

Multi-band Optical Variability of OJ 287 During 2015-2025

(ApJS vol. 286:7, Sept 2026)

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1. Introduction

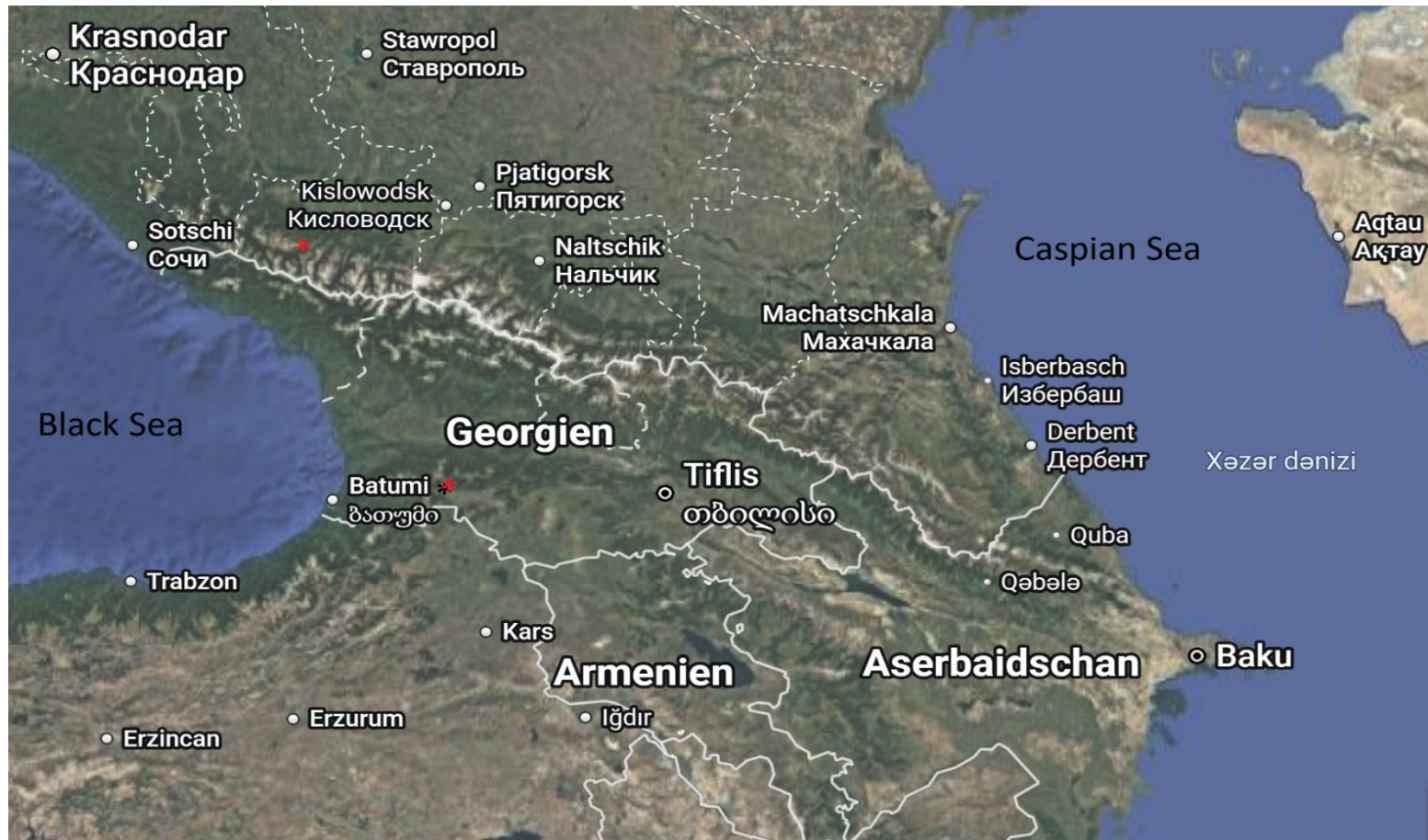
- We present the most densely sampled multiband optical photometric observations of the peculiar BL Lacertae object OJ 287 from 2015 to 2025 with a focus on its optical activity on diverse timescales. *We present a total of 2296, 10,927, 11,484, and 2982 data points in B, V, R, and I bands*, respectively.
- OJ 287 is monitored most thoroughly in optical bands, particularly *V* and *R*. The color variability of blazars is often divided into two subcategories: bluer when brighter (BWB) and redder when brighter (RWB).
- Once we have cleaned and reduced the raw science frames, differential photometry was performed to obtain BVRI magnitudes of OJ 287 using local standard stars 9, 12, and 13 in the blazar field

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2. Multiband Optical Data

The Observatories, Data Collection Periods, and Other Relevant Details

Observatory/Observer	MJD Start	MJD Stop	Origin	Aperture (cm)	Filters	Data Points (N_{obs})	Marker	Color in Figure 1
Abastumani	58126.43	60430.26	Georgia	70	R	707	⬢	Slate gray
A. Darriba ^a	58103.55	59209.66	Spain	35.6	V	76	□	Blue
ARIES ^b	58562.15	59197.48	India	104/130	BVRI	11, 11, 11, 11	+	Lime
ASV ^c	58144.37	59700.35	Serbia	60/140	BVRI	86, 49, 83, 85	◇	Green
Belogradchik	58228.26	60414.33	Bulgaria	60	BVRI	55, 60, 60, 53	⬢	Gold
Crimean	57524.27	59863.59	Russia	70	BVRI	144, 158, 464, 204		Teal
Mark Kidger ^d	57356.42	61139.82	International	Various	BVRI	1104, 9024, 5973, 1408	◇	Purple
Osaka	57295.29	60114.97	Japan	150	B	294	○	Tan
Perkins	60228.53	61030.44	United States	180	BVRI	285, 294, 166, 282	○	Crimson
Rozhen	57369.59	58993.30	Bulgaria	50/70/200	BVRI	53, 62, 85, 63	▽	Black
SATU ^e	57816.00	59558.00	West Indies	40	R	15		Salmon
SMARTS ^f	57353.84	57857.55	Chile	130/150	BVR	111, 110, 111	△	Dark violet
St. Petersburg	57513.32	59938.62	Russia	40	BVRI	66, 80, 314, 202	◁	Olive
Steward ^g	58130.85	58292.65	United States	154/230	VR	34, 34	○	Cyan
Weihai	58121.27	58994.03	China	100	VRI	115, 121, 114	○	Magenta
Paper I ^h	57286.01	57529.48	International	Various	BVRI	40, 190, 437, 45	+	Brown
Paper II ⁱ	57309.32	58103.82	International	Various	BVRI	46, 664, 840, 515	*	Orange
Paper III ^j	57284.00	59993.28	International	Various	R	1122	▷	Pink

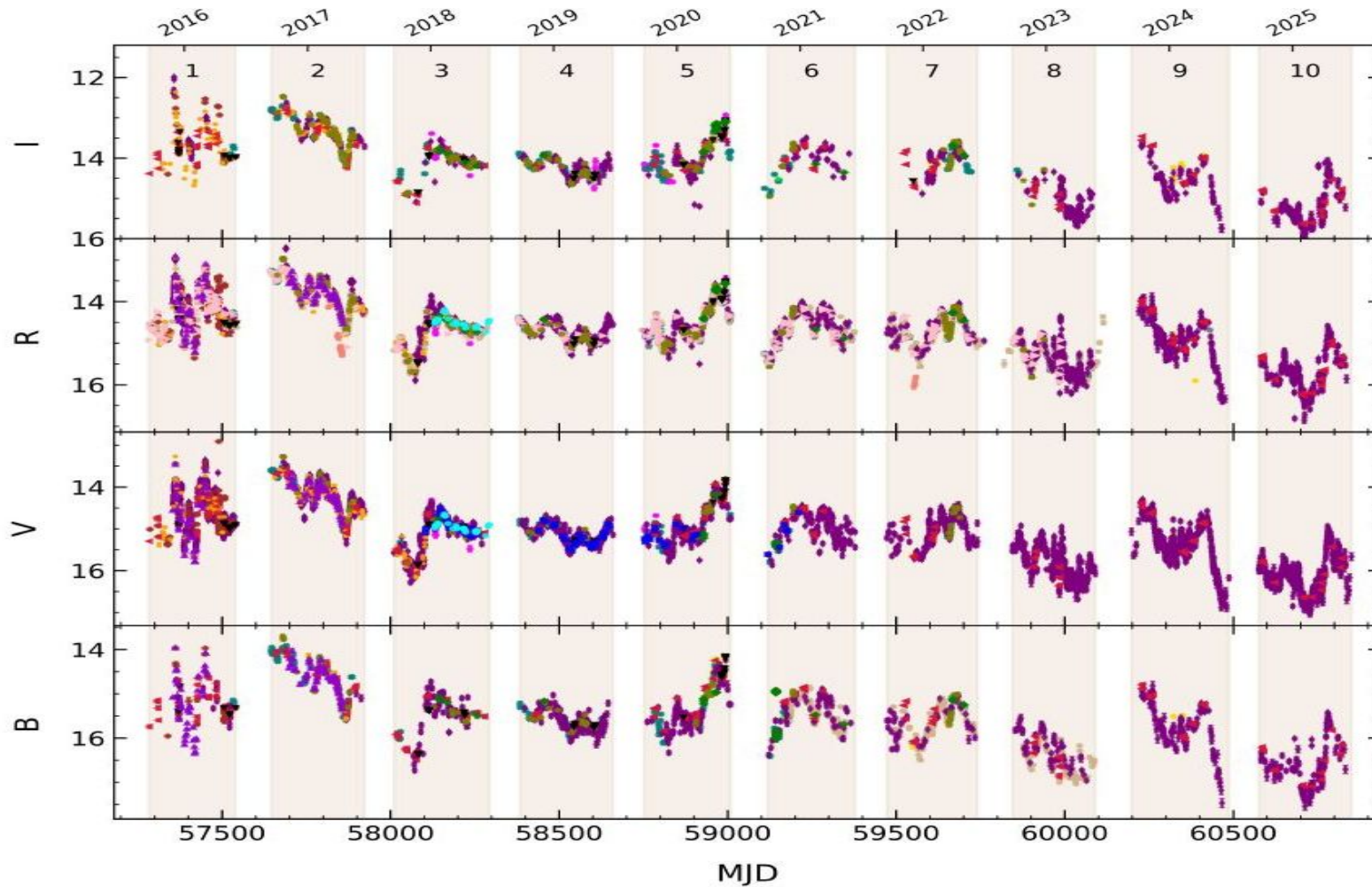


- **Started in March 1997**
 - **Over 70 sources**
 - **4 500 nights of observations
or ~36 000 hours of observations**
 - **Over 500 000 images**
- **About 100 papers published in high IF Journals**

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3. Flux Variability Analysis

Large-amplitude variations can be seen in all four bands on similar timescales.



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- **The light curve across all four bands is divided into 10 segments (or observing seasons) due to yearly seasonal gaps with other gaps for individual observatories caused by weather, maintenance, etc. All segments, as well as the full light curve, have been used to better study the source's variability.**
- **As blazars show variability in the entire EM spectrum and over diverse timescales, we need to quantify these features as they can help to elucidate the emission mechanism along with the physical properties of the emission region.**
- **The variability amplitude is computed for all light-curve segments, the color–magnitude (CM) relationship is studied in detail, and the Z-transformed discrete correlation function is computed for all light-curve pairs.**

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4. Flux Variability Amplitude

$$V_{\text{amp}} = \sqrt{(m_{\text{max}} - m_{\text{min}})^2 - 2\sigma^2}.$$

$$\Delta V_{\text{amp}} = \sqrt{\frac{(m_{\text{max}} - m_{\text{min}})^2(\sigma_{\text{max}}^2 + \sigma_{\text{min}}^2) + 4\sigma^2\Delta\sigma^2}{V_{\text{amp}}^2}},$$

where max, min, and σ are the uncertainties in m_{max} , m_{min} , and σ . In order to have a proper track of how light-curve variability varied over time, V_{amp} has been calculated for all the light-curve segments and bands, with the results given in the next table.

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Total and Segment-wise Variability Amplitudes of OJ 287 from 2015-2025

	Band	V_{amp}		Band	V_{amp}		Band	V_{amp}
Segment 1	<i>B</i>	2.38 ± 0.01	Segment 2	<i>B</i>	1.88 ± 0.06	Segment 3	<i>B</i>	2.00 ± 0.06
	<i>V</i>	2.87 ± 0.02		<i>V</i>	2.08 ± 0.04		<i>V</i>	1.97 ± 0.04
	<i>R</i>	2.45 ± 0.02		<i>R</i>	2.57 ± 0.01		<i>R</i>	2.03 ± 0.03
	<i>I</i>	2.69 ± 0.02		<i>I</i>	1.79 ± 0.01		<i>I</i>	1.72 ± 0.02
Segment 4	<i>B</i>	1.11 ± 0.08	Segment 5	<i>B</i>	2.18 ± 0.06	Segment 6	<i>B</i>	1.56 ± 0.05
	<i>V</i>	0.91 ± 0.05		<i>V</i>	1.98 ± 0.04		<i>V</i>	1.42 ± 0.04
	<i>R</i>	0.96 ± 0.03		<i>R</i>	2.05 ± 0.02		<i>R</i>	1.58 ± 0.02
	<i>I</i>	0.86 ± 0.07		<i>I</i>	2.27 ± 0.03		<i>I</i>	1.45 ± 0.03
Segment 7	<i>B</i>	1.49 ± 0.02	Segment 8	<i>B</i>	1.48 ± 0.08	Segment 9	<i>B</i>	2.67 ± 0.10
	<i>V</i>	1.30 ± 0.08		<i>V</i>	1.75 ± 0.05		<i>V</i>	2.60 ± 0.07
	<i>R</i>	1.98 ± 0.03		<i>R</i>	1.84 ± 0.05		<i>R</i>	2.51 ± 0.11
	<i>I</i>	1.31 ± 0.02		<i>I</i>	1.41 ± 0.03		<i>I</i>	2.28 ± 0.09
Segment 10	<i>B</i>	2.10 ± 0.09	Total light curve	<i>B</i>	3.83 ± 0.09	...	...	...
	<i>V</i>	2.09 ± 0.07		<i>V</i>	4.13 ± 0.06	...	...	...
	<i>R</i>	2.25 ± 0.08		<i>R</i>	4.14 ± 0.07	...	...	...
	<i>I</i>	2.14 ± 0.08		<i>I</i>	4.22 ± 0.06	...	...	...

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5. Color Variability

- Closely related to flux variability is color variability, often called the CM relation, which can hint at possible physical processes mainly in the jet of the blazar. To study the color variability, we plotted the $B - R$ and $V - R$ colors against the B and R magnitudes, respectively, as CM diagrams in Figure 2.
- We chose $B - R$ and $V - R$ to plot differences between widely separated and close bands, respectively, as they have the largest number of color indices. To clearly track each segment's contribution in the CM diagrams, the segments are color coded.
- Although a blazar's spectral energy distribution is dominated by nonthermal emission, imprints of quasi-thermal emission can also be noted, at least in the quiescent/low state of the object under study. Apparently, an overall linear trend is evident in Figure 2 throughout the observation campaign and across all segments.
- To quantify this behavior, we performed linear fits, with their respective slopes, intercepts, Pearson coefficients, r , and Spearman correlation coefficients, ρ , given in Table 3. We obtained 1425 $B - R$ color indices and 2110 $V - R$ color indices, with averages of 0.934 and 0.393, respectively.

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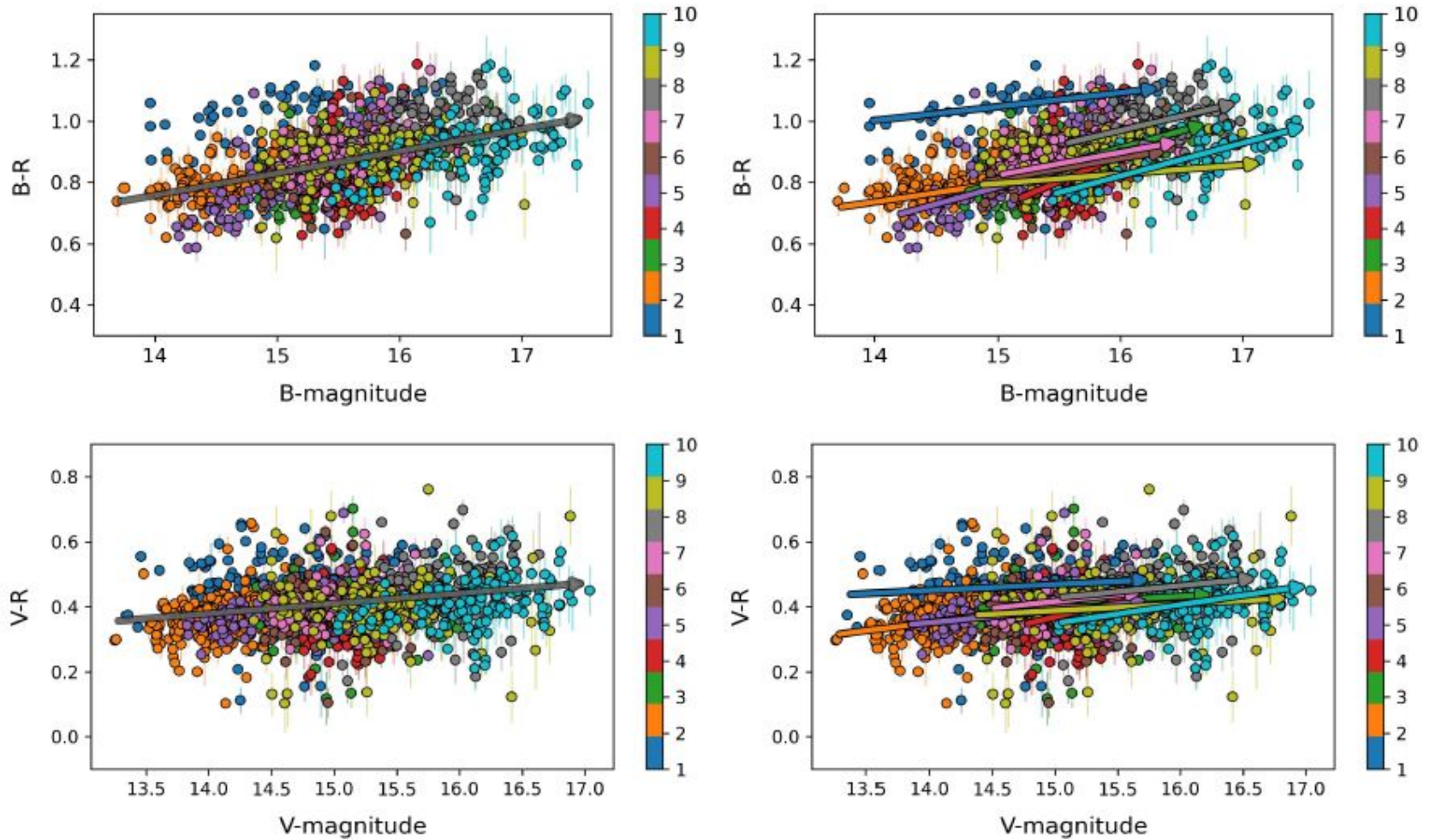


Figure 2. The left panels show the color-magnitude diagrams with a linear fit to all data points, whereas the right panels show the fit to all 10 segments.

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As can be seen of both Figures, the BWB trend becomes more evident as the difference in color between bands increases.

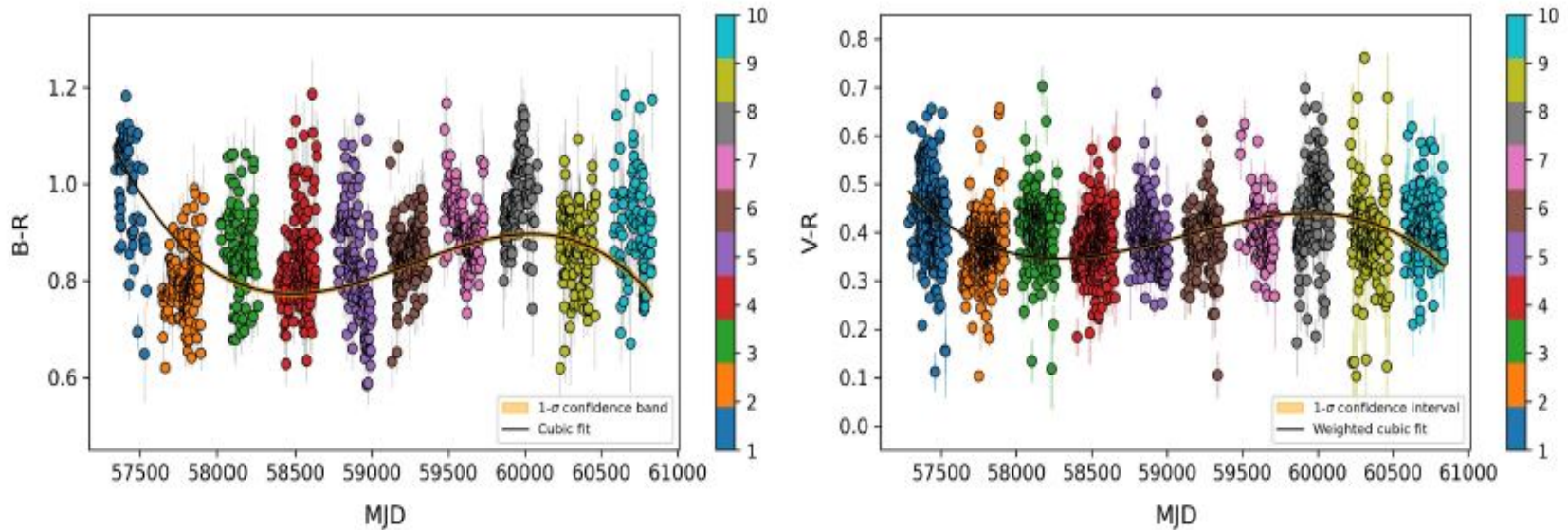


Figure 3. Color versus MJD plots for OJ 287. The plots show a slowly varying component, fitted with a cubic polynomial (in black).

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6. Z-transformed Discrete Correlation Function

- To estimate the cross correlation between these unevenly sampled time series, we employ the z-transformed discrete correlation function (ZDCF), originally introduced by T. Alexander (1997).
- The ZDCF is an improvement over the discrete correlation function (DCF) developed by R. A. Edelson & J. H. Krolik (1988), addressing its statistical limitations by implementing two key modifications: equal population binning and Fisher's z-transformation of the correlation coefficients. Unlike the traditional DCF, which bins time-lag pairs by fixed width, the ZDCF uses bins with an equal number of data pairs, improving statistical reliability across all lag ranges. Let n be the number of (x_i, y_i) pairs in a given time-lag bin, then, for each bin, the correlation coefficient r is computed as

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$$r = \frac{\sum_i^n (x_i - \bar{x})(y_i - \bar{y}) / (n - 1)}{s_x s_y},$$

which is then transformed using Fisher's z-transformation:

$$z = \frac{1}{2} \log \left(\frac{1 + r}{1 - r} \right), \quad \zeta = \frac{1}{2} \log \left(\frac{1 + \rho}{1 - \rho} \right), \quad r = \tanh z.$$

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- Here $\bar{x}$, $\bar{y}$ are bin averages, s_x , s_y are their standard deviations, and ρ is the unknown population correlation coefficient of the bin. Due to the presence of various emitting and absorbing regions surrounding an AGN, variations across different energy bands may not occur simultaneously, leading to observable time differences.
- To implement the ZDCF, we made use of the Python package pyzdcf54 (I. Jankov et al. 2022). The results of the cross correlations are shown in Figure 4. As can be seen, the ZDCFs peak at zero lag, implying co-spatial optical emission.
- The significance of the detected peaks are shown by red dashed lines in following diagram corresponding to a 3.5σ level. The significance is calculated by simulating 5×10^4 light curves, following the procedure discussed in D. Emmanoulopoulos et al. (2013).

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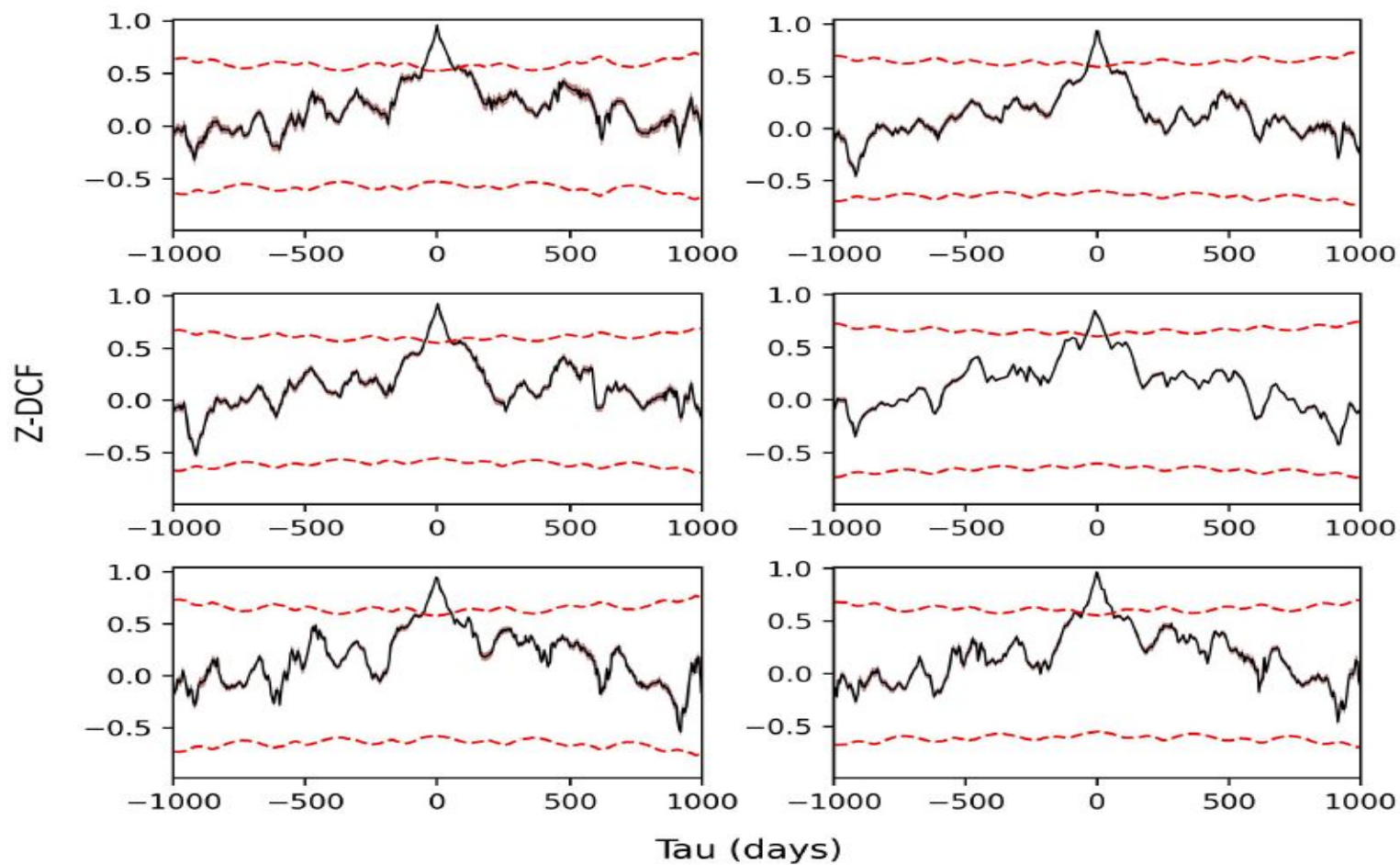


Figure 4. Cross-correlation results between different optical bands. With all ZDCFs peaking at zero lag, one can infer essentially cospatial emission, with the red dashed line representing 3.5σ significance level.

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7. Conclusions

- Due to the seasonal gaps, the light was divided into a total of 10 segments, with the object going through a maximum and minimum magnitude change of ~ 2.87 and 0.86 in the V band (segment 1) and I band (segment 4), respectively.
- The CM relationship for OJ 287 was analyzed both over the entire light curve and across individual segments. A clear “bluer-when-brighter” trend was observed, not only in the full light curve, but also consistently within each segment.
- The discrete correlation function analysis was performed between all bands using ZDCF. All inter-band cross correlations were found to peak at zero lag, implying that the emission is co-spatial in the BVRI bands.
- We combined eight optical spectra of the source to estimate its BH mass by using the width of the [O III] line as a surrogate for σ in the $M-\sigma$ relation, giving a FWHM $\simeq 918$ km/s which translates to a BH mass of $\log MBH = 9.59 \pm 0.40 M_{\odot}$.

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Acknowledgments

- The Abastumani team acknowledges financial support by the Shota Rustaveli NSF of Georgia under contract FR-24-515.
- A.C.G. is partially supported by the CAS “President’s International Fellowship Initiative (PIFI)” with grant No. 2026PVA0040.

O.M.K. thanks Profs. Stefan Wagner and Anton Zensus, Drs. Gotthard Richter and Claudia M. Raiteri for continuous support of Mount Kanobili Blazar Monitoring Program during 30 years.

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Thank You for Your Attention

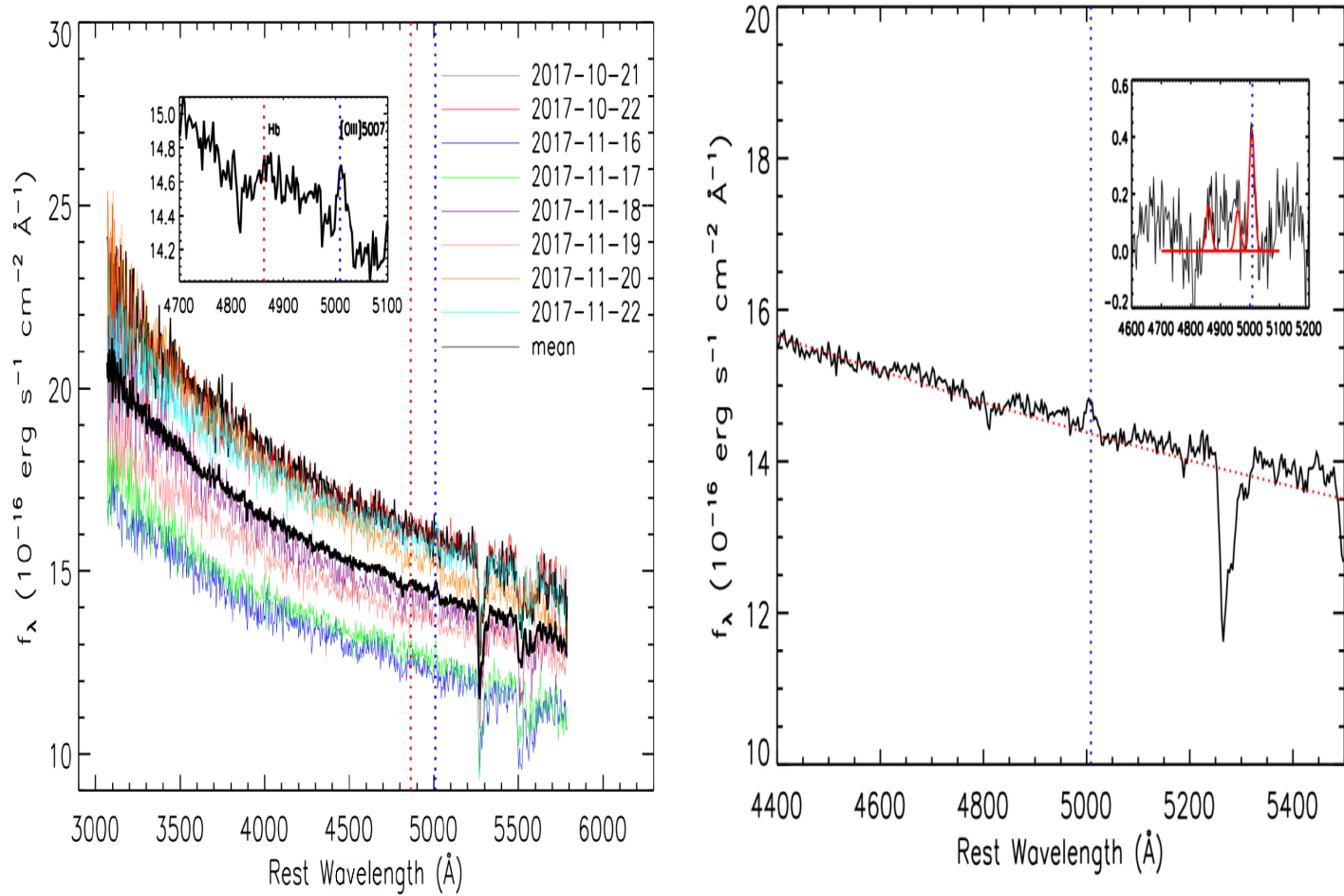


Figure 5. The eight spectra observed in the period of 2017 October 21–2017 November 22 and the flux-averaged spectrum (left). All spectra were corrected for Galactic extinction and shifted to source rest frame, with the position of emission lines of $H\beta$ and $[O\text{ III}] \lambda 5007 \text{ \AA}$ indicated as the vertical red dotted and green dotted lines. The spectral fitting of OJ 287 (right), where the continuum is fitted with a single power law shown as the red dotted line; the black line is the original flux-averaged spectrum and the inset shows the line fitting for $[O\text{ III}] \lambda 5007 \text{ \AA}$.