Astron. Astrophys. 356, L21–L24 (2000)

ASTRONOMY
AND
ASTROPHYSICS

LETTER

Letter to the Editor

ON 231: the testing of 3.8-year period for optical outbursts with multi-peak structure ⋆

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Received 30 August 1999 / Accepted 21 February 2000

Abstract. The extraordinary optical outburst of ON 231 which occurred in spring 1998 (Massaro et al. 1999) and its behavior during 1999 is in very good agreement with the predictions made by use of the 3.8-year period that was found from the analysis of prior observations (all B-band data available in the 1971-1997 time interval). The periodic outbursts of ON 231 have a multi-peak structure that is possibly a more complex variant of the double-peak one detected for periodic outbursts in OJ 287. Some further predictions of variability behavior are given.

Key words: galaxies: BL Lacertae objects: general – galaxies: BL Lacertae objects: individual:

1. Introduction

ON 231 ($z = 0.102$) has been known as a BL Lac object (e.g., Brown 1971) since the early 1970s. In the 1990s ON 231 began to be observed especially intensively and comprehensively. It was discovered as a superluminal source (Gabuzda et al. 1994) and a gamma-ray source (von Montigny et al. 1995) that shows the hardest spectrum among the EGRET AGN detections (Sreekumar et al. 1996).

The special optical monitoring of ON 231 has continued for about 30 years. But its optical history has been followed in outline since 1897 because the optical counterpart was first known as a variable star W Com (Wolf 1916). In the last 5 years ON 231 has kept a very luminous optical state reaching in the spring 1998 outburst a brightness that had never been observed earlier (Massaro et al. 1999). X-ray observations made in May 1998 also showed ON 231 bright and having the extremely flat high-energy spectrum that suggests a very high gamma-ray flux (Tagliaferri et al. 1998).

ON 231 shows significant optical variability on different time scales ranging from decades (Pollock et al. 1974) to hours (Xie et al. 1991). The analysis of its whole optical light curve suggested a possible (quasi)periodicity ∼14 years (Pollock et al. 1974; Liu et al. 1995). Smith & Nair (1995) studying their own 11-year (1972-1982) data set found a 4-year time scale determined as "the time required for a complete cycle of brightening and fading".

Our analysis of the "modern" (1971-1997) part of optical light curve showed evidence for a 3.8-year (1414-day) period (Babadzhanyants & Belokon 1999). The periodic outbursts have multi-peak structure that appears to be nearly stable. Now we present the comparison of the recent extraordinary outbursts of ON 231 which occurred in 1998-1999 with the updated reconstruction light curve obtained from the refined analysis of the 1971-1997 data set. We give also some new predictions on variability behavior of ON 231 during the next observational season that could be used to test the proposed period.

2. The observations and the 1971-1997 light curve

We present recent observations of ON 231 that are used in this paper to verify the conclusions made from the analysis of the prior data. These observations (DSO-data) were made at the Dark Sky Observatory at Appalachian State University during 37 nights in April 1998 - December 1999. Johnson R and B magnitudes for ON 231 have been obtained in connection with current microvariability studies. Observations were made with an f/12, 0.8 meter reflector equipped with a Photometrics 1024x1024 CCD. Aperture photometry was done on dark subtracted, flat fielded images using comparison star A (Fiorucci & Tosti 1996). Table 1 (only available electronically) presents the nightly averaged R and B magnitudes together with other details of these observations.

The "modern" part (1971-1997) of the total optical light curve (Fig. 1) was used to search the optical variability of ON 231 on the months-years time scales. It contains all B-band brightness estimates available in this time interval (26 references containing these data are listed by Belokon et al. 1999). The measurements made during a particular night were averaged. The vast majority of the observations available in 1970s-1980s are photographic with rms errors mainly in the range of

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⋆ Table 1 is only available electronically at the CDS via anonymous ftp 130.79.128.5

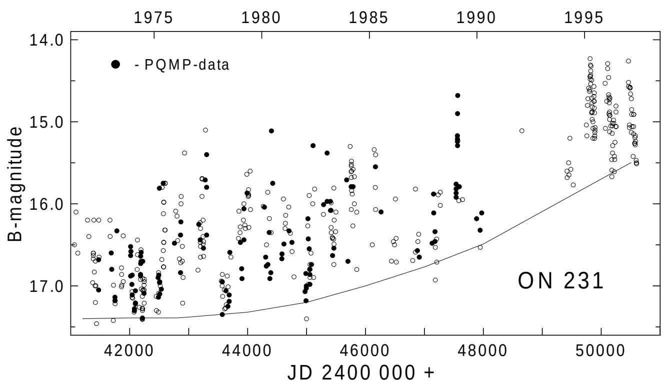

Fig. 1. The B-band light curve (1971-1997) of ON 231 used in the analysis (the references containing the data are listed by Belokon et al. 1999). The data points ($N = 437$) are nightly averaged magnitudes. PQMP-data are marked by filled cycles. The trend (see the text) is shown by solid line.

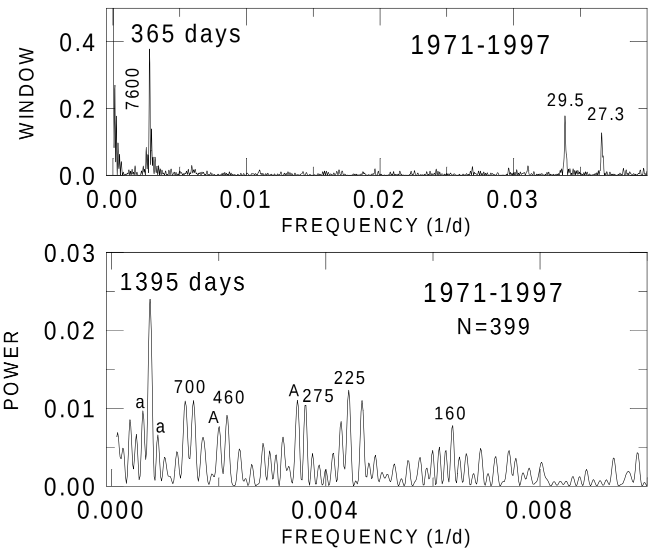

Fig. 2. The power spectrum and window for the 1971-1997 time interval. The spurious peaks are marked by letters.

0.05-0.20mag. The rms errors of CCD data that define the light curve after 1994 are ∼0.02-0.10mag.

The ON 231 light curve (Fig. 1) was significantly supplemented by our 19-year (1972-1990) extensive data set that never was used earlier. These are photographic observations of ON 231 obtained in the course of Petersburg Quasar Monitoring Program (PQMP) carried out at the Astronomical Institute of St.-Petersburg University. ON 231 was observed during 123 nights between April 1972 and March 1990 giving a total of 251 B-band estimates of brightness. The rms errors of the measurements were 0.05-0.15mag depending on the object's brightness. The comparison of the PQMP-data with the "simultaneous" ($\Delta t = 0.04 - 0.42$ days) observations made by other authors showed that their possible systematic differences should be less than 0.1mag. All PQMP-data on ON 231, the details of its reduction and some discussion are presented by Babadzhanyants & Belokon 1999).

3. The results of the updated analysis of the 1971-1997 light curve

The preliminary analysis of the 1971-1997 optical light curve of ON 231 (Belokon & Babadzhanyants 1999) showed evidence for the possible 3.8-year (1414-day) period. We used Fourier analysis modified for unevenly spaced data (Deeming 1975; Horn & Baliunas 1986). The real mean light curve for periodic component was obtained by use of the phase diagram. Its main feature is the outburst with the amplitude of ∼1.5mag and ∼3 years in duration having four-peak structure. The beginning of the next 3-year outburst was predicted to be early 1998.

Intensive monitoring of ON 231 (Tosti et al. 1998b) followed particularly the extraordinary optical outburst occurred in spring 1998 (Massaro et al. 1999) when ON 231 reached a brightness never observed during its whole 100-year history. DSO-data (Table 1) revealed in 1999 new flares. During their maxima ON 231 newly reached the level of brightness that was surpassed only during the spring 1998 outburst. The 1998-1999 extraordinary events give a good possibility to test the proposed 3.8-year period.

Before period verification we refined the analysis of the 1971-1997 light curve. The new analysis differs from the previous one in several aspects: 1) it involves additional data obtained in 1997 (Tosti et al. 1998b) that were unknown at the time of the previous analysis; 2) the baseline trend that should be removed before the analysis was determined more carefully - we used now the data set extended up to 1999 (the trend is obtained as the approximation of all 1971-1999 data by a smoothing cubic spline that was then shifted by nearly 0.7 mag to give the trend as a lower envelope to the light curve). We emphasize that the data obtained in 1998-1999 were used solely for trend determination but not in the power spectrum; 3) a few ($N = 38$) extremely unevenly spaced data available in 1987-1992 were eliminated from the analyzed data set.

Fig. 2 shows the spectral window and the lower frequency part of the power spectrum for 1971-1997 time interval ($N = 399$). In the rest of the power spectrum the peak heights do not exceed 0.006. The spectral window shows prominent peaks at 1 year, both at synodic and sidereal months and at ∼7600 days (due to the large gap in observations). The dominant feature of the power spectrum is the peak at 1395 days (3.8 yr) that indicates the possible true period. The height of this peak normalized to the total variance of the data is ∼1.5 times as large compared with one for the 1414-day peak (Belokon & Babadzhanyants 1999). So, the period is revealed now at a higher confidence level. The spurious peaks arising from the interference of 1395-day harmonic with the features in the data sampling revealed by spectral window are marked by letters. The power spectrum shows also several significant peaks in the range of 160-700 days.

The phase diagram for $P = 1395$ days (Fig. 3) was obtained by using of *all* data points ($N = 437$) available in 1971-1997 time interval. Two internal structural peaks of the periodical outburst presented in the phase diagram for $P = 1414$ days (Belokon & Babadzhanyants 1999) merged now into one broad one. So, the phase interval ∼0.4-0.7 is the region of enhanced level of brightness produced probably by 3-4 flares of ∼50-100 days in duration. The 3rd peak at ∼0.75-0.9 phase interval is formed also by two similar flares. Such structure of these both peaks is clearly seen in distinct cycles also. Unlike both of these, the first peak that is of ∼200 days in duration looks more singular and prominent. But detailed observations in the well-sampled 8th cycle show also some sub-structure formed by variation on the shorter time scales. Besides, the phase diagram shows a double-peak interpulse (phases 0.9-1.1) that occurs between the main 3-year outbursts. It is obvious that the features in power spectrum marked in the range of 160-700 days are produced by the complex structure of periodic outbursts.

Fig. 4 presents the comparison of the observations with the reconstruction light curve obtained as a superposition of the trend and periodical component (its form and the phase are determined by the phase diagram for $P = 1395$ days). The observations demonstrate close similarities in variability behavior in different cycles that correspond to the reconstruction curve. Probably the structural peaks of the outbursts are nearly stable or have a strong tendency to occur at definite phases of 3.8-year period. Up to the 7th cycle the 1395-day reconstruction curve practically coincides with the 1414-day one showing nearly the same correspondence with observed events. But afterwards it shifts somewhat, so, the flare observed in 1997 associates now with the interpulse (the same identification has also the events occurred in the beginning of cycles 3, 4 and 8).

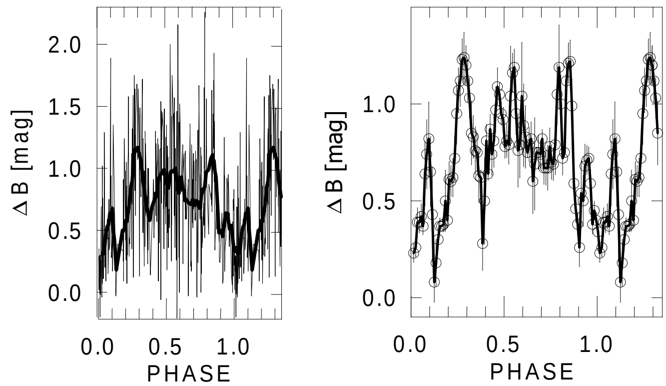

Fig. 3. The phase diagrams for 1395-day period. *Left:* all data points ($N = 437$) are successively connected by lines; by bold line is shown the result of the averaging at phase interval $p = 0.06$ shifted with the step $st = 0.01$. *Right:* $p = 0.03$ and $st = 0.01$; only mean points with their errors are shown.

4. The comparison with more recent data

We compare now the extrapolation of the 1395-day reconstruction light curve outside the analyzed 1971-1997 time interval (Fig. 4) with all data available in 1998-1999 (Tosti et al. 1998b; Efimov & Shakhovskoy 1998; DSO-data from Table 1). R-band data from DSO and Tosti et al. (1998b) that fill the time interval between July and December 1997 were transformed to B by the equation: $B = 1.107 \times R - 0.653$ (Babadzhanyants & Belokon 1999) that suggest a possible systematic difference from true B values within 0.15mag.

All events that occurred during 1998-1999 (8th cycle) are in very good agreement with predicted behavior: the extraordinary outburst occurred in 1998 (Massaro et al. 1999) exactly coincides with the first structural peak of the main outburst and the next three flares observed in 1999 associate with the broad middle peak. Fig. 5 shows as an example the comparison of the 8th cycle with the 2nd and 3rd ones. The close similarity in behavior observed in different cycles appears even in such details as an interpulse (phases 0-0.1 and 0.9-1.0). Note also that the flares observed in 1999 (phases 0.4-0.5 of 8th cycle) are practically the same as were observed in 2nd cycle where this phase interval was also followed. More detail comparison between different cycles confirms that identical details of the periodical outburst structure recur at nearly the same phases of 1395-days period (Belokon et al. 1999). Such recurrent renewal of the details of the periodical outburst structure gives additional independent evidence for the reality of 1395-days period.

The 1395-day reconstruction light curve predicts in mid 2000 the 3rd structural peak that could be as large as outburst observed in the spring of 1998. It may consist of two sub-peaks of ∼50 days in duration as it was observed in 2nd cycle. But we should stress that these predictions suppose that the trend would not break down sharply as happened in 1970 (Tosti et al. 1998a). Besides, there are some uncertainties that may shift the real peak relative to its predicted position. Apart from errors in the determination of the period value and the details of the phase diagram the structural peaks probably may come somewhat earlier or later than it was determined by the phase diagram (see cycles 2 and 3 - Fig. 5). The same property is seen in periodical outbursts in OJ 287 (Sillanpää et al. 1988).

5. Conclusion

The optical light curve of ON 231 in flux units shows the spring 1998 flare as an extraordinary event (Massaro et al. 1999). But at the same time we can consider this flare as an ordinary structural peak of the periodical outburst that has nearly the same amplitude (in magnitudes) as ones which occurred in previous cycles (Fig. 4). The amplitudes of periodical outbursts remain nearly constant (∼2mag) irrespectively of the level of underlying "slow" component - Fig. 5, i.e. the amplitudes of the periodical and a "slow" components expressed in flux units are proportional. So, we should consider as an extraordinary event the extremely high level of the "slow" component which ensures that *all* superimposed structural peaks must be as large (in flux units) as that which occurred in spring 1998. The event putting ON 231 to its present extremely active state started at the beginning of the 1980's when the "slow" increase of brightness began.

If the conclusions made in this paper are confirmed then they should be used for the testing of the blazar models. The multi-peak structure of periodical outbursts in ON 231 poorly

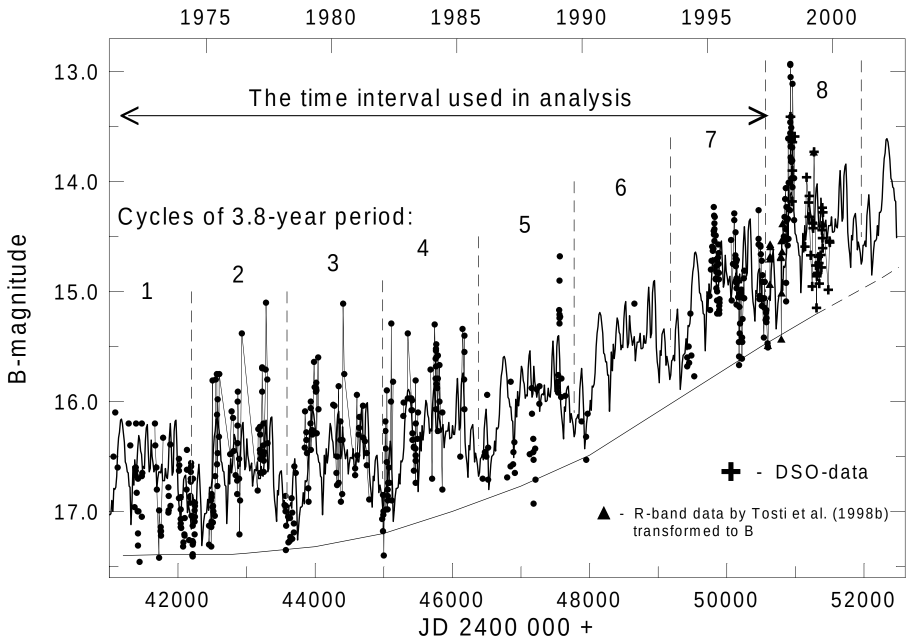

Fig. 4. The reconstruction curve. Its shape and the phase are determined by use of the phase diagram for $P = 1395$ days.

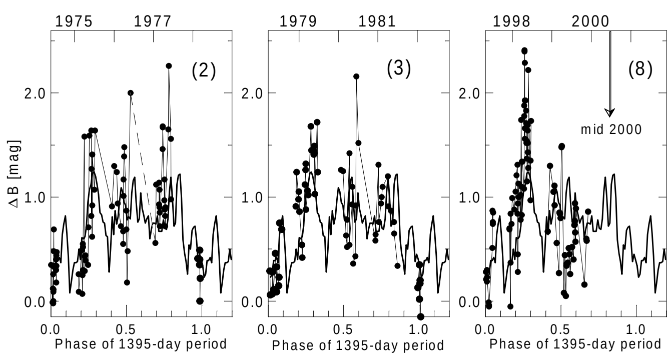

Fig. 5. The comparison of the different cycles of 1395-day period (its numbers are shown in parenthesis); ΔB=B$_{obs}$-B$_{trend}$. The mean light curve for $P = 1395$ days is shown by solid line. *The observations obtained in the 8th cycle were not used in analysis but only for comparison with predicted behavior.*

suits to the basic statement of the model proposed by Lechto & Valtonen (1996) and requires a sufficient correction to one by Villata et al. (1998) that in its present form also explains only the double-peak structure of the periodical outbursts.

Acknowledgements. This work was supported by the RFBR grant N96-02-19731. We also thank NSF and Appalachian State University for their support of the Dark Sky Observatory facility.

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