Polarization behavior of periodic optical outbursts in blazar OJ287

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ABSTRACT

Context. As a characteristic feature of generic blazars the polarization behavior of the quasi-periodic optical outbursts observed in OJ287 is investigated. The optical light-curves of the December/2015 outburst are also simulated in terms of the precessing jet nozzle model previously proposed.

Aims. The polarization behavior of three primary quasi-periodic optical outbursts peaking in ~1983.0, ~2007.8 and ~2015.8 are analyzed in order to understand the nature of their optical radiation.

Methods. A two-component model has been applied, showing that the variations in flux density, polarization degree and polarization position angle can be consistently interpreted with two polarized components: one steady-component with constant polarization and one burst-component with varying polarization (e.g., relativistic shock propagating along the jet-beam axis).

Results. The flux light curves of the December/2015 outburst (including its first flare and second flare) are well model-simulated in terms of 14 elementary synchrotron sub-flares, each having a symmetric profile. The model-simulations of polarization behavior for the three major outbursts (in 1983.0, 2007.8 and 2015.8) demonstrate that they all exhibit rapid and large rotations in polarization position angle, implying that they are synchrotron flares produced in the jet.

Conclusions. Combining with the results previously obtained for interpreting the optical light curves in terms of lighthouse effect for both quasi-periodic and non-periodic outbursts, we suggest that relativistic jet models may be the most appropriate models for understanding the nature of the optical flaring radiation in blazar OJ287: its optical outbursts may comprise a number of blended “elementary synchrotron flares”, each produced by the helical motion of individual superluminal optical knots via lighthouse effect.

Key words. galaxies: active – galaxies: jets – galaxies: polarization – galaxies: nuclei – galaxies: individual OJ287

1. Introduction

Blazars are active galactic nuclei with their relativistic jets pointing at small angles with respect to the line of sight. They emit radiation across the entire electromagnetic spectrum from radio, IR/optical, UV, X-ray through to high energy (TeV) γ-rays. Their emissions are highly variable with a wide range of time-scales from minutes/hours to years (e.g., Angel & Stockman 1980, Aller et al. 2010, 2014, Ackermann et al. 2011).

OJ287 (z=0.306) is a unique blazar: its optical variability not only has the characteristic properties of radiation in generic blazars, but also reveals a ∼12-yr quasi-periodicity with a double-peaked structure at time-intervals of ∼1-2 years (in its optical light curve recorded during more than one hundred years since ∼1890; e.g., Sillanpää et al. 1988, Lehto & Valtonen 1996, Sundelius et al. 1997, Valtonen et al. 2019, Dey et al. 2019, Villata et al. 1998, Britzen et al. 2018, Tanaka 2013).

Many authors investigate the nature and properties of the optical/radio emission, especially, polarization behavior and helical motion of the emitting components (e.g., Usher 1979, Aller et al. 1981, Holmes et al. 1984, Kikuchi et al. 1988, Gabuzda et al. 2011, 2003, 1999, D’Arcangelo et al. 2009, Villforth et al. 2010, Aller et al. 2010, 2014, 2016, Hodgson et al. 2017, Kushwaha et al. 2018a, 2018b, Qian 2018a, 2019a, 2019b, Cohen et al. 2017, 2018, Myserlis et al. 2018).

The ∼12 yr quasi-periodicity is widely suggested to be related to the orbital motion of the putative black-hole binary in the nucleus. The precessing jet model (or binary black hole-impact model) originally proposed by Lehto & Valtonen (1996) and its improved versions (e.g., Valtonen et al. 2019, Dey et al. 2019) suggest that the quasi-periodicity is due to the precessing orbital motion of the binary due to the gravitational interaction between the supermassive secondary and primary holes. The periodic outbursts are caused by the secondary black hole’s penetrating into the precessing optical outbursts and the mechanism for its quasi-periodicity; (4) properties of the putative supermassive black hole binary (precessing orbital motion and accretion processes) and possible tests of general-relativity effects (gravitational radiation, precession of binary orbit and no-hair theorem, etc.).
disk of the primary black hole. The double-flare structure is assumed to be due to the two impacts occurring per one orbital cycle near pericenter and apocenter passages. Each secondary hole’s crossing of the primary disk will produce strong thermal optical outburst from the gas-bubble torn off the primary disk. In addition, the penetrations lead to enhanced accretion onto the primary hole and optical knot ejections from the jet, producing the follow-up synchrotron flares (tidal flares). At present, the disk-impact model can well explain the quasi-periodicity and the double-flare structure, and have successfully predicted the flare times of a few double-outbursts (including the 2015/2019 pair-flares, Laine et al. 2020). The optical light curve has been modeled in terms of the combination of impact flares and tidal flares (e.g., Dey et al. 2013).

Recently, Britzen et al. (2013) have made a detailed analysis of the kinematic properties of the radio jet on pc-scales and suggested that the radio jet precession is related to the orbital motion of the black-hole binary, and the optical variability could be related to the precession and nutation of the radio jet. In order to investigate the nature of optical emission for both quasi-periodic and non-periodic outbursts in OJ287, Qian (2019a) has made model simulations of their optical light curves under the precessing jet nozzle scenario, which has been previously used to study the kinematics of superluminal radio knots (including their helical motion and variable Doppler boosting effects), jet-beam precession, connection between optical and radio variability (including simultaneous radio/optical variations, evolutional relation between optical and radio knots, etc.) in a number of blazars (3C345: Qian et al. 1991a, 2009; 3C454.3: Qian et al. 2014; NRAO 150: Qian 2016; B 1308+326: Qian et al. 2017; PG 1302-102: Qian et al. 2018a; 3C279: Qian et al. 2019a, 2013; OJ287: Qian 2018b, 2015, 2019a, 2019b). The model simulation of the optical light curves are based on two basic assumptions: (1) the optical outbursts are decomposed into a number of elementary synchrotron flares (defined as a single flare with smallest time-scales of ~10 days); (2) each elementary synchrotron flare is produced by an individual superluminal optical knot moving along helical trajectory via lighthouse effect. The optical light curves of the periodic outbursts observed in 1984.0, 1984.1, 1991.6, 2005.7, 2007.8 and 2015.8 and a few non-periodic outbursts were well simulated in terms of the precessing jet nozzle model. The light curve of the periodic outburst in 1995.8 was also model-simulated and its simultaneous optical and radio variations was explained (Qian 2019a).

In our precessing nozzle model we use the following terms to describe the jet phenomenon: jet, jet-beam, jet-nozzle, beam-axis and jet-axis (= precession axis). They describe the picture of jet phenomenon: the plasma/magnetic-field and superluminal knots ejected from the jet-nozzle form the jet-beam and the jet-beam precesses around the precession-axis (i.e. jet-axis) with a period of ~12 yr, producing the jet. Since the superluminal knots (both radio and optical) and magnetized plasma move along helical trajectory around the precessing beam-axis, the term “jet” actually represents the whole jet which is made up of all the magnetized plasma and superluminal knots ejected from the precessing nozzle. The plasma/magnetic-field within the jet should be rapidly swirling and the jet-axis may be also precessing in space, which has not been taken into account in the current precessing nozzle model.

In the precessing jet-nozzle scenario, the optical light curves are assumed to comprise a number of synchrotron subflares for both periodic and non-periodic outbursts. That is, we assume that the double-peaked outbursts observed in the optical light curve are synchrotron flares produced in the relativistic jet and related to the ejection of superluminal optical knots from the core, which are closely related to the mass-accretion onto the primary hole, the rotation of its magnetized disk, the spin of the primary hole and the magnetic acceleration mechanism through strong toroidal fields in its magnetosphere (e.g., Blandford & Znajek 1977; Blandford & Payne 1982; Li et al. 1992; Camenzind 1990; Meier 2013; 2001; Beskin 2010; Vlahakis & Kónigl 2004). The precessing jet nozzle model does not treat the quasi-periodicity in the optical variability and is not able to predict the flare-times of the periodic outbursts. It requires additional model(s) for explaining the quasi-periodicity and double-peaked structure, which can match its interpretation of the quasi-periodic optical outbursts being synchrotron in origin within the jet.

In brief, if the quasi-periodicity with double-flare structure observed in the optical light curve are not involved temporarily, the precessing nozzle model is different from the binary black-hole impact model mainly in two aspects:

- The disk-impact model assumes that the first flares of the double-peaked outbursts are thermal flares produced by the impacts of the secondary black hole penetrating the disk of the primary hole, when gas-bubbles are torn off the primary disk and emit thermal emission. At the same time, the impacts (near pericenter and apocenter passages) result in strong disturbances to the primary disk. The disturbances and tidal effects lead to enhanced accretion onto the primary hole, producing the follow-up flares (“tidal flares”) which are synchrotron flares produced in the relativistic jet of the primary hole. The difference between the precessing nozzle model and the disk-impact model is only in the interpretation of the nature of radiation from the first flares of the double-peaked outbursts: the former claims their origin from synchrotron process, while the latter claims their origin from bremsstrahlung process.

- The impact models involve both thermal and nonthermal flares; it needs dual-energetics for understanding the optical outbursts (thermal and nonthermal). The energy source of the nonthermal flares mainly comes from the spin energy of the primary hole and the angular momentum of its disk. The synchrotron outbursts are strongly Doppler-boosted and their timescales are shortened by Doppler-beaming effect. But the energy source of the impact (thermal) flares mainly comes from the kinematic energy of the orbiting secondary hole. The flux density of the thermal flares is not Doppler-boosted, and their time-scales are not shortened either. Thus the energy source and energetics of the thermal and nonthermal outbursts are completely different. It seems difficult to unify the two kinds of flares (both in flux density scale and time scale) only by scaling the impact energy and impact-induced accretion rate onto the

1 Based on the analysis of the kinematics of the superluminal radio knots, there might have some evidence for the existence of two jets in OJ287 (Qian 2018a).

2 Doppler-amplification factor could be ~10^5 – 10^6.
primary hole (e.g. Dey et al. 2018, 2019). In other words, synchrotron flares gain energy-input from the spin of the primary hole and angular momentum of its disk, which is completely different from the energy source for the thermal outbursts. Thus it seems difficult to understand the observational fact: the non-thermal and thermal outbursts observed in OJ287 could have very similar behaviors in variations of flux density and polarization with similar time-scales (e.g. Valtaoja et al. 2000). In contrast, the precessing nozzle model has no problem in the unification of the energetics. Moreover, the impact-disc model seems not able to explain the structure of the optical outbursts which comprise several spike-like flares on timescales of ~10 days with symmetric profiles, rapid polarization variation on time scales of ~a day; and the simultaneous variations in optical and radio regimes (Valtaoja et al. 2000, Qian 2019a, 2019b). Recently, we have applied the precessing nozzle model with helical motion of the superluminal optical knots to well simulate the R- and V-band light curves of the December/2015 outburst (Qian 2019a). In the following we will investigate the polarization behavior (especially the rotations in polarization position angle observed in the periodic outbursts in 1983.0, 2007.8 and 2015.8, providing further evidence for their origin in synchrotron process.

Recently, Myserlis et al. (2018) observed the fast rotations of polarization position angle in OJ287 at V-band and radio wavelengths (10.5, 8.4 and 4.8 GHz) during December/2015-January/2017 (~JD2457300-800), showing a time-delay of the radio PA rotation with respect to the optical PA rotation. They suggested that these position angle rotations (on time-scales of ~10 day in optical and on time-scales of about a month in radio) are due to the helical motion of the superluminal knots and optical knots, respectively. Rotations in polarization position angle were also observed by Kushwaha et al. (2018a) in the December/2015 outburst. Cohen et al. (2015) have reported observational evidence for polarization angle rotations in the cm-light curves observed in the Michigan Monitoring projects.

These polarization observations seem strongly supporting the precessing nozzle model. According to our precessing nozzle scenario for explaining the optical light curves of the quasi-periodic and non-periodic outbursts (Qian 2019b), superluminal optical knots move along helical trajectories, which would result in fast rotations of polarization position angle. This phenomenon has already been observed in a few blazars in earlier years: for example, in BL Lacertae and 0727-115 (Aller et al. 1981, Sillanpää 1993, Marscher et al. 2008).

In this paper we shall show the rapid variations in polarization position angle during the periodic optical outbursts (in 1983.0, 2007.8 and 2015.8) and discuss the interpretation of their light curves of flux density, polarization degree and position angle as a whole. We would like to note that low polarization degrees alone do not necessarily imply the outbursts being thermal, because thermal flares can greatly reduce the source polarization degree, but cannot cause rapid changes in polarization position angle.

The cavity-accretion flare model proposed by Tanaka (2013) is another type of disk-impact model, which assumes that the primary hole and the secondary hole having comparable masses and are in near-coplanar orbital motion. Hydrodynamic/magneto-hydrodynamic (HD/MHD) simulations for such binaries surrounded by circumbinary disks have shown that cavity-accretion processes would create two gas-flow streams impacting onto the disks of the black holes per pericenter passages, possibly causing the double-peak structure of the quasi-periodic outbursts. This model suggests that the gas-flow impacts produce thermal outbursts, but it is not able to make accurate timing of the quasi-periodic outbursts.

2. The precessing jet-nozzle model

2.1. Introduction

It is widely suggested that blazars are extragalactic sources with relativistic jets pointing close to our line of sight. Recently, Qian (2019a) has tentatively proposed an alternative jet model to understand the phenomena observed in OJ287, which is based on the optical multi-wavelength observation and γ-ray observation performed for OJ287 (e.g., Kushwaha et al. 2018a, 2018b), combining with the distinct features previously found in the optical and radio (flux and polarization) variations (e.g., Sillanpää et al. 1996a, Valtaoja et al. 2000, Usher 1979, Holmes et al. 1984, Kikuchi et al. 1988, D’Arcangelo et al. 2009, Kushwaha et al. 2018a, Britzen et al. 2018, Qian 2019b).

The precessing jet-nozzle model was originally proposed in Qian et al. (1991a) to study the VLBI-kinematics of the superluminal radio components observed in QSO 3C345, which were suggested to move along helical trajectories. This scenario has been further applied to investigate the VLBI-kinematics of several blazars, including 3C345, 3C345.3, OJ287, NRAO 150, B 1308+326 and PG 1302-102, 3C279. These studies have not only made good model fits to the observed kinematic properties (trajectory, core-separation and apparent velocity versus time) of their superluminal radio components, but also obtained some new results, e.g.: (1) Some convincing evidence for the existence of two radio jets in QSO 279 (Qian et al. 2015a), (2) Some evidence for the possible existence of two radio jets in BLO OJ287 (Qian 2018b). (3) Derivation of the precession period of jet-beams (or jet-nozzles) and investigation of the jet-nozzle precession mechanisms (Newtonian-driven precession, Lense-Thirring effect and spin-orbit coupling; Qian et al. 2017, 2018a). (4) Derivation of the kinematic Lorentz (and Doppler) factor and investigation of the intrinsic evolution of superluminal radio components (Qian et al. 1996a). (5) Tentative derivation of the mass and spin of black holes in the nuclei of blazars through precession mechanisms (Qian et al. 2018a, 2017, 2018b). (6) Interpretation of the simultaneous optical and radio outbursts observed in OJ287, helping to clarify the nature of quasi-periodic optical outbursts (Qian 2019b).
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Fig. 1. A sketch of the precessing nozzle scenario with helical motion proposed in a previous work: superluminal optical knots move along helical trajectory around the beam-axis which precesses with a period of 12 yr (left-upper panel). The Lorentz/Doppler factor, apparent velocity and viewing angle versus time are shown for the precession phase $\omega=-2$ rad (helical trajectory in blue). Periodic optical variations with a period of $\sim 90$ days are obtained (details referring to Qian 2019a; $\Gamma=9.5$).

2.2. Formulation of the precessing jet nozzle scenario

we have formulated the scenario to calculate the VLBI-kinematics of superluminal components (optical or radio knots), details referring to Qian et al. (1991a, 1991a, 2018b, 2017). We assume that the jet-nozzle ejects magnetized plasma and superluminal knots (blobs or shocks) which form the collimated jet-beam and move along helical trajectories around the beam-axis. The jet-nozzle and the beam-axis precess around an axis fixed in space (designated as the precession axis) with a certain precession period. The precession of the jet-beam produces the overall jet which occupies the whole region where superluminal components and magnetized plasma ejected at different times move outward in different directions. We chose the following set of parameters to define the precessing nozzle scenario which are the same as used in Qian (2019a, 2018b):

(1) Precession axis is defined by parameters $\epsilon=3^\circ$ and $\psi=0^\circ$.

(2) The axis of the jet-beam is assumed to be rectilinear described by the parameters $z=1$ and $a=0.0402$ as in Qian (2013).

(3) The parameters describing the helical motion of a superluminal optical knot around the beam-axis are: amplitude $A_0=0.0138$ mas and rotation rate $d\phi/dz_0=-7.04$ rad/mas.

(4) The precession phase is chosen to be: $\omega=-2$ rad which corresponds to the blue line shown in Figure 1.

(5) The spectral index $\alpha_{R,V}$ is assumed to be 1.5 ($S_\nu\propto \nu^{-\alpha}$)

(6) The base-level flux density at R- and V-bands are assumed to be $S_{\nu,0}=3.5$ mJy and 3.0 mJy, respectively.

(7) The concordant cosmology model (ΛCDM model) is assumed with $\Omega_m=0.27$ and $\Omega_{\Lambda}=0.73$ and Hubble constant $H_0=71$ km $s^{-1}$ Mpc$^{-1}$ (Spergel et al. 2003, Komatsu et al. 2009). Thus for OJ287, $z=0.306$, its luminosity distance is $D_L=1.58$ Gpc (Hogg 1999, Pen 1999) and angular distance $D_A=0.9257$ Gpc. Angular scale 1 mas = 4.487 pc and proper motion 1 mas/yr is equivalent to an apparent velocity =19.1 c (c–speed of the light).

A sketch describing the precessing jet nozzle scenario is shown in Figure 1, which was proposed for interpreting the $\sim 90$ day periodicity in the light curve of the December/2015 outburst (between the flares in $\sim$JD2457360 and $\sim$JD2457450, Qian 2019a).

In the following we shall make model-simulation for the flux density light curve of the 2015 outburst in Section 6, decomposing it into 14 elementary synchrotron flares.

3. Two-component model for polarization analysis

Blazars are highly variable in their optical continuum and especially in their polarization. Generally, polarization properties are the main characteristics revealing their na-
ture of synchrotron radiation originated from the relativistic jets. For blazar OJ287, there may be a major issue to be solved: whether the first flares of the quasi-periodic optical outbursts are thermal flares originated from the secondary hole penetrating into the disc of the primary hole or they are nonthermal synchrotron flares originated in the jet.

To solve this issue analysis of the polarization properties of the first flares of the quasi-periodic outbursts observed in OJ287 are important. According to Qian (2019a), the periodic optical outbursts in OJ287 can be decomposed into a number of elementary flares, each of which is produced by a superluminal optical knot moving along a helical trajectory in helical magnetic fields due to lighthouse effect. This explanation naturally predicts that their polarization position angle should rotate during the helical motion. PA rotations have been observed in a few blazars on timescales of ∼10 day in optical bands (Aller et al. 1981; Sillanpää et al. 1993; Marscher et al. 2006) or about a month in radio bands (Aller et al. 1981, 2014; Königl & Choudhuri 1985a). Mechanisms for explaining these large-amplitude PA rotations have been suggested (e.g., Blandford & Königl 1979; Königl & Choudhuri 1985b; Björnson 1982; Qian & Zhang 2003; Qian 1993, 1992). Most of the studies prefer the mechanisms in which PA rotations are caused by relativistic shocks moving through helical magnetic fields or the composition of two polarized components.

In order to analyze the polarization properties, especially the rotation of the polarization position angle of the quasi-periodic outbursts observed in blazar OJ287, we will apply a simple method to investigate the polarization behavior of three periodic optical outbursts in 1983.0, 2007.8 and 2015.5 in terms of two component model (Qian et al. 1991; Qian 1993): one steady component (or underlying quiescent jet component) and one variable component (burst component). Both are polarized synchrotron components. Assuming $I_1(p_1, \theta_1)$ and $I_2(p_2, \theta_2)$ being the intensity, polarization degree $(\%)$ and polarization position angle (deg.) of the integrated outburst, component-1 and component-2, respectively, then we have

$$p_2 = \frac{I_1}{I_2} \frac{\tan \theta_1 \sin \theta_2 - \tan \theta_2 \cos \theta_1}{\sin \theta_1 \sin \theta_2}$$

(1)

$$p^2 = \frac{(I_1 p_1)^2 + (I_2 p_2)^2 + 2I_1 p_1 I_2 p_2 \cos(2\theta_1 - 2\theta_2)}{I^2}$$

(2)

Stokes parameters $(Q, U)$ are

$$Q = I p \sin \theta$$

(3)

$$U = I p \sin \theta$$

(4)

Similar equations are for $(Q_1, U_1)$ and $(Q_2, U_2)$. In our case $(I, p, \theta)$ are known, $(I_1, p_1, \theta_1)$ will be appropriately chosen, then $I_2=I - I_1$ is known. Only two parameters $p_2$ and $\theta_2$ need to be determined. And equations (1) and (2) are just sufficient to solve the two parameters.

4. Model simulation of polarization behavior for 1983.0 outburst

As shown above the polarization behavior of the periodic optical flares is a key ingredient to determine the nature of optical outbursts, distinguishing the relativistic models from the disk-impact models. Therefore we will make model simulation of the light curves of flux density, polarization degree and polarization position angle (as a whole) for three periodic optical outbursts in 1983.0, 2007.8 and 2105.8. For the outbursts in 1983.0 and 2007.8 very low polarization degrees $(\sim 0.4\%-2.4\%)$ were observed, and both outbursts were claimed to be thermal flares produced by the bubbles torn off the disk of the primary hole when the secondary hole penetrates into the primary disk. However, alternative interpretations are also possible. For example, a non-thermal (synchrotron) flare can also cause very low polarization degree if the non-thermal flare component has its direction of polarization nearly perpendicular to that of the preexisting polarized component with similar polarized flux. But in this case rapid variations in polarization position angle of the source would be observed. Thus changes in polarization position angle may be particularly important for distinguishing non-thermal flares from thermal flares.

4.1. Introduction

The 1983.0 optical outburst is an instructive event for understanding the nature of the periodic outbursts and distinguishing different models. The multi-waveband observations from IR (JHK) to optical (RVU) carried out by Holmes et al. (1983) also Smith et al. (1987) have provided full information about the flux density, polarization degree and polarization position angle during a 4-day period (7, 8, 9 and 10 January, 1983), which was just coincided with the peaking period of the outburst. A model simulation of its flux density light curve (V-band) is shown in Figure 2 (left panel), and the right panel shows the fits to the data-points obtained during the 4-day peaking period (at V- and R-bands). Some distinct features can be recapitulated: (1) The outburst peaked on 8 January, with very low polarization degrees of 0.4% and 0.8% at R- and V-bands, respectively; (2) The minimum polarization degrees at R- and V-band are concurrent with the peaks of flux density (see left panels of Figure 3); (3) position angles at R- and V-band rotated, especially at V-band: during the 3-day period (7, 8 and 9 Jan.) its polarization position angle rotated clockwise by $\sim 50^\circ$ and then rotated counter-clockwise by $\sim 110^\circ$ (see left/bottom panel of Figure 3); (4) The multi-frequency observations showed that the outburst had convex spectra with a change in spectral index $\Delta \alpha \sim 0.4$ from infrared (\(\alpha \sim 0.9\)) to optical (\(\alpha \sim 1.3\)). Interestingly, the observed features-1 and -2 are just the characteristics of a thermal outburst required by the impact-disk model. But feature-3 (polarization position angle swing) does not support the model, because a thermal outburst can not cause large position angle swing. Feature-4 indicates that the observed spectra are more complex than that of a thermal outburst as predicted by the impact-disk model and very much like that of a synchrotron source with high-frequency steepening due to radiation losses. Therefore, as a whole, the multi-wavelength light curves observed for the 1983.0 outburst (including flux density, polarization degree and polarization position angle) can not be explained in terms of the appearance of a strong thermal outburst.

Holmes et al. (1983) proposed a two component model to explain the observed multi-wavelength light curves of flux density, polarization degree and position angle as a whole. They suggested that the two variable synchrotron (polar-
Fig. 2. Left: Model-simulation of the 1983.0 outburst in terms of the helical-motion model under the precessing jet-nozzle scenario, consisting of three subbursts (reproduced from Qian, 2019a. \( \Gamma = 8.0 \) for the first subburst). Right: The 4-day data-points obtained by Holmes et al. (1984) are well fitted by the model light curves at R- and V-bands for the first flare.

The detailed modeling of the multi-wavelength light curves (especially the wavelength-dependent polarization) performed by Holmes et al. demonstrates that the 1983.0 periodic optical outburst is synchrotron in origin, consistent with the assumptions of our precessing nozzle scenario (Qian 2019a, 2018a).

Although Holmes et al. used a two-component model to simulate the integrated light curves of flux density, polarization degree and position angle, they did not give the modeled light curves specifically for the variable polarized component (or the flare component). In addition, the rotation rate obtained for the component with variable position angle was less than \( \sim 90^\circ \), which is much smaller than the values observed for the integrated polarization position angle. This result seems inappropriately describing the polarization behavior of the component with variable position angle.

In the following we will propose an alternative two-component model to explain the observed features of the 1983.0 outburst, concretely showing the position angle rotation and the Stokes Q-U plot of the flare component.

### 4.2. An alternative model

We suggest an alternative two-component model as follows. We assume that the outburst consists of two polarized components defined by \( (I_1, p_1, \theta_1) \) and \( (I_2, p_2, \theta_2) \) respectively (see Section 3). The vector combination of the two components forms the observed (integrated) polarized outburst described by \( (I, p, \theta) \). Since polarization observations in blazars usually show that just before the beginning or and just after the end of outbursts the position angle keeps to be very near their preferred directions (e.g. in BL Lacertae, Sillanpää et al. 1993), we will choose the steady component to be the underlying quiescent jet component before the outburst. According to Holmes et al. component-1 has a stable position angle \( \sim 100^\circ \). Its polarization degree is constrained by the very low polarization degrees observed at R-band (0.4%) and V-band (0.8%). Its intensity is chosen according to the model simulation of the V-band light curve and the spectral index \( \alpha_{\text{UV}} = 0.8 \) (Qian 2019a). Thus we take:

- R-band: \( I_1 = 5.7 \text{mJy}, \ p_1 = 0.58\%, \ \theta_1 = 104^\circ \)
- V-band: \( I_1 = 5.0 \text{mJy}, \ p_1 = 1.0 \%, \ \theta_1 = 104^\circ \)

Having these values for the component-1, the values of \( (I_2, p_2, \theta_2) \) for the component-2 (the outburst component) can be determined from solving the equations (1) and (2) given in Section 3. The left panels of Figure 3 show the light curves of integrated flux density, polarization degree and polarization position angle. The modeled light curves for the flare component are shown in the right panels. Note that the flare component has similar rotation rates (\( \sim 60^\circ /\text{day} \)) for a force-free helical field (m=1 mode) proposed by Königl & Choudhuri (e.g. for the PA swing in radio wavebands observed in 0727-115 [1985] and 1985a) and Aller et al. 1984b also Qian & Zhang 2009b Qian 1992, in which relativistic aberration leads to position angle swings (of \( \sim 180^\circ \) and more) for a single flaring component (a relativistic shock). In addition, in the present case, there should exist a dominated random field component and the observer’s direction in the shock frame should be nearly perpendicular to the shock front to produce its very low polarization degrees at R- and V-bands (Laing 1980).

For comparison we note that similar polarization behaviors in optical regime have been observed in BL Lac: Sillanpää et al. (1993) observed an event of large polarization position angle swing during 26 September - 1 October 1989, having a minimal polarization degree of \( \sim 3.6\% \) (V-band), while Marscher et al. (2003) observed a large position angle swing of \( \sim 240^\circ \) during 2005.81-2005.83, having minimal...
polarization degrees of ~2-3%. The very low polarization degrees revealed in both events combined with the position angle swings were interpreted in terms of relativistic shocks propagating along helical magnetic fields. In particular, Marscher et al. found that the large position angle swing occurred when a superluminal knot moving through the VLBI core. This association indisputably demonstrates that the low polarization degree and position angle swing are produced in the jet.

Finally, we would like to point out that the assumed and resultant values obtained in the model simulation are by no means unique and more elaborate models are still required for explaining the entire event, especially taking its multi-wavelength spectral properties into consideration.

4.3. Stokes QU-plots

Tracks of the Stokes parameters Q and U for the 1983.0 outburst are shown in Figure 4. Q-U tracks for the integrated polarization and the flare component are shown in the left and right panels, respectively. It can be seen that after reducing the background component, the Q-U track of the flare component reveals its position angle rotation more clearly.
5. Simulation of polarization behavior for 2007.8 outburst

5.1. Introduction

Villforth et al. (2010) have made optical observations to study the polarization behavior of the periodic optical outburst in 2007.8. This outburst showed a very low polarization degree (∼2.4%, R-band at ∼JD2454356.75, near the peak of the outburst) and was thus claimed to be the impact thermal flare predicted by the disk-impact model.

We have collected the data given in Villforth et al. (2010) to investigate its polarization behavior. A model-fit to its light curve in terms of the precessing nozzle model is shown in Figure 5 (left panel), which is reproduced from Qian (2019a). The right panel represents part of the observed light curve where only the flux densities corresponding to the polarization measurements are shown.

The observed (integrated) light curves (during ∼JD2454353.5-366) of flux density, polarization degree and polarization position angle are presented in the left panels of Figure 6. It can be seen that during the peaking stage of the outburst (∼JD2454356.5-361.5) a large position angle swing was clearly revealed: first a clockwise rotation of ∼180° and then a counter-clockwise rotation of ∼180°, forming a “trough” in the light curve of position angle. Obviously, this large position angle swing is a distinct feature of the 2007.8 outburst as for the 1983.0 outburst, which should not be neglected and certainly demonstrate the outburst being synchrotron in origin.

It worths noting that the very low polarization degree (2.4%, at ∼JD2454356.75) occurred earlier than the flux density peak (∼JD2454357.5) by a day, where the position angle only slightly changed. Thus the relations between the variation in flux density and polarization degree or position angle are quite complex, which can not be explained in terms of the disk-impact model.

Here we suggest a two-component model to simulate the observed light curves of flux density, polarization degree and position angle as a whole.

5.2. A two-component model for 2007.8 outburst

We assume that the outburst in 2007.7 consists of two polarized components: one steady component-1 defined by the underlying quiescent jet background before the outburst and a variable flare component-2, which are described by parameters (I₁, p₁, θ₁) and (I₂, p₂, θ₂), respectively. The values for (I₁, p₁, θ₁) are chosen as I₁=7.5 mJy, p₁=8.5%, θ₁ = 163.3°.

The observed (integrated) light curves during the peaking stage (∼JD2454356.75-72454361.5) were well simulated by the two-component model, where the position angle only slightly changed. The value of I₁ is chosen from the model simulation of the light curve (Qian 2019a).

5.3. QU-plots

The QU-plot during the period of ∼JD2454354.5-360.5 for the integrated outburst is shown in Figure 7 (left panel). The QU-track derived for the flare-component (right panel) is similar to that of the integrated outburst. Both QU-tracks reveal large position angle rotations, showing the nature of synchrotron emission of the 2007.8 outburst.

6. Model simulation of the light curves of periodic optical outburst in December/2015

6.1. Introduction

The first flare of the quasi-periodic optical outburst observed in December/2015 (during the period of ∼2015.88-2015.96 with its peak at ∼2015.926) was identified as an unpolarized thermal flare predicted by the disk-impact model (Lehto & Valtonen 1996, Valtonen et al. 2019, Dey et al. 2019). This interpretation is mainly based on the accurate timing of the orbital motion of the putative black-hole bi-
Fig. 5. Left panel: A model-fit to the V-band light curve for the 2007.8 outburst reproduced from Qian (2019a); three elementary subbursts are used ($\Gamma=11.4$ for the first subburst). Right panel shows the model-fit of the R-band data points collected from Villforth et al. (2010).

inary in the nucleus of OJ287, where the secondary black-hole penetrates the disk of the primary hole twice per one orbital cycle, causing the quasi-periodic optical outbursts with double structure through the bubble-production mechanism. The low polarization degrees observed in the first flares of a few periodic outbursts were regarded as firm evidence for their thermal origin. However, there are some distinct features observed in the December/2015 outburst and in other periodic outbursts could not be explained in terms of the impact-disk model. Relativistic jet models may be required, suggesting that these periodic outbursts could be synchrotron in origin. For example,

1. For the December/2015 outburst, Kushwaha et al. (2018a) observed that a GeV $\gamma$-ray flare was simultaneous with the optical flares at R- and V-bands, peaking concurrently at $\sim$2015.96 ($\sim$JD2457361.5). Obviously, the $\gamma$-ray flare could not be co-spatial and associated with the thermal flare produced by the bubble torn off the disk of the primary hole. Both the $\gamma$-ray and optical flares should be produced in the relativistic jet through synchrotron/inverse-Compton mechanism as in generic blazars.

2. The multi-wavelength (J, I, R, V, UV) light curves of the December/2015 outburst are very similar to that of the strongly polarized synchrotron flare occurred in March/2016 (peaking at $\sim$JD2457450). This similarity might imply that the December/2015 optical outburst is synchrotron in origin and this pair of outbursts could be interpreted in terms of the helical motion of a superluminal optical knot through two helical cycles via lighthouse effect, having a period of $\sim$90 days (see right/upper panel of Fig.1; Qian 2019a);

3. Generally, the light curves of the periodic optical outbursts consist of a number of subbursts or elementary flares, each having a symmetric profile, similar to the individual (isolated) non-periodic synchrotron flares occurred during the intervening periods (e.g., Valtaoja et al. 2000). Symmetry in the outburst profiles seems a significant feature (Sillanpää et al. 1996a, 1996b) different from the standard non-symmetric profiles of the thermal outbursts predicted by the disk-impact model (Valtonen et al. 2011). Symmetric profiles are suggested to be explained in terms of the lighthouse model under the precessing jet-nozzle scenario proposed by Qian et al. (2019a).

4. The variability behavior of optical polarization (especially polarization position angle) of the periodic optical outbursts seems particularly important for determining the origin of the emission from the outbursts. For example, a low-polarization degree can be due to the appearance of a thermal outburst, but can also be caused by the appearance of a synchrotron flare which has its polarization perpendicular to that of the pre-existing steady synchrotron component with a similar polarized flux. In this case large changes in polarization position angle should occur. The studies of the polarization behavior for the optical outbursts in 1983.0 and 2007.8 (Holt et al. 1984, D’Arcangelo et al. 2009) Qian 2019a and this paper (Sections 4 and 5) indicate that these outbursts may be synchrotron flares. In section 6 we will investigate the polarization behavior of the first flare of the December/2015 outburst in detail.

5. Some periodic optical outbursts have been observed to exhibit simultaneous radio variations. The 1995.9 optical flare is the best example: Valtaoja et al. (2000) observed the simultaneous optical and radio (at 22 and 37GHz) flares, having similar substructures and envelopes. Obviously, at least this periodic optical outburst must be synchrotron in origin and related to the relativistic jet (Qian 2019b). In general, both the connection between the optical and radio variations and the close correlation between the optical outbursts and the ejection of superluminal radio components from the core may indicate that the optical flares (both periodic and non-periodic) are synchrotron flares (Tateyama et al. 1999, Kikuchi et al. 1988, Britzen et al. 2018). Qian 2019a;

6. The multi-wavelength optical observations of the December/2015 outburst show its color stability (Gupta et al. 2016), which is consistent with the monitoring results of OJ-94 project during the period 1993.8-1996.1 (Takalo 1996a). Takalo et al. (1996a) Sillanpää et al. 1996a, 1996b, 1996c, 2000c). During the OJ-94 project of $\sim$2.5yr time-range both periodic outbursts (the pair of flares in 1994.59 and 1995.81) and a large number of non-periodic synchrotron flares were observed, indicating that the periodic and non-periodic outbursts may origi-
In order to clarify the nature of the quasi-periodic optical outburst observed in December/2015, we have collected some polarization data from the literature (Myserlis et al. 2018, Kushwaha et al. 2018a, Valtonen et al. 2016, 2017, 2019) for investigating its polarization behavior (especially the rotation in polarization position angle of the flaring component) and showing that the helical-motion model proposed by Qian (2019a) may be appropriate to interpret its light curves of flux density, polarization degree and polarization position angle as a whole.

6.2. Internal structure and symmetry in flare-profiles

It has been proposed that the optical outbursts observed in blazar OJ287 may consist of a number of elementary-flares with symmetric profiles (Qian 2019a). The light curves of the December/2015 outburst observed at V- and R-bands are shown in Figures 8 and 9.
Fig. 7. QU-plots for the integrated polarization (left panel) and for the flare component (right panel) of the 2007.8 outburst, both showing a large position angle swing. Triangles indicate the beginning of the QU tracks.

Fig. 8. Model simulation of the light curve of the first flare of December/2015 outburst (V-band, during the period \(~\text{JD}2457350-372\) ), which is assumed to have a structure consisting of a central strong spike-like flare (peaking at \(~\text{JD}2457361.5\) ) and the wing flares on its either side. In the right panel the modeled light curves for the wing flares are extended toward the region of the central spike, showing the different rising and declining slopes for the spike and wing flares. The symmetry of the central spike (red lines) and wing flares (green lines) relative to the peaking epoch \(~\text{JD}2457361.5\) are clearly revealed. Data points are collected from Valtonen et al. (2019 black squares) and from Kushwaha et al. (2018a orange squares).

Fig. 9. Same as in Figure 8, but for R-band.

By visual inspection of the light curves some characteristic features can be seen:

- (1) The December/2015 outburst consists of two flares: the first flare (during \(~\text{JD}2457350-372\) ) and the second flare (during \(~\text{JD}2457372-385\) ). Both have internal substructures. The first flare has a central strong spike between \(~\text{JD}2457360.5\) and \(~\text{JD}2457362.5\) (peaking at \(~\text{JD}2457361.5\) ) with weaker wing bursts on its either side. Although the lower portion of the spike blends with the wing bursts, the smooth and almost completely-
recorded light curve of its upper portion seems demonstrating that this spike flare is an individual elementary flare with a timescale of ∼6 days (see below). Moreover, this strong spike-flare clearly has a symmetric profile relative to its peaking time (see the red lines in Figures 8 and 9; flux density ∝ |t − t_{\text{peak}}|).

- (2) In Figures 8 and 9 the modeled curves for the wing flares are shown in green (for both the rising and declining portions), which are also symmetric relative to the peaking time of the central spike: flux density ∝ |t − t_{\text{peak}}|^{-0.8}. It is quite clear that the wing flares are individual flares independent of the spike flare, because their slopes of the respective rising and declining portions (during ∼JD2457348.0-360.5 and during ∼JD2457363.9-375.1, respectively) are much smaller than the rising and declining slopes of the spike flare (during ∼JD2457360.5-362.5).

- (3) The second flare peaking at ∼JD2457379.2 has an internal substructures similar to that of the first flare: a strong central spike with weaker wing flares on its either side, but having a longer time scale. The spike flare also has a symmetric profile relative to the peaking epoch. The smooth and almost fully-observed light curve pattern also demonstrates that this central relatively strong spike is an individual elementary flare with a timescale of ∼7 days, independent from the wing flares. The model-simulation results for the second flare and its characteristic features can be seen in Figure 10.

The detailed analysis of the structure of the observed light curves for the December/2015 outburst given above may have provided more evidence than before that this optical outburst actually comprise a number of elementary flares. It is particularly important that these elementary flares have symmetric profiles as clearly seen in the strong central spike flares (peaking at ∼JD2457361.5 and JD2457379.2) which have been fully recorded at both R- and V-bands (Valtonen et al. 2019; Kushwaha et al. 2018a). It is known that some single (or individual) non-periodic (synchrotron) flares also exhibit symmetric profiles (Qian 2019a). These investigations lead us to the conclusion that symmetry in the elementary flare profiles is a general property of the outbursts (both periodic and non-periodic) observed in OJ287.

In the precessing jet-nozzle scenario proposed by Qian (2019a) to model-simulate the light curves of the December/2015 optical outburst, its structure consisting of elementary flares and their symmetric profiles are the two basic ingredients, which ensure the observed flux-density light curves to be explained in terms of the helical motion of discrete superluminal optical knots (shocks or blobs) in the relativistic jet via lighthouse effect. In Subsection 6.4 below, we will further investigate the optical polarization behavior of the first flare (during ∼JD2457350-370) of the December/2015 outburst for trying to find out the true nature of its optical emission.

Moreover, the first and secondary flares of the December/2015 outburst have similar internal structures: a central strong spike-like flare with a symmetric profile and weaker wing flares on either side. Two kind of explanations might be proposed: (1) If the first and second flares are independent, then they could be discrete relativistic shocks produced in the jet consisting of a shock-front component (causing the strong spike-like flare) and a weaker wake component (causing the wing flares); (2) If the first and second flares are physically related, they could be a pair of relativistic shocks (both forward and reverse) formed in the collision of relativistic flows in the jet, leading to concurrent outbursts. In this case there would be four emitting regions naturally formed: two shock fronts and two (weaker) wake regions (Bell 1978a; Bell 1978b; Rees 1978; Kong et al. 1982; Hughes et al. 1985; 2011; Lind & Blandford 1985; Carilli et al. 1988; Caithorne & Wardle 1988; Gómez et al. 1994a; 1994b; Cohen et al. 2013). This structure of a pair of shocks might be just sufficient to explain the structure of the December/2015: the two shock fronts produce the two strong spike-like flares, while the two wakes produce the wing flares between the two spikes (during ∼JD2457363-377).

In both the cases suggested above, the December/2015 outburst would be produced via lighthouse effect, when the multiple emitting regions tend to form a stable structure moving along a helical trajectory in the acceleration-collimation zone of the relativistic jet in OJ287 (Camenzind 1983; 1993; Camenzind & Krockenberger 1992; Schramm et al. 1993; Wagner et al. 1995; Dreissigacker 1996a; Dreissigacker & Camenzind 1996a). In addition, there might be also emitting regions formed in front of the forward shocks and/or the reverse shocks due to some kind of flow instabilities, which might be required to help explain the formation of the wing flares at the beginning and at the end of the December/2015 outburst.

The proposed interpretation is only a speculative scenario, detailed theoretical models are required to specifically investigate the model parameters involved for the formation of a pair of shock-wake structures in the collision of relativistic flows in OJ287 (e.g., Kong et al. 1982). We would like to note that the Lorentz factors Γ=14 and 13 adopted in the simulation of the flux light curves respectively for the first and second flares are quite close to those derived from centimeter/millimeter variability and VLBI-imaging studies for OJ287: Γ=15.3 (Aller et al. 2013), 15.1 (Lister et al. 2013), 16.3 (Jorstad et al. 2005).

6.3 Model simulation of flux density light curves

We first discuss the model-simulation results of the flux light curves observed at V- and R-bands in terms of the precessing nozzle model. In comparison with the previous simulation (Qian 2019a), here we have taken into account of the internal structure of the December/2015 outburst. The modeling results are shown in Figures 10 and 11, and Table 1. The December/2015 optical outburst has been assumed to comprise a number of elementary flares, each of which is produced by a superluminal optical knot moving along a helical trajectory via lighthouse effect. 14 elementary flares are used to simulate the observed light curves at V- and R-bands (see Figure 10 and Table 1). The modeled flux density profile, Lorentz/Doppler factor, apparent velocity and viewing angle versus time for the central strong spike-like flares are given in Figure 11. We emphasize that the two spike flares (during ∼JD2457359-364 and ∼JD2457376-384) are very well fitted by the model-simulated symmetric profiles (see Figure 10). The similarity in structure (strong spike with wing bursts) of the first flare and the second flare for the December/2015 outburst may be also in favor of the suggestion that the first flare is also a synchrotron flare as like the second flare.
which was observed to have a very high polarization degree (~40%). The low polarization degree of ~5-6% during the first flare may be a result due to composition of two or more polarized components (see below).

6.4. Polarization behavior of the December/2015 outburst

Investigating the polarization behavior of the periodic optical outbursts in 1983.0 and 2007.8 in Sections 4 and 5, we argued that the polarization behavior (including the light curves of flux density, polarization degree and position angle) of the periodic optical outbursts may be most important for identifying the nature of their optical emission (thermal or nonthermal), and the rapid large position angle swings during the outbursts may become the decisive factor.

In order to clarify the nature of optical emission of the December/2015 outburst, we shall use a two-component model to study the light curves of flux, polarization degree and position angle of its first flare (during ~JD2457350-374) as a whole. It will be shown that its polarization behavior (especially the rotation of the position angle) demonstrates its synchrotron in origin.
Table 1. Model parameters of the 14 elementary flares used to simulate the light curve of the December/2015 optical outburst: epoch of the peak (JD-2457000), Lorentz factor, peak flux density $S_{V,p}$ and $S_{R,p}$ (mJy) at V- and R-bands, the corresponding co-moving flux density $S_{V,co}$ and $S_{R,co}$. The numbers given in the parentheses represent the power index of ten. For the first and second flares $\Gamma=14.0$ and 13.0, respectively. Spectral index is assumed to be $\alpha_{pV}=1.5$.

| epoch | $\Gamma$ | $S_{V,p}$ | $S_{R,p}$ | $S_{V,co}$ | $S_{R,co}$ |
|-------|---------|-----------|-----------|-----------|-----------|
| 353.55 | 14.0    | 1.20      | 1.33      | 3.84(-7)  | 4.92(-7)  |
| 355.07 | 14.0    | 3.04      | 3.90      | 9.78(-7)  | 1.25(-6)  |
| 359.17 | 14.0    | 5.51      | 7.06      | 1.77(-6)  | 2.27(-6)  |
| 361.55 | 14.0    | 12.5      | 16.0      | 4.02(-6)  | 5.15(-6)  |
| 363.84 | 14.0    | 7.07      | 9.06      | 2.27(-6)  | 2.91(-6)  |
| 365.44 | 14.0    | 5.06      | 6.48      | 1.63(-6)  | 2.09(-6)  |
| 367.18 | 14.0    | 3.38      | 4.33      | 1.09(-6)  | 1.39(-6)  |
| 368.33 | 14.0    | 1.41      | 1.81      | 4.54(-7)  | 5.81(-7)  |
| 370.08 | 14.0    | 3.26      | 4.18      | 1.05(-6)  | 1.34(-6)  |
| 372.97 | 13.0    | 2.64      | 3.38      | 1.18(-6)  | 1.51(-6)  |
| 376.07 | 13.0    | 1.98      | 2.53      | 8.84(-7)  | 1.13(-6)  |
| 379.17 | 13.0    | 6.35      | 8.14      | 2.84(-6)  | 3.63(-6)  |
| 382.67 | 13.0    | 1.32      | 1.69      | 5.91(-7)  | 7.56(-7)  |

6.4.1. Measurements of polarization position angle from different authors

We have collected some observational data on the polarization position angle (during ~JD2457336-374; the first flare of the December/2015 outburst), which are shown in Figure 12. The upper panel shows the comparison between the measurements by Kushwaha et al. (2015a; R-band) and Valtonen et al. (2017; R-band). The lower panel shows the comparison between the measurements by Myserlis et al. (2018; V-band) and Valtonen et al. (2017; R-band). These measurements at R- and V-bands are well consistent: especially the large position angle swing during the period ~JD2457370-374. Additionally, there is a large position angle swing clockwise (~80°) first (during ~JD2457358-359) and then counter-clockwise (~90°) during ~JD2457359-362. Note that this CCW position angle rotation appeared near the peak of the first spike-flare.

6.4.2. A two component model

Now we turn to make model simulation of the light-curves for the first flare of the December/2015 outburst. We have already seen in the last subsection that large swings in position angle were observed in this flare. Its integrated polarization degree was also highly variable as shown in Figure 13 (left column/middle panel). During the period ~JD2457350-372 it varied between ~3% and ~15%. The distinct features are: (1) The flux peak (at ~JD2457361.5) of the strong central spike flare is not concurrent with the minimal polarization degree (~3% at ~JD2457359). There are other three epochs when the polarization degree was observed to be between ~2% and ~4%, but all occurred during the declining stage; (2) the light curve of polarization degree does not reveal an inverse-proportion relation with the flux density (right column/middle panel in Figure 13), as expected if the outburst is purely thermal, where the polarization degree should decrease when its flux density increases and vice versa.

As for the 1983.0 and 2007.8 outbursts discussed in Sections 4 and 5, we have applied a two-component model to simulate the light curve of the observed (integrated) flux density, polarization degree and position angle as a whole. We assume that the first flare of the December/2015 outburst consists of two polarized components: one is a stable polarized component (or the steady underlying jet component before the outburst; component-1) and the other is a flaring component with variable polarization (component-2), respectively defined by $(I_1, p_1, \theta_1)$ and $(I_2, p_2, \theta_2)$. We choose the following values for component-1: $I_1=3.5$ mJy (R-band), $p_1=6.0\%$, $\theta_1 = -73^\circ$. The value for $p_1$ is constrained by the drop of polarization degree from ~6.8\% to ~2.8\% during the period ~JD2457356.5-2457358.5 with slight change in position angle (Fig. 13; left column: middle and bottom panels).

With the values of $(I_1, p_1, \theta_1)$ chosen, the values of $(I_2, p_2, \theta_2)$ can then be uniquely determined from solving the combined equations (1) and (2). The modeling results of the flaring component (component-2) are shown in the left column of Figure 14. It can be seen that during the first flare (~JD2457358.0-369.0) the derived polarization degree changes between ~0.9\% and ~20\%. The minimum degree occur at ~JD2457358, not coincided with the flux peaking epoch (~JD2457361.5).

The modeling results in terms of the two-component model clearly exhibit a rapid rotation of polarization position angle of the first flare during the period (~JD2457358-373), as shown in Figure 14 (left column/bottom panel). The position angle of the flaring component changes by ~350°: from ~80° to ~-430°. Its average clockwise rotation rate is approximately ~25°/day. Interestingly, the fastest rotation rate of ~110°/day derived during ~JD2457360-361 is coincident with the peak of the strong spike flare. The derived polarization position angle rotates clockwise with rapid fluctuations, which could be due to the superposition of more than two polarized components (e.g., a spike flare plus a wing flare and the stable component), as the

\[\frac{\text{The pair of clockwise and counter-clockwise rotations will be alternatively interpreted as a continuous clockwise rotation by introducing an ambiguity of } -180^\circ \text{ (Figure 14; left column/bottom panel). The measured values of position angle at } ~JD2457371.8, ~JD2457372.8 \text{ and } ~JD2457373.0 \text{ from Valtonen et al. also have been added by } -180^\circ \text{ for matching with the measurements by Kushwaha et al. and Myserlis et al.}}\]
modeled flux density light curve for the flaring component demonstrates.

The position angle rotations in optical wavebands are much faster (by a factor of ~20) than that observed at radio wavelengths (Myserlis et al. 2018) and the optical PA rotations precede the radio PA rotations. This phenomenon could well be explained in terms of the precessing nozzle scenario with helical motion: (1) both optical and radio PA rotations are produced by superluminal optical and radio knots moving along helical trajectory via lighthouse effect; (2) radio knots may evolve from optical knots, and due to opacity effects in radio-bands radio PA rotations should appear in regions further out in the jet, thus having a time delay relative to the optical PA rotations; (3) the pitch angle of the helical magnetic field may increase further out along the jet, causing the PA rotation rate in radio-bands much smaller than the rotation rate in optical bands; (4) combination of polarized synchrotron radio/optical flares can create various types of polarization behavior as observed in generic blazars.

It seems that the rotation of polarization position angle derived for the first flare of the December/2015 outburst could not be interpreted in terms of the impact-disk model, where the first flare of the December/2015 outburst was interpreted to be purely thermal, because a thermal flare with zero polarization alone can not cause rapid changes in position angle. Our model-simulation results favor the suggestion that the first flare of the December/2015 outburst is synchrotron flare according to its polarization behavior. Polarization position angle swings have been observed in blazars for a quite long time and interpreted by various authors, mostly invoking superluminal knots moving along helical trajectory in helical magnetic fields of jets or two-component model (Aller et al. 1983, Blandford & Königl 1979, Holmes et al. 1983, Kikuchi et al. 1988, Königl & Choudhuri 1985a, 1985b, D'Arcangelo et al. 2009, Marscher et al. 2008, Myserlis et al. 2018, Qian 1992, 1993, 2003).

For interpreting the PA rotations observed in optical and radio regimes in OJ287 the relativistic jet models of superluminal knots moving along helical trajectory in magnetic fields seem the most appropriate and consistent with the precessing nozzle scenario (Myserlis et al. 2018, Qian 2018b, 2019a).

6.4.3. QU-plots

The Stokes QU-plots for the integrated outburst is shown in Figure 15. And the QU-plots for the flaring-component (component-2) is shown in Figure 16. In the left panels are shown the entire Q-U tracks (during ~20 days interval, ~JD2457352-371) which are very erratic, like a drunkard walk. This is because of the very rapid variations in its polarization and the considered time-interval is too long. However, for a shorter time-interval of ~7 day during ~JD2457357-364 for the central strong spike flare, the QU-track clearly reveals its position angle rotation. Same behavior is for the flaring component (component-2) shown in Figure 16.

7. Discussion and conclusion

Based on the precessing jet nozzle scenario previously proposed by Qian (2019a, 2019b, 2018b, 2016) and Qian et al. (1991a, 2014, 2017, 2018a, 2019a, 2019b), we have model-simulated the flux light curve of the December/2015 periodic optical outburst (during ~JD2457358-390; Figure 10). We have also analyzed the polarization behavior of the periodic optical outbursts in 1983.0, in 2007.8 and the first flare of the December/2015 outburst (during period ~JD2457358-372) and showed that the rapid and large rotations in their polarization position angles (Figures 3-4, 6-7 and 13-15) associated with the appearance of low polarization degrees. A few conclusions can be made as follows.

- In order to determine the nature of emission (thermal or nonthermal) from the periodic optical outbursts, the light curves of flux density, polarization degree and polarization position angle \((I(t), p(t), \theta(t))\) should be investigated and consistently interpreted as a whole. Low polarization degrees alone seem not appropriate to be used as a unique factor to recognize the emission from the outbursts being thermal;
- The model-simulations for the three outbursts have revealed that they all show large position angle rotations during the outbursts, implying that the three outbursts should be all synchrotron in origin and produced in the relativistic jets;
- The precessing jet-nozzle scenario may be helpful for understanding the phenomena observed in OJ287. The simulation of the flux density light curve for the first flare of the December/2015 shows that this flare may comprise a number of elementary synchrotron flares, which are produced through a succession of superluminal optical knots moving along helical trajectory via lighthouse effect. Most of the optical/radio emission features observed in OJ287 can be understood in terms of the precessing nozzle model. However, this scenario has been suggested only deal with the emission features. The solution to the mechanism(s) for the quasi-periodicity and double-peaked structure in the optical light curve requires different approaches to work out (e.g., the disk-impact mechanism suggested in Lehto & Valtonen 1996, Sundelius et al. 1997).

The relativistic jet models under the precessing nozzle scenario suggested for OJ287 by Qian (2019a, 2019b, 2018b) may be useful to interpret the basic phenomena of its electromagnetic radiation and its nature of emission, including the following observational aspects.

- (1) The simultaneous \(\gamma\)-ray and optical outbursts observed in the December/2015 flaring event (Kushwaha et al. 2018a) can be interpreted, because both \(\gamma\)-ray and optical outbursts are suggested to be originated within the relativistic jet;
- (2) The quasi-periodic optical outbursts are composed of elementary flares with timescales of ~5-10 days. Each of the elementary flares has a symmetric profile and they blend together to form the very complex light curves of the flux, polarization and position angle. We have well model-simulated the flux light curves for the periodic outbursts in 1983.0, 1984.12, 1994.59, 1995.84, 2005.74, 2007.69 and the 2015.87 optical outburst (Qian 2019a). The symmetric profiles of elementary flares may be caused by the helical motion of the individual superluminal optical knots via lighthouse effect. This mechanism is applicable to both periodic and non-periodic outbursts.
- (3) The simultaneous variations in radio/mm and optical bands (Qian 2019b) can be interpreted: we have
suggested that the superluminal optical and radio knots might have a core-envelope structure with its synchrotron radiation distributed in the direction perpendicular to the direction of the helical motion. In this case the core-region dominates the optical radiation and its envelope dominates the radio/mm radiation, and the motion of this core-envelope structure can produce instantaneous optical and radio/mm flux variations (Qian 2019b). This optical-radio/mm radiation pattern is consistent with the stratification of the magnetic surface predicted by MHD theories for the magnetospheres produced by the black-hole/accretion disk systems (e.g. Camenzind 1991).

- (4) The connection between the optical outbursts and the delayed radio outbursts and ejection of superluminal radio knots can be understood, because the superluminal optical knots evolve into time-delayed radio knots when they move outward to large distances from the core.

- (5) The large-amplitude rotations in polarization position angle of the outbursts can be explained. The helical motion of the superluminal optical knots through the surrounding helical magnetic fields would result in large-amplitude rotations of polarization position angle of the outbursts. This phenomenon has been discovered and studied: e.g, for BL Lacertae and OJ287 (Sillanpää 1993, Marscher 2008, Holmes et al. 1984). In this paper we have also demonstrated the large-amplitude position angle rotations for the 1983.0, 2007.8 and 2015.8 outbursts, providing strong evidence for the helical motion of superluminal optical knots in blazar OJ287. Recently, Myserlis et al. (2018) found the large-amplitude polarization position angle rotations in OJ287 at radio wavelengths (10.5, 8.4 and 4.8GHz), which are delayed with respect to the position angle rotations at optical wavelengths. This is fully consistent with the predictions of the precessing nozzle scenario (Qian 2019a, 2019c): during the optical outbursts the radiation at radio wavelengths can not escape due to opacity effects and radio emission can be observed only when the radio-emitting regions become transparent. At the same time the timescales of the PA rotations at radio wavelengths would be much longer than that at optical wavelengths, because the radio PA rotations occurred in outer jet regions where the pitch angle of the helical magnetic field may be much larger than those in the optical-emitting regions (with coiled magnetic fields). This is just the case as observed in Myserlis et al. during December 2015 to January 2017.

- (6) The analysis of the kinematics of the superluminal radio knots on VLBI-scale at 15GHz in OJ287 (Qian 2018b) has shown that the precessing nozzle model can be used to explain the VLBI-kinematics of the radio knots. The precession of the jet-nozzle is a key ingredient to understand the phenomena in OJ287. A tentative study indicates that OJ287 might have a double-jet structure, because only in this case the kinematics of its superluminal components C11 and C12 (having similar position angles but four-year separation in ejection epochs) can be well fitted (Qian 2018b).

Although the precessing nozzle model OJ287 (Qian 2018b) can be used to understand most of the emission properties of the optical/radio outbursts observed in OJ287, its basic assumptions are still to be tested and confirmed.

In addition, the precessing nozzle model (as a relativistic jet model) is only applied to interpret the emission properties of the outbursts in OJ287. It does not deal with the mechanism of the quasi-periodicity and double-peaked structure, because this subject mainly involves the physical processes occurred in the course of binary orbital motion, e.g. as suggested by the impact-disk scenario. These may include the penetration of secondary hole into the primary disk, interaction between the secondary hole and the magnetosphere of the spinning primary hole, and the consequent effects from the impact-disturbances in mass accretion on the ejection of superluminal optical knots, etc.

Some HD and MHD simulations (e.g., Artyomowicz & Lubow 1996, Artyomowicz 1998, Hayasaki et al. 2008, Cuadra et al. 2009, Farris et al. 2014, Shi et al. 2012, 2015, D’Orazio et al. 2015) have suggested that cavity-accretion models with two-stream accretion flows toward the binary holes could interpret the production of the quasi-periodic pair-flares. However, cavity-accretion models, e.g., as proposed for OJ287 by Tanaka et al. (2013), can only produce a pair of thermal flares which is contradictory to the polarization behavior observed in the quasi-periodic outbursts (Qian, this paper; Myserlis et al. 2018, Holmes et al. 1984). Moreover, this model is not able to provide an interpretation for the quasi-periodicity and prediction of flaring times of the impact-flares.

At present, only the impact-disk model (Lehto & Valtonen 1996, Sundelius et al. 1997, Valtonen et al. 2019) has been proposed to explain the quasi-periodicity and double-peaked structure in the optical light curve. According to Laine et al. (2020) this model has successfully predicted the pair of quasi-periodic outbursts in 2015/2019. Based on the calculations of the precessing orbital motion under the impact-disk scenario, the accurate timing of the quasi-periodic flares can be applied to test general relativity (Einstein 1916, 1918) e.g., gravitational waves, precession of binary orbit, no-hair theorem, etc.). Based on the model simulation of the light curves of flux density, polarization degree and polarization position angle as a whole and the investigation on the nature of emission from the optical outbursts in 1983.0, 2007.8 and 2015.8, we find that these periodic outbursts may be all synchrotron in origin, inconsistent with the predictions from the disk-impact scenario. This issue might be helpful for understanding the entire phenomena observed in blazar OJ287. More multi-wavelength observations (in γ-rays and in optical/radio bands) and theoretical works are required to find some solutions. As a conjecture, for example, we would have to consider the possibility: if the impact-disk scenario for explaining the quasi-periodicity with double-peaked structure is unique and if the suggestion of the periodic outbursts being synchrotron in origin is correct, then there should exist some mechanism(s) directly connecting the ejection of superluminal optical knots with the disk-impacts without producing strong thermal optical outbursts.

Note that there is some evidence for double-jets in OJ287 from the analysis of the VLBI-kinematics of superluminal radio knots (Qian 2018b).
Fig. 11. Modeled flux density profile, Lorentz/Doppler factor, apparent velocity and viewing angle versus time for the central strong spike-like flares. Left column: for the first spike-flare (during \( \sim JD2457359-364, \Gamma=14 \)). The length of the helical trajectory along the beam-axis responsible for the first spike flare is \( \sim 0.42 \) mas, corresponding to \( \sim 1.9 \) pc and a helical period of \( \sim 71 \) day. Right column: for the second spike-flare (during \( \sim JD2457376-384, \Gamma=13 \)). Note: the rising and declining portions of the two spike flares are very well fitted by symmetric profiles (also see Figure 10).
Fig. 12. Comparison between the polarization position angle measurements by different authors for the first flare of the December/2015 quasi-periodic optical outburst. Upper panel: solid black squares from Valtonen et al. (2017), open magenta circles from Kushwaha et al. (2018a). Lower panel: solid black squares from Valtonen et al. (2017), open blue circles from Myserlis et al. (2018). Prominent position angle swings were observed during \(~\text{JD}2457358-362\) and during \(~\text{JD}2457370-374\).
Swings in polarization position angle are clearly revealed. No sign shows the inverse-proportion relation between the polarization degree and the flux density, as required by the impact-disk model.

Fig. 13. Left column: The observed (integrated) light curves of flux density, polarization degree and position angle. Right column: relation between the integrated flux density and the position angle (top panel); relation between the polarization degree and the position angle (middle); relation between the integrated polarization degree with the position angle. Swings in polarization position angle are clearly revealed. No sign shows the inverse-proportion relation between the polarization degree and the flux density, as required by the impact-disk model.
Fig. 14. Modeling results for the flare component (Component-2). Left column: the modeled light curves of flux density, polarization degree and position angle. Right column: relation between the modeled flux density and the position angle (top panel); relation between the polarization degree and the position angle (middle); relation between the modeled polarization degree and the position angle. Rotations in polarization position angle are clearly revealed. No sign shows the inverse-proportion relation between the polarization degree and the flux density, as required by the impact-disk model.
Fig. 15. Left: Stokes Q-U plot for the integrated outburst (during \( \sim \) JD2457351.8-371.0). Right: Stokes Q-U plot for part of the outburst during \( \sim \) JD2457357-364, which clearly reveals the polarization position angle swing. Black triangles represent the start of the tracks.

Fig. 16. Left: Stokes Q-U plot of the modeled flare-component (Component-2) during \( \sim \) JD2457352-2457371. Right: Stokes Q-U plot for part of the flare-component during \( \sim \) JD2457351-2457364, including the central strong spike. Black triangles represent the start of the tracks.