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

Pankaj Kushwaha* (ARIES, Nainital 263001, India)
K. P. Singh (*IISER-Mohali, Punjab 140306, India*), A. Sinha (*LUPM-UM, Montpellier, France; IUCAA, Pune 411007, India*), Main Pal (*CTP-JMI, New Delhi 110025, India*), G. Dewangan (*IUCAA, Pune 411007, India*), and A. Agarwal (*RRI, Bengaluru 560080, India*)
*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.

OJ 287

OJ 287, located at a cosmological redshift of 0.306 [1], belongs to the BL Lac (BLL) subclass of blazars – active galactic nuclei (AGNs) with a relativistic jet pointed roughly towards the Earth and characterized by featureless emission spectra or a weak signal of emission lines superimposed over the continuum. It is one of the most dynamic and well-explored BL Lac objects and show flux variability on all timescales from hours and even less to decades and more [e.g. 2]. The broadband emission shows the characteristic double-humped spectral energy distribution of with a low-energy peak around near-infrared (NIR) energies and a high-energy peak around 100 MeV. Modeling of broadband SED in the leptonic scenario show that MeV-GeV is due to external Comtonization of a thermal photon field of ~250 K while X-ray is due to synchrotron self-Compton (SSC) [3].

OJ 287 is been exhibiting continuous multi-wavelength activity in phases, one followed by the next since the start of an activity in the end-2015 ([4,5,6], within the facility operational constraints). A surprising and unique fact about these activities is that each activity phase is spectrally different from the preceding one. Multi-wavelength studies have reported strong spectral changes in all energy bands from NIR to GeV-TeV gamma rays. The include a break in the NIR-optical spectrum, hardening and peak shift MeV-GeV emission, first-ever reported VHE activity, the discovery of a soft X-ray excess, and an extremely soft X-ray spectrum [4,5,6,7].

The X-ray light curve and spectral index from the best-fit *power-law* (PL) or *log-parabola* (LP) since end-2015 (MJD 57350) are shown in **Figure 1.** The shaded regions mark the different activity phases of the source and vertical lines mark the *AstroSat* observations.

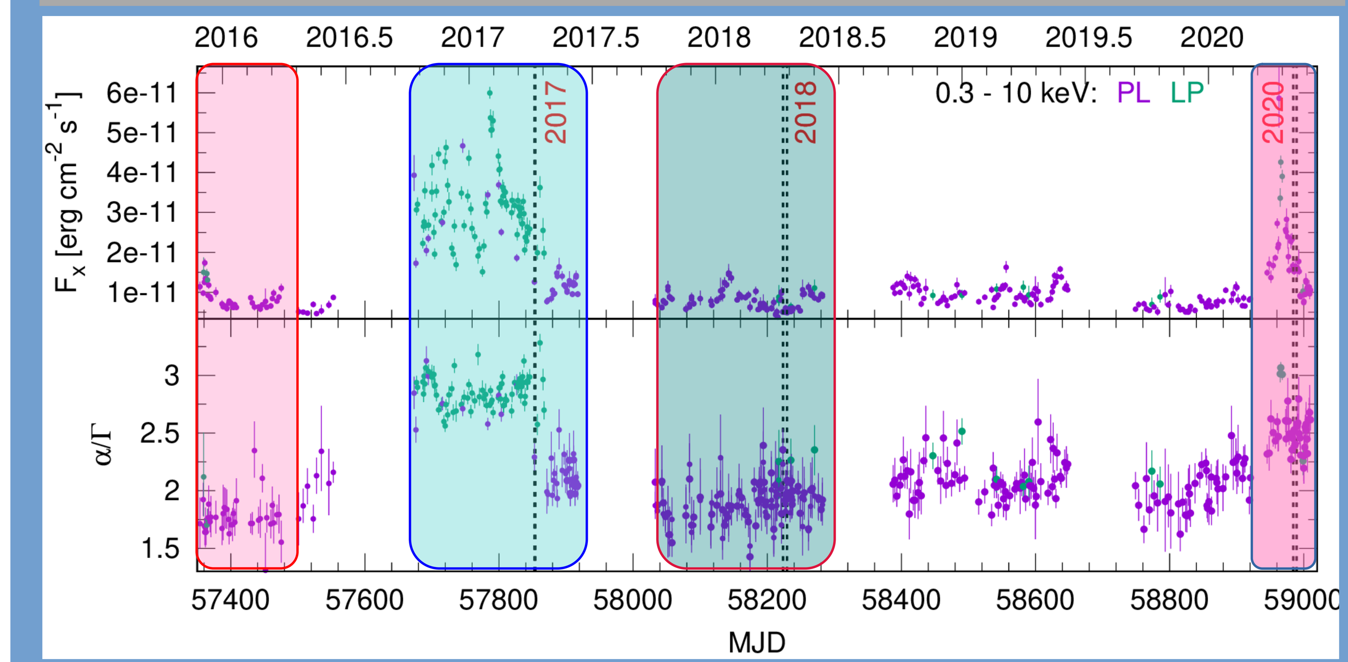

Figure 1: The X-ray light curve and spectral index from the best-fit power-law (Γ) or log-parabola (α) model between November 24, 2015 to June 10, 2020 (MJD: 57350 – 59010). The vertical lines mark the period of *AstroSat* pointing periods.

AstroSat Observations

AstroSat targeted OJ 287 on three occasions – in 2017, 2018, and 2020, each in a different X-ray flux state. Our data exploration found useful data only in two of the payloads – the Soft X-ray Telescope (SXT) and Ultraviolet Imaging Telescope (UVIT). The data from the other two – Large Area X-ray Proportional Counter (LAXPC) and Cadmium Zinc Telluride Imager (CZTI) are noise-dominated.

Following the standard and recommended data reduction prescription, we analyzed the SXT and UVIT data and found both to be non-variable. The X-ray spectrum of all three is consistent with a power-law spectrum (N (E) ~ $E^{-\Gamma}$) 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 2** shows the best-fit X-ray spectra from the three *AstroSat* observations. The 2017 *AstroSat* pointing was simultaneous with *NuSTAR* and thus, we have also used it.

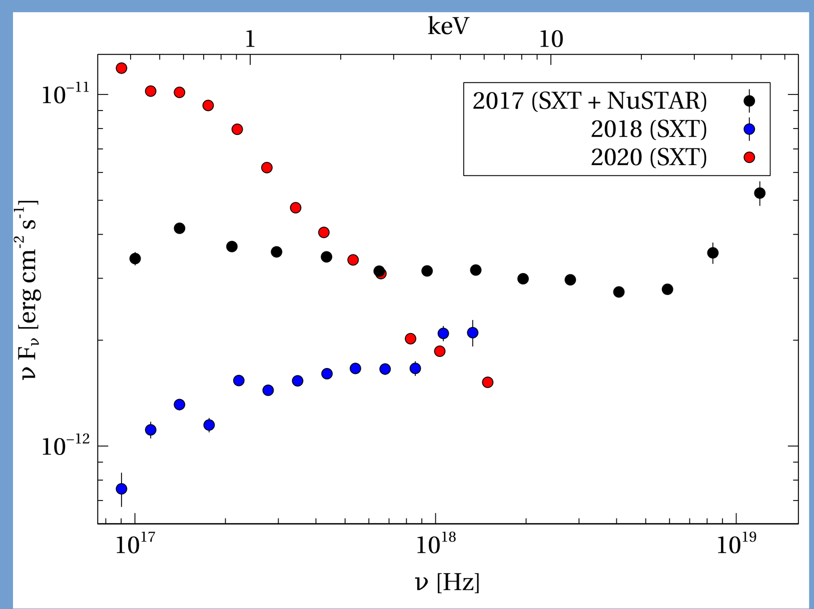

Figure 2: X-ray spectra of OJ 287 from the three *AstroSat* observations. The 2017 SED also includes X-ray data from the *NuSTAR.*

Results: Spectral Changes

Strong spectral changes in all the energy bands from optical to MeV-GeV gamma-rays (ref. **Figure 3**).

(1) **2018:** *Lowest* X-ray flux but the *hardest* spectrum, spectral steepening/cutoff in the optical-UV spectrum: Well-known spectral state, considered typical of the OJ 287

(2) **2020:** *Highest* X-ray flux but an extremely soft spectrum, hardening at UV and GeV energies

(3) **2017:** *Intermediate* X-ray flux and spectrum, flat MeV-GeV spectrum

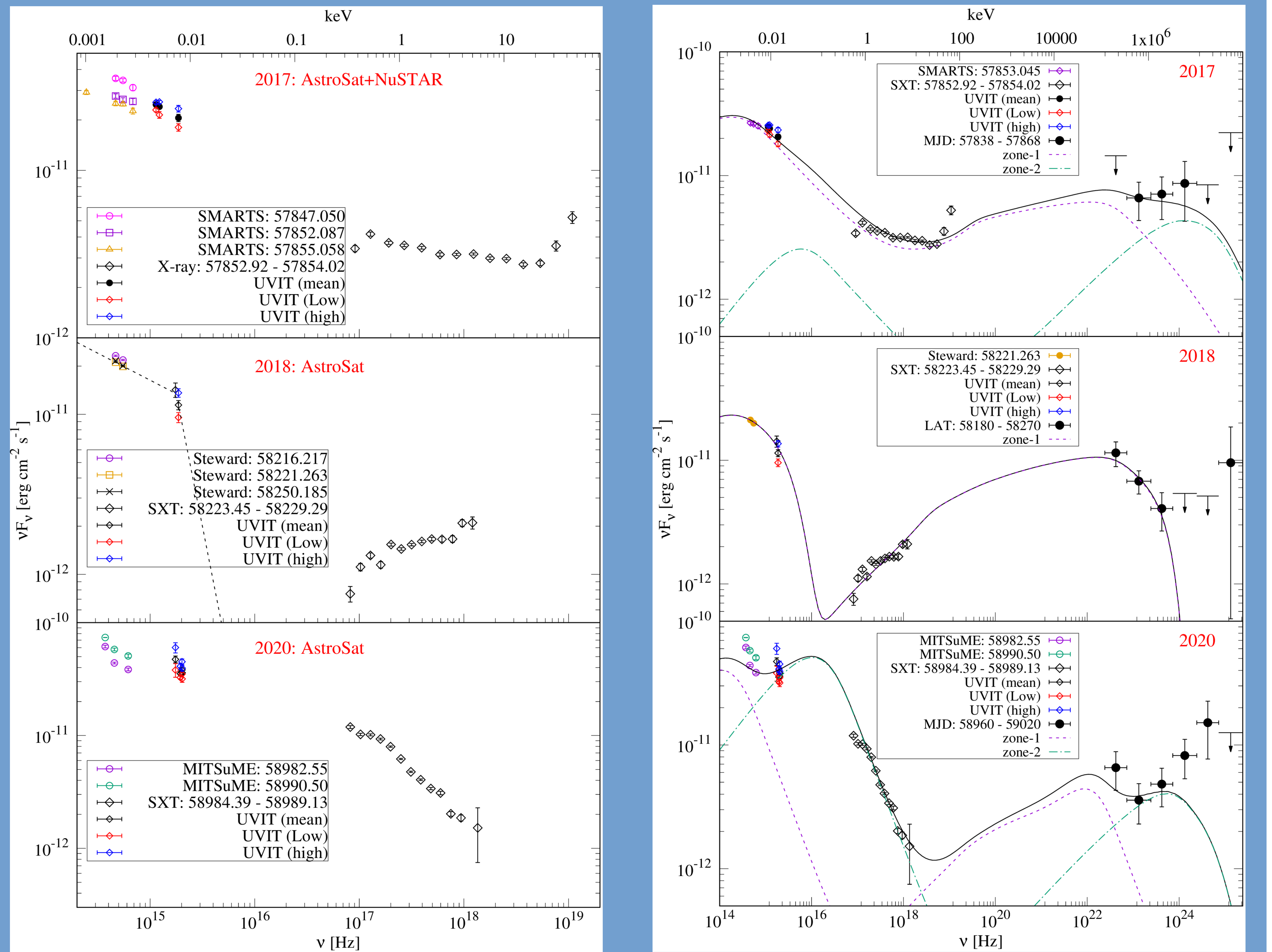

Figure 3: **Left:** Optical to X-ray spectra of OJ 287 from AstorSat with contemporaneous optical data from other facilities. The dotted curve in the 2018 SED is the best fit power-law model, showing the spectral steepening/cutoff in the optical-UV spectrum. **Right:** Broadband SED and the modeled spectra from relativistic leptons (e^-), employing synchrotron, synchrotron self-Compton, and external Compton processes. The dotted and dashed curves respectively show the well-known LBL and the HBL spectra (synchrotron and SSC only).

Spectral Changes: Modeling

SEDs modeling assuming leptonic scenario – synchrotron and inverse Compton processes show that (ref. **Figure 3,** [3, 5])

(1) One-zone emission model can reproduce 2018 SED

(2) 2020 SED needs an additional emission zone emitting HBL spectrum with X-ray due to synchrotron and MeV-GeV hardening due to SSC.

(3) 2017 SED also needs an additional emission zone but X-ray spectral change is primarily due to the evolution of the typical optical-UV synchrotron spectrum.

References

(1) M. L. Sitko and V. T. Junkkarinen, PASP 97 (1985) 1158
(2) A. Goyal et al, ApJ 863 (2018) 175
(3) P. Kushwaha, et al., MNRAS 433 (2013) 2380
(4) P. Kushwaha et al., MNRAS 473 (2018) 1145
(5) P. Kushwaha et al., MNRAS 479 (2018) 1672
(6) S. Komossa et al., MNRAS 498 (2020) L35
(7) O. Brien et al., ICRC2017, PoS