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

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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 the 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.

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1. Introduction

OJ 287 is a BL Lacartae (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 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 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 (MW) 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 has been exhibiting continuous MW 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]. It 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 the first-ever activity at very high energies [VHEs; 7] by OJ 287. With the weakening of the new HBL-like component, the source slowly returned to its typical LBL spectral state but only for a comparatively short duration of $\sim$ 50 days, and the HBL-like component slowly and steadily started gaining 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 observation is around the end-phase of the HBL driven activity phase of 2016–2017 [10], 2018 is around the period when this additional component has started to gain strength after disappearance [6], and the 2020 is after the peak of re-emerged HBL driven activity phase [6]. In the next section (§2), we provide a brief

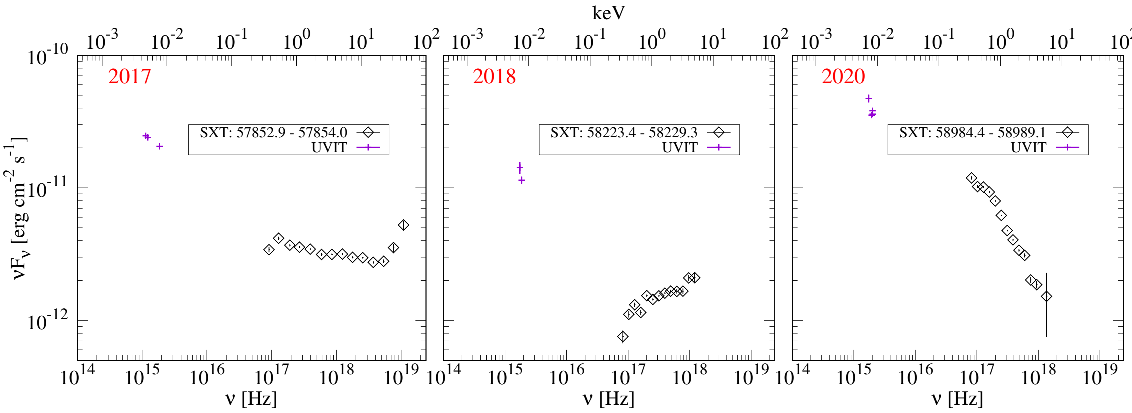

Figure 1: Multi-wavelength SEDs of OJ 287 from the three long-exposure observations with *AstroSat* in 2017, 2018, and 2020 respectively (ref §2).

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, Γ 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 2.4×10^{20} cm^{-2}. Figure 1 shows the MW SEDs constructed using the *AstroSat* data [see 17, for details]. 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 correspond to three distinct X-ray spectral phases of

[1] FUV/NUV data show variations at a level of few percent that has negligible effect on overall SED.

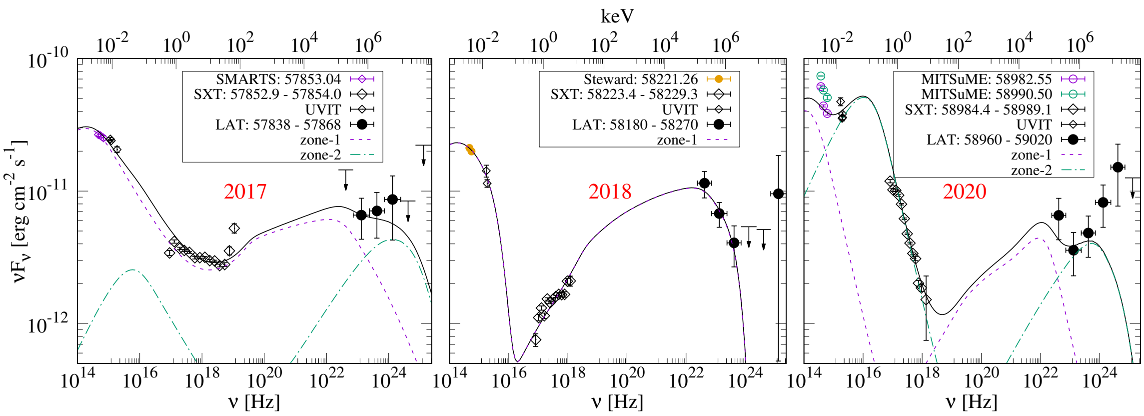

Figure 2: Broadband SEDs and the model spectra (solid black curves) of OJ 287 corresponding to the three *AstroSat* observations. The broadband SED of 2018 is well-explained by a one-zone leptonic model. For the 2017 and 2020 SEDs, an additional emission zone (two-zone) with an HBL-like spectrum is needed to reproduce the observed spectra.

the source. Together, the X-ray spectra shown in figure 1 covers the entire range of spectral shapes 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 possible reasons for the primary driver of the different X-ray spectral states, 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 power-law continuation of optical-UV synchrotron spectrum to the X-ray band, also 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 spectrum to X-ray energies. A significantly weaker (by a factor of ~ 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. The model 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 cover the whole range of spectral phases exhibited by the blazar class – from a hard in 2018, an 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 fairy well. For the 2017 and 2020 SEDs, an additional emission zone emitting an HBL spectrum is needed. The HBL component in the 2017 model spectrum 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 driven primarily by the evolution of the high-energy-end of the optical-UV synchrotron spectrum.

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