Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **439,** 639–643 (2014) doi:10.1093/mnras/stt2487
Advance Access publication 2014 January 28

Optical photopolarimetry of blazar OJ287★

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Accepted 2013 December 23. Received 2013 December 23; in original form 2013 November 12

ABSTRACT

We present results from an original observational campaign comprising five epoch optical photopolarimetrical observations of the BL Lac-type AGN OJ287 in the period 2012 November–2013 April. The data are gathered with the Focal Reducer Rozhen 2 (FoReRo2) on the 2-m RCC telescope at NAO Rozhen, Bulgaria. We derive photometry and polarization in the *R* band as well as position angle (PA). There are indications for correlation between polarization and brightness in the *R* band. Furthermore, observed variation in PA corresponds to a rotation of the plane of polarization of 5.80 deg d^{-1}.

Key words: techniques: polarimetric – galaxies: active – BL Lacertae objects: general – BL Lacertae objects: individual: OJ287 – galaxies: nuclei – quasars: general.

1 INTRODUCTION

Blazars are very powerful and extremely variable sources of polarized radiation. At $z = 0.306$, the BL Lac-type object OJ287 is one of the most well-observed blazars. In fact, observations of its light curve date back to the year 1891 (Valtonen & Ciprini 2012). But OJ287 is one of the most peculiar AGNs as well. It shows well-defined period of 12 yr (Sillanpää et al. 1996). Different theoretical models has been proposed to explain its characteristically double-peaked flaring activity during outburst (Sillanpää et al. 1988; Katz 1997; Sundelius et al. 1997; Villata et al. 1998; Valtaoja et al. 2000). The favoured current model is of a binary black hole system with relativistic precession (Valtonen & Ciprini 2012). It is interesting to note that, according to Neronov & Vovk (2011), the relativistic beamed emission may come from the jet, produced by the smaller secondary black hole.

The analysis of polarization behaviour plays a key role in the study of blazars (Barres de Almeida et al. 2010). Polarization measurements for OJ287, especially during outburst (Valtaoja et al. 2000), are of crucial importance. The motivation is that the first of the two flares in OJ287 during outburst is thermal (i.e. not polarized). This is shown by the lack of corresponding radio emission (Valtaoja et al. 2000). But the second flare is model dependent and could be due either to synchrotron radiation, which is polarized (Valtaoja et al. 2000), or can be unpolarized or low-polarized bremsstrahlung (Valtonen & Ciprini 2012). The polarization is a key factor to distinguish among different theoretical models.

A number of multiwavelength observational campaigns have been performed in the last years (Valtaoja et al. 2000; Efimov et al. 2002; Ciprini et al. 2007; Nieppola et al. 2009; Villforth et al. 2010; Valtonen & Ciprini 2012). Results from the 2005–2010 observational campaign show that the flare during the 2005 outburst is due to bremsstrahlung radiation instead of a synchrotron one (Valtonen & Ciprini 2012). This provides strong background to the binary black hole model with ultrarelativistic precession. This also allows for the use of OJ287 as a test of general relativity (Valtonen & Ciprini 2012). Surprisingly, in 2012 April, OJ287 showed a peak in brightness (Santangelo 2012) that was not expected by any of the current models. Possible theoretical explanations according to the binary black hole model can be found in Pihajoki et al. (2013).

There are indications that position angle (PA) change is between 2 deg (D'arcangelo et al. 2009) and 5 deg d^{-1} (Efimov et al. 2002). But there is a real shortage of optical photopolarimetrical campaigns. Possible correlation between optical flux and polarization degree for OJ287 is suggested by observations from Takalo, Sillanpää & Nilsson 1994, but is not well established so far (Jorstad et al. 2007 Villforth et al. 2010).

Complete data of polarization behaviour and PA measurements, combined with simultaneous photometrical data of OJ287, are important for understanding the underlying physics of this peculiar object. But our work is not aimed at discussing the various theoretical models for OJ287. Instead, we focus on original observational photopolarimetrical study and, as a result, we get some exciting new insights.

2 OBSERVATIONS AND DATA REDUCTION

We present original photopolarimetrical study of OJ287 with the focal reducer Rozhen 2 – FoReRo2 (Jockers et al. 2000) on the 2-m Ritchey–Cretien–Coudé (RCC) telescope at NAO Rozhen, Bulgaria. The observational data are taken on the nights of 2012 November 17 and 18 (preliminary results of these two nights are

★ Based on data collected with 2-m RCC telescope with FoReRo2 at Rozhen National Astronomical Observatory, Bulgaria.
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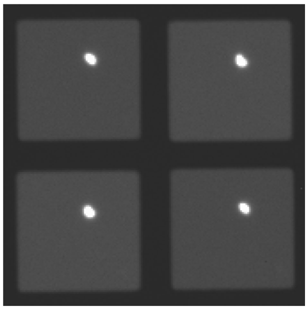

Figure 1. CCD image from the polarizer with two combined Wollaston prisms. Each of the four squares correspond to a polarized beam orientations at (respectively) 0, 90, 45 and 135 deg.

published in Bozhilov, Borisov & Ovcharov 2013), 2013 January 13, 2013 April 04 and 2013 April 05. Data from the last three nights are published for the first time, as well is the full-scale analysis of our observational campaign on OJ287.

We use colour splitter that transmits redder than 5800 Å light into the red channel and reflects bluer than 5100 Å one into the blue channel of the reducer. Polarimetrical measurements in the *B* are not performed, but the *B*-band data are used for photometrical measurements (Bozhilov et al. 2013). We used a special optical element with two Wollaston prisms. They are combined to form a single polarizer. The PA of the prisms differ by 45 deg. Thus, we get four polarized beams with orientations at 0, 90, 45 and 135 deg each. These are simultaneously captured by the CCD detector. In Fig. 1 is shown an example of real-life image.

Armed with this experimental setup, we can perform polarization determination using Stokes equations (see Landi Degl'Innocenti & Landolfi 2004, chapters 1.6 and 1.7 for elaborate details). A detailed description of the method of measurements and the calculations can be found in Geyer et al. (1996).

Details on the observations of OJ287 and standard stars, number of images, exposures and total integration time are presented in Table 1.

In order to determine instrumental optical polarization, according to Stokes equations (Geyer et al. 1996), we used low-polarization standard stars HD 10476, HD 90508, HD 144287 and high-polarization standard stars HD 14433, HD 43384, HD 154445 for the nights of 2012 November, 2013 January and April, respectively (see Table 2). Here, we have to note that the deviation of the measured PA for the high-polarized stars are relatively high. Thus, we see the need to perform a special observation campaign just to test the instrumental polarization of our setup.

3 RESULTS AND DISCUSSION

Results for the polarization and PA are shown in Table 3. Photometrical measurements are shown in Table 4.

In Table 5, we present the standard stars' measured polarization and the catalogue values. The discrepancy accounts for the intrinsic instrumental polarization. The errors are pretty large, but still, given the number of observing nights and weighting all the observations, we can get relatively good approximations. In addition, note that the observed optical polarized flux is contaminated by unpolarized flux and this strongly affects the polarization and PA determination using Stokes parameters, as explained in Villforth et al. (2010).

OJ287 polarization and PA are known to vary extremely rapidly, even in a matter of hours (Takalo et al. 1994; D'arcangelo et al. 2009). Polarimetrical and PA measurements from 2012 November

Table 1. OJ287 observational data for 2012 November–2013 April.

Object	JD-245 6200 (d)	Images	Exp (s)	Total integration time (s)
HD 10476	49.3960	30	0.2	6
HD 14433	49.4071	30	0.5	15
OJ287	49.4946	30	60	1800
OJ287	49.5233	30	60	1800
OJ287	49.5521	30	60	1800
OJ287	49.5878	30	60	1800
OJ287	49.6176	30	60	1800
OJ287	49.6465	20	60	1200
OJ287	50.4909	10	60	600
OJ287	50.5003	10	60	600
OJ287	50.5097	10	60	600
HD 90508	106.4322	10	3	30
HD 90508	106.4354	10	1	10
HD 43384	106.4541	10	1	10
OJ287	106.3641	10	300	3000
OJ287	106.4956	10	300	3000
HD 144287	187.4698	5	0.5	2.5
HD 144287	188.4083	5	0.5	2.5
HD 154445	187.4837	5	0.1	0.5
HD 154445	188.4776	5	0.2	1
OJ287	187.4481	3	300	900
OJ287	188.3593	15	300	4500

(Bozhilov et al. 2013) indicated an agreement with previous data (Takalo et al. 1994; Efimov et al. 2002; Villforth et al. 2010).

Efimov et al. (2002) argue that the plane of polarization angle rotates at a rate of about 5 deg d^{-1}. Our preliminary two-epoch results (Bozhilov et al. 2013) showed a change of 10.8 deg d^{-1}. Considering the observation error limits of that preliminary analysis, we concluded that our data are not in contradiction with previous measurements (Efimov et al. 2002). But when we analyse the full data set, as presented in Tables 3 and 4, we can further improve on our previous work.

We can represent the data in the column PA in Table 3 using

$$\mathrm{PA} = \omega \times \mathrm{d}T - k \times 360, \quad (1)$$

where PA is the observed position angle, ω is the change of PA in deg d^{-1}, $\mathrm{d}T$ is the difference in time between two consecutive observational nights, k is the number of complete turns of the plane of polarization.

That is done in order to determine the rotation of the plane of polarization and to account for the number of complete circles of the plane. This is the meaning of column PA(k) in Table 3. Some details are important regarding the determination of the parameter k. Here, we assume that one full circle of the plane of polarization is somewhere between 5 deg d^{-1} (value according to Efimov et al. 2002) and no more than 10.8 deg d^{-1} (according to our previous work in Bozhilov et al. 2013). Thus, for the 81 d between the observations on the night of 2013 January 13 and 2013 April 04, we conclude that the plane of polarization could have made one additional circle. This, combined with the inherent 180 deg ambiguity of the electric vector PA measurement, motivates our choice of $k = 2.5$ in Table 3. Note that we have made tests with different values of k (e.g. $k = 2, 3$) with different rotation of the polarization plane, but the fit to observational data was not so good.

Table 2. Standard stars' characteristics.

Star	RA (2000) ($^{h\ m\ s}$)	Dec. (2000) ($^{\circ\ \prime\ \prime\prime}$)	mV (mag)	Polarization (max) (per cent)	PA(cat) (deg)	PA(measured + error) (deg)	PA(measured) + PA(cat) (deg, corrected for 360 deg rotation)
HD 10476	01 42 29.8	+20 16 07	5.2	–	–	–	–
HD 14433	02 21 55.4	+57 14 34	6.39	3.9 at lmax = 0.51 μm	112	355.53 (± 2.52)	107.53(± 3.01)
HD 90508	10 28 03.9	+48 47 06	6.44	–	–	–	–
HD 43384	06 16 58.7	+23 44 27	6.29	3.0 at lmax = 0.53 μm	170	333.18(± 2.18)	143.18(± 2.68)
HD 144287	16 04 03.7	+25 15 17	7.06	–	–	–	–
HD 154445	17 05 32.3	−00 53 31	5.64	3.7 at lmax = 0.57 μm	90	65.72 (± 0.76)	155.72 (± 1.26)

Table 3. Polarization and PA measurements for OJ287.

JD-245 6200	Polarization (per cent)	Error (per cent)	PA (deg)	Error (deg)	k	PA(k) (deg)
49.4946	9.80	2.72	73.29	3.15	0	73.29
49.5233	9.84	2.69	74.52	3.15	0	74.52
49.5521	9.71	2.67	74.77	3.15	0	74.77
49.5878	9.89	2.76	74.62	3.15	0	74.62
49.6176	9.45	2.78	73.53	3.16	0	73.53
49.6465	9.48	2.76	72.53	3.16	0	72.53
50.4909	9.27	6.56	62.60	3.37	0	62.60
50.5003	9.54	5.31	64.45	3.29	0	64.45
50.5097	9.53	5.34	64.17	3.29	0	64.17
106.364	4.93	5.10	117.33	3.20	1	−242.67
106.496	5.07	3.91	117.91	3.07	1	−242.09
187.448	25.59	13.90	163.65	1.53	2.5	−736.35
188.348	19.37	10.52	172.35	1.53	2.5	−727.66
188.385	19.35	9.91	172.37	1.52	2.5	−727.63

Table 4. Photometry of OJ287.

JD-245 6200	Magnitude (R)	Error
49.4655	14.614	0.006
49.4659	14.606	0.006
49.4664	14.614	0.006
49.4676	14.604	0.006
49.4681	14.610	0.005
49.4685	14.603	0.005
49.4715	14.602	0.005
49.4725	14.603	0.005
49.5694	14.599	0.005
49.5700	14.602	0.004
49.5705	14.598	0.004
49.6536	14.611	0.005
49.6541	14.619	0.006
49.6545	14.617	0.005
50.4812	14.656	0.008
50.4816	14.662	0.008
50.4821	14.663	0.007
106.3364	15.413	0.005
106.3399	15.412	0.005
106.3427	15.420	0.005
187.4144	14.667	0.003
187.4206	14.666	0.003
187.4223	14.666	0.003
188.4181	14.707	0.004
188.4197	14.708	0.003
188.3279	14.711	0.003
188.3295	14.713	0.003
188.3311	14.719	0.004

We derive PA change of 5.80 (±0.03) deg d^{-1}. Results are plotted in Fig. 2. This is closer to the observed change in Efimov et al. (2002). Note that this change in PA is likely due to underlying changes in the magnetic field of the structure (Homan et al. 2002). Efimov et al. (2002) and Valtonen & Pihajoki (2013) attribute the rotation of the plane of polarization to the helical structure of magnetic field of the jet in OJ287.

The change of polarization versus photometric variability is shown in Fig. 3. Efimov et al. (2002) did not found significant results to establish a correlation between change in brightness and polarization variation. Jorstad et al. (2007) and Villforth et al. (2010) got to the same conclusion. But D'arcangelo et al. (2009) showed that there is a clear tendency for higher polarization when the optical flux is stronger e.g. when the object is getting brighter. This is an expected theoretical result in some models (Valtonen & Sillanpää 2011). In our results, we also observe such behaviour. In Fig. 3, you can see the photometrical and polarization change during our observational campaign. Our data are in concordance with some previous work by other authors (D'arcangelo et al. 2009) and support the expected photopolarimetrical dependence by Valtonen & Sillanpää (2011).

4 CONCLUSIONS

The blazar-type AGN OJ287 is one of the most well-observed blazars. Yet, it still remains a riddle. Numerous models have been proposed to explain its observed properties (Valtonen & Ciprini 2012). Since optical polarization measurements could be useful to distinguish among various theoretical models, our observations further complete the existing data on this peculiar object. Our original five-epoch study of the optical photometry, polarization and PA of OJ287 shows good correlation with previous data and gives strong background to further measurements with NAO Rozhen's focal reducer FoReRo2 on the 2-m RCC telescope. We observe variation in PA that corresponds to rotation of the plane of polarization of 5.80 deg d^{-1}. Thus, our work builds on and improves recent previous research on OJ287 (D'arcangelo et al. 2009; Bozhilov et al. 2013). We also observe dependence of the polarization behaviour with change of optical brightness, as expected by the Binary Black Hole model (Valtonen & Sillanpää 2011).

ACKNOWLEDGEMENTS

The authors would like to thank Dr Petko Nedialkov from the Department of Astronomy, Faculty of Physics, Sofia University, as well as Dr Galin Borisov and Dr Tanyu Bonev from the Institute of Astronomy for valuable advices and guidance. The authors gratefully acknowledge observing grant support from the Institute

Table 5. Standard stars catalogue and observed polarization.

Star	Polarization (max) (per cent)	JD	Polarization (per cent)	Error (per cent)
HD 10476	–	245 6249.395 80	1.19	9.89
HD 14433	3.9 at lmax = 0.51 μm	245 6249.406 64	2.34	11.89
HD 90508	–	245 6306.431 2037	3.37	6.52
HD 43384	3.0 at lmax = 0.53 μm	245 6306.454 097	3.13	13.51
HD 144287	–	245 6387.469 3056	19.78	17.99
HD 154445	3.7 at lmax = 0.57 μm	245 6387.483 692	20.18	30.77

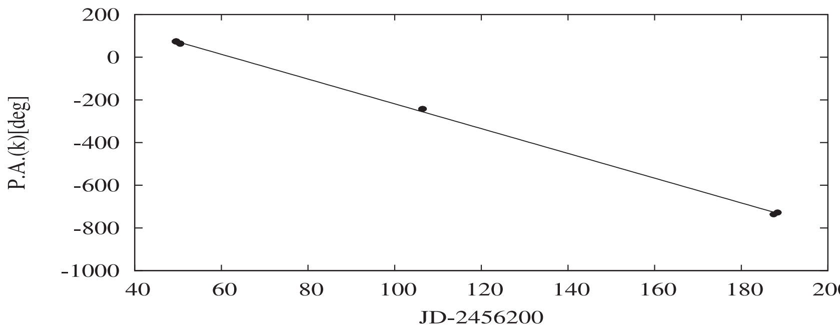

Figure 2. PA (k) for OJ287 from Table 3. Observed PA change corresponds to rotation of 5.80($\pm$ 0.03) deg d^{-1}.

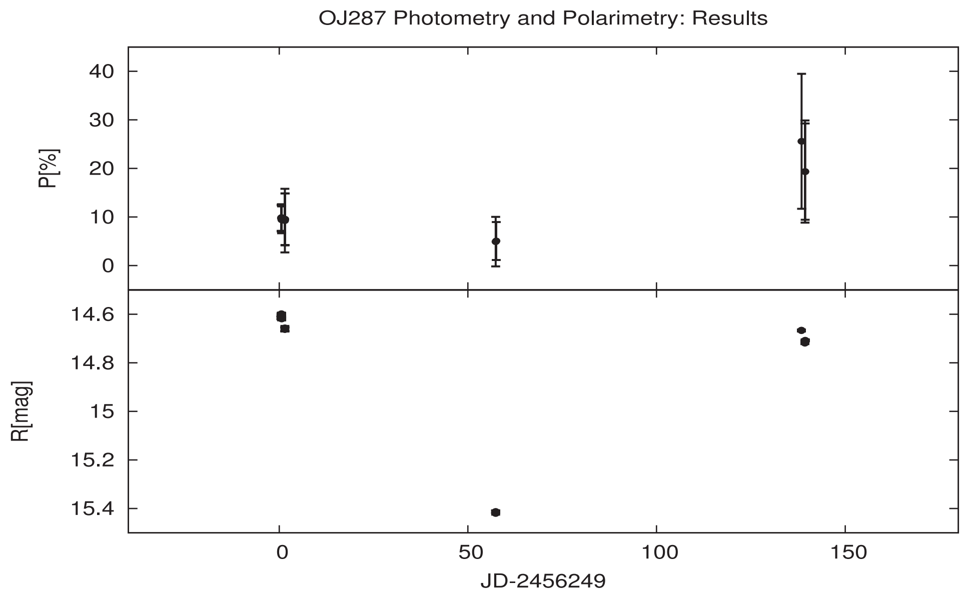

Figure 3. Photopolarimetry for OJ287 based on the observational data from Tables 3 and 4.

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REFERENCES

Barres de Almeida U., Ward M. J., Dominici T. P., Abraham Z., Franco G. A. P., Daniel M. K., Chadwick P. M., Boisson C., 2010, MNRAS, 408, 1778

Bozhilov V., Borisov G., Ovcharov E., 2013, Bulg. Astron. J., 19, available at: www.astro.bas.bg/AIJ/issues/n19/VBozhilov.pdf

Ciprini S. et al., 2007, Mem. Soc. Astron. Ital., 78, 741

D'arcangelo F. D. et al., 2009, ApJ, 697, 985

Efimov Yu. S., Shakhovskoy N. M., Takalo L. O., Sillanpää A., 2002, A&A, 381, 408

Geyer E. H., Jockers K., Kiselev N. N., Chernova G. P., 1996, Ap&SS, 239, 269

Homan D. C., Ojha R., Wardle J. F. C., Roberts D. H., Aller M. F., Aller H. D., Hughes Ph. A., 2002, ApJ, 568, 99

Jockers K. et al., 2000, Kinematika Fiz. Nebesnykh Tel Suppl., 3, 13

Jorstad S. G. et al., 2007, AJ, 134, 799

Katz J. I., 1997, ApJ, 478, 527

Landi Degl'Innocenti E., Landolfi M., eds, 2004, Astrophysics and Space Science Library, Vol. 307, Polarization in Spectral Lines. Kluwer, Dordrecht, p. 15

Neronov A., Vovk Ie., 2011, MNRAS, 412, 1389

Nieppola E., Hovatta T., Tornikoski M., Valtaoja E., Aller M. F., Aller H. D., 2009, AJ, 137, 5022

Pihajoki P. et al., 2013, ApJ, 764, 5

Santangelo M. M. M., 2012, Astron. Telegram, 4020
Sillanpää A., Haarala S., Valtonen M., Byrd G., 1988, ApJ, 325, 628
Sillanpää A. et al., 1996, A&A, 305, L17
Sundelius B., Wahde M., Lehto H., Valtonen M., 1997, ApJ, 484, 180
Takalo L. O., Sillanpää A., Nilsson K., 1994, A&AS, 107, 497
Valtaoja E., Teräsranta H., Tornikoski M., Sillanpää A., Aller M. F., Aller H. D., Hughes P. A., 2000, ApJ, 531, 744
Valtonen M., Ciprini S., 2012, Mem. Soc. Astron. Ital., 83, 219
Valtonen M., Pihajoki P., 2013, A&A, 557, A28
Valtonen M., Sillanpää A., 2011, Acta Polytech., 51, 76
Villata M., Raiteri C. M., Sillanpaa A., Takalo L. O., 1998, MNRAS, 293, L13
Villforth C. et al., 2010, MNRAS, 402, 2087

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