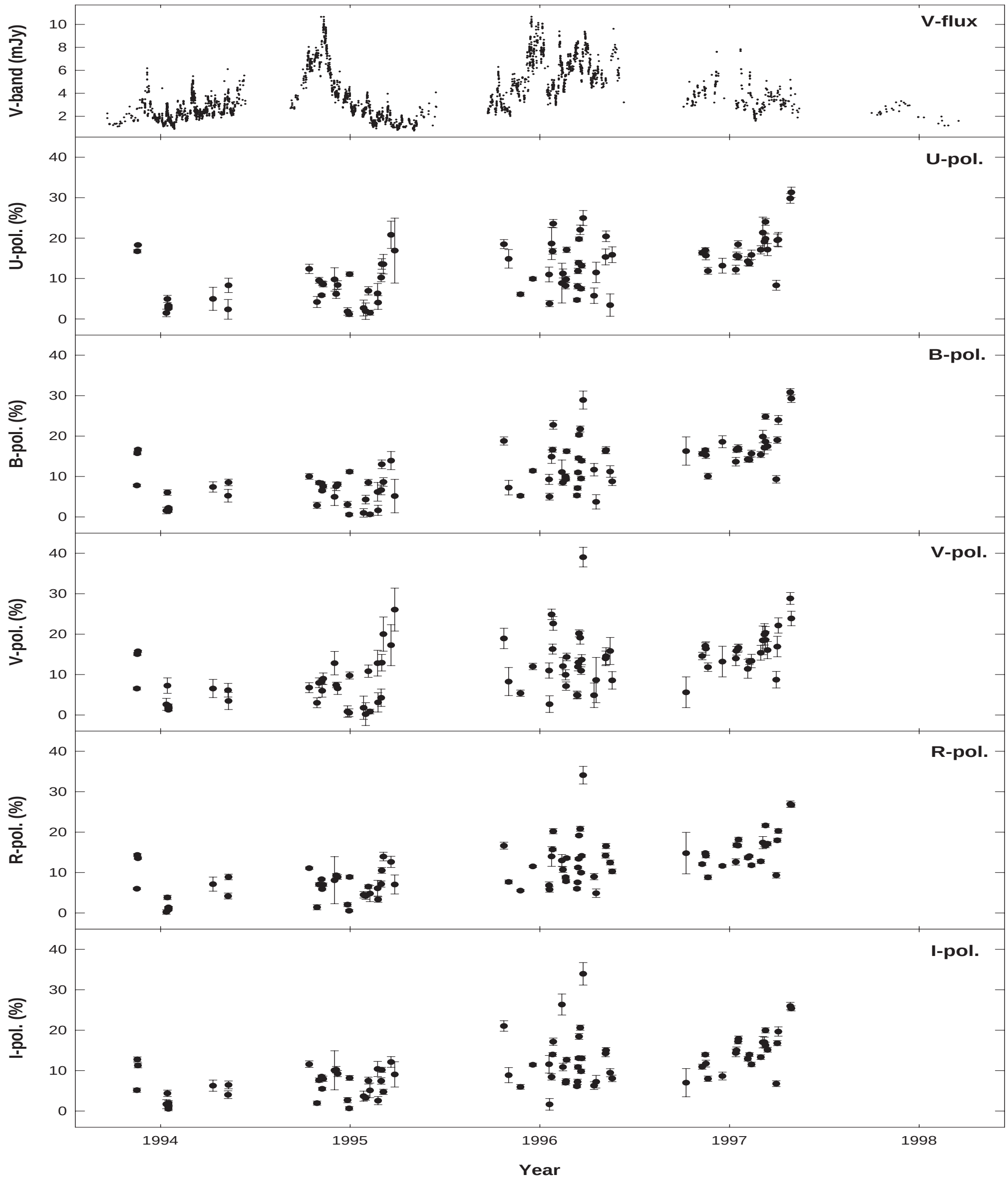

Fig. 4. The polarisation level in different optical bands observed in OJ 287 during the OJ-94 project

made at 90 and 230 GHz. Details of the instrumentation, observing strategies and data reduction can be found at Tornikoski et al. (1996).

Small amount of UV data was obtained with the IUE-satellite during the first outburst. We observed OJ 287 with IUE for ten days in November 1994, using both cameras. The spectra were extracted using IUESIPS routine and with a locally developed MIDAS-based version of the GEX procedure (Urry & Reichert 1988). The flux distributions have been calibrated with the curves provided by Bohlin et al. (1990, SWP) and Casatella et al. (1992, LWP). The extraction of the spectra shows that there is a small systematic difference between the results from different routines, but they are compatible within the errors. We will use only the GEX extracted spectra in the following analysis. These UV data were dereddened for the Galactic interstellar extinction, using $A_v = 0.18$ (Stark et al. 1992). The dereddened spectra were coadded in order to increase the signal-to-noise ratio, searching for spectral features, but no emission features were found.

The project archive contains also the data published by Arimoto et al. (1997), Fan et al. (1998b), Jia et al. (1998) and Stevens et al. (1994). These data will be also used in the following sections of this article.

All the reduced observations were sent to the project archive, which is maintained at Tuorla Observatory.

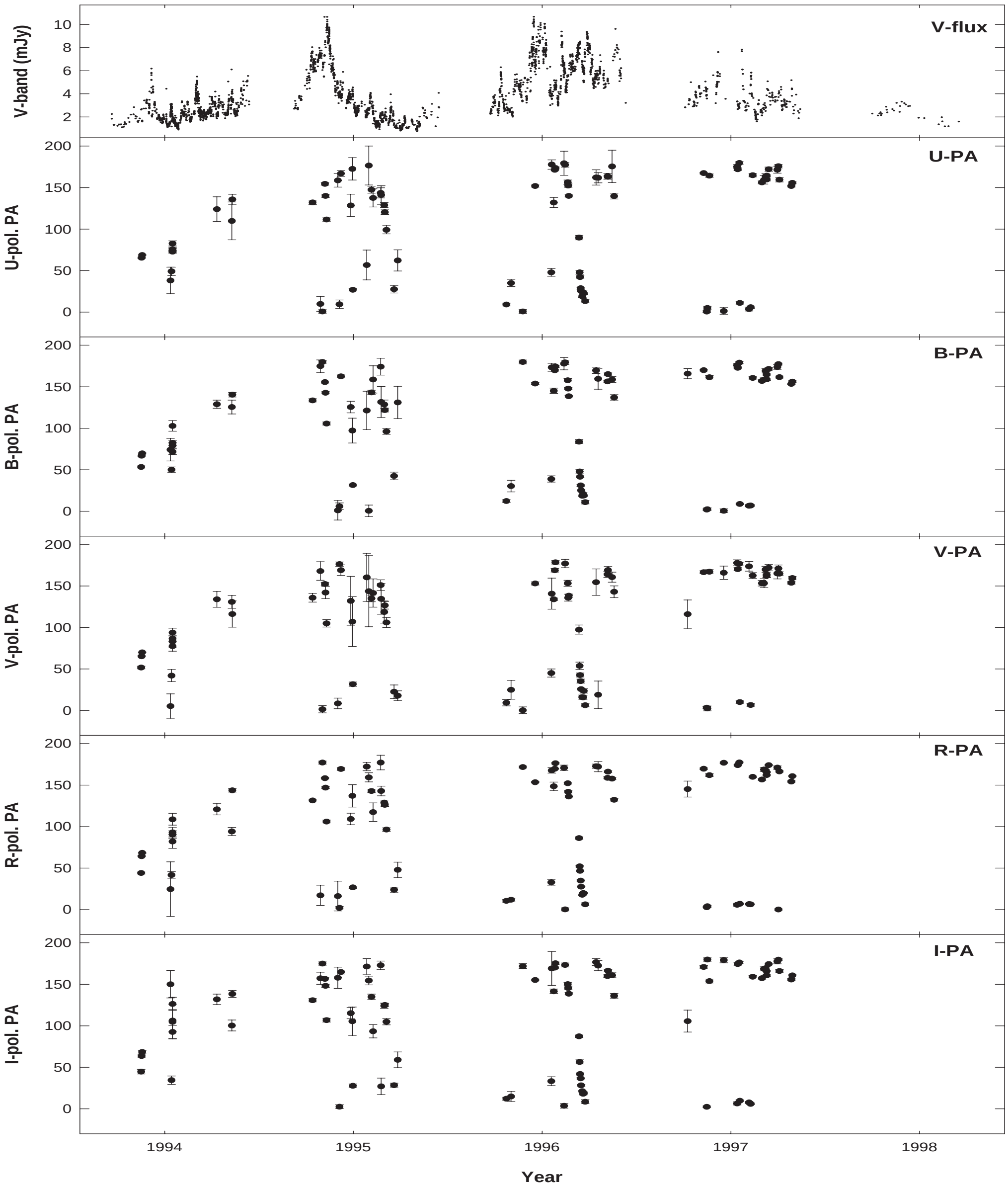

Fig. 5. The optical polarisation position angle for OJ 287 observed during the OJ-94 project

Optical data were sent to the archive in two different formats, either in OJ 287 magnitudes or as differences between OJ 287 and the calibration stars. The archivists (T. Pursimo & H. Lehto) then transformed the optical data into one format; magnitudes and errors. The archive contains now about 10000 optical, 200 infrared, and 2000 radio observations on OJ 287. No "screening" of the data has been performed, ALL the data sent to the archive has been used here. This is by far the largest data collection on any extragalactic object. The archive can be accessed from the project home page (http://www.astro.utu.fi/oj94). A description of the archive can be found from Pursimo et al. (1998). The photometric data available in the archive and used here are mostly hourly averages in the optical and infrared bands. These averages are calculated for a single telescope, i.e. if a telescope observed OJ 287 within an hour we calculate the average, but if several telescopes observed OJ 287 during a particular hour, we calculate the average datapoint for each telescope. In the optical bands some data with better time resolution is also available in the archive. The radio and optical polarisation data are nightly averages.

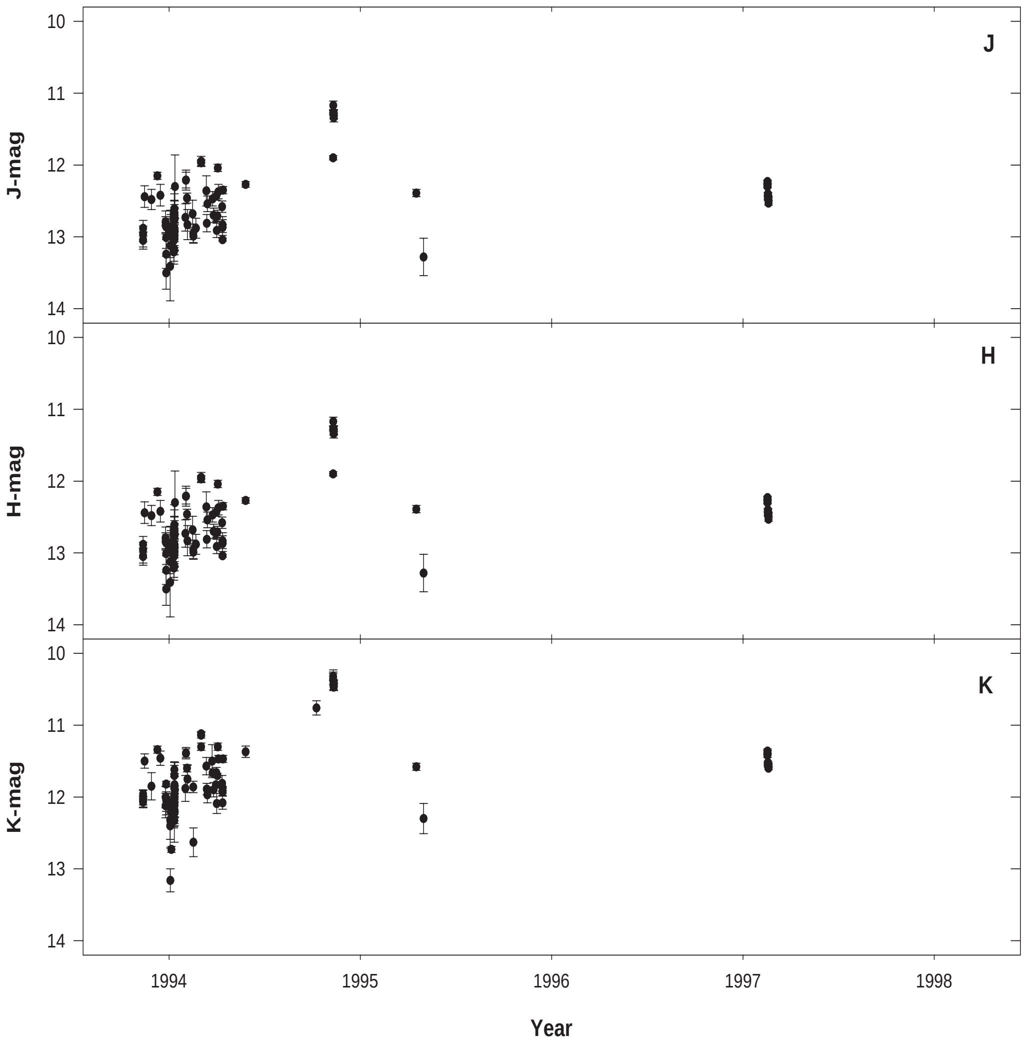

Fig. 6. The infrared observations of OJ 287

4. Results

The main results from this monitoring are shown in Figs. 1-12, which show the observed light curves. We have transformed the optical and infrared magnitudes to flux units shown in some of these figures, using the calibration given by Mead et al. (1988). Figure 1 displays the historical light curve with the new data included. As can be seen from this figure (and Fig. 2) the outbursts were detected close to the predicted times (see Sillanpää et al. 1996a,b for details). Using these new outbursts together with the historical data we can now find an exact period for the outbursts of 11.86 years (see also Sillanpää 1999; Valtaoja et al. 2000). In determining this period we have taken into account the fact that there are always two outbursts, separated by 1.1 years. These optical outbursts have been explained by the "old" binary black hole model (Sillanpää et al. 1988), with a "new" version of this model (Lehto & Valtonen 1996; Sundelius et al. 1997; Valtonen & Lehto 1997), with a precessing jet model (Katz 1997), and with a binary curved-jet model (Villata et al. 1998). All these models can explain (at least) part of the observations, but there are problems with the combined data, especially with the radio observations. The comparison between optical and radio light curves (e.g. Figs. 2, 9 and 12) observed during the latest outbursts show clearly that during the first optical flare the radio bands showed minimum flux (see Valtaoja et al. 2000).

4.1. Optical data

Figure 2 shows the observed optical light curves, displaying clearly the outbursts in November 1994 and end of December 1995 (Arimoto et al. 1997; Fan et al. 1998b; Kidger et al. 1995; Sillanpää et al. 1996a,b).

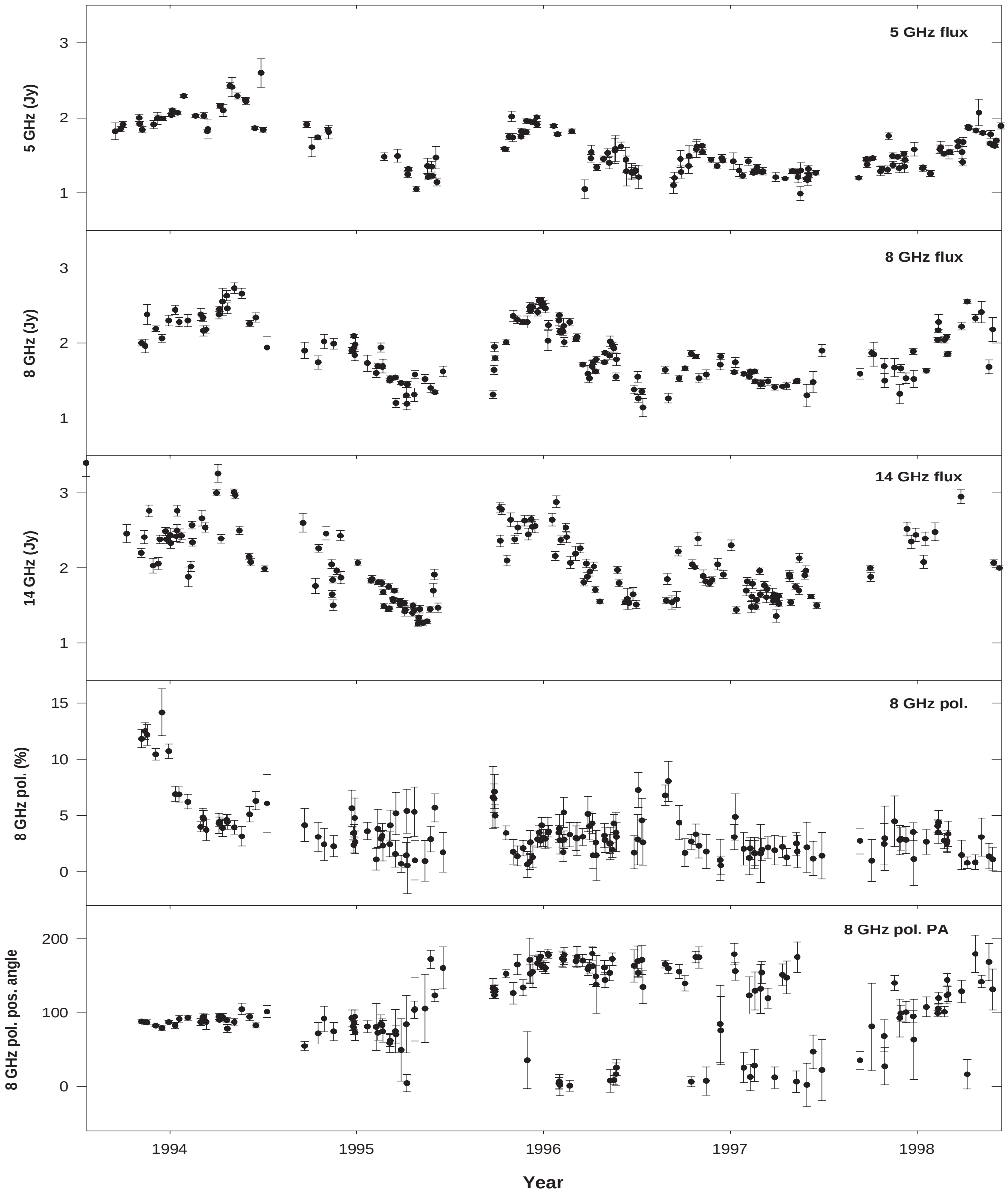

Fig. 7. The radio light curves and polarisation observed in OJ 287 at Michigan

The separation between these two outbursts is 1.1 years (Sillanpää et al. 1996b; Valtonen & Lehto 1997), which is very similar to the one observed in 1972/73 and 1983/84 (Sillanpää et al. 1988). As can be seen from the figures the shape of these two outbursts is very different, the first one being fairly sharp and the second one much broader. In the first case we can also define the time of the peak quite accurately ($V = 13.92$ on November 10th 1994). But during the second outburst the timing of the peak is much more difficult because of the broadness of the outburst and the small gaps in the data. Since late 1996 the brightness of OJ 287 has declined quite rapidly, and the brightness is now back at the preoutburst level (see also Pietilä et al. 1999).

It is also apparent from the data that OJ 287 is varying all the time, we cannot define any quiescent level from these data. The light curves can be characterized by flaring activity with time scales from days to about a week and amplitudes up to one magnitude (see Lehto 1994). An example of this kind of behaviour is shown in Fig. 3, where we show the V-band light curve with increasing time resolution during the first outburst. The variability in different time scales can be clearly seen. On top of the flaring activity we see small amplitude flickering with a time scale from tens of minutes to hours

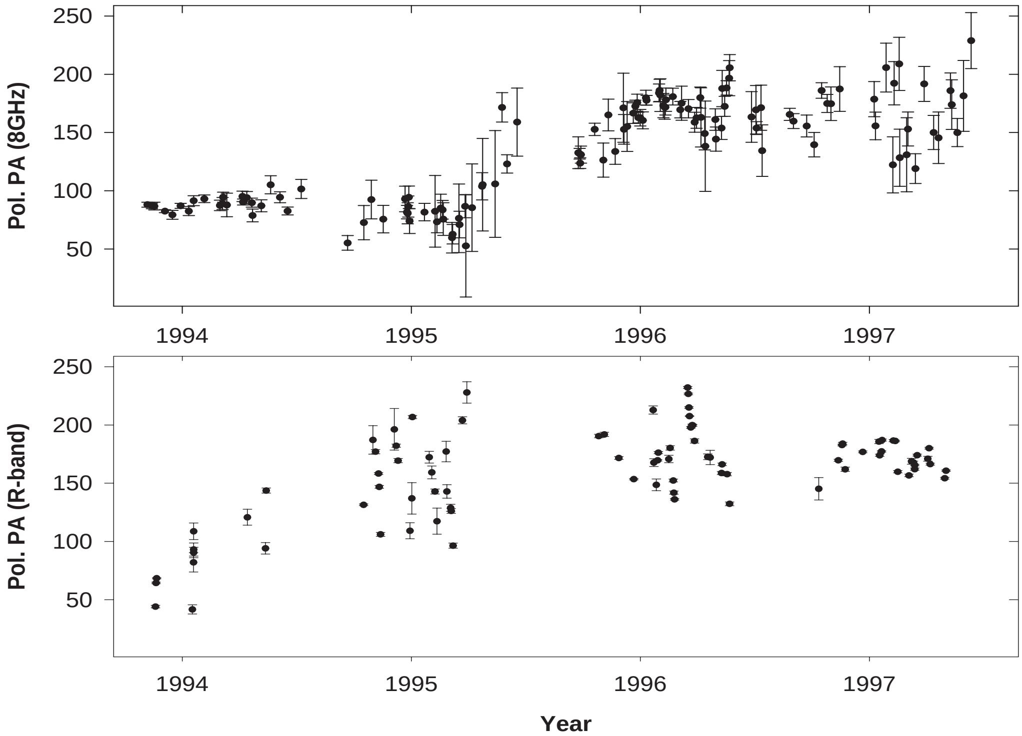

Fig. 8. Comparison of the polarisation position angle behaviour between R-band and radio observations. In this figure we have "corrected" for the 180 degree ambiguity of the polarisation position angle

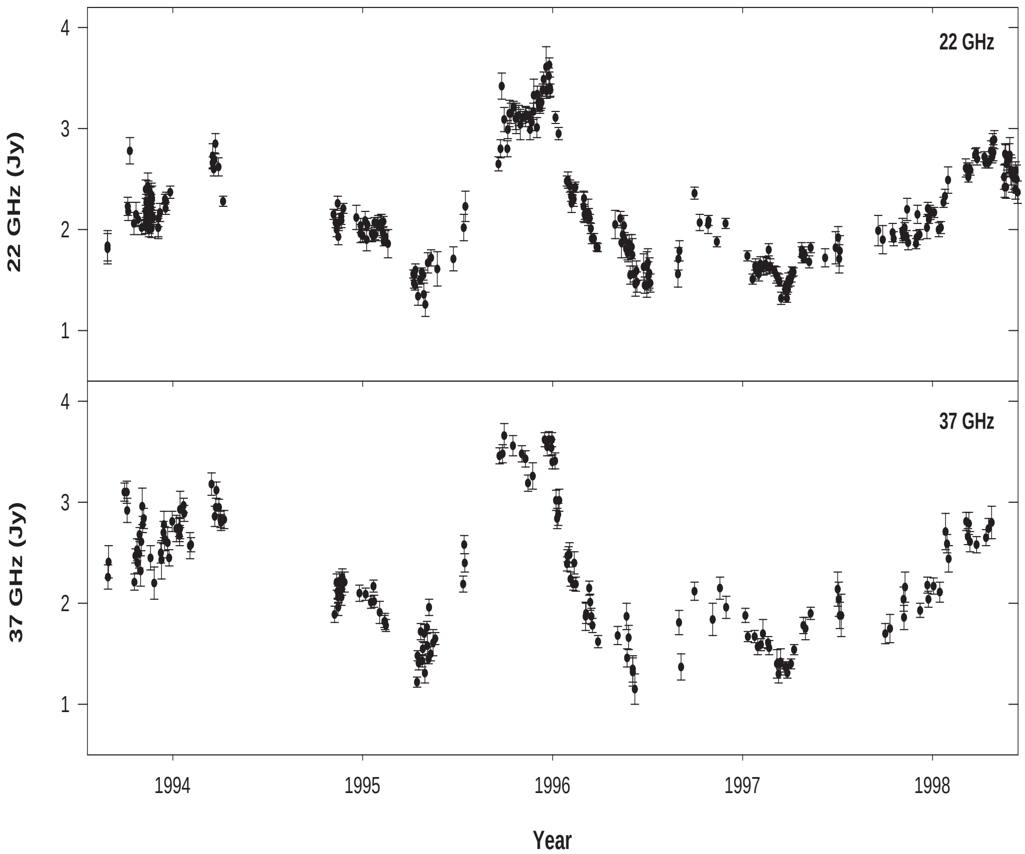

Fig. 9. The Metsähovi radio monitoring of OJ 287

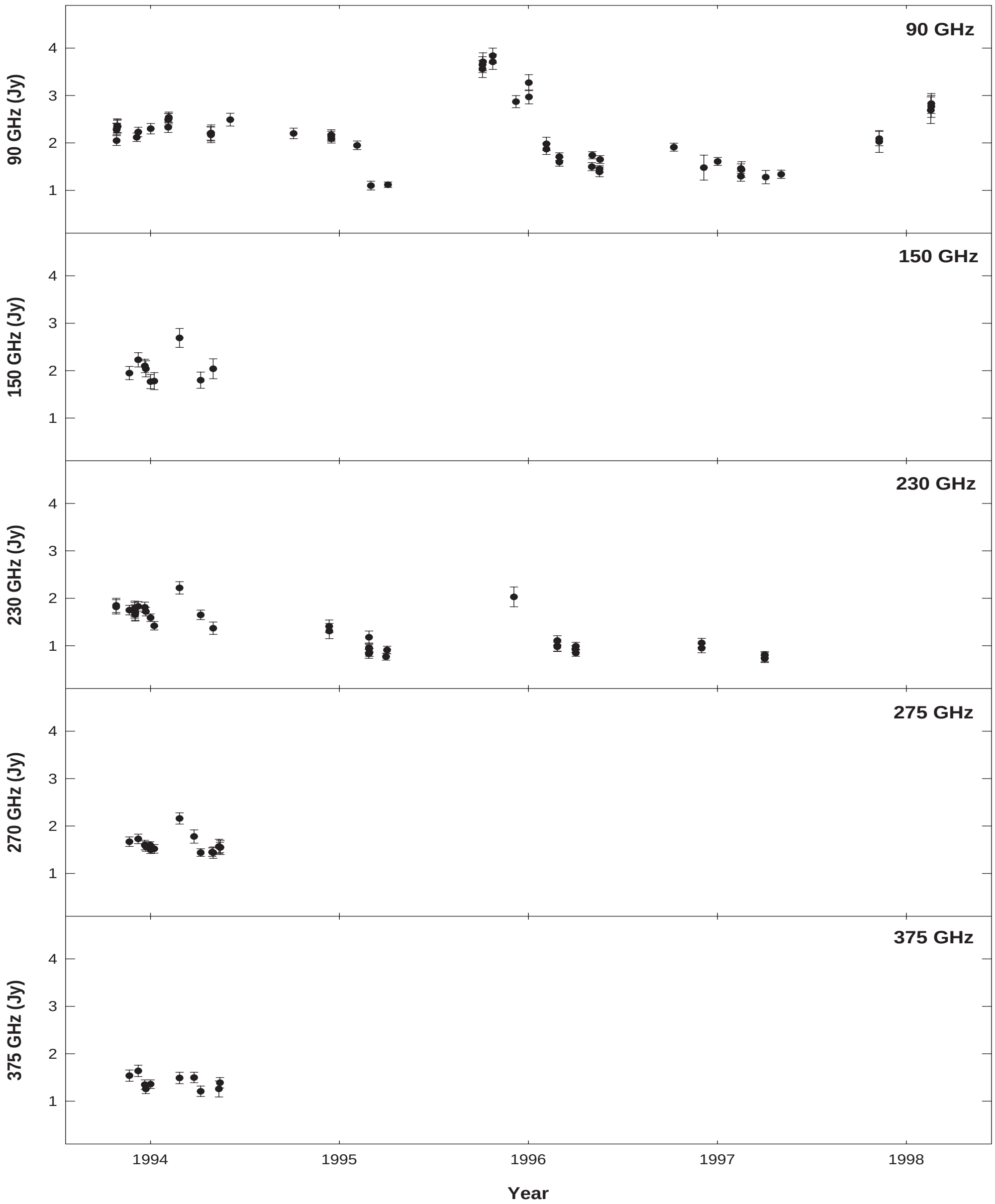

Fig. 10. The light curves from high frequency radio monitoring of OJ 287

(Dultzin-Hacyan et al. 1997; Jia et al. 1998). The behaviour is very similar in all optical bands (Hagen-Thorn et al. 1998; Lehto 1994; Sillanpää et al. 1996b). Most of these flares have very similar shape with a very fast increase in brightness and a slower declining phase. It is also evident that this flaring activity continues after the outbursts, but with smaller flare frequency and amplitude (see Fig. 2).

4.2. Optical polarisation

Linear optical polarisation light curves are shown in Figs. 4 and 5. The shown data are all nightly mean values. As can be seen from Fig. 4 the polarisation showed large random variability. The behaviour is seen to be very similar in all five bands. Noticeable is the fairly low polarisation level observed during the outbursts, especially the November 1994 outburst. Similar behaviour was observed also during the 1983/84 outburst (Takalo 1994 and references therein). The level of polarisation increased substantially (up to 25%) after the November outburst.

Also the polarisation position angle shows large variability. But it seems that the "average" position angle rotated from the typical value of 90 degrees (e.g. Takalo 1994) to 150 degrees around the time of the first optical outburst (Fig. 5). This is similar value than the one observed during the previous outburst in 1983/84 (Smith et al. 1987). Note that in Fig. 5 we show the polarisation data without "correcting" for the 180 degree ambiguity.

Table 1. Observatories and instruments used during the 1993-1998 monitoring. Pol = Photopolarimetric and Phot = Photometric observations with a photometer

Telescope	Size	Inst.	Filters
Nordic Optical Telescope	2.5 m	CCD	*BVRI*
		Pol.	*UBVRI*
Jacobus Kapteyn Telescope	1.0 m	CCD	*UBVRI*
Heidelberg	70 cm	CCD	*R*
Torino Observatory	1.05 m	CCD	*BVR*
Tuorla Observatory	1.03 m	CCD	*V*
Calar Alto	1.2/2.2 m	CCD	*UBVRI*
Boltwood	17 cm	CCD	*VRI*
IAC-80	82 cm	CCD	*BVRI*
Capilla Peak Observatory	61 cm	CCD	*BVRI*
Cananea	2.2 m	CCD	*R*
Lowell Observatory	1.06 m	CCD	*BVRI*
Rome	50 cm	CCD	*BVRI*
Crimea Observatory	1.25 m	Pol.	*UBVRI*
San Pedro Martir	2.1/1.5 m	CCD	*BVRI*
RoboScope	41cm	CCD	*V*
Perugia Observatory	40 cm	CCD	*VRI*
Abastumani Observatory	70 cm	CCD	*VRI*
Carlos Sánchez Telescope	1.5 m	Phot	*JHK*
UKIRT	3.8 m	Phot	*JHK*
Michigan Radio Telescope	26 m	Cont.	4.8,8,14 GHz
Metsähovi Radio Telescope	14 m	Cont.	22, 37 GHz
SEST	15m	Cont.	90, 230 GHz

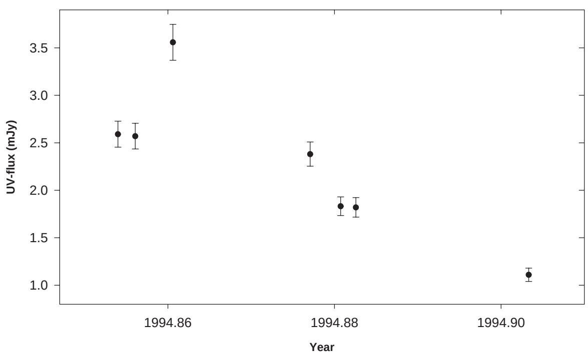

Fig. 11. The observed IUE light curve at 2500 Å

4.3. Infrared data

We have infrared data mostly from the first observing period 1993-1994. The light curves are shown in Fig. 6. As can be seen from the figure the behaviour is very similar, with the flaring activity, to the one seen in optical bands. Small flares with an amplitude up to one magnitude are seen in time scales of a few days. The behaviour seems to be more active than what was observed earlier, before the outburst (Takalo et al. 1992). Also the first (November 1994) outburst is clearly seen in the infrared bands (see Kidger et al. 1995).

4.4. Radio data

The radio data is shown in Figs. 7-10. The most noticeable feature in these light curves are the low flux levels observed during most of this time. Observations taken during 1993-94 are among the faintest ever observed for OJ 287 (for comparison see Aller et al. 1992, 1999; Takalo et al. 1990; Teräsranta et al. 1998; Tornikoski et al. 1996). This is a very different behaviour when compared to the previous outburst, seen in 1983/84, when also the radio flux was in a high level at the time of the optical outbursts (Takalo 1994; Valtaoja et al. 1999), but without any noticeable radio outburst. A radio outburst was observed simultaneously with the second optical outburst in December 1995. The peak of this outburst was at the time of the optical peak. But the radio outburst was much faster than the optical outburst, which lasted almost an year (compare Fig. 2 with Figs. 7, 9 and 12). After the outburst the radio flux returned very rapidly to the level seen before the outburst. The flux level also remained at low levels, until 1998, when the radio flux started to increase again. Note, however, that the optical flux was still decreasing at this time. Small amplitude variations in time scales from days to weeks are seen throughout the monitoring period.

4.5. Radio polarisation

The observed radio polarisation and position angles are shown in Fig. 7. We show only the data at 8 GHz, because both 4.8 and 14 GHz show very similar behaviour. The radio polarisation behaviour was very similar to that observed in the optical bands. The observed polarisations gave very low values, like the ones observed during the 1983/84 outburst (Aller et al. 1999; Takalo 1994). The polarisation level stayed also fairly stable at about 2% level. The highest polarisation values were observed about one year before the outburst, again resembling to what was seen in 1983/84.

The position angle shows almost constant values at PA = 90° at the begining of this monitoring. But, a few months after the first optical outburst, the position angle turned to PA = 170 degrees, where it remained thereafter. This behaviour is similar to the position angle seen in the optical polarisation, but with the difference that the optical position angle turned to this value before the radio one, this is shown in Fig. 8. This similarity suggests, that the radio and optical emitting regions (or at least their magnetic field orientations) are related. The position angle in radio bands showed also small amplitude short term variability. Similar behaviour was seen during the 1983/84 outburst (Aller et al. 1999; Takalo 1994). Taking into account the 180 degree ambiguity in the position angle values, it seems thatnoticeable rotation is present in the radio position angle during the radio brightening towards the

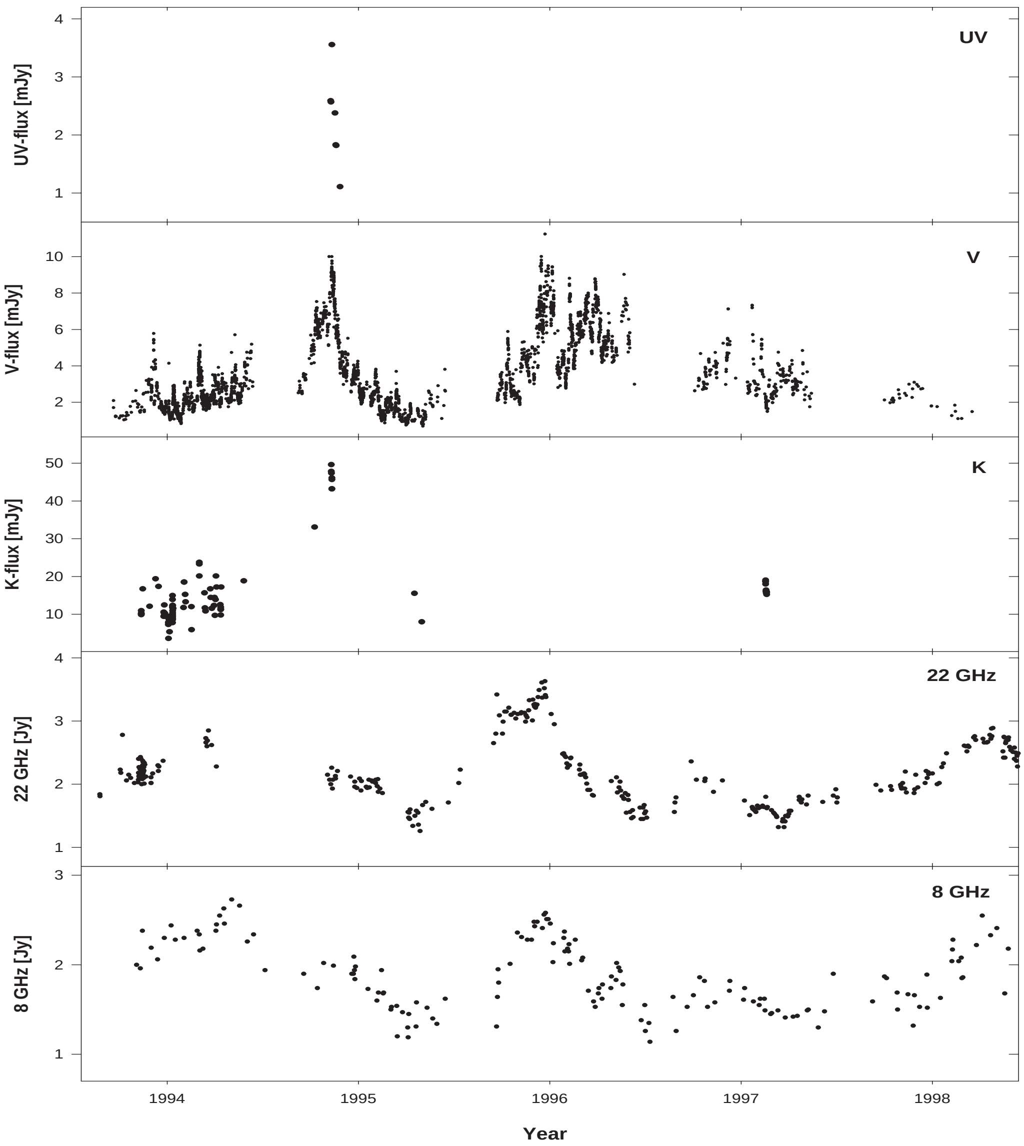

Fig. 12. Comparison of the behaviour of OJ 287 at different wavelengths. Note different scales in the y-axis

end of our observations. The level of the polarisation is low and stable at this time.

4.6. UV data

After the brightening of OJ 287 in late 1994, we observed OJ 287 with the IUE. The observed light curve at 2550 Å is shown in Fig. 11. As can be seen, a small outburst is visible. The UV flux was lower by a factor of two than the maximum UV flux recorded during the previous outburst in 1983 (see Pian et al. 1996; Takalo 1994). This UV flare lasted only about a week. The spectrum ($f \propto \nu^{-\alpha}$) was remarkably steep during these observations, with a slope of $\alpha = 1.8$ in the entire IUE range (Pian et al. 1996).

4.7. X-ray and γ-ray data

After detecting and reporting the brightening of OJ 287 during autumn 1994, ASCA observed OJ 287 on November 18-19 1994 (Idesawa et al. 1997). The flux density was 0.76 μJy at 1 keV, being rather low when compared to previous X-ray observations obtained even at low optical states (see Idesawa et al. 1997 and references therein). They observed also variability in time scales of a few hours with a typical amplitude of 20%. Previous X-ray observations have not shown these kind of short time scale variations (see Takalo 1994; Idesawa et al. 1997 and references therein).

OJ 287 was observed with the *Rossi* X-ray Timing Explorer (RXTE) since 2 November 1996 to the end

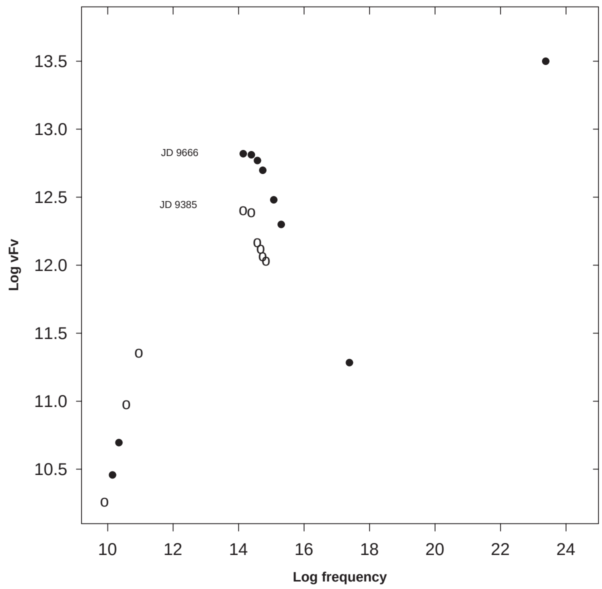

Fig. 13. Examples of the spectral energy distribution and its variability. The dates indicate the Julian date of the observations

of the campaign reported here. The observations were carried out about once per week, with two-month gaps during the summer when the object was too close to the sun. Aside from a 3.6-σ detection on 25 February 1997, OJ 287 was not detected by RXTE. The typical 2-σ noise level in the $2 - 10$ keV band was 8.4 10^{-13} erg cm^{-2} s^{-1}. If we consider this to be the upper limit to the non-detections, we can state that the X-ray flux in this band was at least 6 times fainter than during the Nov. 1994 outburst (5.1 10^{-12} erg cm^{-2} s^{-1}; Idesawa et al. 1997).

After the brightening of OJ 287 during autumn 1994, we received some ToO time for OJ 287 with the EGRET onboard the CGRO. EGRET observed OJ 287 for five days (November 10-15. 1994), getting a marginal detection at the 3.5 σ level of $F = 2.9\ 10^{-7}$photons/cm^2/s (see Shrader et al. 1996; Webb et al. 1996). This is a factor of three larger than the flux observed earlier, when OJ 287 was in a low optical state.

5. Conclusions

We have presented the best ever observed light curves of BL Lac object OJ 287. The predicted outbursts have been confirmed in the UV, optical and infrared bands, the second one also in radio frequencies. This can be seen from Fig. 12, where we display the observed light curves in selected wavelengths from UV to radio. The first outburst is clearly seen simulaneously in all other bands except in radio, which showed low flux levels. During the second optical outburst radio bands also showed increased flux values (unfortunately we have no infrared or UV data at this time), this could be a coincidence or could also indicate time delays between these frequencies (see Valtaoja et al. 2000 for a possible explanation). This intensive monitoring clearly suggests that (at least) in the optical bands OJ 287 is varying to the shortest time scales studied here.

In Fig. 13 we show examples of the observed spectral energy distribution (SED) during the observations. These spectra are collected from observations taken almost simultaneously, in any case within a day in radio to optical bands. The satellite observations in X-ray and gamma frequences cannot be considered truly simultaneous, since the observations lasted a few days, and we present only the averaged values. As can be seen there is very little variations in the radio part of the spectrum. But in the infrared and optical frequencies there are substantial variations in the flux levels and smaller ones in the spectral shape. JD 9666 refers to the time of the first optical outburst when we also had satellite observations on OJ 287, the other spectrum was observed before the outburst.

This project has produced a huge data base for studying the behaviour of blazars, but it seems that it has also raised a lot of new questions instead of giving definite answers to questions of blazar phenomenon (see e.g. Marscher 1998; Valtaoja 1998). Detailed analysis of these data is expected to give some indications of the emission regions and mechanisms in these objects. Especially intriguing is the question of the difference between the radio behaviour during the two optical outbursts, this fact may help us to discriminate between different models explaining the outbursts. But, it may well be that we have to wait until the next outburst at 2006/7 for a deeper understanding of OJ 287.

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