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DETECTION AND 2-POINT SPECTRAL INDEX ANALYSIS OF NEW RADIO-SYNCHROTRON COMPONENTS IN THE KPC JET OF OJ287

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Abstract. The blazar OJ287, located at z = 0.306 is a very unusual object, as it is suspected of hosting a binary black hole system which powers a relativistic blazar jet. New LOFAR observations of this source, reduced including its international baselines, have allowed us to match the resolution of instruments such as the VLA and Chandra, thereby resolving the knots in the kpc jet of OJ287. We report the discovery of new jet components discovered at low frequency with LOFAR, and study the evolution of the spectral index (spi) along the jet using two radio observations (made with LOFAR at 144 MHz and the VLA at 1.4 GHz).

Keywords: LOFAR, LOFAR-VLBI, radio, binary black hole, blazar, OJ287, jet

1 Introduction

The famous BL Lac object OJ 287*, $z = 0.306$ (Stickel et al. 1989) is an object whose exceptional optical variability (e.g. Takalo 1994; Hudec et al. 2013) suggests the possibility of a binary black hole system (Sillanpaa et al. 1988; Lehto & Valtonen 1996; Cho et al. 2024) driving its active galactic nucleus jet, motivating ongoing monitoring across the electromagnetic spectrum to this day†. Therefore, OJ 287 benefits from exquisite multi-wavelength coverage, making it an extremely interesting target for a range of science cases, from AGN and blazar studies to multi-messenger astronomy (Chen & Zhang 2018). This multi-wavelength coverage revealed a relativistic jet featuring significant relativistic bulk motion detected up to Mpc scales (Marscher & Jorstad 2011). Although OJ 287's radio and X-ray properties are consistent with those of a Fanaroff-Riley type-I AGN (Fanaroff & Riley 1974), as expected for BL Lac sources (Urry & Padovani 1995), its Mpc relativistic bulk motion is unusual for FR I type radio galaxies. This makes OJ 287 a good candidate to study synchrotron, IC/CMB and local re-acceleration models along the jet.

In this proceeding, we report the discovery of new, steep-spectrum radio-synchrotron components connecting the jet structures previously observed at high frequencies. At lower frequencies, "fossil" radio-synchrotron emission from older cosmic rays populations remains detectable (Kardashev 1962; Pacholczyk 1970; Jaffe & Perola 1973; Harwood et al. 2013) while they are undetectable at higher frequencies. To mitigate the degradation in resolution associated with going to low frequency, we made use of the International LOFAR Telescope (ILT). This consists of the LOFAR array (van Haarlem et al. 2013) used to its full extent, i.e. with the inclusion of its numerous international stations. This allows LOFAR to achieve sub-arcsecond resolution at its observing frequency of 144 MHz, where radio-synchrotron emission from older, low-energy cosmic rays may still be detected (Kardashev 1962; Pacholczyk 1970; Jaffe & Perola 1973; Harwood et al. 2013).

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*Other names include: PKS 0851+202, S3 0851+20, B2 0852+20, PG 0851+202 in literature, and 1ES 0851+203, RX J0854.8+2006, 3EG J0853+1941, 3FGL J0854.8+2006 in high-energy bands

†E.g. `https://stach.oa.uj.edu.pl/sz/oj287.html`

2 Data & Reduction

Our work used now-public data taken on 13/06/2019 at 12h22, using 24 core stations, 14 remote stations and the 13 international stations available at the time (PI S. Mooney, project LC12_022, SASID 723584). The core stations were used in HBA_DUAL mode as per the standard LOFAR survey configuration, doubling the effective number of core stations for a total of 75 array elements in the final interferometric array. The observation lasts 4 hours, for an adequate uv-coverage, and uses the full LOFAR bandwidth of 120 - 187 MHz.

Our data was reduced with the standard LOFAR Initial Calibration (`LINC`) pipeline[‡], and the the LOFAR-VLBI pipeline[§] (Morabito et al. 2022). The solution time intervals was at least 10 minutes in all case, to avoid suppressing physical emission from OJ287. Finally, using the final self-calibration model as a starting point, The final image quality was improved using `NeReVar`[¶], a modern, stand-alone implementation of the gain-variance-based weighting scheme described in Bonnassieux et al. (2018). This allowed us to decrease the pollution from calibration artefacts, revealing more structure in the jet of OJ287 than would be possible from the pipeline alone; the result is shown in Fig. 2.

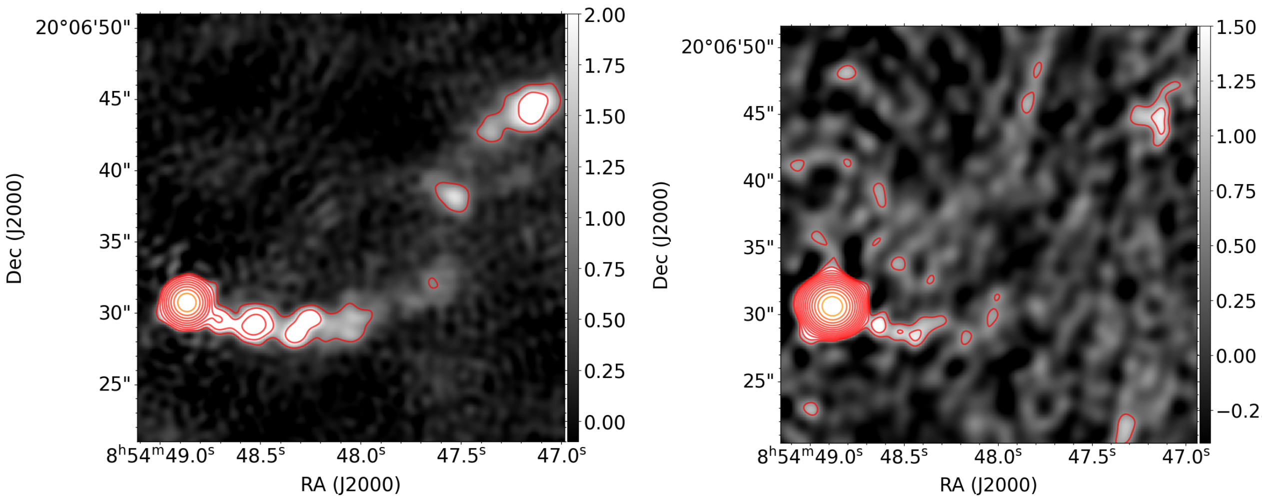

Fig. 1. Left: LOFAR map of OJ287 brightness distribution, in units of mJy/beam. The image overlay has 10 levels starting at 0.95 mJy/beam and going to the peak value. **Right:** VLA map of OJ287 brightness distribution, in units of mJy/beam. The image overlay has 10 levels starting at 0.69 mJy/beam and going to the peak value.

For our index analysis, we downloaded archival visibility data of OJ287 from the VLA data archive[‖] (L-band, 1.4 GHz). The associated image is shown in Fig. 2. Both images used for spectral index analysis require as similar a uv-coverage as possible, to cover the same physical scales. Both datasets were thus re-imaged with matching uv constraints, including a uv-taper targeting a resolution of $1''$. All imaging was done using `wsclean` (Offringa et al. 2014). We used the `CASA imfit()` task to measure the flux density in regions around each visually-identified component above 5σ in the LOFAR map. Where `imfit()` failed to find components in the VLA map due to low signal-to-noise, we used the 1σ root-mean-square noise in the image as an upper limit. A final absolute flux scale correction was applied to this component catalogue, as the self-calibration and imaging introduced a drift in the flux scales.

[‡]The documentation and code can be found at `https://linc.readthedocs.io/en/latest/index.html`; its process is described in Williams et al. (2016); van Weeren et al. (2016); de Gasperin et al. (2019)

[§]The documentation and code can be found at `https://lofar-vlbi.readthedocs.io/en/latest/`

[¶]Can be found at `https://github.com/ebonnassieux/Scripts/blob/master/NeReVar.py`

[‖]Website can be found here: `https://science.nrao.edu/facilities/vla/archive/index`

3 Results & Analysis

The result of this proceeding is the measurement of the radio-synchrotron spectral index evolution along the Mpc-scale jet of OJ287. This is done on a per-component basis, for components identified above a 5σ noise level in our LOFAR map. The spectral indices are shown in Fig. 2 below, using the convention $S_\nu \propto \nu^\alpha$.

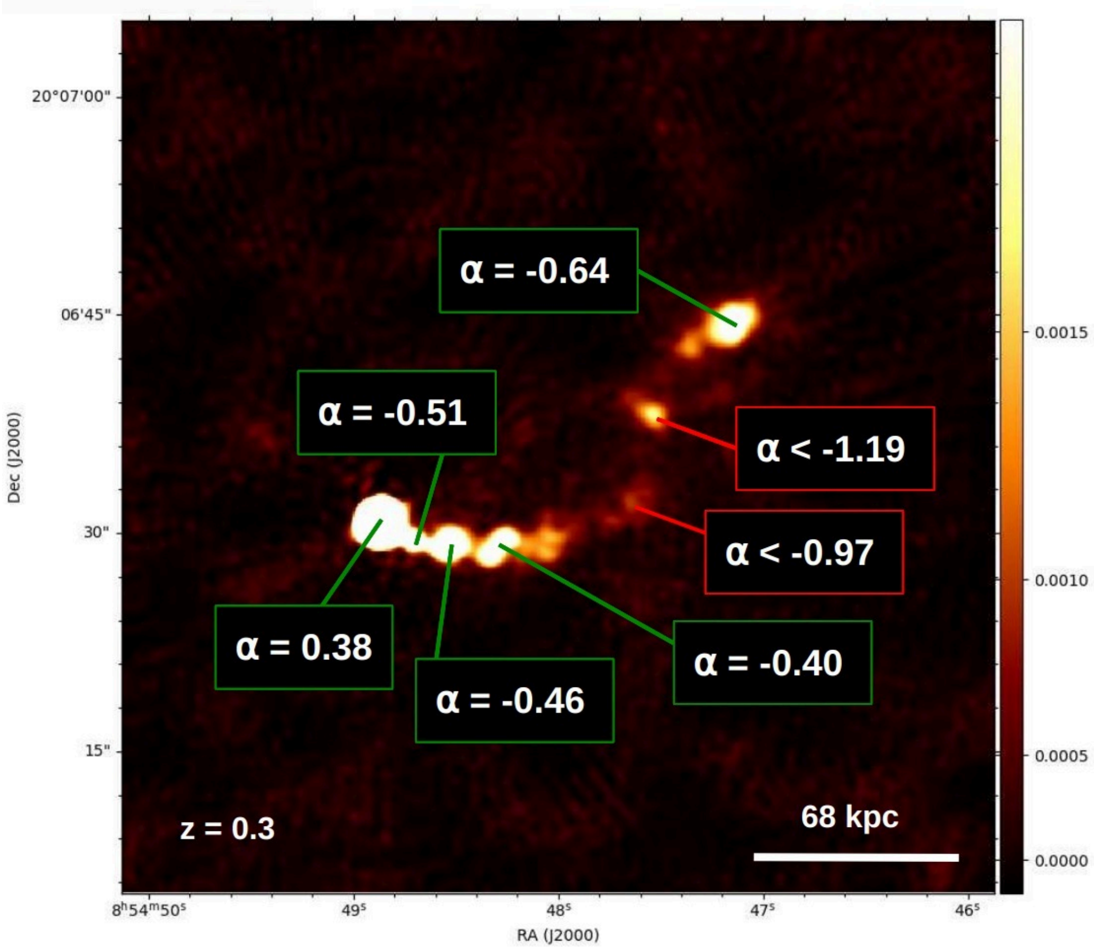

Fig. 2. Spectral index values of components in the jet of OJ287. Red boxes indicate an upper limit spectral index value. Physical scale conversion from Marscher & Jorstad (2011). Spectral index values are from 144 MHz to 1.4 GHz.

Of all the components identified, only the core shows evidence of spectral turnover (i.e. is brighter at 1.4 GHz than 144 MHz). This is consistent with this component becoming optically-thick to radio-synchrotron emission, particularly at parsec jet scales. Further studies using the uGMRT to cover the missing frequency window between 144 MHz and 1.4 GHz will be very valuable to constrain the overall spectral curvature of the core of OJ287, and therefore the parsec-scale jet physics of this source.

The bright kpc-jet components tend to show flattening spectral indices as distance along the jet increases, from $\alpha = -0.51$ to $\alpha = -0.46$ to $\alpha = -0.40$. This behaviour can be explained with various physical models. The emitting regions could become optically thick, causing synchrotron self-absorption, though this is unlikely as the flattening increases with distance, while the plasma density can be expected to remain relatively constant or decrease with jet distance. Another mechanism which could explain this behaviour would be re-acceleration of the synchrotron-emitting cosmic rays as they travel down the jet. This would be consistent with the presence of stationary shocks along the jet, as well as the presence of X-ray flux detected for these components Marscher & Jorstad (2011). Further investigation will require improving the frequency coverage.

Two components are detected clearly in LOFAR but only barely with the VLA, and both show evidence of very steep radio-synchrotron spectra. These are compatible with an old population of cosmic rays being re-accelerated, and therefore emitting with a much steeper radio-synchrotron spectrum. Their detection allows us to bridge the already-known components and the last-detected component, firmly associating the latter with the Mpc jet of OJ287.

The spectral index of this potentially terminal component, $\alpha = -0.64$, is consistent with self-absorption of a portion of the component in classical "AGN hotspot" behaviour, with the plasma surrounding this hotspot keeping to a classical $\alpha \sim -0.8$ radio-synchrotron spectrum. However, no counter-jet components appear to be detected at all; we therefore cannot rule out the possibility that this component is only the latest detected, and that more sensitive observations could detect further emission along the jet. In such a case, the spectral index behaviour would be consistent with the presence of mild local re-acceleration.

4 Conclusions

The International LOFAR Telescope is pushing the frontiers of what can be learned about blazar jets, including for canonical sources such as OJ287. This is because the low-frequency regime appears to allow for direct observation of both blazar-specific physics as well as more general AGN jet physics, simultaneously, for blazar sources. This may prove key to understanding critical questions such as the origin point of γ-ray bursts, constraining multi-zone emission models, and possibly exploring hadronic models of blazar neutrino production.

However, a simple two-point analysis between the LOFAR band and the VLA L-band cannot lift degeneracies between physical models one can invoke to explain the observed spectral behaviour. Filling the gap with further observations with the uGMRT will allow for a complete analysis, and observations in its bands 3 and 4 have already been taken (PIs: Hrishikesh Shetgaonkar and Janhavi Baghel, respectively). We expect that they will allow for a full Spectral Energy Distribution analysis, extending to the X-ray regime, of both known and new components of this jet.

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