ASTRONOMY & ASTROPHYSICS
SUPPLEMENT SERIES

Astron. Astrophys. Suppl. Ser. **129**, 577-582 (1998)

Monitoring of AO 0235+164 during a faint state*

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Received June 11; accepted October 31, 1997

Abstract. We present the results of the optical and radio monitoring of the BL Lac object AO 0235+164 during a faint state. In both optical and radio bands the source has been observed at the faintest ever recorded levels, reaching $V = 19.80$ and $F_{22\mathrm{GHz}} = 0.34$ Jy. In the optical bands we still see variability with amplitudes up to 1.5 magnitudes on timescales from days to weeks. The radio variability is less dramatic, but in general follows the optical behaviour. A correlation between general trends in the optical and radio behaviour of AO 0235+164 may be recognized in the data from the present monitoring as well as in the historical light curves, suggesting a "base" mechanism responsible for the emission at both frequencies. A good candidate is a synchrotron process in the relativistic jet. Optical flares with no corresponding radio counterparts have been observed too. These events may be interpreted in terms of microlensing by a foreground galaxy.

Key words: Bl lac objects: general; gravitational lensing—AO 0235+164

1. Introduction

The BL Lac object AO 0235+164 is one of the most complex and interesting extragalactic sources. It has shown variability in all observed frequencies, from γ-rays (von Montigny et al. 1995) to radio bands (e.g. Teräsranta et al. 1992). The variability amplitude in the optical bands has spanned more than five magnitudes (Webb & Smith 1989). These variations are often seen as fast, very intensive flares (Webb & Smith 1989 and references therein). Schramm et al. (1994) observed a 1.60 mag brightening in 47.5 hours in February 1989. AO 0235+164 is characterized by a very steep optical spectrum, the observed range in the spectral index being $-2 \gtrsim \alpha \gtrsim -4$ (Smith et al. 1987). Polarization measurements have revealed a large and rapid variability (Impey et al. 1982; Smith et al. 1987) and values up to 44% have been detected (Impey et al. 1982). This source has been claimed to display simultaneous variations in optical and radio bands (e.g Rieke et al. 1976; Balonek & Dent 1980).

In reality, AO 0235+164 is a system consisting of several objects with three different redshift values. These are: the BL Lac itself, with $z = 0.94$, a pair of galaxies at $z = 0.524$, and a so far unknown system with $z = 0.851$ (see Nilsson et al. 1996 and Burbidge et al. 1996 for a detailed description of the system). Because of the intervening galaxies and the monochromatic variability, AO 0235+164 has been considered as one of the best candidates for BL Lac objects in which the variability is caused by microlensing (Stickel et al. 1988; Rabbette et al. 1996).

2. Observations and results

The observations presented here were obtained during the OJ-94 Project (Takalo 1996). We have been monitoring AO 0235+164 in the optical bands (mostly in the V, R and I bands) since fall 1993. The optical telescopes used for these observations are listed in Table 1; all of them were equipped with CCD cameras. Details on the observing and data reduction procedures can be found in Katajainen et al. (1997), Fiorucci & Tosti (1996), Takalo et al. (1996) and Villata et al. (1997). The results of the optical monitoring are shown in Table 2. Magnitudes have been calculated using the calibration sequence given by

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[*] Table 2 is only available in electronic form at the CDS via anonymous ftp 130.79.128.5 or http://cdsweb.u-strasbg.fr/Abstract.html

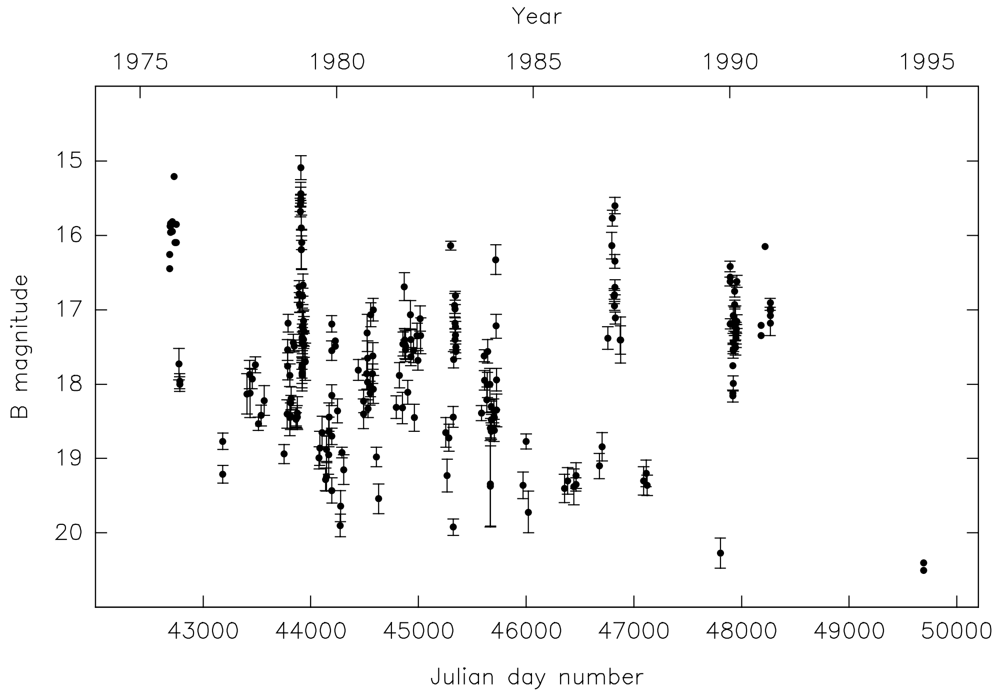

Fig. 1. The historical B-band light curve of AO 0235+164. This light curve is based on the data from Pica et al. (1976); Webb & Smith (1989); Takalo (1990); Takalo et al. (1992); Barbieri et al. (1982); Webb et al. (1988); Pollock et al. (1979); Smith et al. (1987); Xie et al. (1992); Sillanpää et al. (1988)

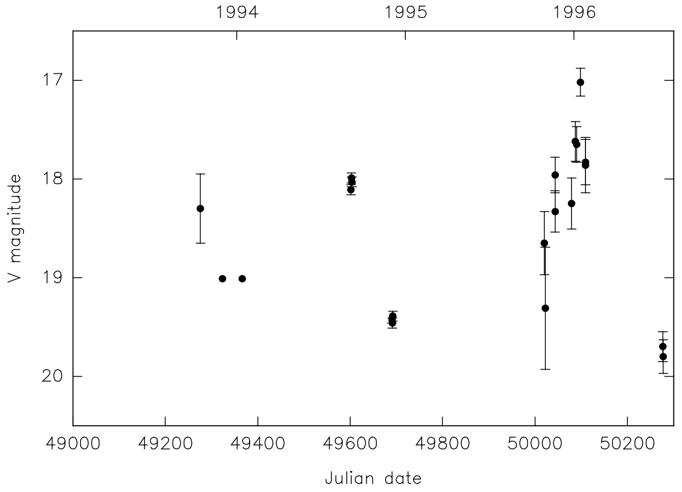

Fig. 2. The observed V-band light curve of AO 0235+164

Smith et al. (1985) and Nilsson et al. (1996). The radio observations have been done at the Metsähovi radio telescope in connection with their ongoing monitoring program (e.g. Teräsranta et al. 1992 and references therein).

Figure 1 shows the historical B-band light curve with our observations included. The minimum brightness level previously observed for AO 0235+164 has been around $B = 20.0$. By adopting an approximate B-V colour index of 1.2, our observation of $V = 19.80$ corresponds to $B = 21.0$, which is the faintest value ever recorded for

Table 1. The used optical telescopes. The code refers to the observers used in Table 2 to identify the telescopes

Telescope	Size	Filters	Code
NOT	2.5 m	$BVRI$	NOT
JKT	1.0 m	VR	JKT
Torino	1.05 m	R	TO
Tuorla	1.03 m	V	TU
Boltwood	17 cm	VRI	BO
Perugia	40 cm	VRI	PE

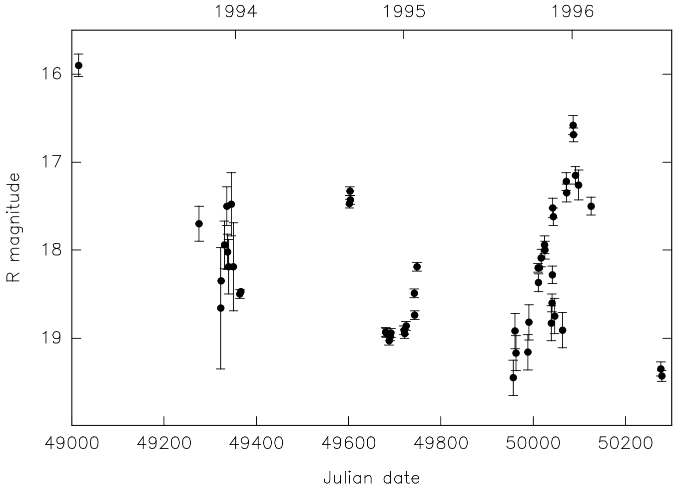

Fig. 3. The R-band light curve obtained during spring 1996. Note the sharp flare at JD 50040

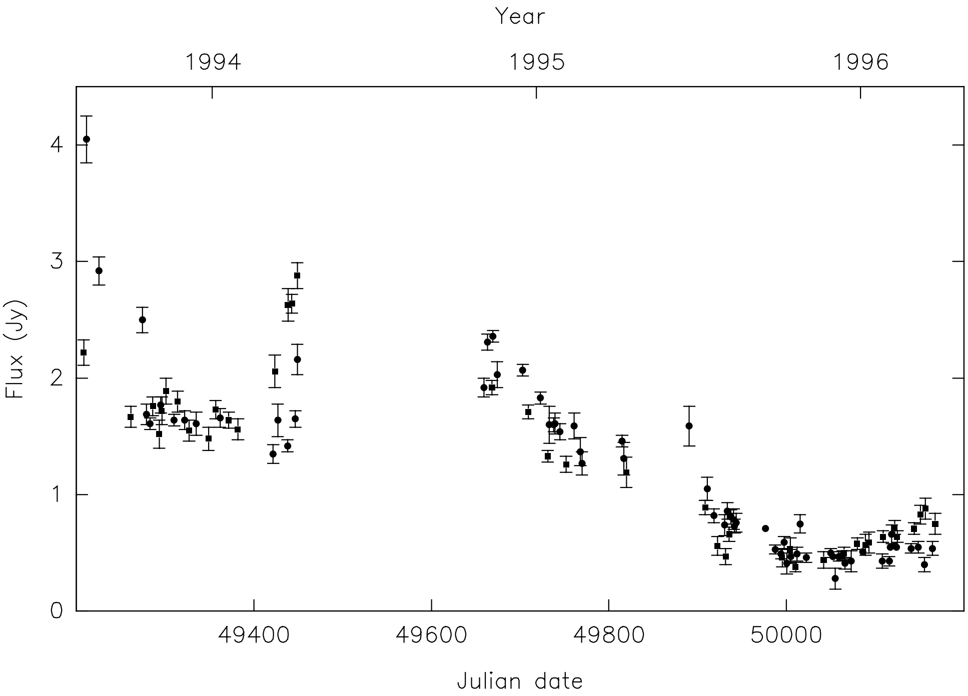

Fig. 4. The observed radio light curves. The dots mark the 22 GHz and the black squares the 37 GHz data

this object in this band. We have to mention, however, that the colour of the object is also variable (e.g. Webb & Smith 1989). In Figs. 2 and 3 show our V and R light curves, while Fig. 4 displays the radio observations. In Fig. 5 we show our sampling dates at the different frequences. As can be seen there are a lot of simultaneous observations (data taken during the same day). Although both the optical and radio light curves have extended gaps in the data, some trends can still be recognized. The optical light curves show the object in a faint state, with some large variability. The quick brightening at JD 9750 and toward the end of the observations is very well documented. During spring 1996 (after JD 49900) AO 0235+164 brightened by almost 3 magnitudes in three months. During this phase we observed an intense activity: the most noticeable event was a one magnitude flare, lasting at most a couple days (Fig. 3). When AO 0235+164 became observable again, after conjunction, it was again very faint (Table 2, Fig. 2). This kind of flaring behaviour is typical for AO 0235+164 (e.g. Webb & Smith 1989; Schramm et al. 1994).

For the nights where data of different bands are available, colour indexes have been derived: the result is $B-V = 0.98$ and 1.11 from the two nights with B observations. These values are slightly larger than those observed during outbursts in this object (Webb & Smith 1989). The $V-R$ values we measured range between 0.44 and 0.93. These are 0.2 to 0.5 magnitudes smaller than what has been observed when the object was in a bright state (e.g. Webb & Smith 1989). Our data reveal a clear tendency for $V-R$ to be larger when the object is brighter. By fitting a power-law to the observed fluxes ($f_\nu = k\nu^\alpha$), we obtained a spectral index of -2.7 between the B and I bands. This is very similar to the value measured by Nilsson et al. (1996) from a spectrum of this object taken during January 1994. Thus the spectrum is flatter than seen during the outbursts (Webb & Smith 1989). Incidentally, now that AO 0235+164 is really faint, the intervening galaxies along the line of sight

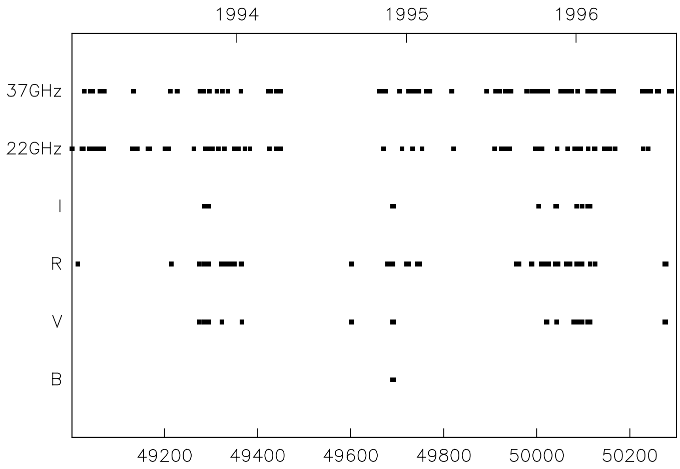

Fig. 5. A scatter plot, showing our sampling at the different observed frequences

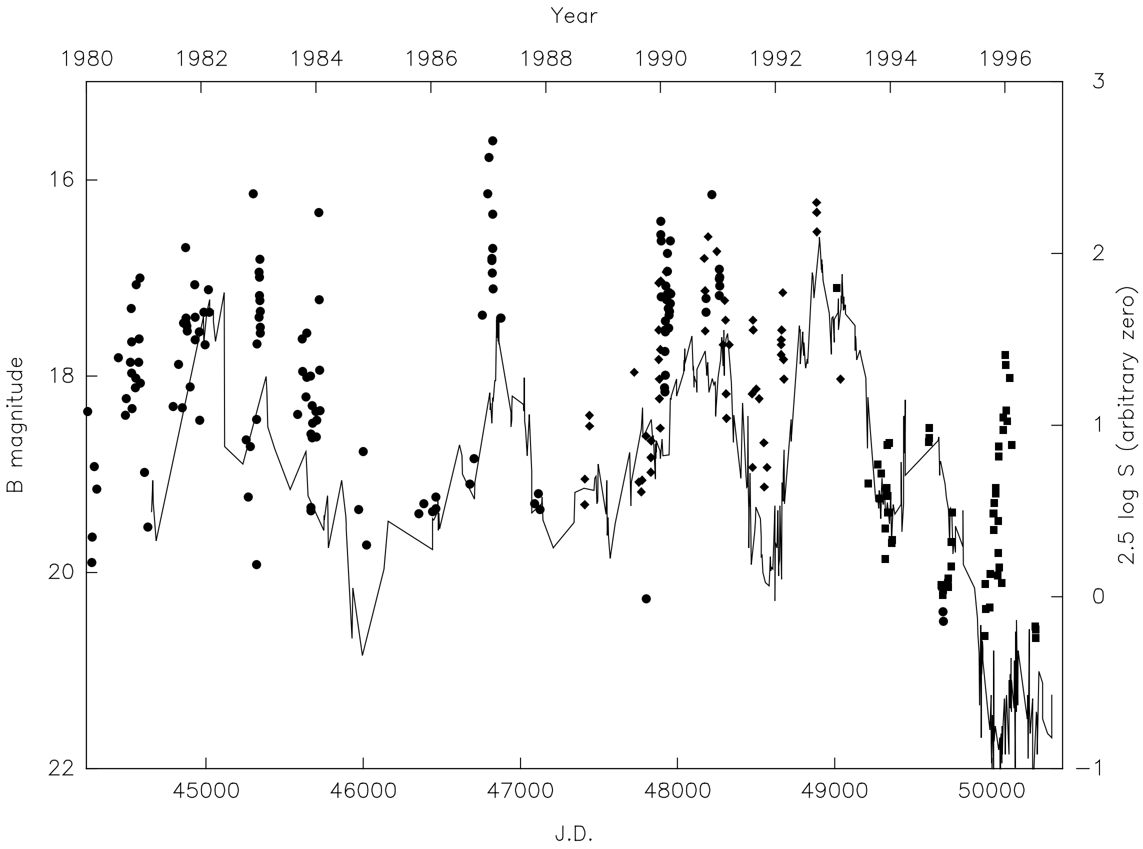

Fig. 6. The historical optical (dots) and radio (solid line) light curves. Here the dots represent the historical B-band data, the diamonds the data from Schramm et al. and the sguares data from these observations (see text for details). Both curves are plotted in logarithmic scale. Notice the similarity of the base levels in the brightness

are expected to contribute more to the overall brightness, especially in the R and I-bands.

A less violent behaviour has characterized the emission in the radio bands (Fig. 4). A very sharp increase in the flux is evident at JD 9450, when unfortunately optical data are lacking. There was a weak detection of AO 0235+164 by the EGRET instrument onboard CGRO in γ-rays and by ASCA in X-rays at this time (Madejski et al. 1996). From the light curve shown in Fig. 4, it seems that a huge outburst was actually starting with this flux increase, which would end with the minimum registered on JD 10020. This minimum radio flux is the lowest level ever measured at these frequencies for AO 0235+164. The extent of this outburst cannot be clearly defined, since there is a large gap in the data. There are some indications that the radio flux is slowly increasing towards the end of the observations.

3. Radio-optical correlations

AO 0235+164 is one of the first sources for which correlated radio and optical variations have been claimed (MacLeod et al. 1976; Ledden et al. 1976; Rieke et al. 1976; Balonek & Dent 1980). The main evidence consists of two sharp optical flares, or spikes, in 1976 and 1979, coincident with radio outburst maxima (Balonek 1982). Recently, Clements et al. (1995) have performed a DCF analysis between Florida optical and Michigan radio monitoring data, finding a positive correlation with a delay of $0-2$ months from optical to radio. In order to study possible correlations, we have plotted the historical optical light curve together with the combined 22 GHz and 37 GHz Metsähovi fluxes in Fig. 6. For completenes, we have included in this plot also the R-band data from Schramm et al. (1994) and from this paper. These R-band magnitudes have been converted to B-band magnitudes using a $B-R$ value of 1.2. This $B-R$ give consistent B-magnitudes for the flare during JD 48000. This method can produce a small error to the obtained B-magnitudes, but this will not affect the overall behaviour of the light curve.

Although AO 0235+164 is very variable also in the radio, it is clear that there are no sharp spikes comparable to those in the optical. The time coverage in the radio bands is much better than in the optical bands, so such sharp radio spikes should be noticeable in the radio light curves (see also Teräsranta et al. 1992). Sharp optical

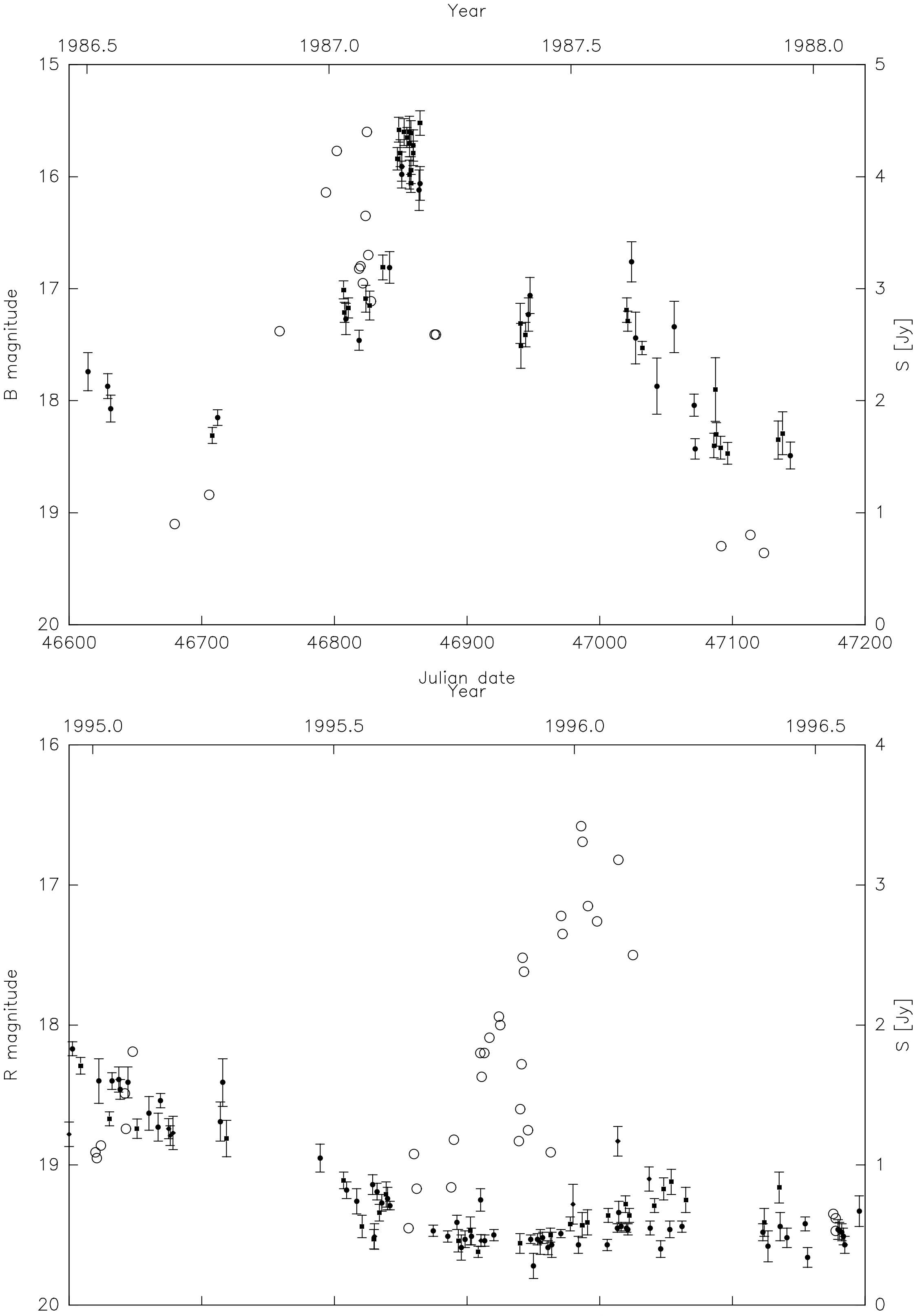

Fig. 7. Examples of the correlation between the flaring behaviour in optical and radio bands, see text for details. Here open circles are the optical, black dots the 22 GHz, black squares the 37 GHz and black diamonds the 90 GHz data, respectively

flares are seen quite frequently, occurring at least once a year (and perhaps more often, considering the gaps in the data). While some of these spikes appear to be coincident with radio flares (e.g., the 1987 events, Fig. 7a), others have no radio counterparts (e.g., the 1990-1991 optical flaring and the 1996 spike shown in Fig. 7b). The scarcity of data especially in the optical bands does not allow a more detailed comparison. The well-documented lack of correlations, especially during our 1995-1996 monitoring, indicates either that there are at least two different mechanisms producing optical spikes, one also producing radio emission and the other not, or that the above cases of simultaneous radio and optical flares are just coincidental occurrences. Although neither hypothesis can at present be proved, we suggest that the latter is more likely.

However, a closer inspection of the historical light curves of Fig. 6 reveals a new feature, which is not very apparent unless both the optical and the radio fluxes are plotted in logarithmic scale: the overall, average behaviour is very similar in both the frequency regimes. In general, when AO 0235+164 is bright in the radio frequencies, it is also bright in the optical bands. Accordingly, periods of low radio flux seem to correspond to low levels in the optical bands (e.g., the lowest ever recorded optical and radio fluxes during 1995-1996). If we exclude the optical spikes, the "base" emission in the optical (the lower envelope of the optical data points) corresponds quite well to the 22/37 GHz radio flux emission. This suggests that the "base" optical emission is due to the same mechanism as the radio emission, and is therefore likely to be synchrotron emission from the relativistic jet. The optical spikes without corresponding radio flares could be caused by another mechanism, for example by microlensing or by flares in the accretion disk. Even though gravitational lensing is achromatic, the simultaneous optical and radio flares are unlikely to be caused by this mechnisim, since the shocked radio emitting regions are too large to be microlenced (e.g. Gear 1991). However optical radiation from more compact regions in the accretion disk or in other parts of the jet could be microlenced by stars in an intervening galaxy. More data are needed in order to draw a more detailed picture.

4. Conclusions

We have presented the results of an optical and radio monitoring campaign on the BL Lac object AO 0235+164 during a faint state. Large amplitude (up to three magnitudes) variations were observed in the optical bands. At radio frequencies the behaviour has been less dramatic. An inspection of the historical and current data suggests that there are at least two different processes involved in the optical emission of this blazar. One of them would be responsible for the similar general trends in the optical and radio bands and could be identified with the synchrotron process in the relativistic jet. On the other hand, the optical flares not showing radio counterparts could be due to a microlensing effect by a foreground galaxy. A further observational effort is required in order to shed light on this issue.

Acknowledgements. Part of the observations presented here were taken during the 5% international time on the Canary Island telescopes awarded to the OJ-94 Project. This work was partly supported by the Finnish Academy of Sciences.

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