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The multi–spectral–range behavior of OJ 287 in 2005–2010

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Abstract. The BL Lac object OJ 287 is well known to exhibit quasi-periodic optical double outbursts every ∼12 years, the latest reported between 2005 and 2008. We have been monitoring the source monthly at 43 GHz (VLBA imaging), 86 GHz (IRAM 30m), and optical frequencies, including polarimetry, since 2006. This program is supported by parallel monitoring observations at several other spectral ranges, and by publicly available X-ray and γ–ray data. Analysis of the VLBA images since 2005 shows an unexpected bright feature propagating at a subluminal speed southward from the core. This new projected direction of ejection of the jet does not support a binary black hole system with a ∼12 years period as the origin of the previously known jet wobbling in the source. We propose a jet perturbation (i.e., a Kelvin–Helmholtz instability) as the origin of the dramatic change of structure of the jet in OJ 287. We also report on the time coincidence of two γ–ray flares with two mm and sub-mm flares produced in the 43 GHz VLBI core, and two sharp increases of linear polarization degree in the core region. In contrast, we do not find any obvious relation between the R–band total flux light curve of OJ 287 and those at the other spectral ranges.

1. Introduction

During the past ∼ 40 yr, OJ 287 has shown quasi–periodic double–peaked optical outbursts (separated by 400 to 700 days) every ∼ 12 yr, the last of which occurred between 2005 and 2007 (e.g., Villforth et al. 2010). This quasi–periodicity has been used as the main argument supporting binary black–hole (BH) models, or other, less exotic, scenarios such as instabilities in the accretion disk of the AGN or in its corresponding jet (see Villforth et al. 2010, for a discussion about these different scenarios). Consistent with the latter scenario, Tateyama & Kingham (2004) reported a jet wobbling behavior from their long-term 8 GHz VLBI study, which they explain with a ballistic jet precession model, also with a periodicity of ∼ 12 yr.

Here we present a new observational approach on OJ 287 from 2005 to 2010 that aims at investigating the overall multi–spectral–range (and mm and optical polarimetric) properties of this blazar and their relation to its double flaring state during the 2005–2010 time range.

2. The observations

We have monitored OJ 287 with a time sampling of one month or better with 43 GHz VLBA polarimetry (Fig. 1), 86 GHz IRAM 30 m polarimetry, and optical (Calar Alto, Lowell, Crimean Astrophysical, and St. Petersburg State University Observatories) polarimetry (Figs. 2 and 3) since the beginning of 2006. These programs are also supported by several other independent 43 GHz VLBA observations dating back to 1995 (with a gap in 2002–2004), by total flux monitoring SMA observations at 230 and 350 GHz since late 2002, and by publicly available X–ray (*Swift*–XRT) and γ-ray (*Fermi*–LAT) data starting in mid-2005 and mid-2008, respectively (see Fig. 2). Moreover, most of the comprehensive set of photo–polarimetric R–band optical data presented in Fig. 3 was taken from Villforth et al. (2010), to which we refer the reader for details on the data acquisition and reduction.

The reduction of VLBA, optical polarimetric, *Swift*–XRT, and *Fermi*–LAT data was performed following Marscher et al. (2010) and Jorstad et al. (2010), whereas the IRAM data was reduced following Agudo et al. (2010). The SMA data reduction was performed according to Gurwell et al. (2007).

3. Total flux results

3.1. The innermost jet as seen by the VLBA at 43 GHz

Fig. 1–left shows a clear clockwise wobbling behavior of the jet in OJ 287 consistent with the one reported by (Tateyama & Kingham 2004). However, their periodic precession model predicted a jet structural position angle ∼ −95° in 2009, whereas we measure a drastically different and persistent inner jet position angle of ∼ 160°. Clearly, the present jet structure shown in Fig. 1 does not follow Tateyama & Kingham's regular 12 yr periodic precession model. This result argues against the idea that the jet wobbling in OJ 287 is directly induced by precession in a binary BH system with a 12 yr period.

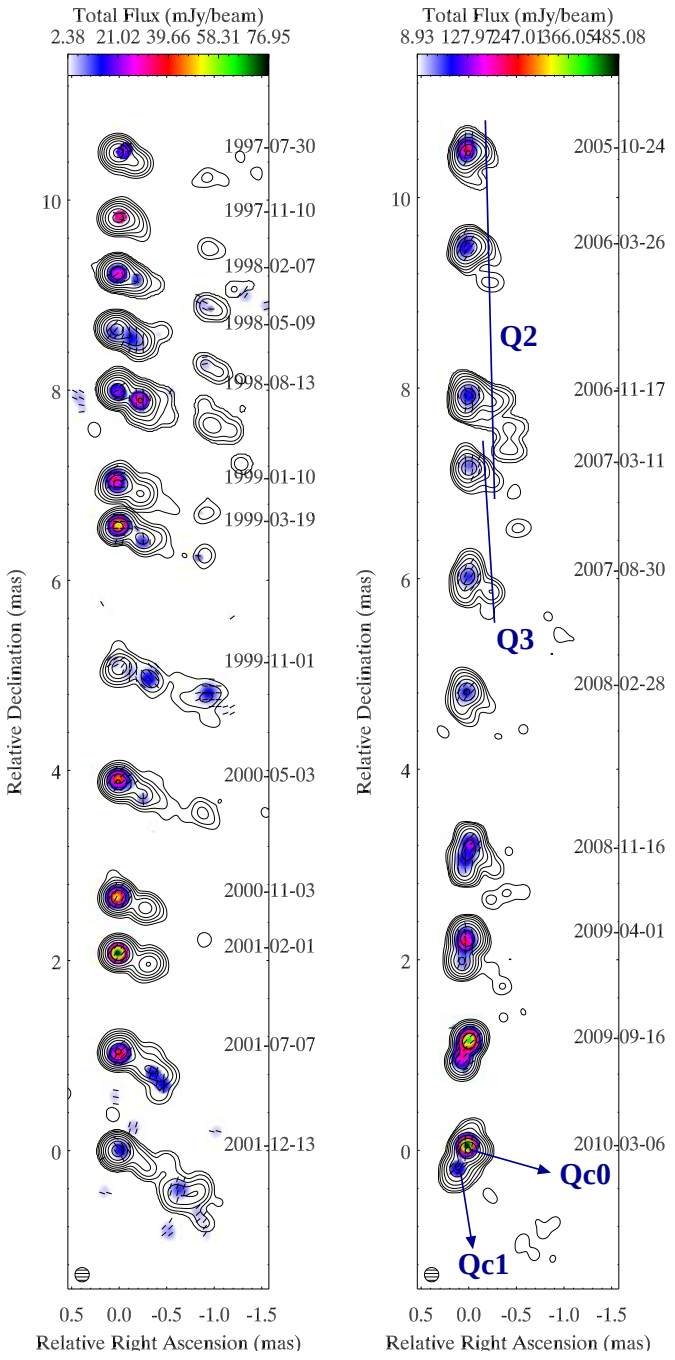

Fig. 1. Sequence of 43 GHz VLBA images of OJ 287 taken from mid-1997 to the end of 2001 (left) and from the end of 2005 to the beginning of 2010 (right). All images were convolved with a circular Gaussian beam with FWHM = 0.15 mas. Contours represent the observed total intensity, the color scale indicates the linearly polarized intensity, whereas the superimposed sticks show the orientation of the polarization electric vector position angle.

For the time range from 2005, we modeled the inner jet region containing a completely new ejection angle to the south with two circular Gaussian components labelled Qc0 (the northern one, which we identify with the core) and Qc1 (the southern one). These two features have generally contained $\gtrsim$ 90 % of the 43 GHz VLBA integrated emission of the entire source during the time range since Qc1 first appeared (in 2005), and hence currently govern the total flux evolution of OJ 287 at mm wavelengths.

Qc1 separates from the core at an essentially ballistic trajectory with subluminal speed $\sim 0.6c$ and estimated ejection time of 2005.48 ± 0.27. In contrast, jet features seen in our maps propagating along trajectories typical before 2002, i.e. to the west or southwest (e.g., Fig. 1-left), exhibit considerably faster, superluminal speeds and much lower fluxes. This is the case for Q2, another jet feature close to the core (see Fig. 1–right), which we estimate to have been ejected contemporaneously with Qc1 (in 2005.50 ± 0.28), but along a position angle typical of the range of position angles of the jet before 2002 (i.e., at $-105°$). Q2 propagates at a superluminal speed of $\sim 1.6c$ and displays much lower flux density than Qc1 ($\bar{S} \approx 0.2$ mJy). Q3 follows a similar evolution as Q2, separating from the core along position angle $\sim -112°$ with a low mean flux, $\bar{S} \approx 0.2$ mJy, and an even larger mean superluminal speed of $\sim 6.9c$.

3.2. Light curves from mm wavelengths to γ-rays

The 230 and 350 GHz light curves from the SMA (see Fig. 2) reveal a relatively quiescent state (at $\sim$ 2 Jy) of sub–mm and mm emission between 2005 and 2008.5, whereas the [2008.5, 2010.4] time range is characterized by two of the largest (sub–)mm–wave flares detected thus far in OJ 287. These two emission peaks had fluxes of 8.28 ± 0.43 Jy and 7.02 ± 0.45 Jy on RJD=54873.1 (2009–02–10) and RJD=55202.9 (2010–01–06), respectively. Our 43 GHz VLBA model fits allow us to identify the two mm flares displayed by the SMA light curves with flux enhancements of the core (i.e., Qc0) in the 43 GHz images. No new jet features related to these two prominent flares have yet been detected separating from the core.

The optical R–band light–curve (Figs. 2 and 3) includes the two optical flares in 2005 and 2007 recently discussed by Villforth et al. (2010, see also references therein).

The 0.3–10 keV flux evolution curve from XRT presented in Fig. 2 shows an overall higher flux level ($[4, 13] \times 10^{-12}$ erg/cm^2/s) in the time range from mid 2008 to the beginning of 2010. This contrasts with the low X–ray levels displayed by the source in the time range from the beginning of 2005 to mid 2008 ($\lesssim 4\times10^{-12}$ erg/cm^2/s). This behavior is consistent with that shown by OJ 287 in the mm range (Fig. 2), suggestive of a connection between the X–ray and the mm emitting regions. In contrast, the optical light curve shows radically different long-term variability behavior than that at X–ray and (sub–)mm wavelengths.

The *Fermi*-LAT γ–ray light–curve of OJ 287 shows a prominent flare peaking on RJD~55129.0 (2009–10–24). This peak has a 0.1–300 GeV photon flux of $(4.91 \pm 0.66) \times 10^{-7}$ phot/cm^2/s, which is a factor $\sim$ 5 larger than the quiescent γ–ray level of the source ($\sim 1 \times 10^{-7}$ phot/cm^2/s). Fig. 2 also shows another, much less pronounced, γ–ray flare one year before, on RJD~54744.0 (2009–10–04), with photon flux = $(2.19 \pm 0.46) \times 10^{-7}$ phot/cm^2/s.

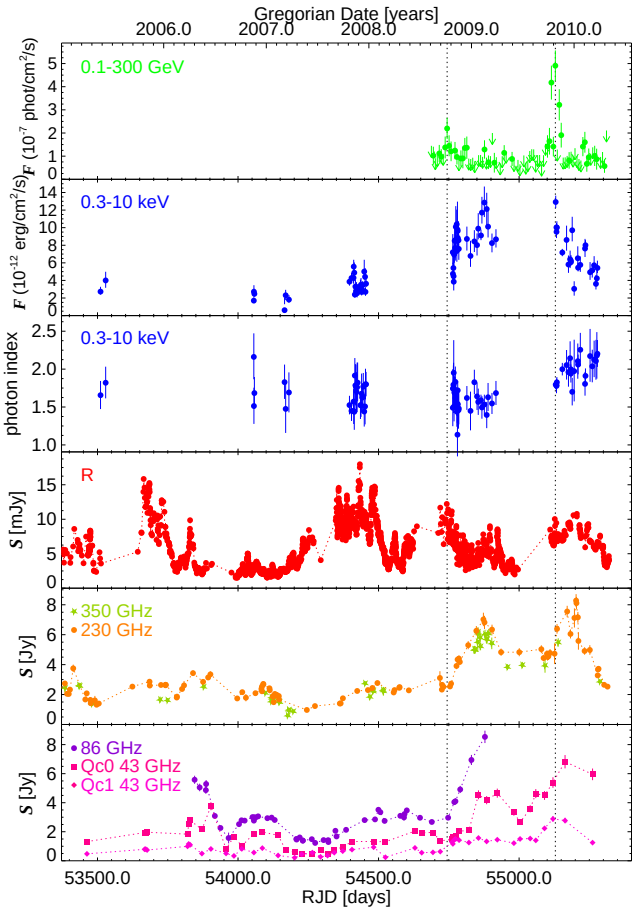

Fig. 2. OJ 287 evolution curves from the γ–ray to the mm spectral ranges. The γ–ray and X–ray data (in the 0.1–300 GeV and 0.3–10 keV energy ranges) were acquired by *Fermi*–LAT and *Swift*–XRT, respectively. The optical R–band data are those also presented in Fig. 3, whereas the 230, 86, and 43 GHz measurements were obtained by the SMA, the IRAM 30 m Telescope and the VLBA, respectively. The vertical lines symbolize the peak times of the two γ-ray flares discussed in the text. RJD = Julian Date - 2400000.

We cannot draw a firm conclusion about the possible relation between the two γ–ray flares and any peak in the optical light curve. This is because of the lack of sharp optical flares in the time range of the *Fermi*–LAT observations—as those in PKS 1510−089 (Marscher et al. 2010) or 3C 454.3 (Jorstad et al. 2010). Moreover, the fast and frequent optical variability of OJ 287 would allow us to associate a variety of different such optical peaks with the γ–ray flares. Longer-term monitoring of the source is needed to clarify the possible optical to γ–ray connection in OJ 287.

In contrast, the connection between γ–ray flares and (sub–)mm flares appears clearer in view of Fig. 2. The two γ–ray flares reported above happened just before the two (sub–)mm flares of OJ 287 at the beginning of 2009 and 2010, which we locate in the 43 GHz core. Moreover, the two γ–ray flares, which are much sharper than those at mm wavelengths (i.e., with time duration $\lesssim$ 50 days) occur at about the time when the mm flares (with longer durations $\lesssim$ 240 days) start to rise, i.e., when the mm–VLBI core starts to increase in flux.

4. Linear polarization results

During 2005–2010, it was very unusual to detect linear polarization in OJ 287 in our 43 GHz images at more than a few tenths of mas from the core (see Fig. 1). Indeed, only Qc0 and Qc1 show linear polarization at essentially all observing epochs when they were detected. Fig. 3 shows that these two features govern not only the total mm flux light curve of OJ 287 but also the evolution of the VLBA integrated linear polarization degree (m, with mean $\bar{m} = (6 \pm 2)$ % in 2005–2010) and electric vector position angle (χ, with mean $\bar{\chi} = (170 \pm 15)^\circ$). The 86 GHz and 43 GHz linear polarization evolution curves correspond to each other rather well. Although there is some χ variability, the polarization angle of OJ 287 at 43 GHz during this time span is surprisingly stable in the direction of propagation of Qc1, except for two large turns of $\sim 90^\circ$ from mid 2006 to beginning of 2007 when the linear polarization was very low. No clear emergence of a new, orthogonally polarized component appears to have occurred to explain this decrease of m. Despite the similarities of the polarization properties between Qc0 and Qc1, they differ in their m behavior, which exhibits two sharp peaks of 13.76 % and 22.43 % for Qc0 in 2008-11-04 and 2009-10-16, respectively. The fact that these dates are close to those of the reported γ–ray flares makes these sharp increases in polarization of special interest.

One of the most salient results regarding optical polarization in OJ 287—already pointed out by Villforth et al. (2010)—is the large level of polarization angle stability at mean polarization angle $\bar{\chi} = (169 \pm 55)^\circ$. This stability is only greatly altered by sporadic short-term (10–20 days long) rotations of χ by up to 180° (see Villforth et al. (2010)), consistent with turbulent plasma behavior (D'Arcangelo (2009)). The mean optical linear polarization angle is essentially the same as that observed in the mm range, which suggests that both the optical and mm emitting regions posses the same overall magnetic field configuration in OJ 287.

Both the mean level of optical polarization degree ($\bar{m}_{\rm opt} = 17 \pm 8$ %), and its variability amplitude are considerably larger than at mm wavelengths. This, along with the similar magnetic field directions at the two wavebands, can be explained by the model proposed by Marscher & Jorstad (these proceedings), according to which the optical emission occurs only in a limited number of cells inside the overall region emitting at mm wavelengths.

There is an interesting linear polarization event in our optical polarization evolution curves. About 50 days after the larger γ–ray peak, there is a systematic and dramatic m decrease from ~ 30 % to ~ 5 %. This is accompanied by a linear polarization angle rotation of $\sim 80^\circ$. This phenomenon is expected if, in the presence of a stationary linearly polarized jet feature with $\bar{\chi} \sim 170^\circ$, another component with orthogonal polarization angle appears in the jet. If this is the actual case in OJ 287, and if the portion of the jet between the optical emitting region and the farther downstream mm core is straight, we can predict a $\sim 90^\circ$ swing of χ at mm wavelengths in the near future. Within this scenario, the new moving feature is a plane perpendicular shock, and it should propagate to the west-southwest direction in order for $\chi \sim -100^\circ$ to occur.

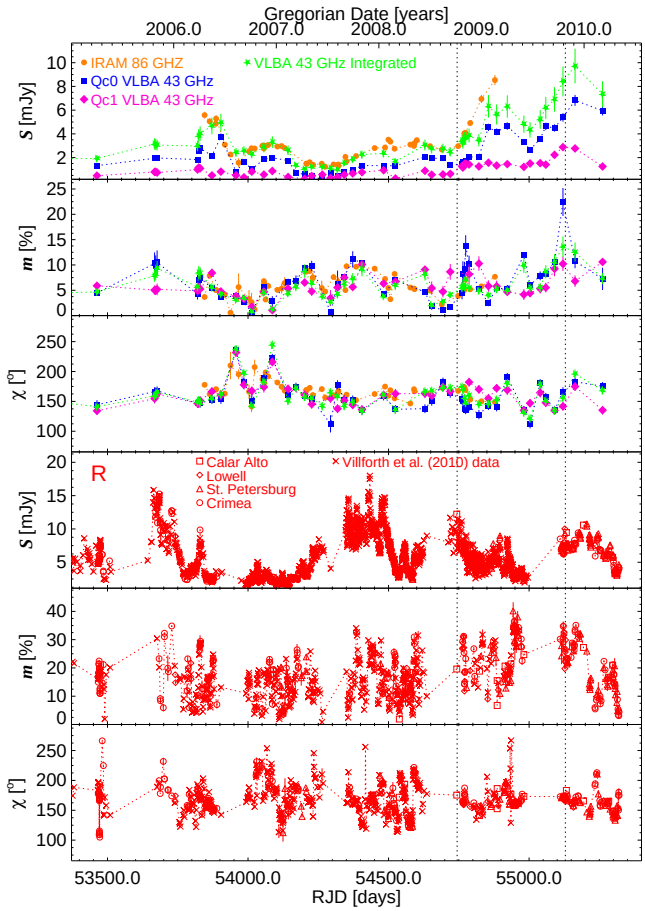

Fig. 3. Total flux (S) and linear polarization (m, and χ) evolution curves of OJ 287 at mm wavelengths (three first plots) and in the optical R band (last three plots). The vertical lines symbolize the times at which the γ-ray light curve had its two strongest peaks (see Fig. 2).

5. Discussion

The match between the estimated ejection times of Qc1 and Q2 tempts us to relate both moving jet regions with the same physical feature propagating down the jet. We can explain this if we allow the innermost jet regions to point almost at 0° to the line of sight, and the jet to contain a moving kink that does not disrupt the flow (i.e., Kelvin–Helmholtz or current driven instability). Within this scenario, the unexpected direction of propagation of Qc1 may be explained as the result of the outward propagation of such a kink at a tiny angle to the line of sight (hence the large flux and small subluminal speed of Qc1) after crossing the line of sight from the typical projected jet direction (to the southwest) to a new direction (almost to the south). In this case, Q2 (as well as Q3) would be a bent jet region at the opposite side of the line of sight and at a larger angle to the line of sight (hence displaying lower flux, but faster apparent speeds). Such a phenomenon does not require strong intrinsic curvature in the jet, only a nearly zero mean angle to the line of sight.

Together with the contemporaneous time of ejection of both Qc1 and Q2, our observations contain a number of relevant coincidences in the multi-spectral range behavior of OJ 287 that will be the subject of further interpretation and modeling elsewhere. This includes: *i)* the two γ–ray flares, *ii)* the two mm and sub-mm flares associated with the flux increase in the 43 GHz core, *iii)* the sharp increase of linear polarization degree in the mm core at times close to the γ–ray flares, and *iv)* a plausible connection of the X–ray with the mm wavelength emission.

We do not find an obvious relation between the R–band total flux light curve of OJ 287 and those at the other spectral ranges studied here. This contrasts with the behavior of other blazars for which their optical emission has been reported to be correlated with flares at γ–ray energies, among other spectral regions (see, Jorstad et al. 2010; Marscher et al. 2010; Abdo et al. 2010, for the cases of 3C 454.3, PKS 1510-089, and 3C 279, respectively).

Even the large optical flares in 2005 and 2007, related to the proposed ~ 12 yr quasi–periodicity of OJ 287, do not show a clear correspondence at other spectral ranges in our data, which suggests that either their corresponding emitting regions or their emission mechanisms (or a mix of both) are driven by different conditions. Perhaps an explanation may come from the idea that such major optical flares, and part of the optical emission in OJ 287 in non flaring states, comes from the accretion disk (either in a binary black hole scenario or not). In this case, no direct correlation with the jet emission at other spectral ranges would be required. This issue, which lies beyond the scope of this paper, is not easy to quantify, since it is known that some connection between the accretion disk and the jet may exist in radio loud AGN (e.g., Marscher et al. 2002).

Our new 43 GHz VLBA images have revealed that the time scale of the long term jet wobbling of OJ 287 (>> 15 yr) – which we cannot assure that it is periodic, i.e. precession like– is much longer than that suggested by the optical variability. The large difference between these time scales is against the explanation of such jet wobbling as the result of tidally induced disk precession in a binary BH system with an orbital period of ~ 12 yr.

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