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BVR_cI_c monitoring of ON 231 during the great outburst in 1994-1997*

G. Tosti[1], M. Fiorucci[1], M. Luciani[1], N. Rizzi[1], M. Villata[2], C.M. Raiteri[2], G. De Francesco[2], L. Lanteri[2], M. Chiaberge[2], A. Peila[2], M. Cavallone[2], G. Sobrito[2], M. Maesano[3], E. Massaro[3], F. Montagni[3], R. Nesci[3], G. Ghisellini[4], L.O. Takalo[5], A. Sillanpää[5], S. Katajainen[5], P. Heinämäki[5], K. Nilsson[5], and T. Pursimo[5]

[1] Cattedra di Astrofisica, Università di Perugia, Via A. Pascoli, I-06100 Perugia, Italy
[2] Osservatorio Astronomico di Torino, Strada Osservatorio 20, I-10025 Pino Torinese, Italy
[3] Istituto Astronomico, Università di Roma "La Sapienza", via G.M. Lancisi 29, I-00161 Roma, Italy
[4] Osservatorio Astronomico di Brera, via Bianchi, 46, I-22055 Merate, Italy
[5] Tuorla Observatory, Tuorla, FIN-21500 Piikkiö, Finland

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Abstract. We present the most continuous data base of optical multiband data ever published on the BL Lacertae object ON 231 (W Com). The data have been collected during an intensive and coordinated BVR_cI_c monitoring campaign carried out in the period from March 1994 to March 1997. During our campaign, the source brightness was at the highest level ever observed. The light curve shows a complex structure, characterized by the presence of three major outbursts having the observed maxima in March 1995, February 1996, and January 1997, when ON 231 reached its historical maximum ($B \simeq 14.2$). Variability on time scales from a few hours up to a month have frequently been observed and the light curve seems to be the superposition of many flares with different amplitudes and time scales. The broad-band optical spectral energy distribution is characterized by a spectral slope which correlates with the flux level. In particular, the higher is the flux the flatter is the spectrum.

Key words: BL Lacertae objects: general; individual — ON231

1. Introduction

ON 231 (1219+285, $z = 0.102$) is one of the few radio sources whose optical counterpart was already known as a variable star (W Com) discovered by Wolf (1916), at the epoch of its classification as a BL Lacertae object (Browne 1971).

Its historic light curve dates back to more than 100 years and shows several interesting features (see Sect. 4). Most of the observations of ON 231 reported during the past 30 years were obtained photographically mainly in the B band and only a few data have been obtained via photoelectric or CCD photometry in the $BVRI$ bands.

Furthermore, after the photographic B band observations taken during the Rosemary Hill monitoring program reported by Webb et al. (1988), only sporadic data are available (e.g., Xie et al. 1990, 1992).

Massaro et al. (1992) found the source at the highest brightness level since 1968. This high state was qualitatively confirmed by the work of Schramm et al. (1994): they reported an uncalibrated R (Johnson) light curve of ON 231 obtained during the period 1989–1992, from which an increasing trend of the source brightness is evident over all their observational period, with a maximum in 1992. More recent observations of ON 231 are lacking in the literature.

It is known that the source shows variability on time scales from hours to years (see, e.g., Smith & Nair 1995; Xie et al. 1992). But previously published light curves are not so densely sampled to allow a sufficiently detailed study of structure and occurrence of the short term variations.

Worral et al. (1986) and Lorenzetti et al. (1990) found that the optical-near-infrared spectrum of ON 231 becomes steeper when the source is fainter. In the optical band this effect has been attributed to the underlying galaxy (Worral et al. 1986), but Lorenzetti et al. (1990) excluded the host galaxy as the possible cause of the

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

near-infrared spectral variability observed in ON 231. Also in this case the spectral analysis of the optical continuum was performed only over a limited period of time and during relatively faint states of the source: there is no information on the behaviour of the spectral slope during a large outburst or during rapid flares.

Moreover, γ-ray emission from ON 231 has been detected by the EGRET experiment on board the Compton Gamma Ray Observatory CGRO (von Montigny et al. 1995). This γ-ray emission was revealed only above 300 MeV. The derived photon spectral index was $\sim$ 1.27, which makes the ON 231 spectrum one of the hardest ever observed within the whole EGRET blazars sample (Sreekumar et al. 1996). The source was included in the supplement to the second EGRET Catalog, built after the completion of the CGRO phase 3 (Thompson et al. 1996).

According to the current models, the optical emission could be strongly coupled to the high energy γ-rays (see, e.g., Ghisellini et al. 1997). In this contest, simultaneous observations in the optical and γ-ray bands could be crucial to understand the nature of the γ-ray emission in blazars.

Starting from the above considerations, ON 231 was intensively observed within a coordinated optical monitoring of a selected sample of γ-ray loud BL Lac objects carried out by the Perugia, Roma, Torino and Tuorla groups.

In this paper we present and discuss in detail the BVR_cI_c light curves of ON 231 obtained during the period 1994–1997, when the source was found at the highest brightness state ever observed.

2. Observations

Our photometric observations were carried out with several telescopes: the 1.05 m astrometric telescope of the Torino Observatory, the 0.4 m Automatic Imaging Telescope (AIT) of the Perugia University Observatory, the 0.5 m telescope of the Astronomical Station of Vallinfreda, and the 1.0 m telescope at Tuorla Observatory. All the telescopes were equipped with CCD cameras and Johnson-Cousins BVR_cI_c filters. Details on each telescope and observing procedures can be found in Villata et al. (1997), Tosti et al. (1996), Massaro et al. (1996) and Katajainen et al. (1997). Data reduction was performed with the standard IRAF, MIDAS, and other locally developed procedures such as Robin (see Villata et al. 1997) and REDUCE, the automatic reduction software developed by the Perugia group (Fiorucci & Tosti 1996). The comparison among the data acquired with different telescopes in the same night is fully satisfying: the mean differences are always less than one standard deviation, while the maximum differences do not exceed two standard deviations. Furthermore, no significant colour effect was found.

The V, R_c, I_c magnitudes of the comparison stars in the field of ON 231, used by all the groups to reduce the data, have been published by Fiorucci & Tosti (1996a). We extend now this sequence also to the B band; the B magnitudes of stars A, D, and C1 (see the finding chart reported by Fiorucci & Tosti 1996a) are: 12.64 ± 0.03 (star A), 16.37 ± 0.05 (star D), and 17.71 ± 0.05 (star C1). The B values derived for the stars A and D are in agreement with the ones reported by Wing (1973).

3. Results

The photometric observations presented in this paper cover the period March 1994 - March 1997. We observed the source during 234 nights, out of the 1121 possible ones, obtaining more than 1100 BVR_cI_c photometric points.

Table 1 gives a summary of the whole campaign reporting, for each visibility period of the source, the measured magnitude range and the number of observations (in parenthesis) in each filter.

The list of the observations is given in Table 2, which can be retrieved from CDS/authors. On some occasions ON 231 was observed more than once within the same night with different telescopes in this case only the nightly averaged magnitudes are reported in Table 2.

Our B, V, R_c and I_c light curves are shown in Fig. 1. This plot, drawn using the whole set of data, show three well sampled outbursts reaching the maximum around March 1995, February 1996 and January 1997, respectively. The best sampled curves are those in the V and R_c bands, while the poorest is that in the B band. The total variation amplitudes observed in the different bands are similar: $\Delta B = 1.54$, $\Delta V = 1.65$, $\Delta R_c = 1.64$, $\Delta I_c = 1.53$. In the following subsections we will discuss in detail the source behaviour in each campaign separately.

3.1. The 1994–1995 light curve

In the period March–July 1994 (JD = 2449416 − 537), ON 231 was observed only by the Perugia and Rome groups. The source was apparently stable with small fluctuations around $V \sim 15.2$. A small flare likely occurred at the end of April 1994, when the source was observed only once at $V = 14.82$ (JD = 2449470).

We started to observe again ON 231 in January 1995: the R_c light curve is shown in Fig. 2a. The object brightened by $\sim$ 1.5 magnitudes from JD = 2449729 to JD = 2449788, following a quasi linear trend with rapid flares superimposed on it.

The decline from the maximum of the outburst (R_c = 13.36, in March 1995) shows a complex structure: a first fading of about $\Delta R_c = 0.5$ in ten days was soon followed (at JD = 2449808) by a flare having a total duration of about 60 days. This flare is characterized by a quite rapid increase (about two days), a rapid flickering (amplitude of about $\Delta R_c = 0.1$) around the maximum value ($R_c \sim 13.9$) for about 30 days, and a further decline of $\sim$ 0.8 mag for other 30 days.

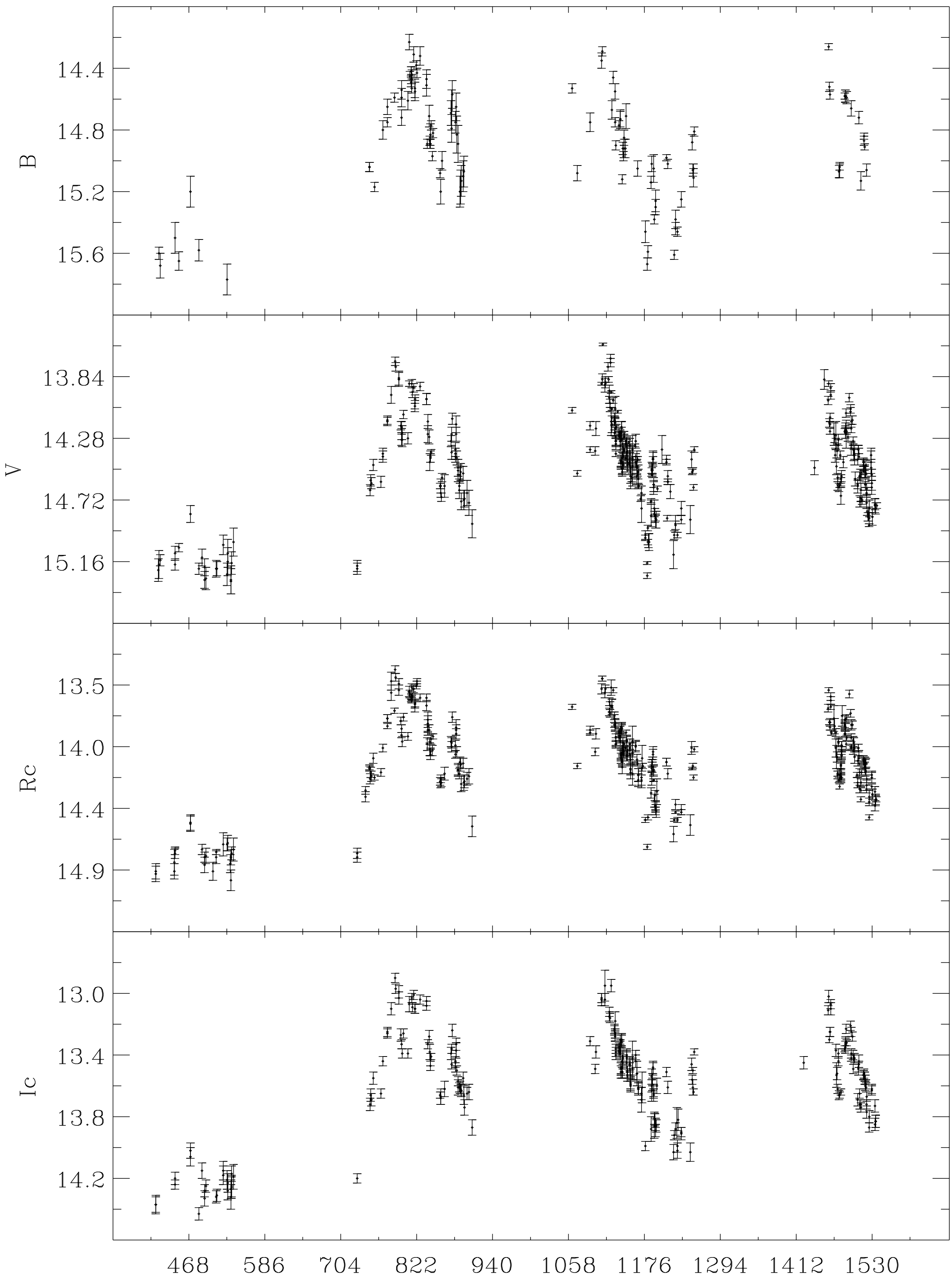

Fig. 1. The B, V, R_c and I_c Light curves of ON 231

Table 1. Summary of the optical monitoring (1994.03.05-1997.03.29)

Obs. Period	B	V	R	I
1994-95	14.23 – 15.77 (61)	13.73 – 15.30 (98)	13.36 – 15.00 (113)	12.90 – 14.43 (86)
1995-96	14.29 – 15.67 (42)	13.61 – 15.26 (176)	13.38 – 14.74 (137)	12.95 – 14.03 (111)
1996-97	14.26 – 15.13 (17)	13.86 – 14.87 (100)	13.52 – 14.51(106)	13.02 – 13.87 (61)

Around JD = 2449861 a new flare emerged with a brightness increase of ~ 0.5 mag in 12 days and a decline lasted ~ 30 days. Several rapid variations with amplitude of ~ 0.2 mag and duration of ~ 3 days are superimposed to the major trend of this flare.

3.2. The 1996 light curve

When ON 231 was newly observed in December 1995 (JD = 2450063), it was found in a bright state (V = 14.08). The V light curve to June 1996 is shown in Fig. 2b. The observed maximum of the 1996 outburst reached $V = 13.61$ at JD = 2450111. Bad weather prevented us from getting a well sampled monitoring before this date, so that we cannot say whether the observed maximum was the real maximum of the outburst. It is likely that it was actually the historic one, since by assuming the same $B-V$ of the previous night we can estimate $B \simeq 14.04$. After the peak ON 231 faded, with a regular trend, to $V = 14.46$ in about 30 days. Apart from flickering, which was always present during this decline, a rapid flare having a duration of only two days and an amplitude $\Delta V \sim 0.3$ was observed at JD = 2450122. The source brightness remained quite constant ($V \sim 14.4$) from JD = 2450140 to JD = 2450165, then it faded to V = 15.26 in two weeks. After this minimum, the object brightened again to $V = 14.43$ in 9 days and then it fell to $V = 14.82$ in two days. Another, scarcely sampled, $\Delta V \sim 0.5$ flare is visible from JD = 2450195 to JD = 2450221. At the end of the observational season (June 1996), the source was brightening again.

3.3. The 1997 light curve

At the beginning of the last observational season (December 1996), the source was found at an intermediate level of brightness ($V \sim 14.5$, at JD = 2450440), during the raising to the observed maximum of the 1997 outburst ($V = 13.86$ at JD = 2450455). This very bright state lasted for about 10 days; after then, ON 231 declined to V = 14.85 in about two months. During this period many rapid flares, with $\Delta V \sim 0.2-0.3$ and time scales of 2–3 days, were also observed superimposed to the descending trend. Figure 2c also shows a flare of $\Delta V \sim 0.5$ occurring from JD = 2450480 to JD = 2450507, which was soon followed by other two rapid flares of small amplitude, peaked at JD = 2450508 and JD = 2450516.

3.4. The optical light curve during the CGRO pointings

In order to study the possible correlation between the optical and the γ-ray luminosities, we intensified our monitoring during the CGRO pointings of ON 231.

ON 231 has been detected by EGRET during phases 1 and 2 (May 1991 – September 1993) (von Montigny et al. 1995). During these periods no optical data are available.

The source was in the field of view of EGRET several times during September 1993 – October 1994 (CGRO phase 3). The strongest γ-ray emission was observed in the period from November 23 to December 1, 1993. This occurred a few months before the starting of our monitoring program. We have only a few sporadic observations during the viewing periods 322 (April 5–19, 1994; JD = 2449448 – 462) and 326 (May 10–17, 1994; JD = 2449483 – 490). In both cases EGRET was unable to detect γ–ray emission, while in the optical band the source was in a faint state ($V \sim 15.1$).

We obtained a well sampled light curve of ON 231 during the CGRO phase 4 pointing of April 25 – May 9, 1995 (JD = 2449832 – 847), when the source was in a quite bright and active state ($R_c = 13.60 - 14.02$; see Fig. 2a). As far, no EGRET data are available to allow a comparison with our optical data.

EGRET observed again ON 231 in February 20 – March 5, 1996 (JD = 2450134 – 148) and found it in a relatively bright state (Maisack et al. 1997). This occurred only a few days after the peak of the 1996 optical outburst (see Fig. 2b), when the source was in very bright state.

Considering the EGRET data so far available, ON 231 seems to show variability also in the γ-ray spectral region. Moreover, by comparing the γ data with the optical ones obtained by us in 1994–1997, the existence of a possible temporal association between the brightness level observed in the two spectral regions can be suggested.

4. The historical light curve of ON 231

The historical B-band light curve of ON 231 covers a period of about 100 years. In Fig. 2d we plotted our B band data together with all the photometric data we were able to find in the literature since 1935. We did not plot the photographic measures by Romano (1972) (he used a panchromatic emulsion without filters) from January, 1962 to December, 1971, and those of Hoffleit (1973), who used a wrong comparison sequence (see Pollock et al. 1974).

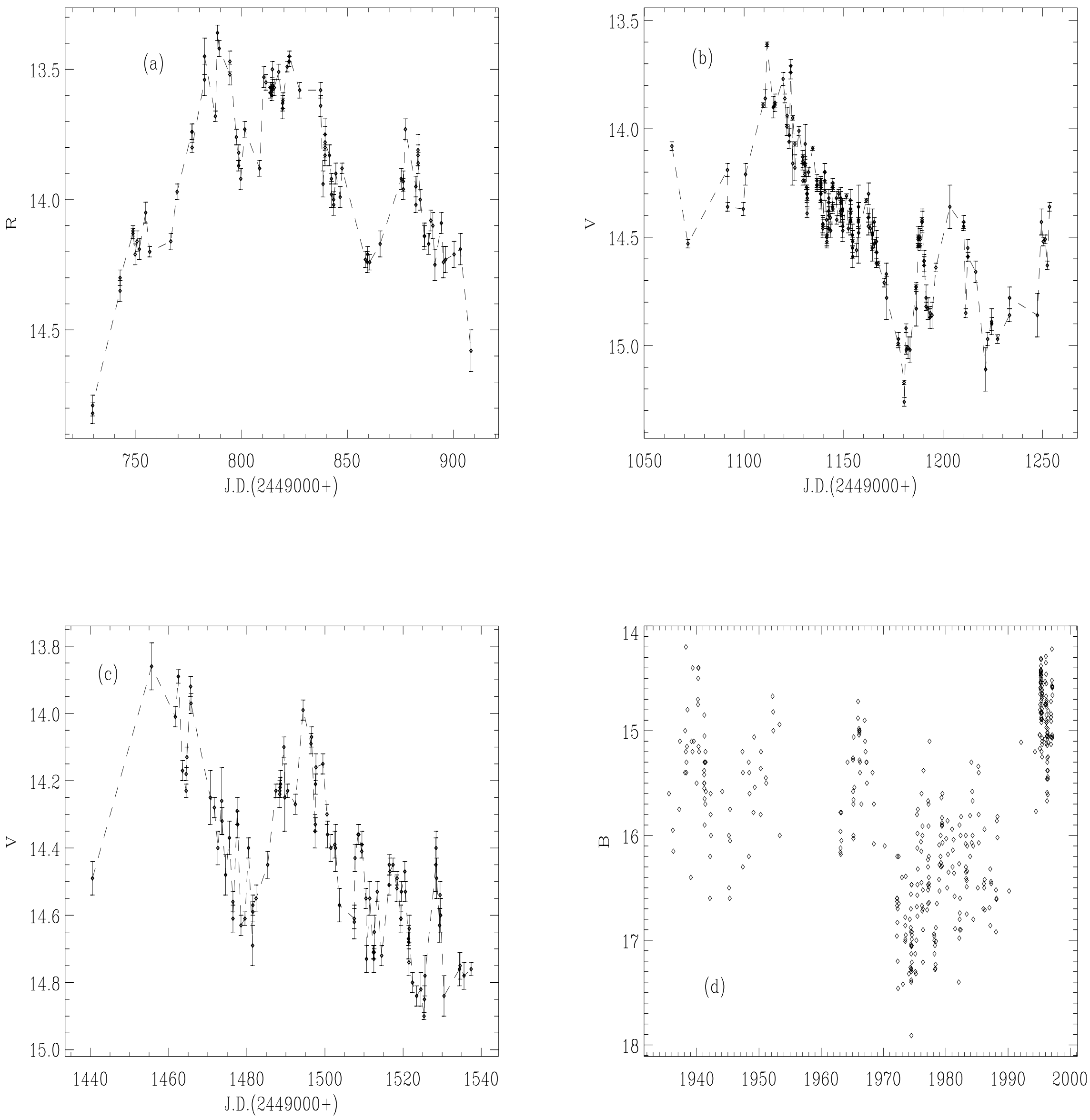

Fig. 2. a) The R_{c}-band light curve during the 1995 flare. **b)** The V-band light curve during the 1996 flare. **c)** The V-band light curve during the 1997 flare. **d)** The historical B-band light curve of ON 231. This lightcurve is based on the data from: Kurochkin (1971); Pollock et al. (1974); Wing (1973); Zelk et al. (1981); Markova & Fomin (1975); Barbieri & Romano (1981); Barbieri et al. (1988); Tapia Craine & Johnson (1976); Strittmatter et al. (1972); Xie et al. (1987); O'Dell et al. (1978); Craine & Warner (1973); Schaefer (1980); Battistini et al. (1974); Webb et al. (1988); Xie et al. (1988); Xie et al. (1990); Xie et al. (1992); Massaro et al. (1992), this paper

Although the whole data set is somewhat inhomogeneous because of the different photometric techniques, reduction strategies and comparison sequences used in the past, the variability pattern showed in Fig. 2d appears significant. It shows the presence of several variable components characterized by different time scales. Two well sampled outbursts have been observed around 1940 and 1968. Another one occurred around 1953, but it is poorly sampled. These outbursts have an amplitude of one magnitude and an overall duration of about 6 years, and seem to be imposed on a slower secular variation of the total brightness of the source. After the deep minimum observed in 1972–74, the brightness of ON 231 began to increase following a slow, quasi linear trend, with a small outburst visible in the period 1979–1981. Superimposed on this trend there are complex variations characterized by a total amplitude of about one magnitude and a time scale of about 4 years (Smith & Nair 1995). From a visual inspection of the historic light curve, Pollock (1974) suggested a possible quasi-periodicity of about 14 years for the outbursts, a value which agrees with the period of 13.6 ± 1.3 years recently proposed by Liu et al. (1995).

During our monitoring campaign the source brightness was at the highest value ever observed since 1940, reaching the historical maximum of $B \sim 14.2$. This shows that the increasing luminosity trend, started more than 20 years ago, is still going on.

As a last note we would like to point out that the 1995–1997 outbursts occurred at the epoch foreseen on the base of the 14 years period. However, the historic data have long gaps and hence we must wait for future observations to have a confirmation of the existence of such a cyclic variation in the light curve of ON 231.

5. The spectral behaviour

Our measurements represent the most continuative B, V, R_c and I_c data base available on this source and allows to study the spectral changes and in particular to search for a correlation between the spectral slope of the optical continuum and the flux level on time scales from days to years.

In order to evaluate the spectral slope of the broad band energy distribution, the BVR_cI_c magnitudes were converted into flux values using the zero magnitude fluxes given by Mead et al. (1990). The correction for the galactic interstellar reddening was performed by using the colour excess $E_{(B-V)}$ deduced by the relation $N_{(H)}/E_{(B-V)} = 5.2\ 10^{21}$ (Shull & Van Steenberg 1985), where $N_{(H)}$ is the equivalent hydrogen absorbing column density due to our Galaxy, and by adopting the value $R = 3.1$ (Riecke & Lebofsky 1985) for the ratio $A_V/E_{(B-V)}$. By using the value $N_{(H)} = 1.88\ 10^{20}$ cm^{-2} derived by Lamer et al. (1996) from the data reported by Stark et al. (1992), we found $A_V = 0.11$ in the direction of ON 231. The BR_cI_c extinction coefficients $A_B = 0.15$, $A_R = 0.09$ and $A_I = 0.07$, were calculated with the interpolation formula given by Cardelli et al. (1989).

We estimated the spectral index α and its uncertainty for all our observations with measurements in at least three different bands by fitting a power-law ($f_\nu = k\nu^\alpha$) to the observed fluxes. In order to minimize the errors, and to eliminate effects due to possible intranight rapid variations, we included in our analysis only BVR_cI_c observations separated by no more than 30 min and made from a single site. Following this criterion we obtained 143 points to estimate the spectral slope of ON 231 in 1994-1997. In Fig. 3 we plotted the temporal behaviour of the spectral index during our monitoring. The spectral slope varied closely following the flux variations also in the course of rapid flares.

By comparing the mean value $\alpha = -1.25 \pm 0.12$ derived by us with that reported in the past by Cruz-Gonzales & Huchra (1984), Worral el al. (1986) and Weistrop et al. (1985), who found $\alpha \sim -1.6$ when the source was in a faint state ($V \sim 15.5 - 16.3$), a general flattening of the optical continuum of ON 231 is evident. This could be directly correlated to the quasi constant raising of its brightness during the last 20 years.

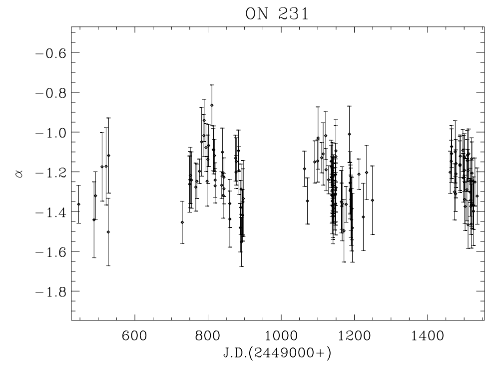

Fig. 3. Plot of the spectral index vs. Julian Day

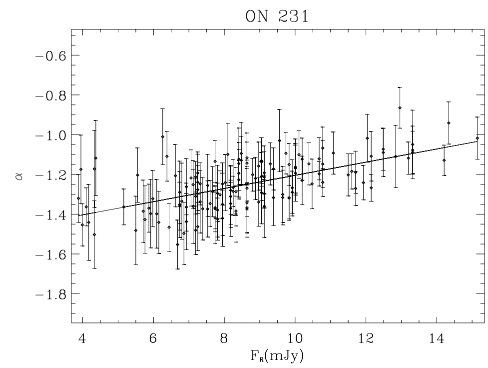

Fig. 4. Plot of spectral index vs. F_R. The straight line represents a best fit to the data

The spectral index plotted *vs* the flux in the R_c band is shown in Fig. 4: the existence of a positive correlation is apparent. The linear correlation coefficient r is equal to 0.61, which is significant at a confidence level $> 99.9\%$. A nonparametric correlation analysis, using the Spearman rank correlation, which is more robust than linear correlation, gives $r_s = 0.63$ (confidence level $> 99.9\%$) confirming the previous result.

Weistrop et al. (1985) have shown the presence of an elliptical nebulosity surrounding the central point source and estimated a total magnitude $V \sim 17.3$. To investigate if the correlation between spectral slope and flux could be due to the effect of the underlying galaxy, we have subtracted such a contribution by assuming $V = 17.3$, $z = 0.102$ ($H_0 = 75, q_0 = 0.5$) and $B - V = 1.00, V - R = 0.65, V - I = 1.35$ as the typical color index value of the host galaxy, which were derived from the standard model of elliptical galaxies reported by Arimoto & Yoshi (1987).

Subtracting this contribution does not alter the significance of the correlation. In fact we found $r = 0.40$ (confidence level $> 99.9\%$) and $r_s = 0.43$ (*c.l.* $> 99.9\%$). Also the mean value of the spectral slope changed little after galaxy subtraction ($\alpha = -1.15 \pm 0.12$).

To completely remove this correlation we must assume that the galaxy contribution amounts to $V \sim 16.1$, but ON 231 has been observed as faint as $V \sim 16.8$ (see e.g. Battistini et al. 1974), so we must exclude such a high value of the host component. This result is not surprising becouse we observed the source in a very high state and then the galaxy contribution to the flux could be much less important than during faint state.

The correlation of the spectral index with flux is much more evident if we consider only the data relatives to each of the three major bursts reported in Figs. 2a,b,c. In this case the Spearman correlation coefficient resulted be $r_s = 0.80$ ($c.l. > 99.9\%$) for the 1995 burst, $r_s = 0.65$($c.l. > 99.9\%$) for the 1996 burst and $r_s = 0.59$ (c.l. $> 99.9\%$) for the 1997 one.

The variations of the spectral index with the flux level could be explained assuming that the mechanism responsible for the flares observed in ON 231 is the injection of relativistic electron which then decay radiatively (see, e.g., Brown et al. 1990).

6. Conclusions

We have reported the results of a systematic BVR_cI_c monitoring of the BL Lac object ON 231 in the period March 1994 - March 1997. The source brightness was at the highest level ever observed. The flux behaviour was characterized by three major bursts, separated each other by about 300 days, in which ON 231 reached practically the same maximum level (historical maximum), and with a total amplitude of about 1.5 mag in all the four bands. Superimposed to each burst there is a series of flares with a typical duration of 20–60 days. Variations of a few tenths of magnitude lasting about a week are always present in the light curve. More rapid events with time scales of 2–3 days or less were mainly observed when the source was in a faint state.

We have found a positive indication of a correlation between the spectral index and the source optical luminosity, in the sense that the spectrum becomes flatter when the flux increases, which could be related to the aging of the synchrotron emitting electrons.

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