A comprehensive study of 2019-2020 flare of OJ 287 using AstroSat, Swift, and NuSTAR

Raj Prince,1* Gayathri Raman,2 Rukaiya Khatoon,3 Aditi Agarwal,4 Varun,5 Nayantara Gupta,4 Bożena Czerny,1 and Pratik Majumdar,6

1Center for Theoretical Physics, Polish Academy of Sciences, Al.Lotnikow 32/46, Warsaw, Poland
2Department of Astronomy and Astrophysics, Pennsylvania State University, 325 Davey Lab, University Park, PA 16802, USA
3Tezpur University, Napaam-784028, Assam, India
4Raman Research Institute, Sadashivanagar, Bangalore 560080, India
5Argykhatta Research Institute of Observational Sciences (ARIES), Manora Peak, Nainital 263002, India
6Saha Institute of Nuclear Physics, HBNI, Kolkata, West Bengal, 700064, India

Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT
OJ 287 is a well studied binary black hole system, that occasionally exhibits bright X-ray and optical flares. Here we present a detailed spectral study of its second brightest X-ray flare observed during 2019-2020 using archival Swift and NuSTAR observations along with ToO observations from AstroSat. The entire flaring period is divided into three states, defined as low, intermediate, and high state. The variation of hardness ratio (HR) with 0.3-10.0 keV integrated flux suggest a “softer-when-brighter” behavior, as also previously reported based on flux-index variations. Simultaneous high state X-ray spectra obtained using Swift, NuSTAR and AstroSat is very steep with a power law index $>2$. A significant spectral change is observed in AstroSat-SXT and LAXPC spectrum which is consistent with Swift-XRT and NuSTAR spectrum. Together, optical-UV and X-ray spectrum during the high flux state, suggesting the emergence of a new high BL Lacertae (HBL) component. We have modeled the synchrotron peak with publicly available code named GAMERA for low, intermediate, and high flux state. Our modeling suggests the need of high magnetic field to explain the high state under the leptonic scenarios. Increase in the magnetic field value inside the jet could be linked to the increase in accretion rate as expected in the BH-disk impact scenario. The color-magnitude diagram reveals a “bluer-when-brighter” spectral energy distribution chromatism during the flaring period. Different chromatism or no chromatism at various occasions suggests a complex origin of optical emission, which is believed to be produced by disc impact or through synchrotron emission in the jet.

Key words: galaxies: active – galaxies: jets – galaxies: nuclei – quasars: individual (OJ 287) – X-rays: galaxies

1 INTRODUCTION
Blazar OJ 287, having the most massive black hole among all blazars, is located at a redshift 0.306 (Mao 2011). It is classified as BL Lac object in the 3FGL (Acero et al. 2015) & 4FGL (Abdollahi et al. 2020) catalog. It is known for its high radio, optical, X-ray, and γ-ray variability. The variability time scale ranges from hours to decades across the wavebands (Goyal 2018). OJ 287 got more attention after the detection of high optical activity recurring at a regular interval of 12 years periodicity. In fact, this was the first AGN classified as a blazar, whose periodic behavior was observed after analysing its century long optical light curve, which challenges the general scenario of blazars where flares or high activity states are randomly produced or in other words blazars have very stochastic variability across the electromagnetic spectrum. Periodic behavior observed in optical light curve encouraged many authors to study this source in detail and provide the possible physical explanation of periodic behavior that is new to a blazar. In literature, Sillanpaa et al. (1988) proposed a model of binary black hole system where they associated the periodic variations to tidally induced mass inflows from accretion disk into the black hole (BH). They suggested that during the periastron passage, i.e., when the secondary black hole passes close to the primary BH, an optical outburst is produced. It has been observed that sometimes flares appear a bit earlier or a bit later than their predicted time, which is difficult to explain from first principles for a binary BH model. Later, Lehto & Valtonen (1996), have performed a detailed analysis of substructure inside the major flares and they modified the binary BH model to explain the sharp flare. In their model the secondary BH crosses the ac-
cretion disk of primary BH and produces the major optical flares. Other possible models have also been proposed in the recent past. The study of Britzen et al. (2018) considering the 15 GHz radio observation suggests the highly Doppler-boosted jet emission for major flare and the precession of jet to explain the periodicity in the light curve. Their model suggests that the optical emission is produced due to synchrotron radiation of relativistic electrons inside the jet. Many more studies suggest that the BBH model is more successful in explaining the double-peaked optical flare (Dey et al. 2018). In the Binary BH model it is shown that the impact of the secondary onto the accretion disk of the primary BH creates two hot bubbles of gas on both sides of the disk which radiate in optical through thermal Bremsstrahlung after becoming optically transparent. Since the secondary BH crosses the disk two times in each orbit, a double-peaked flare is observed/produced. The orbital period of the secondary BH is associated with the ~12 years periodicity seen in the light curve. Recent study by Dey et al. (2018) has confirmed the presence of 24 optical flares between 1885 to 2015 by the BBH model. The 2015 flare was also explained by Dey et al. (2018) in the context of binary black hole model. Valtonen et al. (2019) have estimated the values of the physical parameters of the impact of secondary onto the accretion disk of the primary BH in the BBH model.

In the past decade many broadband studies have been carried out on this source. In the broadband analysis, this source is classified as a low-peaked BL Lac source where the synchrotron emission is constrained by NIR to soft X-ray frequencies, with SED lies below 10$^{14}$ Hz. The high energy hump of the SED generally covers the X-ray and gamma-ray frequencies, with the peak at around 0.1 GeV to few GeV (Abdo et al. 2010, Kushwaha et al. 2013). Synchrotron self-Compton (SSC) is the most well accepted mechanism that can explain the second SED peak. However, in some flares it has been found that the SSC model is not sufficient to explain the high energy part of the spectrum and hence people have used additional external thermal field to explain this. In Kushwaha et al. (2013), they have used external photon field at a temperature of 250 K as a source of external seed photons. These photons get up-scattered by the highly relativistic electrons present in the jet through the inverse-Compton mechanism.

In X-rays, this source has been studied in detail during several active states. The maximum number of observations with the longest durations have been carried out with the Swift-XRT telescope, which nicely covered many bright X-ray flares of OJ 287. From the earlier X-ray flares it has been found that OJ 287 sometimes shows a significant change in the optical-UV and X-ray spectrum and that eventually leads to the shift in synchrotron peak towards higher energy during flare. Significant change in the X-ray spectrum and emergence of new HBL component is very rare in blazars. However, this kind of behavior has been seen in a few sources studied in the past (Plan et al. 1998, Raiteri et al. 2015, Kapanadze et al. 2018, Kushwaha et al. 2018a,b, 2020).

In 2020, a bright optical-UV, and X-ray flare was reported in various ATels\footnote{http://www.astronomerstelegram.org/?read=13677} (Zola et al. 2020, Komossa et al. 2020a, Reinhart et al. 2020, Hosokawa et al. 2020, Komossa & Grupe 2020). Recently, Komossa et al. (2020a), Komossa et al. (2021a); Komossa et al. (2021b,c) presented a detailed analysis with the data from XMM-Newton and NuSTAR telescopes. Many XMM-Newton archival observations along with recent 2018 and 2020 observations were analysed and they found that the spectrum in 2020 behaves very differently from archival observations including the year 2018. They suggested a non-thermal origin of the 2020 flares. We have performed a broadband SED modeling of the flares during 2017–2020 and it is presented in Prince et al. (2021a).

In this work, we provide a detailed analysis of Swift-XRT and UVOT instrument data and report the emergence of a new HBL component which eventually leads to the shift in synchrotron peak towards higher energy. The synchrotron emission is constrained by the optical-UV and X-ray data. Emergence of HBL component in low BL Lac blazars is very rare. We also carried out a Target-of-Opportunity (ToO) observation of the source using India’s first space-based multi-wavelength mission, AstroSat (Agrawal 2017). The results from Soft X-ray focusing Telescope (SXT) and Large Area X-ray Proportional Counter (LAXPC) instrument of AstroSat are also discussed in this work. At the end we have discussed the color-magnitude diagram followed by the summary and conclusions.

2 X-RAY ANALYSIS

Swift-XRT: OJ 287 is continuously monitored by the Swift telescope under the project summarised in Komossa et al. (2016). On February 3, 2017, an X-ray flare was observed by the Swift telescope (Gehrels et al. 2004), and the results were reported in Atel 10043 (Grupe et al. 2017). It is reported as the brightest flare ever detected since the monitoring of the Swift telescope. A long-term light curve is presented in Komossa et al. (2020a) where multiple flares were observed in X-rays. Swift-XRT is a soft X-ray telescope onboard the Swift Satellite and is sensitive in 0.3–10.0 keV energy band. The BL Lac OJ 287 was observed by Swift-XRT telescope during the multiple flaring episodes between the period November 2019 to May 2020. We have followed the standard analysis procedure to reduce the raw Swift data as it was done in Komossa et al. (2020a). The spectral fitting is done for an energy range of 0.3–10.0 keV with the Galactic absorption column density $n_H = 3.04 \times 10^{20}$ cm$^{-2}$ from Dickey & Lockman (1990).

AstroSat-LAXPC: The SXT observations were carried out in the Photon Counting (PC) mode and the Level-1 data was further reduced using the sxtpipeline1.4b (Release Date: 2019-01-04) to generate the Level-2 data products (Singh et al. 2016, 2017). The events from the various orbits were merged using the SXTMERGERTOOL in Julia. Further, we used the merged event list for temporal and spectral analysis. The merged event files were accessed by the tools Xselect where a source region of 10 arcsec was chosen around the source and the blank sky for the background. The response files and the background spectra are provided by the SXT-POC (Payload Operation Center) team. Finally, the grouped spectra were fitted in Xspec in the 0.3–10 keV band, and $\chi^2$ statistic was obtained for the best fit.

AstroSat-LAXPC: LAXPC (Yadav et al. 2016) is de-
X-ray study of OJ 287

Figure 1. Long-term X-ray light curve from Swift-XRT. WT: Window timing, PC: Photon Counting, Hard: 1.5–10.0 keV, Soft: 0.3–1.5 keV.

signed to observe sources in a very wide range of X-rays ranging from 3 keV to 80 keV. It has three identical proportional counters (LAXPC10, LAXPC20, & LAXPC30) onboard the AstroSat satellite. Data used in this work is taken from the LXP20 detector. The LAXPC30 detector is switched off due to gain instability issues. The data reduction and further processing of Level-1 were carried out using the LAXPC data analysis pipeline version 3.1\textsuperscript{2}. The pipeline code combines data from multiple orbits and also filters out overlapping segments between each orbit. Using the standard pipeline laxpc\_make\_event, we generate the cleaned event file. A good time interval (GTI) window was applied during the processing using the laxpc\_make\_stdgti tool, in order to exclude the time intervals corresponding to the Earth occultation periods, SAA passage and standard elevation angle screening criteria. Since Blazars are observed as faint sources in LAXPC, we adopted the faint source pipeline for the spectral analysis. In order to reduce background contribution from all LAXPC layers, only the top detector layer was used for the timing and spectral analysis of the LXP20 data.

**NuSTAR:** We also searched the archive for the NuSTAR observations. A ToO observation in NuSTAR (Harrison et al. 2013) was performed during the high X-ray flux state on 2020-05-04 starting at 20:36:09 UTC with an effective exposure time of 29.5 ks by Komossa et al. (2020a). The data reduction is made using the latest NuSTAR data analysis software (NuSTARDAS) version 1.9.2 provided by HEASOFT. To extract the source spectrum and the background spectrum, a circular region of 20" and 50" were chosen around the source and away from the source, respectively.

3 OPTICAL AND UV OBSERVATIONS

Having the Swift Ultraviolet/Optical Telescope (UVOT, Roming et al. 2005) on board with Swift-XRT has the advantage of getting simultaneous observations in Optical and UV bands. Swift-UVOT has also observed the OJ 287 in all of the available six filters U, V, B, W1, M2, and W2, simultaneously with the X-ray observations. A long-term optical-UV light curve is presented in Komossa et al. (2020a). We have used the archival data for the period between 2019-2020, and the standard analysis procedure is followed to extract the mag and the flux as it was done in Komossa et al. (2020a). We have considered the region of 5 arcsec around the source as the source region, and the region away from

\textsuperscript{2} Data analysis software was obtained from http://astrosat-ssc.iucaa.in/?q=laxpcData
The source is the background region. The magnitudes are corrected for galactic extinction by using the reddening $E(B-V) = 0.0241$ from Schlafly & Finkbeiner (2011) and zero points from Breeveld et al. (2011). Moreover, the magnitudes are converted into flux by multiplying by the conversion factor estimated by Poole et al. (2008) and the ratios of extinction to reddening from Giommi et al. (2006).

4 RESULTS

4.1 X-ray Light curves

XRT: We have produced the long term X-ray light curve of OJ 287, using Swift-XRT observations which is shown in Figure 1. The XRT observed the source in two different modes Photon Counting (PC) mode and Window Timing (WT) mode. In Figure 1, it is observed that the source showed a very bright soft-X-ray flare in 2016-2017, which was studied in detail earlier by Kushwaha et al. (2018b). In 2020, the second brightest soft-X-ray flare was observed as also marked by color patch in Figure 1. Our focus is to study the 2020 flare in detail and compare it with the older 2016-2017 flare.

Figure 2 shows the patched part of the light curve. The soft (0.3–1.5 keV) and hard (1.5–10.0 keV) count-rate light curves are shown in the top panel, and the lower panel shows the hardness ratio, which is defined as the ratio of hard counts to soft counts. From the upper panel it is clear that the blazar OJ 287 is highly variable and flaring in soft X-rays, while the count rate is lower and the source is far less variable in the hard X-ray band. In the beginning of the light curve (at MJD 58800), the counts are almost similar in both the bands, but as time passes, the soft X-ray part starts rising slowly with respect to hard X-ray. During April 2020 (≈MJD 58940), the soft X-ray counts are almost four times higher than the hard X-ray counts. It remained in a very high state for an entire month till May 2020 because of which the flare was eventually recognized as the second brightest X-ray flare in the history of OJ 287. It was first recognised by the Komossa et al. (2020a).

To characterize the variability in the soft and hard X-ray band, we have estimated the fractional variability ($F_{var}$) am-
plitude (Vaughan et al. 2003). The source is found to be more variable in 0.3–1.5 keV band with $F_{\text{var}} = 0.38\pm0.01$ and less variable in 1.5–10 keV band with $F_{\text{var}} = 0.27\pm0.01$. In the lower panel it can be seen that, as the source counts increases, the hardness ratio starts to shift towards the lower value. To see the clear trend in the hardness ratio (HR), we have plotted the hardness ratio against the total (0.3–10.0 keV) counts in Figure 3. The HR is anti-correlated with the total counts with Pearson’s correlation coefficient 0.61, suggesting a “softer-when-brighter” trend, as also previously reported by Komossa et al. (2020a). This trend in X-ray is a prevalent behavior in history of OJ 287 except the flare in 2015 where the spectrum was rather harder with flux. Comparing the softer behavior detected in the current flaring state, with the harder behavior observed in the 2015 flare, we conclude that these flares may have different origins.

**SXT:** We carried out a Target of Opportunity (ToO) observation using *AstroSat* (ObsID: 9000003672) during the X-ray flare in May 2020, since an enhanced X-ray flux was reported in several ATels. The source was observed from 15th–19th May, 2020. We have analyzed all the observations separately. In some of the observations, *AstroSat* detected a very low count rate and was heavily background dominated. Due to poor statistical quality of the data from those Obs IDs, we did not carry out any timing or spectral study for those observations. The SXT spectral products corresponding to May 15, 2020 had a good signal to noise ratio (SNR) for meaningful spectral study, which we have discussed in Section 4.4.

**LAXPC:** Along with SXT, simultaneous LAXPC observations were carried out between May 15, 2020 to May 19, 2020 (ObsID: 9000003672). We carried out a similar data reduction process for all the observational data taken during this period. As was the case with SXT, only the data of the observation corresponding to May 15 had a good SNR and is therefore presented in this paper. All the other observations were of poor statistical quality and background dominated and we do not utilize them for this study. The simultaneous observations by LAXPC with SXT provide an opportunity to model both the spectra together. The result of this joint fit is discussed in section 4.4.

**NuSTAR:** We also looked for the timing analysis in *NuSTAR*, but were unable to extract any light curve. Therefore, the study is focused on understanding the spectral behavior. Detailed discussion is provided in Section 4.4.

### 4.2 Optical-UV and $\gamma$-ray Light Curves

In Figure 4, we have shown the simultaneous gamma-ray, X-ray, optical and UV light curves during the flaring period of the source from MJD 58800 to 59012. It can be seen that the optical-UV emissions follow the X-ray emission; Komossa et al. (2020a) show a increase in brightness with time using long-term optical and UV light curves. However, in our study, we have focused on the detailed structure of light curve during the short period between 2019-2020. Based on the average values of magnitudes (shown by a solid green line) observed in the optical-UV band, we divided the light curves into three different parts, namely, low state, intermediate state, and high state. The solid green lines which represent the average values of the magnitudes in three different states are jointly represents a step function structure. In X-ray, the flux follows a similar kind of step function, but no apparent trend is seen. These three different states are used for the further study. No evident activity is seen in the $\gamma$-ray light curve shown in the uppermost panel. The flux observed in $\gamma$-rays is very low and mostly constant over time (fluctuating around the mean). The average flux during the flaring period is obtained as $2.78\times10^{-8}$ ph cm$^{-2}$ s$^{-1}$ and shown by a horizontal dashed line. Similarly, the 4FGL catalog flux is also represented by the horizontal dashed line in Figure 4 which is way below the average flux of the source during this period. Previous studies on the flares detected in 2015 and 2016-2017 by Kushwaha et al. 2018a,b also show no strong activity in $\gamma$-ray, though the source was flaring in optical-UV and X-rays.

### 4.3 X-ray Spectral Analysis

We have produced the X-ray spectrum of all the three states identified in Figure 4. The spectra are fitted with the simple power-law and the log parabola models, in built in *Xspec*, and a galactic absorption $\text{tbabs}$ is added to the model. The final model we used is $\text{tbabs}\times	ext{powerlaw}/\logparabola$ and the best fit model parameters are presented in Table 1. We also present F-test results to compare the different model fits and find with a p-value of $>0.01$, power-law is preferred over log parabola model.

We also compute flux using the $\text{cflux}$ model in *XSPEC*. The power-law spectral index can be seen changing from low state to high state. Details of our spectral fit results including the fluxes and spectral index, for all the three states, are presented in Table 1. We observe a clear trend of “softer-when-brighter” behavior of the source OJ 287 on a longer time-scale. The spectrum produced for all the three states is shown in Figure 5, which clearly show that the shape of the spectrum is also changing when the source transitions from the low state to the intermediate state and finally to the high state. The spectral fitting of all the individual observations since 2015 are done in Komossa et al. (2020a) with a single power law and they report a range of spectral index between 1.6-3.0. Our results are based on shorter time scale from 2019 to 2020 and estimated for three different flux states by modeling with the PL and LP spectral models.

We have also extracted the spectrum from the optical-UV band. The combined optical-UV and X-ray spectrum for all the three states is shown in Figure 6. Similar to the case in X-ray spectrum, a significant change is noticed here as the source transitions from the low state to the high flux state, which leads to an emergence of a new HBL component and a shift in the synchrotron peak towards higher energy as was previously reported by Komossa et al. (2020a); Komossa et al. (2021c). As a result, OJ 287, a well-known LBL (Nilsson et al. 2018) blazar, behaves like an HBL type source. A recent study of the kinetic features of radio jet blazars classifies OJ 287 as IBL type blazar (Hervet et al. 2016). The details about the new HBL component are discussed in section 5.

In Figure 6, the shape of the spectrum is flapping around a pivotal energy value corresponding to $\sim10^{15}$ Hz as the source changes its states. In the UVOT spectrum, it is found that the spectrum is quite steep during the low state, and then it becomes flat in the intermediate state, and finally, in the high state, it is increasing with energy. In the section 5, we
Figure 4. Broadband light curve created for period starting from November 2019 to current flaring state May 2020. Panel 1: represents the γ-ray data from Fermi-LAT; Panel 2: shows the X-ray data from Swift-XRT; Panel 3 and 4: shows the optical and UV data from Swift-UVOT. Step plot in optical-UV is shown to identify the step-wise increase in their flux.

have modeled the UVOT and X-ray spectrum for a better understanding of the synchrotron peak during various states.

4.4 AstroSat, Swift-XRT, and NuSTAR Spectral Analysis

In this section, we present the spectral analysis of simultaneous X-ray observations shown in Figure 7. We have used the observation of NuSTAR performed on May 04, 2020 (MJD 58973.86) by Komossa et al. (2020a), and one observation of AstroSat-SXT on May 15, 2020 (MJD 58984.0) performed by us. Simultaneous Swift observations were also made under the program run by Komossa et al. (2016); Komossa et al. (2020a), Komossa et al. (2021a); Komossa et al. (2021b,c), we have taken the data from the archive.

In the case of the simultaneous NuSTAR and Swift-XRT observations, we have fitted the joint Swift-XRT and NuSTAR spectrum to have a clear understanding of the broadband spectrum. The Swift-XRT observation with ObsID:35905053 is simultaneous to the NuSTAR observation, and hence a joint XRT+NuSTAR fit is produced, and a joint spectral fit of XRT+NuSTAR observations is shown in Figure 8. The joint fitting is performed in xspec with a power-law spectral model. It is found that a single power-law can explain the total spectrum ranging from 0.3-50.0 keV. The model used for fitting is \texttt{const*tbabs*powerlaw}. The component \texttt{const} is added to match the normalization of both the data group and \texttt{tbabs} is used to account for galactic absorption. The best fit power-law index is found to be 2.37±0.09 and the flux estimated in 0.3-10.0 keV is $(2.10\pm0.07)\times10^{-11}$ erg cm$^{-2}$ s$^{-1}$ and the flux in 3.0-50.0 keV is found to be $(6.34\pm0.20)\times10^{-12}$ erg cm$^{-2}$ s$^{-1}$.

AstroSat SXT and LAXPC observations are simultaneous as marked in Figure 7. The joint SXT+LAXPC spectral fit-
The X-ray study of OJ 287

Figure 5. The Swift-XRT X-ray spectrum for all the three states fitted by powerlaw. Lower panel show the residuals of the fit.

Figure 6. Combined Swift-XRT and UVOT broadband spectrum of all states. A clear spectral change is observed from low state to higher state.

XRT+NuSTAR and SXT+LAXPC are consistent with each other.

The best fit parameters of all the simultaneous and quasi-simultaneous spectra are presented in Table 2. NuSTAR spectrum is also fitted in Komossa et al. (2020a) with powerlaw spectral model and they found the spectral index $2.36 \pm 0.06$ and $2.20 \pm 0.20$ below $10.0$ keV and after the $10.0$ keV, respectively. Our joint spectral fitting of XRT+NuSTAR with single powerlaw shows the spectral index $2.37 \pm 0.09$ which is consistent with theirs below $10.0$ keV spectrum. We have also did the joint spectral fitting of SXT+LAXPC with single powerlaw and the joint spectral index estimated to be $2.43 \pm 0.09$ which shows consistency with our XRT+NuSTAR joint fit. Here the SXT and LAXPC joint fit is important since the spectrum is highly simultaneous and the exposure time is $\sim 30$ ks. Due to the higher exposure time AstroSat-SXT spectrum is much better than the Swift-XRT spectrum used in the joint fitting (Figure 8 & 9).

5 MODELING THE SYNCHROTRON PEAK: HBL LIKE COMPONENT

The synchrotron peak in blazars can be constrained by the near-infrared and optical-UV emission along with the soft X-ray emission. Previously, a log-parabolic function (Massaro et al. 2004; Kapanadze et al. 2018) and a log-cubic function (Raiteri et al. 2013) have been used to model the NIR, optical-UV, and X-ray spectrum. In our work, we have used a different approach, where we modeled the optical-UV and X-ray data points with the synchrotron process using the publicly available code GAMERA; modeling details can be found in Prince et al. (2021b).

We found that during the low state of the source, the synchrotron peak is observed at around $\sim 10^{14}$ Hz, which is the synchrotron peak assigned for the LBL type source (Padovani & Giommi 1995, Abdo et al. 2010). During the intermediate state, the X-ray spectrum does not change much,
Figure 7. Broadband light curve of 2020 along with the simultaneous observations in other X-ray low and high energy band. Panel 1 shows the \textit{Swift} -XRT light curve and Panel 2 and 3 represents the \textit{Swift} -UVOT light curves. Star symbol marked on the panel 1 represents the time of NuSTAR observations and the symbol + sign inside circle represents the time of AstroSat SXT and LAXPC observations.

Figure 8. Joint XRT+NuSTAR fitting of the simultaneous observations. Black data points shows the \textit{Swift} -XRT result and the red data points are the simultaneous NuSTAR results. Lower panel shows the residual of the fit.

however a marginal shift of the synchrotron peak towards the higher energy is observed because of change observed in UVOT spectrum (Figure 10). During the high flux state, the shape of the UVOT and X-ray spectrum both have changed significantly compared to the low flux state, suggesting the emergence of a new HBL component in this source. The fitting of the parameters using GAMERA shows that a higher magnetic field (\(\sim 6.7\) G) is required in high flux state. However, in the low and intermediate state the magnetic field is found to be \(\sim 4.1\) G. The LP electron distribution is provided to GAMERA to model the synchrotron peak. The spectral index, \(\alpha\) is 1.8 for low and intermediate state and a steeper spectral index of 2.65 is required for the high state. Our modeling also suggests the need for higher energy electrons during high state compared to low and intermediate state. The values of the parameters obtained in this work are consistent with the parameters estimated in Prince et al. 2021 (under review). Modeling of the synchrotron emission shows that the synchrotron peak is shifted towards the higher energy, and the current peak location is around \(10^{16}\) Hz, which is the ideal case for the HBL type BL Lac source (Padovani & Giommi 1995, Abdo et al. 2010). The shift is two orders of magnitude in frequency which is very rarely seen in a single blazar. The results suggest that during the flaring period, the source exhibits very different spectral properties compared to when it is in a normal state. The result is shown in Figure 10. In OJ 287, this behavior was also seen before during the flare of 2016-2017 (Kushwaha et al. 2018b) where the synchrotron peak was shifted towards the higher energy. The first appearance of the HBL component was seen in a flare of 2017, the study of Kushwaha et al. (2020) discussed the disappearance of the HBL component in 2018. Again the HBL component appeared in the flare of 2020 as mentioned by Komossa et al. (2020a), Kushwaha et al. (2020), which has also been found in the present study. This finding suggests that the source is highly variable and changes its behavior during high flux state and fluctuates between LBL and HBL type source, and has an identity crisis. The blazar classification into FSRQ and BL Lac, and further the classification of BL Lac objects into LBL, IBL, and HBL is based on the fixed location of the synchrotron peak (Abdo et al. 2010). Therefore, the change in the synchrotron peak is not very common, and if it does occur, it challenges the understanding of the underlying physical mechanisms in these types of sources. Blazar OJ 287 is a well accepted binary black hole system, and the significant change in the optical-UV and X-ray spectral state has an identity crisis. The blazar classification into FSRQ lying physical mechanisms in these types of sources. Blazar...
impact scenario, the appearance of new HBL components in April-May 2020 is still puzzling and needs more future study to draw any reliable conclusion. One of the possible explanations for the new HBL component could be the increase in the accretion rate (Komossa et al. 2020a) post BH-disk impact and consequently it could trigger the flare produced in the jet after a few months. The time delay observed around nine months between the impact and the time of flare is not easy to understand, since various physical conditions could be responsible for that (disk/corona properties and geometry, magnetic field geometry, shock formation in the jet).

In our first paper, we have modeled the broadband SED of 2020 flare along with a low state, and we found that one emission zone is sufficient to explain the total SED (Prince et al. 2021a).

Recent study by Komossa et al. (2021c) has discussed the long term X-ray spectral behavior of the source. They analysed the XMM-Newton and Swift data from 2005–2020, and found that the X-ray spectrum is highly variable. They also mentioned that the X-ray spectrum covers all the behaviors seen in blazars from significant flat to very steep.

6 COLOR-MAGNITUDE DIAGRAM

Simultaneous monitoring of OJ 287 in various optical (U, B, V) bands allow us to study the color variation of the source. The color-magnitude diagram helps in understanding the origin of different physical processes responsible for the flux variations in blazars. We fit the plots of colour indices (CI) vs. magnitude (M) with straight lines (i.e. CI = m*M + c) using which we estimated the fit values of the slope, m, the Spearman correlation coefficient r along with the corresponding null hypothesis probability, p which are summarized in Table 3. A positive slope (when the p value is < 0.05) indicates significant positive correlation between CI and blazar magnitude, which in turn points towards a bluer when brighter (BWB) or redder when fainter trend (H.E.S.S. Collaboration et al. 2014) in the target, while a negative slope implies the opposite i.e. redder when brighter (RWB) trend (Agarwal et al. 2019).

We have plotted the four color-magnitude diagram defined among B-V vs. B, U-V vs. U, U-B vs. U, and U-B vs. V, which are shown in Figure 11. The estimated values of r and p for all the cases are mentioned in each plot. In three cases, we have seen a strong correlation with a correlation coefficient of 0.69, 0.84, and 0.77, respectively, suggesting a “bluer-when-brighter” chromatism (Figure 11). In the case of B-V vs. B, we did not find any strong correlation; however, the slope suggests RWB chromatism but could not be confirmed.

Previous study on the color-magnitude diagram have shown various trends, including the BWB and RWB. BWB chromatism has been previously reported in the B and V bands between 1973–1976 (Carini et al. 1992), in the R and V bands between 1993–1997 (Dai et al. 2011), in the V and J bands (weaker correlation) between 2008–2010 (Ikejiri et al. 2011) and in the Ringo3 bands in 2015 (Jermak et al. 2016). A recent study by Wierzcholska et al. (2015) found weak or no correlation on longer timescales in the B and R bands, while they claim the BWB chromatism at shorter isolated intervals in the long-term light curve. Another study by Siejkowski & Wierzcholska (2017) did not find correlation in any combination of color-magnitude diagrams. Gupta et al. (2019) found BWB chromatism in V-R and R-I colors with respect to R band magnitude. However, their Pearson’s correlation coefficient is below 50%.

A clear BWB and RWB and occasional lack of correlation in the color-magnitude diagram of OJ 287 indicate a complex nature of the physical process responsible for the optical emission in this blazar.

Figure 10. Broadband SED fit during the low, middle, and high state. The data points are from Swift -XRT/UVOT and the synchrotron peak is fitted with code GAMERA.
Observation ID | PL $F_{0.3-10\text{keV}}$ | $\Gamma$ | $\chi^2$ (dof) | LP $F_{0.3-10\text{keV}}$ | $\alpha$ | $\beta$ | $\chi^2$ (dof) | F-test | p-value |
---|---|---|---|---|---|---|---|---|---|
low state | 5.15±0.15 | 1.89±0.07 | 85.30(86) | 4.98±0.20 | 1.86±0.09 | 0.12±0.21 | 84.46(85) | 0.84 | 0.36 |
intermediate state | 7.14±0.08 | 2.15±0.04 | 166.40(145) | 7.22±0.10 | 2.16±0.05 | 0.04±0.11 | 166.01(144) | 0.34 | 0.56 |
high state | 14.72±0.09 | 2.56±0.02 | 206.14(227) | 14.60±0.12 | 2.55±0.02 | 0.04±0.07 | 205.04(226) | 1.21 | 0.27 |

Table 1. Modeled parameters for the X-ray spectrum during low state, intermediate state, as well as of high state. The fluxes are in unit of $10^{-12}$ erg cm$^{-2}$ s$^{-1}$.

| Instruments and Dates | PL $F_{0.3-10\text{keV}}$ | $\Gamma$ | $\chi^2$ (dof) |
|---|---|---|---|
| SXT + LAXPC | 0.91±0.04 | 2.43±0.09 | 40.25(57) |
| (0.96$^-$) |
| XRT + NuSTAR | 2.10±0.17 | 2.37±0.09 | 119.22(134) |
| (0.63±0.04) |

Table 2. Modeled parameters for the simultaneous X-ray spectrum from XRT, SXT, NuSTAR, and LAXPC during various occasions. The fluxes are in unit of $10^{-11}$ erg cm$^{-2}$ s$^{-1}$.

Further, we have also estimated the average optical spectral index following the expression from Wierzcholska et al. (2015),

$$\langle \alpha_{BR} \rangle = \frac{0.4(B - R)}{\log(\nu_B/\nu_R)}$$  

(1)

Where $\langle B - R \rangle$ is the average color from any two bands, and the $\nu_B, \nu_R$ are the effective frequency of the corresponding B, and R bands. The optical spectral index estimated for the Swift U, B, V bands vary between 0.89 to 1.15, suggesting a significantly harder spectrum in optical bands. The optical spectral index is shown in Table 3. A significant spectral hardening in the optical emission is also seen in Kushwaha et al. (2020). During the same period, a significant spectral softening is observed in Figure 3, suggesting an anti-correlation with optical spectral index. Wierzcholska et al. (2015) find that OJ 287 has a significantly steep optical spectrum, between $\alpha_{BR} \sim 2.3$. In our study, the anti-correlation between optical and X-ray spectral index might suggests they are produced through different processes. Many more optical and X-ray study is required to come up with any concrete conclusions.

7 SUMMARY AND CONCLUSIONS

In this work, we present a joint X-ray and UV-optical study of the interesting blazar OJ 287 during its flaring activity between 2019–2020 using AstroSat, NuSTAR and Swift observations. The study includes the data from AstroSat-SXT and LAXPC instruments. We categorized the long term $Swift$ light curve as low state, intermediate state, and high state (Figure 4). The flare of 2020, which is categorized as a soft X-ray flare, shows a “softer-when-brighter” behavior. Joint spectral fitting of simultaneous observations of Swift-XRT and NuSTAR, and the AstroSat-SXT and LAXPC indicate consistent power-law spectral index values of 2.37±0.09 and 2.43±0.09 in the 0.3–50.0 keV and 0.3–20.0 keV bands, respectively. Since AstroSat -SXT has a longer exposure compared to Swift-XRT, it has been very useful in generating sufficient SNR to better constrain the source spectral properties. Our spectral study indicates a shift in the synchrotron peak of the source towards the higher energy which suggests an emergence of HBL components during the high flux state. We have modeled the synchrotron peak with the physical model implemented in publicly available code GAMERA. Our modeling suggests that a higher value of magnetic field is required to explain the high state compared to low state in leptonic scenario. Results from our study of the color-magnitude behavior of the source during this bright state show significant correlations in all bands, except in the B-V vs. B bands, suggesting a strong “bluer-when-brighter” chromatism. A significant harder spectrum is observed in optical which is anti-correlated with the X-ray emission. The different behaviors of OJ 287 observed during various flux states suggest a complex nature of the source. Much more detailed optical and X-ray study would be required for better understanding of this proposed binary black hole system.

ACKNOWLEDGEMENTS

The project was partially supported by the Polish Funding Agency National Science Centre, project 2017/26/A/ST9/00756 (MAESTRO 9), and MNiSW grant DIR/WK/2018/12.
DATA AVAILABILITY

The data and softwares used in this research are available at NASA’s HEASARC webpages with the links given in the manuscript.

REFERENCES

Abdo A. A., et al., 2010, ApJ, 716, 30
Abdollahi S., et al., 2020, ApJS, 247, 33
Acero F., et al., 2015, ApJS, 218, 23
Agarwal A., et al., 2019, MNRAS, 488, 4093
Agrawal P. C., 2017, Journal of Astrophysics and Astronomy, 38, 27
Breeveld A. A., Landsman W., Holland S. T., Roming P., Kuin N. P. M., Page M. J., 2011, in McEnery J. E., Racusin J. L., Gehrels N., eds, American Institute of Physics Conference Series Vol. 1358, American Institute of Physics Conference Series. pp 373–376 (arXiv:1102.4717), doi:10.1063/1.3621807
Britzen S., et al., 2018, MNRAS, 478, 3199
Carini M. T., Miller H. R., Noble J. C., Goodrich B. D., 1992, AJ, 104, 15
Dai Y., Wu J., Zhu Z.-H., Zhou X., Ma J., 2011, AJ, 141, 65
Dey L., et al., 2018, ApJ, 866, 11
Dickey J. M., Lockman F. J., 1990, Annual Review of Astronomy and Astrophysics, 28, 215
Gehrels N., et al., 2004, The Astrophysical Journal, 611, 1005
Giommi P., et al., 2006, A&A, 456, 911
Goyal A., 2018, Galaxies, 6
Grupe D., Komossa S., amp Falcone A., 2017, The Astronomer’s Telegram, 10043, 1
Gupta A. C., et al., 2019, AJ, 157, 95
Harrison F. A., et al., 2013, ApJ, 770, 103
Hervet O., Boisson C., Sol H., 2016, A&A, 592, A22
Hosokawa R., Adachi R., Murata K. L., Niwano M., Ogawa F., Nakamura N., Yatsu Y., Kawai N., 2020, The Astronomer’s Telegram, 13755, 1
Ikejiri Y., et al., 2011, PASJ, 63, 639
Jermak H., Steele I. A., Lamb G. P., Valtonen M., Zola S., 2016, Proceedings of the International Astronomical Union, 12, 241–242
Kapanadze B., et al., 2018, The Astrophysical Journal Supplement Series, 238, 13
Komossa S., Grupe D., 2020, The Astronomer’s Telegram, 13785, 1
Komossa S., et al., 2016, Proceedings of the International Astronomical Union, 12, 168–171
Komossa S., Grupe D., Parker M. L., Valtonen M. J., Gómez J. L., Gopakumar A., Dey L., 2020a, MNRAS, 498, L35
Komossa S., Grupe D., Gomez J. L., 2020b, The Astronomer’s Telegram, 13658, 1
Komossa S., et al., 2021a, Publications de l’Observatoire Astronomique de Beograd, 100, 29
Komossa S., et al., 2021b, Universe, 7
Komossa S., et al., 2021c, Monthly Notices of the Royal Astronomical Society, 504, 5575
Kushwaha P., Sahayanathan S., Singh K. P., 2013, Monthly Notices of the Royal Astronomical Society, 433,
