AstroSat View of Blazar OJ 287: A complete evolutionary cycle of HBL Component from end-phase to disappearance and Re-emergence

Pankaj Kushwaha, a,f,* K. P. Singh, b A. Sinha, c,d Main Pal, e G. Dewangan d and A. Agarwal f

a Aryabhatta Research Institute of Observational Sciences (ARIES), Nainital 263001, India
b Indian Institute of Science Education and Research Mohali, Knowledge City, Sector 81, SAS Nagar, Punjab 140306, India
c Laboratoire Univers et Particules de Montpellier, Université de Montpellier, CNRS/IN2P3, CC 72, Place Eugène Bataillon, F-34095 Montpellier Cedex 5, France
d Inter-University Centre for Astronomy and Astrophysics, Ganeshkhind, Pune 411 007, India
e Centre for Theoretical Physics, Jamia Millia Islamia, New Delhi-110025, India
f Raman Research Institute, C. V. Raman Avenue, Sadashivanagar, Bengaluru 560080, India

E-mail: pankaj.kushwaha@aries.res.in

We report three AstroSat observations of BL Lacertae object OJ 287. The three observations caught it in very different flux states that are connected to different broadband spectral states. These observations trace the source spectral evolution from the end-phase of activity driven by a new, additional HBL like emission component in 2017 to its complete disappearance in 2018 and re-emergence in 2020. The 2017 observation shows a comparatively flatter optical-UV and X-ray spectrum. Supplementing it with the simultaneous NuSTAR monitoring indicates a hardening at the high-energy-end. The 2018 observation shows a harder X-ray spectrum and a sharp decline or cutoff in the optical-UV spectrum, revealed thanks to the Far-UV data from AstroSat. The brightest of all, the 2020 observation shows a hardened optical-UV spectrum and an extremely soft X-ray spectrum, constraining the low-energy peak of spectral energy distribution at UV energies – a characteristic of HBL blazars. The contemporaneous MeV-GeV spectra from LAT show the well-known OJ 287 spectrum during 2018 but a flatter spectrum during 2017 and a hardening above 1 GeV during 2020. Modeling broadband SEDs show that 2018 emission can be reproduced with a one-zone leptonic model while 2017 and 2020 observations need a two-zone model, with the additional zone emitting an HBL radiation.

37th International Cosmic Ray Conference (ICRC 2021)
July 12th – 23rd, 2021
Online – Berlin, Germany

*Presenter
†Aryabhatta Postdoctoral Fellow
1. Introduction

OJ 287 is a BL Lacertae (BL Lac) object located at a cosmological redshift of 0.306 [1, 2]. The BL Lac designation was originally coined for sources with very weak or completely absent emission line features but showed strong and rapid variations in continuum flux, polarization, and have an inverted radio spectrum. The source has been extensively studied and shows an entirely jet-dominated continuum spanning the entire accessible electromagnetic spectrum from radio to GeV/TeV gamma-rays [e.g. 3–5, and references therein].

The broadband emission from OJ 287 shows the characteristic double-humped spectral energy distribution of blazars with a low-energy peak around near-infrared (NIR) bands and a high energy peak around \( \sim 100 \text{ MeV} \) [e.g. 3, 4]. In terms of SED based classification scheme, OJ 287 is a low-energy-peaked (LBL) blazar. Modeling of SEDs constructed using simultaneous/contemporaneous data with constraints from observations in different energy bands show that the MeV-GeV gamma-ray emission is due to external Comptonization (EC) of a \( \sim 250 \text{ K} \) thermal photon field while X-ray is due to synchrotron self-Compton (SSC; 4). Though blazars show flux variability overall observationally feasible timescales, significant spectral evolution indicating a new emission component or change of spectral sequence are rare [e.g. 6, references therein]. For OJ 287, however, multi-wavelength observations show that OJ 287 is a spectrally very dynamic blazar with strong spectral changes in all energy bands for a much-extended duration [e.g. 7–12, and references therein].

OJ 287 is been exhibiting continuous multi-wavelength activity in phases, one followed by the next, since the end-2015 [e.g. 12–14], with each activity phase being spectrally distinct compared to the preceding one [e.g. 6–12, 15–17]. MW spectro-temporal and spectral studies of the first phase (\( \sim \) end-2015 – mid-2016) of activity discovered a distinct NIR-optical spectrum with a break consistent with a thermal feature, a hardening of the MeV-GeV spectrum with a shift in the location of high-energy hump [9], as well as the discovery of a soft X-ray excess for the first time in any BL Lac object [11]. This was followed by an intense and bright X-ray to optical flux activity phase (\( \sim \) mid-2016 – mid-2017), driven by an extremely soft X-ray spectrum [8] with the resultant broadband SED similar to a combined presence of the typical LBL SED of OJ 287 and an additional high-energy-peaked (HBL) like emission component [10] but with some peculiar timing features [10, 12]. During this phase, VERITAS reported its first ever activity at very high energies [VHEs; 7]. With the weakening of this new component, the source slowly returned to its typical LBL spectral state but only for a comparatively short duration of \( \sim 50 \) days but the HBL-like component slowly and steadily gained prominence [6], leading to another activity with a very soft X-ray spectrum in 2020 [12].

In this proceeding, we report our MW spectral analysis and modeling of the long-exposure observations of OJ 287 by AstroSat taken respectively in 2017, 2018, and 2020 that correspond to the different X-ray flux states of the source during different activity phases mentioned above. The 2017 is around the end-phase of the HBL drive activity phase of 2016–2017, 2018 is around the period when this additional component has started to gain strength after disappearance and the 2020 is after the peak of re-emerged HBL driven activity phase. In the next section (§2), we provide a brief overview of AstroSat
observations and the results of our spectral analysis. In §3, we discuss our findings in the context of jet physics and conclude with a summary in §4.

2. AstroSat Observations

AstroSat is the first Indian multi-wavelength facility launched in 2015 [18] with four data acquisition payloads for simultaneous astronomical observations – the Ultraviolet Imaging Telescope [UVIT; 19], Soft X-ray Telescope [SXT; 20], Large Area X-ray Proportional Counter [LAXPC; 21], and Cadmium Zinc Telluride Imager [CZTI; 22]. Together these provide simultaneous coverage of the electromagnetic spectrum from optical to hard X-rays. The UVIT and SXT have focusing optics while LAXPC and CZTI are open detectors.

AstroSat targeted OJ 287 on three occasions – in 2017, 2018, and 2020 respectively with the source being in 3 different X-ray flux states. We explored these observations and found useful data only in UVIT and SXT. Data from the other two – LAXPC and CZTI were noise-dominated and thus, are not considered.

For data reduction, we followed the standard recommended prescription for UVIT and SXT, and detailed treatment is presented in [17]. We found no appreciable variability in the SXT and UVIT\(^1\) light curves. The X-ray spectrum of all three is consistent with a power-law spectrum \((N(E) \sim E^{-\Gamma})\) with a photon spectral index, \(\Gamma\) of 2.08 ± 0.03, 1.82 ± 0.06, and 2.5 ± 0.04 respectively for 2017, 2018, and 2020 observations assuming a fixed Galactic neutral hydrogen column density of \(2.4 \times 10^{20}\) cm\(^{-2}\). Figure 1 shows the MW SEDs constructed using the AstroSat data. The X-ray spectrum of 2017 also includes the X-ray data from the NuSTAR facility.

3. Discussion

We found that the three AstroSat observations performed during three different X-ray (0.3 – 10 keV) flux states of the source actually correspond to three distinct X-ray spectral

\(^1\)FUV/NUV data show variations at a level of few percent that has negligible effect on overall SED.
phases of the source. Together the X-ray spectra shown in figure 1 covers the entire range of spectral shape seen in blazars, from a hard – the 2018 spectrum, intermediate – the 2017 spectrum, to an extremely soft – the 2020 spectrum. The corresponding broadband SEDs shown in figure 2 shows spectral changes at UV and MeV-GeV gamma-rays (from Fermi-LAT; [23]), indicating the spectral changes to a broadband emission component. Note that the source is too weak at MeV-GeV energies over the AstroSat monitoring periods and thus, a much longer duration data is used to extract the gamma-ray spectra. Any strong spectral changes are expected to be preserved though the intensity may be reduced substantially. Our focus here is overall broadband spectral changes and not its level and thus, extraction using data from a longer duration is perfectly fine.

To explore the possible reason for the primary driver of the X-ray spectrum state, we modeled the 2018 and 2020 SEDs as the two-ends of the overall spectral evolution sequence. The NUV-FUV data during 2018 show a sharp softening/cutoff at the high-energy-end of the optical-UV spectrum. We found that a one-zone model with emission resulting from a relativistic electron population emitting synchrotron, SSC, and EC of a $\sim 250$ K blackbody photon field as proposed in [4] can satisfactorily reproduce the 2018 broadband SED. For the 2020 SED, the hardening seen at UV energies with respect to the optical and a similar trend at MeV-GeV energies is inconsistent with the one-zone scenario employed for 2018 SED and indicates a new emission component. A power-law extrapolation of the X-ray spectrum to UV energies indicates a peak around UV energies – a characteristic of the HBL emission component. Thus, we modeled the 2020 SED with a two-zone model [e.g. 10, 17] with the additional zone emitting an HBL spectrum incorporating only synchrotron (optical to X-rays) and SSC (gamma-rays) as typically invoked for HBL blazars and found it sufficient to reproduce the 2020 broadband SED.

The above modeling for 2018 and 2020 SEDs presents two plausible scenarios for the X-ray spectrum of 2017 (intermediate between 2018 and 2020 X-ray spectra) – a continuation of optical-UV synchrotron spectrum to the X-ray band, supported by the NUV-FUV data or a much weaker HBL component. We found that the intermediate X-ray spectrum is primarily due to the continuation of the synchrotron to X-ray energies. A significantly
weaker (by a factor of $\sim 4$) contribution of the HBL component with respect to the LBL component is needed to reproduce the observed X-ray spectrum but at MeV-GeV, its contribution is significant. These modeled spectra for all the three SEDs are shown in figure 2 (ref [17] for details).

4. Summary

We presented a spectral analysis of the three long-exposure observations of OJ 287 with AstroSat taken during three distinct X-ray flux states and found these to be spectrally distinct too. Together these X-ray spectra covers the whole range of spectral phases exhibited by the blazar class – from a hard in 2018, intermediate state in 2017, to an extremely soft X-ray spectrum in 2020.

The NUV-FUV data of 2018 show a spectral sharpening/cutoff in the high-energy-end of the optical-UV spectrum and a one-zone leptonic emission model can reproduce the broadband SED fairly well. For the 2020 SED, an additional emission zone emitting an HBL spectrum is needed while for 2017, the X. The HBL component has almost negligible contribution at X-ray energies but contributes significantly at MeV-GeV energies, indicating that in the LBL state, the X-ray spectral changes are primarily driven by the evolution of the high-energy-end of the optical-UV synchrotron spectrum.

Acknowledgments

PK acknowledges financial support from ARIES Aryabhatta Postdoctoral Fellowship (A-PDF) grant (AO/A-PDF/770).

References

[1] M.L. Sitko and V.T. Junkkarinen, Continuum and line fluxes of OJ287 at minimum light, PASP 97 (1985) 1158.

[2] K. Nilsson, L.O. Takalo, H.J. Lehto and A. Sillanpää, H-alpha monitoring of OJ 287 in 2005-08, A&A 516 (2010) A60 [1004.2617].

[3] A.A. Abdo, M. Ackermann, I. Agudo, M. Ajello, H.D. Aller, M.F. Aller et al., The Spectral Energy Distribution of Fermi Bright Blazars, ApJ 716 (2010) 30 [0912.2040].

[4] P. Kushwaha, S. Sahayanathan and K.P. Singh, High energy emission processes in OJ 287 during 2009 flare, MNRAS 433 (2013) 2380 [1305.5065].

[5] A. Goyal, Ł. Stawarz, S. Zola, V. Marchenko, M. Soida, K. Nilsson et al., Stochastic Modeling of Multiwavelength Variability of the Classical BL Lac Object OJ 287 on Timescales Ranging from Decades to Hours, ApJ 863 (2018) 175.
[6] P. Kushwaha, M. Pal, N. Kalita, N. Kumari, S. Naik, A.C. Gupta et al., 
Multi-wavelength activity of the BL Lac Blazar OJ 287 After its First VHE Activity: 
Spectro-temporal Evolution and Remergergence of the HBL like Component, arXiv e-prints (2020) arXiv:2010.14431 [2010.14431].

[7] S.O. Brien and VERITAS Collaboration, VERITAS detection of VHE emission from 
the optically bright quasar OJ 287, in 35th International Cosmic Ray Conference 
(ICRC2017), vol. 301 of International Cosmic Ray Conference, p. 650, Jan., 2017.

[8] S. Komossa, D. Grupe, N. Schartel, L. Gallo, J.L. Gomez, W. Kollatschny et al., The 
Extremes of AGN Variability, in New Frontiers in Black Hole Astrophysics, 
A. Gomboc, ed., vol. 324, pp. 168–171, Jan., 2017, DOI.

[9] P. Kushwaha, A.C. Gupta, P.J. Wiita, H. Gaur, E.M. de Gouveia Dal Pino, 
J. Bhagwan et al., Multiwavelength temporal and spectral variability of the blazar OJ 
287 during and after the 2015 December flare: a major accretion disc contribution, 
MNRAS 473 (2018) 1145 [1709.04957].

[10] P. Kushwaha, A.C. Gupta, P.J. Wiita, M. Pal, H. Gaur, E.M. de Gouveia Dal Pino 
et al., The ever-surprising blazar OJ 287: multiwavelength study and appearance of 
a new component in X-rays, MNRAS 479 (2018) 1672 [1803.10213].

[11] M. Pal, P. Kushwaha, G.C. Dewangan and P.K. Pawar, Strong Soft X-Ray Excess in 
2015 XMM-Newton Observations of BL Lac OJ 287, ApJ 890 (2020) 47 
[1912.02730].

[12] S. Komossa, D. Grupe, M.L. Parker, M.J. Valtonen, J.L. Gómez, A. Gopakumar 
et al., The 2020 April-June super-outburst of OJ 287 and its long-term 
multiwavelength light curve with Swift: binary supermassive black hole and jet 
activity, MNRAS 498 (2020) L35 [2008.01826].

[13] A.C. Gupta, A. Agarwal, A. Mishra, H. Gaur, P.J. Wiita, M.F. Gu et al., Multiband 
optical variability of the blazar OJ 287 during its outbursts in 2015-2016, MNRAS 
465 (2017) 4423 [1611.07561].

[14] S. Komossa and D. Grupe, Multiple flares during the April-June 2020 outburst of the 
blazar OJ 287, The Astronomer’s Telegram 13785 (2020) 1.

[15] B. Kapanadze, S. Vercellone, P. Romano, P. Hughes, M. Aller, H. Aller et al., Strong 
X-ray flaring activity of the BL Lacertae source OJ 287 in 2016 October-2017 April, 
MNRAS 480 (2018) 407.

[16] R. Prince, A. Agarwal, N. Gupta, P. Majumdar, B. Czerny, S.A. Cellone et al., 
Multi-wavelength Analysis and Modeling of OJ 287 During 2017-2020, arXiv e-prints 
(2021) arXiv:2105.04028 [2105.04028].

[17] K.P. Singh et al., Three Spectral States of OJ 287 blazar from Multi-wavelength 
Observations with AstroSat, submitted (2021).
[18] K.P. Singh, S.N. Tandon, P.C. Agrawal, H.M. Antia, R.K. Manchanda, J.S. Yadav et al., ASTROSAT mission, in Space Telescopes and Instrumentation 2014: Ultraviolet to Gamma Ray, T. Takahashi, J.-W.A. den Herder and M. Bautz, eds., vol. 9144 of Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, p. 91441S, July, 2014, DOI.

[19] S.N. Tandon, A. Subramaniam, V. Girish, J. Postma, K. Sankarasubramanian, S. Sriram et al., In-orbit Calibrations of the Ultraviolet Imaging Telescope, AJ 154 (2017) 128 [1705.03715].

[20] K.P. Singh, G.C. Stewart, S. Chandra, K. Mukerjee, S. Kotak, A.P. Beardmore et al., In-orbit performance of SXT aboard AstroSat, in Space Telescopes and Instrumentation 2016: Ultraviolet to Gamma Ray, J.-W.A. den Herder, T. Takahashi and M. Bautz, eds., vol. 9905 of Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, p. 99051E, July, 2016, DOI.

[21] H.M. Antia, J.S. Yadav, P.C. Agrawal, J. Verdhan Chauhan, R.K. Manchanda, V. Chitnis et al., Calibration of the Large Area X-Ray Proportional Counter (LAXPC) Instrument on board AstroSat, ApJS 231 (2017) 10 [1702.08624].

[22] V. Bhalerao, D. Bhattacharya, A. Vibhute, P. Pawar, A.R. Rao, M.K. Hingar et al., The Cadmium Zinc Telluride Imager on AstroSat, Journal of Astrophysics and Astronomy 38 (2017) 31 [1608.03408].

[23] W.B. Atwood, A.A. Abdo, M. Ackermann, W. Althouse, B. Anderson, M. Axelsson et al., The Large Area Telescope on the Fermi Gamma-Ray Space Telescope Mission, ApJ 697 (2009) 1071 [0902.1089].