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Extreme photopolarimetric behaviour of the blazar AO 0235+164*

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ABSTRACT

We present optical photopolarimetric observations with high temporal resolution of the blazar AO 0235+164. Our data, the first to test the photopolarimetric behaviour of this object at very short time-scales, show significant micro-variability in total flux, colour index, linear polarization degree and position angle. Strong inter-night variations are also detected for these parameters. Although no correlation between colour index and total flux was found, our data seem to support the general bluer-when-brighter trend already known for this object. The polarization degree, in turn, shows no correlation with total flux, but a clear trend in the sense that colour index is redder (the spectrum is softer) when the measured polarization is higher.

Key words: BL Lacertae objects: individual: AO 0235+164 – galaxies: active – galaxies: photometry.

1 INTRODUCTION

The BL Lacertae object AO 0235+164 is one of the most intensively monitored and variable blazars (e.g. Webb et al. 1988). Very rapid changes in its flux density have been reported across the entire electromagnetic spectrum, from radio frequencies (Quirrenbach et al. 1992; Romero et al. 1997; Kraus et al. 1999) to gamma-ray energies (Hartman et al. 1999).

At optical wavelengths, rapid variations of a few tenths of a magnitude within a single night have been repeatedly detected (Rabbette et al. 1996; Heidt & Wagner 1996; Noble & Miller 1996). Romero, Cellone & Combi (2000) found the most extreme variability event ever reported for this object: changes of up to 0.5 mag in the R and V bands were detected within a single night, whereas night-to-night variations reached up to 1.2 mag.

The historical optical light-curve of AO 0235+164 has been compiled by Fan & Lin (2000), while several international follow-up campaigns have provided detailed multiwavelength monitoring for this object (Raiteri et al. 2001, 2005). Those data suggested the existence of a ~5.7 yr quasi-periodical behaviour, then leading to an interpretation in terms of a binary supermassive black hole system at the core of the source (Romero, Fan & Nuza 2003; Ostorero, Villata & Raiteri 2004). Recent multifrequency observations by Raiteri et al. (2006), however, have suggested a longer (~8 yr) periodicity.

On the other hand, as the optical emission in blazars is expected to be dominated by synchrotron radiation from the relativistic jet, optical polarimetry is a useful tool to probe the innermost regions of these objects, especially when high time-resolution data are obtained (Andruchow et al. 2003). In spite of this fact, polarimetric observations of blazars are still scarce, and the first attempts to characterize the polarimetric microvariability of different blazar classes have just recently been done (Andruchow, Romero & Cellone 2005). In the particular case of AO 0235+164, previous studies revealed high degrees of optical polarization (e.g. Mead et al. 1990), with inter-night random fluctuations (Takalo et al. 1992), but nothing was known about its polarimetric behaviour on very short time-scales.

In this Letter we present the first insight into the polarimetric micro-variability of AO 0235+164. Our high-temporal resolution data show significant variations both in the linear polarization degree and the position angle at intra-night as well as at inter-night time-scales. Simultaneous differential photometry (at the B and R bands) shows that no apparent correlation exists between variations in polarized and total flux. However, there is a clear trend in the sense that the $(B - R)$ colour gets redder (i.e. the spectrum gets softer) when the polarization degree is higher.

We present our observational data in Section 2, we give the photometric and polarimetric variability results in Section 3, and we close with a short discussion and our conclusions in Section 4.

2 OBSERVATIONS AND DATA REDUCTION

We observed AO 0235+164 over six nights in 2005 November and two additional nights in 2005 December, using the Calar Alto Faint Object Spectrograph (CAFOS) in its imaging polarimetry mode, at

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the Calar Alto (Spain) 2.2-m telescope. In this instrumental set-up, a polarizer unit, consisting of a Wollaston prism plus a rotatable half-wave plate, is inserted into the light beam, thus producing two orthogonally polarized images of each object on the focal plane, separated by 18.9 arcsec. The detector was a SITE#1d CCD, with 2k × 2k 24 μm pixels, a gain of 2.3 electrons adu^{-1}, and a read-out noise of 5.06 electrons.

In order to avoid any possible overlapping of the ordinary (O) image of one object with the extraordinary (E) image of a different object, a mask with alternate blind and clear stripes is placed before the detector. Hence each polarimetric frame consists of alternate O and E ∼20-arcsec wide stripes. This procedure also enhances the signal-to-noise (S/N) ratio by reducing the sky contribution to half its otherwise value, although, as a drawback, half of the field of view is lost.

Four frames, each taken with a different position of the half-wave plate (0°, 22°.5, 45°, 67°.5) are needed to obtain the normalized Stokes parameters (U, Q) for linear polarization. The relevant expressions for U and Q can be found in e.g. Lamy & Hutsemekers (1999) and Zapatero Osorio, Caballero & Béjar (2005). From them, the degree of linear polarization and its corresponding position angle are calculated in the usual way:

$$P = \sqrt{Q^2 + U^2}, \tag{1}$$

$$\Theta = \frac{1}{2}\arctan\left(\frac{U}{Q}\right). \tag{2}$$

On the other hand, by adding the fluxes corresponding to the O and E images of the same object within each frame, photometric data are also obtained. This allowed us to simultaneously study both the photometric and the polarimetric behaviours of our target with time. Hence, our observational program consisted of unit blocks with the following form.

(i) Four consecutive frames, taken with the polarizer unit in the light path, with half-wave plate angles 0°, 22°.5, 45°, and 67°.5, respectively, all obtained through an R (Cousins) filter. From these we obtained one polarimetric data point and four photometric, R-band, data points.

(ii) One B frame, without the polarizer unit. This gave us a photometric B-band data point.

A sequence of N such five-frame blocks was obtained for AO 0235+164 each night, with $3 \leqslant N \leqslant 11$, depending on the observing conditions. This procedure gave us N polarimetric (R-band) data points, N photometric B data points, and $4N$ photometric R data points per night. The exception is the night of 2005 November 03–04, when just two photometric R data could be obtained, due to bad weather. Individual integration times ranged from 360 to 450 s for B, and between 240 and 360 s for R (all four R-band frames within a given polarimetric block were obtained with identical exposure times). Several standard highly polarized and unpolarized stars from Turnshek et al. (1990) were also observed (at least two polarimetric cycles each) for calibration purposes.

Atmospheric conditions were dissimilar throughout the whole observing time, ranging from high-quality photometric nights to rather mediocre conditions due to poor seeing and/or passing cirrus. However, given that both polarimetry and differential photometry are robust against poor observing conditions, these had no systematic impact on our data, except for a loose in S/N ratio. We shall discuss this further below (see Section 3).

All science frames were bias-corrected using a master bias prepared from 30 individual bias frames, and flat-fielded using twilight sky flats. Standard routines within the IRAF[1] package were used for image processing and all subsequent data extraction.

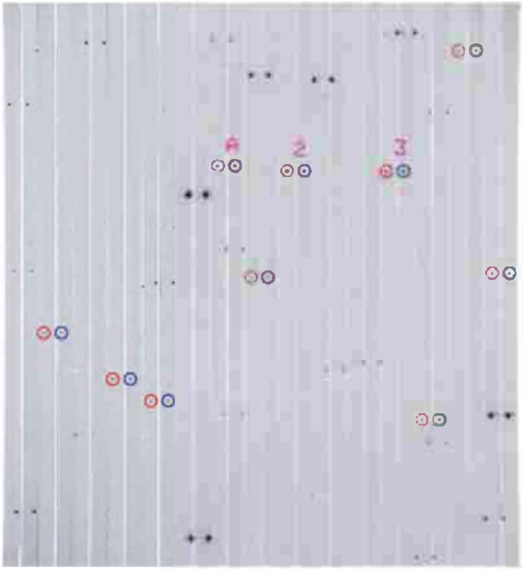

Figure 1. Polarimetric frame of the observed field (R-band). For each measured object, red and blue circles mark the ordinary and extraordinary images, respectively. AO 0235+164 (A) as well as stars used for differential photometry are labelled. East is up, north is to the right.

We obtained the instrumental magnitudes corresponding to both the O and E images of AO 0235+164 on each frame, using the aperture photometry task APPHOT. The same was done for nine stars evenly distributed on the field and suitably placed within the mask stripes (i.e. we rejected stars close to the edge of a stripe). These stars were used to evaluate the instrumental/foreground polarization, while two of them were used to construct the differential photometry light-curves (see Section 3). All the measured objects in the field are shown in Fig. 1; for each object, red and blue circles mark the O and E images, respectively. Our target (AO 0235+164) as well as the two stars used for differential photometry (see Section 3.1) are labelled.

A 3-arcsec radius aperture was always used. Blazar photopolarimetry can be affected by spurious variations due to the host galaxy (Cellone, Romero & Combi 2000; Andruchow 2006), but this should not be relevant for AO 0235+164 given its relatively high redshift ($z = 0.94$). However, a possible error source is an active galactic nucleus (AGN) lying ∼2 arcsec south of AO 0235+164 (named ELISA in Raiteri et al. 2005), which we resolve on our best-seeing images, but which appears merged with our target on the rest. We checked for any spurious effect on the photopolarimetric variability of AO 0235+164 by comparing data obtained through different apertures against each other. Except for a change in S/N ratio, there was no significant difference. We also checked for any correlation between photopolarimetric variability and changes in the seeing full-width at half-maximum (FWHM), finding none. Hence,we conclude that no systematic errors due to this nearby object significantly affect our variability results. However, constant shifts are expected in total and polarized flux due to ELISA and a faint absorbing galaxy

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[1] IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the NSF, USA.

~1.3 arcsec east from AO 0235+164 (G1 in Nilsson et al. 1996), respectively. We shall return to this point in Section 3.

A local sky value was measured, as usual, within an annulus surrounding each aperture. As both O and E images of the same source are close (~20 arcsec) to each other on the polarimetric frames, all pixels corresponding to the E image (including sky) were masked out when measuring the O image, and vice-versa.

3 RESULTS

3.1 Photometry

The differential light-curve for AO 0235+164 was obtained in the usual way, using a non-variable star (here named star 2) in the field as comparison (e.g. Howell & Jacoby 1986), while another star (3) was used to construct a second differential light-curve against star 2, to be used for control purposes (see Fig. 1). These two stars are the same ones we used in our previous studies of AO 0235+164 (Romero et al. 2000, 2002); star 2 is also star 8 in Smith et al. (1985) and star 10 in González-Pérez, Kidger & Martín-Luis (2001).

The results are shown in Figs 2 and 3 for the R and B bands, respectively. Strong inter-night as well as significant intra-night variations are clearly seen, with similar behaviours in both bands. Note the stability of the control light curves (lower panels). The statistical significance of intra-night variations was assessed following Howell, Warnock & Mitchell (1988), i.e. defining a scaled confidence parameter $C\Gamma^{-1}$ which depends on the dispersions of both light-curves (target–comparison and control–comparison) and on a corrective factor that equalizes their respective instrumental errors (see also Cellone, Romero & Araudo 2007). Table 1 gives the date (column 1), number of R-band data points (column 2), target–comparison light-curve dispersion (column 3), control–comparison light-curve dispersion (column 4), scaled confidence parameter (column 5) and variability classification, which is 'YES' when $C\Gamma^{-1} \geqslant 2.576$ (column 6).

For the first, fourth and fifth nights we have well-sampled light-curves displaying significant intra-night variability. We get a formally very high value of $C\Gamma^{-1}$ for the second night, although with only two data points in R. Despite this poor sampling due to bad weather, these data follow the inter-night trend: AO 0235+164 brightened by ~0.95 mag from the first to the third nights. During the last night in November and both December nights, AO 0235+164 displayed no significant intra-night variability.

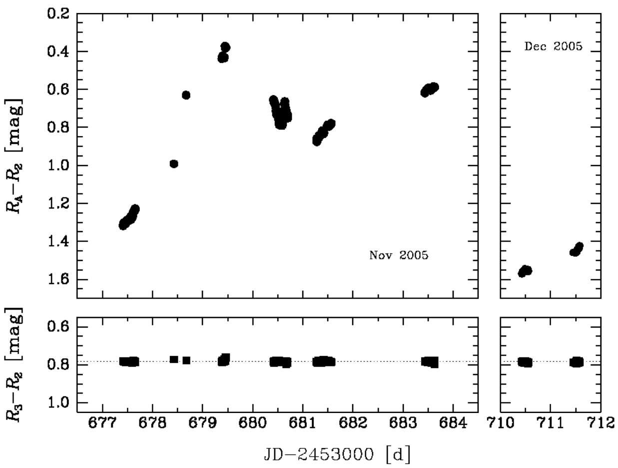

Figure 2. R-band differential light-curve for AO 0235+164 versus comparison star (upper panels) and for control-star versus comparison star (lower panels) for the whole campaign (left: 2005 November, right: 2005 December).

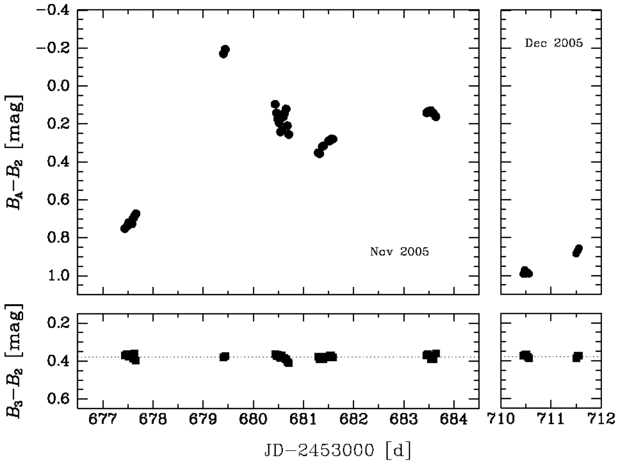

Figure 3. Same as Fig. 3 for the B-band.

Table 1. Variability parameters for the R light-curve on different nights.

Night	N	σ_{A-2} (mag)	σ_{3-2} (mag)	$C\Gamma^{-1}$	Variable?
November 2–3	32	0.026	0.004	6.559	YES
November 3–4	2	0.256	0.003	102.992	YES
November 4–5	12	0.026	0.007	3.980	YES
November 5–6	44	0.042	0.004	11.065	YES
November 6–7	40	0.030	0.004	7.698	YES
November 8–9	28	0.008	0.004	1.942	NO
December 5–6	20	0.008	0.005	1.570	NO
December 6–7	16	0.013	0.005	2.556	NO
Whole campaign	194	0.357	0.005	78.327	YES

We also calculated R and B magnitudes for AO 0235+164 in the standard system. To do so, we used photometry of field stars from our own previous data (star 2: $R_2 = 15.828$, Romero et al. 2000) and from the literature (Smith et al. 1985; González-Pérez et al. 2001). During our observations, AO 0235+164 ranged between $16.2 \lesssim R \lesssim 17.4$ mag; i.e. it was at a state of moderate brightness as compared to its historical light-curve, and about 2 mag fainter than during its major outbursts (e.g. Raiteri et al. 2005). $B - R$ colour indices were calculated by interpolating R and B magnitudes to common time-instants.

We verified that subtracting the flux contribution from ELISA and correcting for Galactic plus foreground absorption does not change our micro-variability results in any significant way, except for nearly constant shifts in the light curves (~1.2 and ~1.8 mag brighter in R and B, respectively). However, the colour index is significantly affected. We thus obtained a corrected colour index $(B - R)_0$ following Raiteri et al. (2005), and we transformed it to spectral index α ($F_\nu \propto \nu^{-\alpha}$), using $\lambda_B = 0.44$ µm, $\lambda_R = 0.64$ µm (Bessell 1979).

3.2 Polarimetry

We obtained the linear polarization percentage (P) and position angle (Θ) for AO 0235+164 using equations (1) and (2), as outlined in Section 2. The contribution from instrumental polarization was derived from data on unpolarized standard stars, while foreground polarization was estimated from star 2, which lies at 76 arcsec from

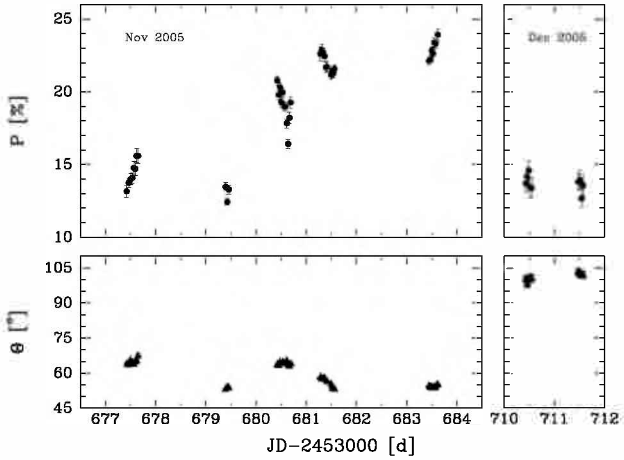

Figure 4. *R*-band polarization (upper panels) and position angle (lower panels) against time for the whole campaign.

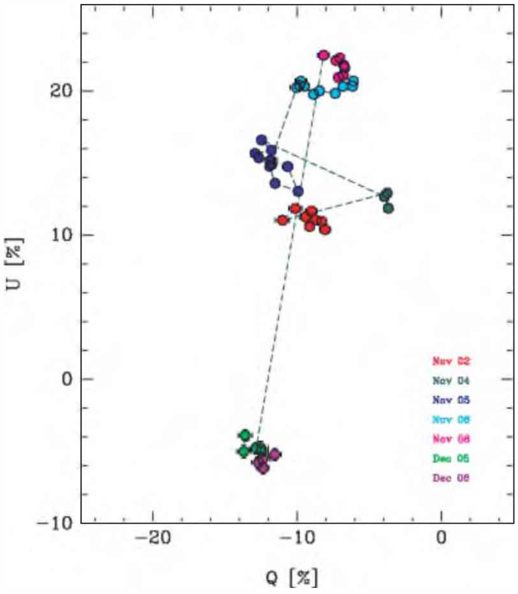

Figure 5. Evolution of the polarization on the Stokes plane. Different colours are used for data corresponding to different nights.

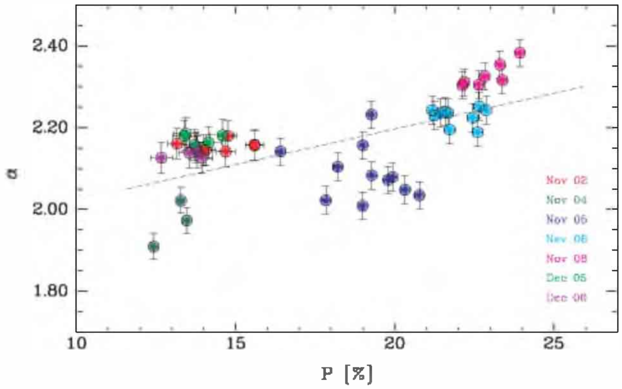

Figure 6. Spectral index against polarization. Different colours are used for data corresponding to different nights. The total least-squares fit (equation 3) is shown with a dashed line.

AO 0235+164. Foreground polarization is small (<0.5 per cent), in agreement with the low Galactic extinction towards AO 0235+164. We also checked for any dependence of instrumental polarization with position on the CCD. Stars near the border of the field tend to display relatively large *P* values; however, because AO 0235+164 was always centrally placed on the field, no systematic effect is expected on our polarimetric curves. The position angle was transformed to the Equatorial system using data from highly polarized standard stars.

Fig. 4 shows the behaviour of *P* and Θ throughout the whole campaign. The degree of polarization was high ($12.5 \lesssim P \lesssim 24.0$ per cent) and clearly variable, both at intra- and inter-night time-scales. The position angle was also variable, although no clear connection between the behaviours of both parameters can be seen. In fact, some of the nights AO 0235+164 displayed conspicuous variability in *P* without any significant change in Θ, while the converse is also true.

The significance of *P* and Θ variability for AO 0235+164 can be assessed by comparing it with the behaviour of these same parameters for field stars. We found that the dispersions of the *P* and Θ curves against time for the stars strongly depend on their magnitudes, as expected because in this case any variability should be due to errors. From these relations, we estimated the dispersions in polarization degree and position angle for AO 0235+164, expected just from errors, to be $0.10 \lesssim \sigma_P \lesssim 0.39$ per cent and $0.^\circ23 \lesssim \sigma_\Theta \lesssim 0.^\circ84$, respectively. As a result, five out of seven nights with polarimetric data available show statistically significant ($>3\sigma$) microvariability in *P*, while just two of them show significant microvariability in Θ. Note that intra-night variability amplitudes up to $\Delta P \simeq 4.4$ per cent ($\sim 8\,\sigma_P$) and $\Delta\Theta \simeq 5^\circ$ ($\sim 6\,\sigma_\Theta$) were detected. Dust absortion from the foreground galaxy G1 would introduce a constant shift in *P* amounting to, at the very most, ~ 2.8 per cent, but with no variability effect.

The behaviour of AO 0235+164 on the Stokes plane is shown in Fig. 5. Note the different location of the 2005 December data ($Q \approx -13$ per cent, $U \approx -5$ per cent) as compared to those at the beginning of our campaign, despite their similar *P* values. This underscores that there is no correlation between *P* and Θ. Neither there is any correlation between *P* and the source brightness or the variability gradient of the observed flux.

A well-defined correlation appears to exist, instead, between *P* and the corrected colour index $(B-R)_0$ (or spectral index α). As shown in Fig. 6, *P* tended to be lower when the spectrum was harder, although the relation displays a significant scatter.

4 DISCUSSION AND CONCLUSIONS

Fan & Lin (2000) suggest a two-component origin for the optical emission of AO 0235+164, given that its colour index versus magnitude relation seems to show two different behaviours, depending on the overall flux level of the source. Previous micro-variability data (Romero et al. 2000) have suggested, although with a low confidence level, a mean trend in the sense that the optical emission of AO 0235+164 became brighter when its spectrum was harder. Our present data span rather limited ranges both in magnitude and colour index [$\Delta R \simeq 1.4$ mag; $\Delta(B-R)_0 \simeq 0.19$ mag], so this may be the reason why we did not detect any definite trend between colour index and magnitude. In any case, our data fall at the low-luminosity end of the relation shown in Raiteri et al. (2001, their fig. 7), which displays a redder-when-fainter behaviour. The relatively large scatter of this relation would thus be intrinsic, as micro-variations usually do not follow the general trend.

As mentioned in the previous section, we did not detect any clear correlation between polarization degree and total flux. This lack of correlation seems to be a common feature of microvariability in blazars (e.g. Tommasi et al. 2001). However, a well-defined relation between polarization degree and spectral index does show up from our data (Fig. 6). Note that this relation is in the opposite sense of that which would result if the decrease in polarization degree were due to a higher relative contribution from the (redder, unpolarized) host galaxy light.

The spectral index ranged from 1.91 to 2.38, and we obtained the following linear relation against polarization degree:

$$P(\text{per cent}) = (56.3 \pm 1.4)\,\alpha - (103.7 \pm 3.1). \tag{3}$$

This relation is in qualitatively good agreement with those found for 3C 66A (Efimov & Primak 2006) and OJ 287 (Efimov et al. 2002), suggesting that, despite the different time-scales involved in those studies, a similar mechanism could be operating in all three objects. Efimov & Primak (2006) propose that the polarization degree decreases when the ratio between the strength of the regular and the chaotic components of the magnetic field decreases due to blobs moving along the jet, thus breaking up the ordered structure of the field. The higher degree of disorder in the magnetic field also leads to a hardening of the spectrum.

Alternatively, Ballard et al. (1990) suggested that the frequency dependency of the polarization can be interpreted in terms of an inhomogeneous model, with two components contributing to the optical emission. One is a polarized component with a high-energy cut-off that could be identified with the radiation produced by shock-accelerated electrons in the compressed magnetic field lines. The other component would have a steeper spectral index and slight polarization and could correspond to the underlying jet emission. Changes in the cut-off, due to variable energy losses, would lead to a harder spectrum (lower α) when the unpolarized component dominates the optical emission.

Raiteri et al. (2006) have recently presented observational support for an additional component, in the form of a UV–soft X-ray bump, lying between the synchrotron and inverse Compton peaks in the spectral energy distribution of AO 0235+164. They suggest this extra component may arise from a thermal accretion disc or from a distinct region in an inhomogeneous jet. In either case, changes in P, spectral index and total flux are expected.

In the present Letter we have reported the existence of extremely rapid variability in the optical flux and, for the first time, in the optical polarization of the blazar AO 0235+164. There is no correlation between the variability of both parameters, but a clear correlation is observed between the spectral index and the polarization, in the sense that the polarization is lower when the spectrum is harder. Such a behaviour might be the effect of shocks moving through the inner jet of the source. These shocks could be formed by collisions of relativistic plasma outflows with different velocities. Alternatively, a two-component model, particularly if the UV–soft X-ray bump has a thermal origin, could naturally lead to correlated variability in polarization and spectral index. Long-term polarization observations could reveal whether this phenomenology is present on other time-scales, yielding then useful information to further constrain the different models.

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