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LETTER

Letter to the Editor

Extreme intranight variability in the BL Lacertae object AO 0235+164

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Abstract. We present results of two-colour photometry with high time resolution of the violently variable BL Lac object AO 0235+164. We have found extreme intranight variability with amplitudes of ~ 100% over time scales of 24 hours. Changes of 0.5 magnitudes in both R and V bands were measured within a single night, and variations up to 1.2 magnitudes occurred from night to night. A complete outburst with an amplitude ~ 30% was observed during one of the nights, while the spectrum remained unchanged. This seems to support an origin based on a thin relativistic shock propagating in such a way that it changes the viewing angle, as recently suggested by Kraus et al. (1999) and Qian et al. (2000).

Key words: galaxies: BL Lacertae objects: individual: AO 0235+164 – galaxies: photometry – radiation mechanisms: non-thermal

1. Introduction

The BL Lac object AO 0235+164 is one of the most intensively studied blazars. It is a very compact source (e.g. Jones et al. 1984, Chu et al. 1996) which ejects superluminal components with apparent velocities up to $\sim 30c$ (see Fan et al. 1996 and references therein). The object presents emission lines at a redshift of $z = 0.94$ and foreground absorption features at $z = 0.85$ and $z = 0.524$, which have led several authors to study a gravitational microlensing scenario for this source (e.g. Stickel et al. 1988, Abraham et al. 1993).

The historical lightcurves at different optical frequencies of AO 0235+164 have been recently compiled by Fan & Lin (2000). This source is one of the most optically variable BL Lac objects (e.g. Webb et al. 1988). Very rapid changes of its flux density have been reported across the entire electromagnetic spectrum. Quirrenbach et al. (1992), Romero et al. (1997), and Kraus et al. (1999) have detected intraday radio variability. At optical wavelengths, Rabbette et al. (1996), Heidt & Wagner (1996), and Noble & Miller (1996) have found rapid changes of a few tenths of a magnitude within a single night. Schramm et al. (1994) reported extreme optical microvariability (1.6 mag in 48 hours), although not with high time resolution. At high energies, AO 0235+164 has also displayed significant variability (see Hartman et al. 1999).

In this Letter we present the results of two-colour optical CCD photometry with high time resolution of AO 0235+164 carried out with the 2.15-m CASLEO telescope. Our observations revealed one of the most extreme variability events ever observed at optical frequencies in any blazar. The observational results can be used to shed some light on the mechanisms that generate the short-term flux changes in this puzzling object.

2. Observations and data analysis

The observations were carried out during 6 consecutive nights in November 1999 with the 2.15-m CASLEO telescope at El Leoncito, San Juan, Argentina, as part of an extensive program of optical monitoring of gamma-ray blazars. A cryogenically-cooled CCD camera with an excellent cosmetics Tek-1024 chip (with a read-out-noise of 9.6 electrons and a gain of 1.98 electrons adu^{-1}) was used. Originally, several blazars were scheduled for observation with a Johnson V filter, but when it became obvious that A0 0235+164 was undergoing extraordinary brightness variations we focused only on this source and incorporated observations with a Kron-Cousins R filter in order to achieve two-colour photometry and a high time resolution. These conditions were obtained from the third to the last night. Typical integration times were ~ 100 s. The CCD frames were bias subtracted and flat-fielded using dome-flats and twilight frames in order to correct the pixel-to-pixel variations of the CCD. Standard stars selected from Landolt (1992) were also observed each night for magnitude calibration.

Each target frame contained, in addition to the BL Lac object, several stars which were used for comparison and control purposes following the procedures described in detail in Romero et al. (1999). Data reduction was made with the IRAF software package. The aperture routine APPHOT was applied to perform the differential photometry, and lightcurves were calculated as

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target minus comparison star, as usual in this kind of studies (e.g. Carini et al. 1991). In order to avoid possible spurious variability introduced by seeing fluctuations that could affect the blazar but not the point-like stars, we have followed the recommendations of Cellone et al. (2000) and selected an 8-pixel (6.5 arcsec) radius aperture. Checks using plots of the PSF FHWM vs. time confirmed that the aperture was correctly selected, and that the magnitude changes were real and not originated in varying light contamination from the weak foreground galaxies induced by small changes in seeing conditions.

The standard deviation (σ) of comparison minus control stars was adopted as a measurement of the observational errors. The average variability errors were $\sigma_R \approx 0.011$ mag and $\sigma_V \approx 0.012$ mag, whereas the individual photometric errors were typically ~ 0.004 mag and ~ 0.005 mag for the R and V bands, respectively.

Absolute calibration to the standard system was performed for AO 0235+164 and the field stars, tying all nights to the best (photometric) one. The expected zero-point error is 0.01 mag for both R and V bands, although internal consistency in the $V-R$ colours should be better than this. The blazar's standard magnitudes were corrected for Galactic extinction adopting $E_{B-V} = 0.08$ (Schlegel et al. 1998), and absolute flux densities in both bands were calculated using the calibrations of Bessell (1979). Tables with the resulting values of the flux densities of AO 0235+164 from November 3 to November 8 1999 are available upon request from G.E. Romero[1].

Spectral indices for the blazar were computed fitting a power-law spectrum $F \propto \nu^{\alpha}$ and errors adequately propagated from the flux values. Spectral index variability during the observation span was additionally controlled using the scatter of the spectral indices obtained for the field stars $|\sigma_\alpha| \sim 0.074$.

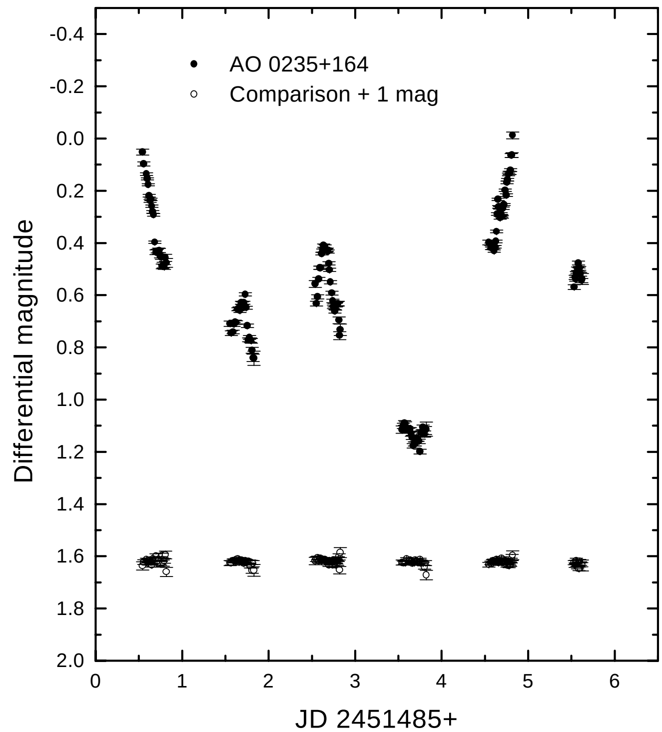

Fig. 1. Differential lightcurve in the V band for AO 0235+164 and comparison star during 6 consecutive nights in November, 1999.

Table 1. Results of optical intranight variability observations of AO 0235+164 (entire campaign)

Band	UT Date	σ (mag)	t_v (hours)	C	Y (%)	FV	$\langle F \rangle$ mJy
R	Nov 5-8, 1999	0.011	26.8	30.9	99.3	1.74	0.872
V	Nov 3-8, 1999	0.012	26.8	26.2	109.4	2.04	0.563

3. Results

The complete differential V-band lightcurve of AO 0235+ 164 is presented in Fig. 1 along with the corresponding curve for the stellar comparison. The confidence of the variability is at a 26.3 σ level. For the R band the confidence is even higher: 30.9 σ. In Table 1 we present a summary of the results obtained from the observations; from left to right we list the observing band, the UT date, the variability error σ obtained from the scatter of the field stars, the timescale of the variability defined as $t_{\rm v} = \Delta F (dF/dt)^{-1}$, the confidence level C of the observed variability estimated as the ratio between the scatter in the BL Lac lightcurve and the observational errors: $C = \sigma_{\rm Bl}/\sigma$, the variability amplitudes defined as in Heidt & Wagner (1996): $Y = 100[(\triangle F)^2 - 2\sigma^2]^{1/2}/\langle F \rangle$ (where $\langle F \rangle$ is the averaged flux density), the fractional variability index defined as $FV = \triangle F/F_{\rm min}$, and, finally, the average flux density in mJy.

The lightcurve shown in Fig. 1 presents one of the most extreme forms of optical variability reported in the literature since the introduction of CCD cameras. Between the fourth and the fifth nights the source brightness changed by ~ 1.2 mag in about 24 hours. Translated to flux density this means a change of about 100%: the source doubled its flux density in one day. During the fifth night there was a variation of ~ 0.5 mag in six hours. This extreme behaviour is even more violent than the very strong outbursts observed in 1990 and 1991 by Noble & Miller (1996) in this same object, when intranight amplitudes of ~ 0.25 mag were registered.

In Fig. 2 we show the spectral index evolution during the observations (starting on the third night when the R filter was incorporated). The average index is $\langle \alpha \rangle = -3.04$ (i.e., $\langle (V-R)_0 \rangle = 0.68$), a steep value in agreement with the very red colour indices quoted by Véron-Cetty & Véron (2000). Some day-to-day variability seems to be present in the spectral index, but the confidence level ($C = 1.65$) is too low as to be conclusive. A Pearson's correlation analysis yields values of $r = 0.87$ for the linear correlation between both bands and the spectral index, whereas it is $r \approx 0.5$ for the stars, as expected just from correlated observational errors. This could mean a trend in the sense that the source becomes brighter when the spectrum gets harder, as observed in other blazars (e.g. Romero et al. 2000

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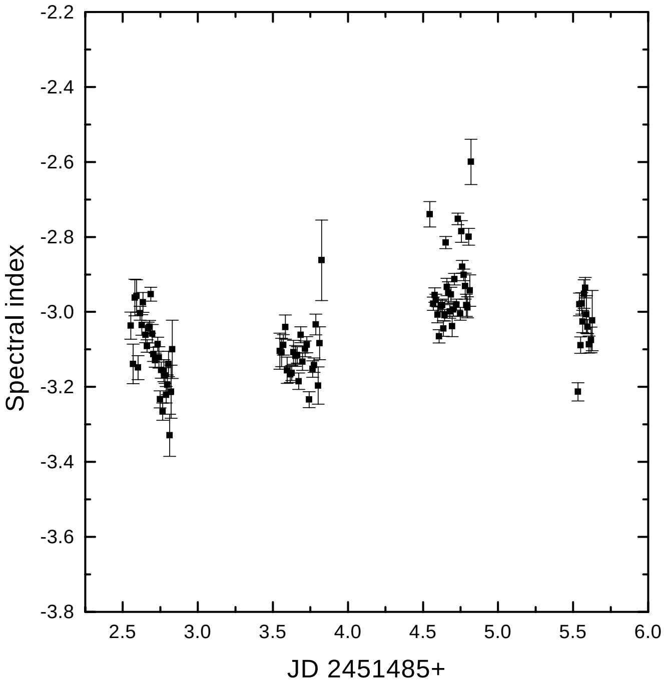

Fig. 2. Spectral index during the observations.

and references therein). But, we emphasize, the confidence level is too low as to allow any conclusion in this respect.

A correlation analysis using an interpolated correlation function (ICF) gives a time lag of just 14.7 minutes for the entire lightcurves, in the sense that variations appear first at higher frequencies. However, the associated error, determined as in Gaskell & Peterson (1987), is 31.5 minutes, hence the variations can be considered as simultaneous at both bands.

On the night of November 5, a complete outburst was observed. The flux density in the V-band changed from $F_{\min} \approx 0.46$ mJy to $F_{\max} \approx 0.63$ mJy at a rate of $\langle dF/dt \rangle \approx 0.04$ mJy/hr and returned to its original value in 6 hours. This means a fluctuation with an amplitude $Y \approx 30.4\%$ in the V band. In the R band the variation was similar: $Y \approx 29.4\%$, with identical timescale. The ICF analysis is consistent with no time lag at all: $\langle \mathrm{lag} \rangle = 1.3 \pm 5.7$ minutes. During the outburst, the spectral index did not undergo significant changes; its average value was $\langle \alpha \rangle = -3.11$, with a scatter of $\sigma = 0.09$ for the entire night. In Fig. 3 we show the lightcurves in both bands for this event as well as the spectral index behaviour.

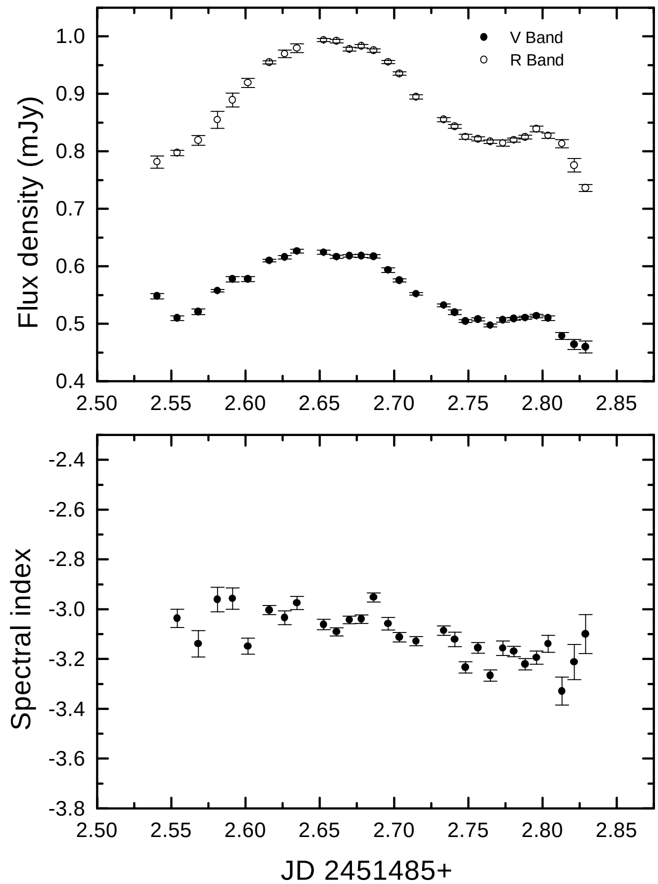

Fig. 3. Outburst observed on November 5, 1999.

4. Discussion

Several models have been proposed to explain the rapid variability of AO 0235+164. Interstellar scintillation is only relevant at cm-wavelengths (e.g. Romero et al. 1997, Kraus et al. 1999), but relativistic shocks and gravitational microlensing can produce important changes in the flux density at optical wavelengths. Accretion disk instabilities are also often invoked as a source of optical variations in AGNs (e.g. Wiita 1996), but any accretion disk model would have enormous difficulties to explain outbursts of about 100% in a few hours. Extremely large and rapid optical variations require the introduction of relativistic effects in order to be explained (e.g. Marscher 1992). These effects are present if an important part of the emission received by the observer is originated in a superluminal feature, such as a thin relativistic shock propagating down the jet of the source. Rapid variability, then, arises when the shock interacts with density inhomogeneities or turbulent features in the flow (e.g. Marscher 1990, Qian et al. 1991, Romero 1995). The shock evolution, however, is not achromatic: radiative losses make the source brighter when the spectrum flattens (e.g. Marscher 1997). This is not the case for the rapid outburst shown in Fig. 3, although the evolution of the source during the entire observational campaign could be consistent with this behaviour (as we mentioned above the confidence on this point is not too high). The rapid change observed on November 5 1999, on the contrary, suggests a geometric origin because of its lack of spectral variability and time symmetry.

Kraus et al. (1999) outlined a precessing jet model for AO 0235+164 where the trajectory of the shocked components is determined by collimation in the magnetic field of the perturbed beam, which can develop an helical configuration. This model has been recently expanded by Qian et al. (2000) in order to include aberration effects. If the relativistic source changes the viewing angle due to its propagation through the helical path, the Doppler factor should vary, introducing important changes in the observed flux density. For a Lorentz factor $\Gamma = 25$ (Qian et al. 2000), a small change from 0° to 1° in the direction of the shock with the line of sight would result in a change from 50 to 42 in the Doppler factor, and, consequently, in a flux variation of $\sim 70\%$ for the emitting component at all optical wavebands. If the contribution from this component represents a significant fraction of the total flux density, changes of $\sim 30\%$ can be easily obtained without variations in the spectral index. If aberration effects are included, then the helical beam model can also explain the radio behaviour observed by Kraus et al. (1999), as it is shown by Qian et al. (2000), as well as possible rotations of the polarization angle (e.g. Königl & Choudhuri 1985, Romero et al. 1995a).

Alternatively to intrinsic models involving shocks, superluminal gravitational microlensing (e.g. Romero et al. 1995b) could explain the rapid and time symmetric outbursts observed in AO 0235+164. This is also an achromatic phenomenon; small lenses in the interposed galaxies could amplify the emission from a thin shock producing fast variations superposed to the longer ones, which are due to the shock propagation. Although this mechanism probably fails at radio frequencies because temperatures in excess to the inverse Compton limit are demanded for the emitting region in the blazar, at optical bands it cannot be ruled out at present (see Rabbette et al. 1996 for additional details and numerical estimates). The fact that a similar outburst was observed on the night of November 4 (only in the V band) opens the question of how frequently these outbursts occur. A large number could pose problems to the microlensing interpretation because a high density of small lenses would be required in the interposed galaxy, leading to a "smearing out" of the individual outbursts.

Future simultaneous radio-optical observations with high time resolution, as well as rapid polarimetric observations, would be very helpful to improve our understanding of this extraordinary blazar.

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