Model simulation of optical light curves for blazar OJ287

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ABSTRACT

Context. The light curves of optical outbursts observed in blazar OJ287 during 1983–2015 are analyzed and model-simulated to investigate the nature of its optical radiation.

Aims. It is shown that the December/2015 outburst has its multi-wavelength variability behavior very similar to that of the synchrotron outburst in March/2016, indicating that the 2015 outburst may originate from synchrotron process.

Methods. In combination with helical motion of superluminal components, the precessing jet nozzle scenario previously proposed is used to model-simulate the light curves of all the optical outbursts discussed.

Results. The optical light-curves for both periodic and non-periodic outbursts observed in blazar OJ287 can be well interpreted in terms of lighthouse effect due to the helical motion of superluminal optical knots, showing their common origin in synchrotron process.

Conclusions. A coherent and compatible framework is tentatively suggested to understand the entire phenomena in OJ287. The double-peak structure of the periodic outbursts might be explained by invoking the cavity-accretion flare models for comparable-mass binary systems in eccentric motion.

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

1. Introduction

OJ287 (z=0.306) is an optically violent variable BL Lacertae object (BLO) and also one of the bright Fermi γ-ray sources (Ackermann et al. 2011; Hartman et al. 1999; Agudo et al. 2012). Its strong variability has been observed in all the wavebands from radio to γ-rays with various timescales (hours/days to years).

Its optical variability is particularly exceptional. The optical light curve recorded since 1890s reveals quasi-periodic outbursts with a cycle of ∼12 yr (Sillanpää et al. 1988). Up to now four periodic outbursts with double-peaked flares have been observed in 1972–73, 1982–83, 1994–95 and 2005–2007. The first flare of the fifth periodic outburst has been observed in December/2015 and its second flare is predicted to peak on July 31 2019 (Valtonen et al. 2018; Dey et al. 2018 and references therein). The long-lasting quasi-periodicity is believed to be related to the orbital motion of a black hole binary in the center of its host galaxy. In the early works Brown et al. (1989a, 1989b) showed that the variations at infrared (IR), optical and ultraviolet wavelengths are well correlated. Correlation between spectral index and flux density was observed at near-infrared (NIR) wavelengths (Gear et al. 1985); the source spectrum becomes steeper when it becomes fainter and vice versa. But Sillanpää et al. (1996b, 1996c) found that the optical spectral index (or spectral color) was very stable during the period 1994–1996 (OJ-94 project, Takalo 1996a). Recently, the multi-wavelength observations performed by Gupta et al. (2016) during 2015–2017 also demonstrate the stability of the optical spectral color in OJ287.

Variations observed at centimeter wavelengths usually lag the optical variations (Valtaoja et al. 2000; Aller et al. 1994, 2014). The radio time-delays can be attributed to shock evolution combined with opacity effects. But there are some observations revealing simultaneous variations at millimeter and optical wavelengths (Sillanpää et al. 1996b; Valtaoja et al. 2000).

OJ287 is a well-known superluminal source on parsec scales and VLBI observations reveal that it has a core-jet structure and superluminal components are steadily ejected from the core (Britzen et al. 2018; Hodgson et al. 2017; Agudo et al. 2012; Cohen 2017; Qian 2018 and references therein). It has been found that there is a close connection between the optical flares and the emergence of superluminal components (Tateyama et al. 1999; Qian 2018). Recently, based on the analysis of the kinematics of superluminal components, Britzen et al. (2018) have made an elaborated relativistic jet model (invoking jet precession plus nutation) to explain the radio variability and the kinematics on parsec scales. Based on a potential double-jet scenario, Qian (2018) tentatively derived the total mass of the binary in the range 10^8–10^9 M⊙, which is consistent with the estimation by Gupta et al. (2012) as well as Villforth et al. (2010; Valtaoja et al. 2000).

Recently Kushwaha et al. (2018) and Gupta et al. (2016) have monitored the multi-wavelength variations in the NIR-optical-UV bands during December/2015–May/2016, providing new information about the variability behavior in OJ287. They showed that the source has a stable color during that period, confirming the finding by Sillanpää et al. (1996a) and supporting the “single mechanism” for the optical flares (periodic major outbursts and non-periodic synchrotron bursts) in OJ287. Kushwaha et al. (2018) have found that the December/2015 optical outburst was as-
associated with a simultaneous γ-ray flare. In addition, another strong synchrotron outburst with polarization degree of 30% was observed in March 2016 which have its temporal and spectral variations very similar to those observed in the December 2015 outburst.

The phenomena in OJ287 are very complex and may involve several different mechanisms producing its variations from radio to γ-rays. Its multi-wavelength variations reveal many prominent features: (1) 12 yr quasi-periodic optical variability; (2) double-peak structure of the periodic optical outbursts; (3) symmetry of individual optical flare profiles; (4) multi-component structure of the major optical outbursts; (5) similarity in the variability behavior of individual bursts and major periodic outbursts; (6) large range of optical polarization degrees (from <2% to ~40%); (7) stability of optical spectral index (color stability); (8) connection between radio and optical variations; (9) synchronous radio and optical variations (simultaneity and similar profiles); (10) ejection of superluminal components and jet precession; (11) association of γ-ray flares with optical flares, etc.

A number of models have been proposed (referring to the discussions in Villforth et al. 2010, Qian 2018, 2019). On the whole, these models can be divided into two categories, both involving a black hole binary system in the nucleus of OJ287:

- The precessing binary model (or disk-impact model) originally proposed by Lehto & Valtonen (1996) improved versions: Valtonen 2007, Valtonen et al. 2006, Valtonen et al. 2013, Dey et al. 2015 has been steadily elaborated to interpret the variability behavior in OJ287, putting the emphasis on the accurate timing of the first major flares of the periodic outbursts, which were suggested to be bremsstrahlung in origin (unpolarized flares) and produced by the secondary hole penetrating the accretion disk of the primary hole. In the case of an highly eccentric orbital motion, two impacts would occur near pericenter passages and thus explain the double-peak structure of the periodic outbursts. The recent December 2015 optical outburst was studied and interpreted in detail by Valtonen et al. (2016, 2017). This model requires a high inclination angle (i ~ 50° – 90°) and a high eccentricity (e ~ 0.66) and a strong constraint on the total mass of the binary, reaching 2 x 10^8 M⊙ with a mass ratio m/M ~ 0.007. This disk-impact model mainly concentrates on the interpretation of the quasi-periodicity of the 12 yr, double-peak structure and the accurate timing of the periodic outbursts, regarding the periodic outbursts being thermal flares due to the impact of the secondary hole penetrating the primary disk. This model suggests that the follow-up and non-periodic outbursts could be interpreted in terms of the enhanced accretions (disturbances induced by the secondary impacts and tidal effects near pericenter passages). But it can not be used to analyze the complicated phenomena observed in the entire emission (from radio to γ-rays) and the relationship between the emission properties and the kinematic behaviors on parsec scales. This model is based on very accurate solution of orbital motion by including the post-Newtonian strong gravitational effects, but invoking a fixed (not variable) disk model.

In contrast, Tanaka (2013) considered a different mechanism (cavity-accretion flare model) for explaining the double-peak structure, assuming the binary having a comparable-mass in a coplanar motion. According to the results of hydrodynamic/magnetohydrodynamic (HD/MHD) simulations for binary systems surrounded by circumbinary disks, the cavity-accretion processes characteristic of comparable-mass binary systems would create two gas streams impacting onto the disks of both the black holes near pericenter passages, thus causing the double-peaked outbursts. This model also suggests that the periodic outbursts are bremsstrahlung flares caused by the impacts of the gas streams. It is not able to provide accurate timing of the periodic outbursts. This cavity-accretion flare model does not discuss the accretion processes during the intervening periods and the interpretation of the follow-up and non-periodic outbursts and the related jet behavior.

- Relativistic jet models have been applied to understand the optical and radio variability behavior in OJ287 and discussed by many authors since the earlier years (e.g., Sillanpää et al. 1996, Valtaoja et al. 2000), because these models are considered to be paradigmatic for explaining the variations (from radio to γ-rays) observed in blazars. Villalta et al. (1998) considered a precessing double-jet model to explain the periodic double-peak structure. Villforth et al. (2010) suggested that the periodic outbursts could be interpreted in terms of the resonant disk accretion of magnetic field lines. Qian (2015) investigated the possibility that lighthouse effect could cause the double-peak structure of the periodic outbursts. Recently, based on the analysis of the kinematics of the radio superluminal components, Britzen et al. (2013) proposed an elaborated model to interpret the radio and optical variations, emphasizing the precession and mutation of the relativistic jet being the key ingredients causing the complex phenomena in OJ287. In addition, Qian (2013) tentatively suggested that the periodic optical outbursts could be synchrotron flares produced by the superluminal optical knots moving along parabolic trajectories. But the explanation of the double-peak structure might have to invoke the cavity-accretion process for comparable-mass binary systems (e.g., Tanaka 2013, Artymowicz & Lubow 1996, Hayasaki et al. 2008). Relativistic models do not involve disk-impacting events, which cause strong thermal flaring events and the optical/radio phenomena in OJ287 may be explained only by invoking the enhanced disk-accretion near pericenter passages and ejection of superluminal optical knots.

It might be worth noticing that, based on the modeling of the kinematics of the superluminal components in OJ287 (Qian 2013), the total mass of the potential binary has been tentatively determined to be ~ 10^8 – 10^9 M⊙ which is consistent with the estimations obtained by Gupta et al. (2012), Villforth et al. (2010) and Valtaoja et al. (2000). These values seem to favor a binary system with comparable-mass in a coplanar

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1 In this case the jet associated with the secondary hole might not be pointed toward us with a small angle, if its spin axis (and jet axis) is approximately parallel to the orbital angular momentum.

2 Mass ratio m/M ~ 0.3.
motion. In this case both the jets associated with the binary holes can point toward us with small angles.

Unfortunately, all the models currently available can only interpret part of the phenomena observed in OJ287. Some basic issues are remained to be clarified: mass of the binary, double peak structure mechanism, color stability, synchronous radio-optical variations, symmetry in burst light curves, similar variability behavior of the flares, simultaneity in optical and γ-ray flares, etc. A comprehensive and coherent framework is imperatively needed to solve all these issues.

In this paper we will apply the precessing jet-nozzle model previously proposed for several blazars (3C345: Qian et al. [1991a, 2009], 3C279: Qian 2011, 2012, 2013, Qian et al. 2019, 3C454.3: Qian et al. 2013, NRAO 150: Qian 2016, B 1308-326: Qian et al. 2017, PG 1302-102: Qian et al. 2018, OJ287: Qian 2018) to investigate the kinematics of the optical superluminal components in OJ287 and propose an interpretation for the multi-wavelength light curves of the optical outbursts in December/2015 and March/2016 obtained by Kushwaha et al. (2018). We will also perform model simulation of the V-band light-curves of the six periodic major outbursts in 1983.00, 1984.10, 1994.75, 2005.76, 2007.70 and 2015.87 by using lighthouse effect due to the helical motion of superluminal optical knots. In particular, the multi-wavelength light curves of both the outbursts in December/2015 and in March/2016 will be simulated and compared, demonstrating the distinct similarity in their temporal and spectral variations (multi-wavelength light curves with similar rising and decaying time scales and similar broken power-law spectra). Since the outburst in March/2016 is a highly polarized synchrotron flare, the similar variability behaviors of the December/2015 outburst (peaking at 2457360) and the March/2016 outburst (peaking at 2457450) may imply that they have a common emission mechanism and the December/2015 outburst may be synchrotron in origin.

### 2. Assumptions and approaches

In order to better understand the entire phenomena observed in the blazar OJ287, we would perform detailed simulation of the light curves of its optical outbursts, which include not only the periodic major outbursts (or the "impact outbursts" claimed to be bremsstrahlung flares caused by the evolving gas-bubbles torn out from the primary disk by the secondary-hole penetrations), but also the non-periodic outbursts (usually recognized as synchrotron flares with high polarization). The multi-wavelength light curves of the December/2015 outburst (peaking at 2457360) and the March/2016 outburst (peaking at 2457450) are analyzed and compared for finding their common properties: the symmetry of their light-curves and similarity in their temporary and spectral variations.

We will apply the precessing jet-nozzle model previously proposed for several blazars (3C345: Qian et al. [1991a, 2009], 3C279: Qian 2011, 2012, 2013, Qian et al. 2019, 3C454.3: Qian et al. 2013, NRAO 150: Qian 2016, B 1308-326: Qian et al. 2017, PG 1302-102: Qian et al. 2018, OJ287: Qian 2018) to investigate the kinematics of the optical superluminal components in OJ287 and propose an interpretation for the multi-wavelength light curves of the optical outbursts in December/2015 and March/2016 obtained by Kushwaha et al. (2018). We will also perform model simulation of the V-band light-curves of the six periodic major outbursts in 1983.00, 1984.10, 1994.75, 2005.76, 2007.70 and 2015.87, suggesting a coherent scenario to understand the entire phenomena in OJ287.

We describe the main assumptions and relevant approaches for the model simulation of the outburst light curves as follows.

#### 2.1. Parameters of precessing nozzle model

In order to make model simulation of the light curves of the optical outbursts in OJ287, we would need to use an appropriate and specific scheme of the precessing nozzle model. Here we adopt the geometric parameters applied in the previous precessing nozzle models (details referring to Qian 2018) and introduce the parameters of helical motion.

We assume that the superluminal optical knots move along helical trajectories around the jet axis which precesses around the precession axis, as shown in Figure 1 (left panel). The precession axis is defined by parameter ε = 3° and ψ = 0.0 rad. The jet axis is assumed to be a straight line with parameters a = 0.0402 and x = 1.0 (details referring to Qian 2018), which precesses around the precession axis with a period of 12 yr. Optical superluminal knots are assumed to be ejected from the jet nozzle, moving outward along helical trajectories. The helical motion of the optical

### Table 1. Model parameters for the helical trajectories of optical knots.

| Parameter | Fixed value |
|-----------|-------------|
| ε        | 3°          |
| ψ        | 0.0 rad     |
| ω        | -2.0 rad    |
| a        | 0.0402      |
| x        | 1.0         |
| A₀       | 0.0138 mas  |
| dφ/dz₀   | -7.04 rad/mas |

### Table 2. Base-level (underlying jet) spectrum for OJ287.

| Waveband | Flux (mJy) |
|----------|------------|
| K        | 8.0        |
| J        | 5.0        |
| I        | 6.2        |
| R        | 3.5        |
| V        | 3.0        |
| B        | 2.0        |
| U        | 1.5        |
| UVW1     | 0.8        |
| UVW2     | 0.8        |

### Table 3. Parameters for model simulation of the periodic outburst in December/2015 (peaking at JD2457360) and the March/2016 outburst (peaking at JD2457450): Γ–Lorentz factor of the optical knot, maximum Doppler factor δmax, ratio δmax/δmin, S_{int}(mJy)–intrinsic flux density of the optical knot, base-level (underlying jet) flux density S_{b}=(3.5}\,mJy at R-band, FWHM (full width at half maximum of the modeled light curve; day). $t$ = flare time = day–2457000.

| $t$ (JD) | Γ   | δmax | δmax/δmin | S_{int} (mJy) | FWHM |
|---------|-----|------|-----------|---------------|------|
| 360     | 9.5 | 18.88| 4.11      | 1.16×10^-4    | 5.9  |
| 450     | 9.5 | 18.88| 4.11      | 1.16×10^-4    | 5.9  |
Fig. 1. Left panel: A sketch of the precessing jet nozzle scenario with helical motion. The straight lines denote the precessing jet axis (projected on the plane of the sky) which is described by the precession phases of $\omega=0.0\,\text{rad}$, $-2.0\,\text{rad}$ and $-4.0\,\text{rad}$, respectively. The helices indicate the trajectories of the optical knots moving along the jet axis in perfect collimation zones. The helical trajectory defined by $\omega=-2.0\,\text{rad}$ is used to simulate the light curves of the optical outbursts in December/2015 and March/2016. The corresponding Lorentz and Doppler factors are shown in the right panel. The helical motion in the perfect collimation zone is assumed to start at $z=0$.

Fig. 2. Left panel: the modeled broken power-law synchrotron spectrum with a spectral break at V-band of $\Delta \alpha=0.5$ (from $\alpha=0.8$ to $\alpha=1.3$, $S_\nu \propto \nu^{-\alpha}$). The base-level spectrum is shown in the middle panel. The modeled intrinsic flux densities (in the comoving frame of the optical knot) at I-, V- and U-bands are shown in the right panel (unit=$10^{-4}\,\text{mJy}$).

knots are sketched shown in Figure 1 (left panel). Using the precessing nozzle model we can study the helical motion of superluminal optical knots ejected at different precession phases. For concrete model simulations, we will assume that the superluminal optical knots are ejected along the jet axis defined by the precession phase $\omega=-2.0\,\text{rad}$, moving along the helical trajectories which are defined by parameters $A_0$ and $d\phi(z)/dz$: $A_0$ represents the amplitude of the helical trajectories and $d\phi(z)/dz$ represents the rotation rate of the helical motion. We will take $A_0=0.0138\,\text{mas}$ and $d\phi(z)/dz=-7.04\,\text{rad}/\text{mas}$. The model parameters are summarized in Table 1. In order to demonstrate the common features of helical motion of the superluminal optical components, parameters $A_0$ and $d\phi(z)/dz$ are assumed to be constant for all the optical flares and only their bulk Lorentz ($\Gamma$) and intrinsic flux density ($S_{\text{int}}$) are chosen to model-fit their light curves. Constant $A_0$ and $d\phi(z)/dz$ describe uniform helical motion in a perfect collimation zone.

2.2. March/2016 outburst: a synchrotron flare

As shown by Kushwaha et al. (2018), the strong optical outburst observed in March/2016 (peaking at 2457450) is a synchrotron flare with a high polarization degree of $\sim 30\%$ (at R-band). This is consistent with the observations made by Valtonen et al. (2017). Both the optical polarization observations rule out the possibility that the March/2016 outburst is a bremsstrahlung-dominated flare. The reason is: if this outburst comprised of two components (one thermal and one synchrotron) and was thermal-dominated, then in order to explain its 30% polarization, the synchrotron component would be required to have a polarization degree of at least $>60\%$. Such high polarization degrees have never been observed in OJ287 (e.g., see the photopolarimetric light curves (R-band) during 2005–2008 in Villforth et al. 2010). Thus we suggest that the March/2016 outburst (peaking at 2457450) originates from synchrotron process, definitely a non-thermal flare.

Introducing $A_0$ and $d\phi(z)/dz$ as functions of distance $z$, one can study various patterns of helical motion.
(Fig.4 in Kushwaha et al. 2018 also see Figures 4–9 displayed below). The SED of both the outbursts reveals two prominent features: (1) an offset between the visible spectrum and the near-infrared (NIR) spectrum; (2) a transition from a rather steep visible spectrum to a flatter UV spectrum. Superficially, these features look like those observed in other blazars (e.g., 3C345, 3C454.3, BL Lac and AO 0235+106; Bregman et al. 1986; Raiteri et al. 2007; Villata et al. 2001–2002; Raiteri et al. 2005), which have been claimed to be constructed from the “big blue bump" and "little blue bump" produced by the accretion disks and emission lines in the broad-line regions (BLR). However, in the case of OJ287, the variations in the UV-band are simultaneous with the NIR-optical variations and no color changes occur during the March/2016 synchrotron outburst (as well during the December/2015 outburst). This variability behavior seems indicating that the emission from the NIR-optical to the UV-bands are all produced in the jet and the emitting source might have a peculiar inhomogeneous structure (Raiteri et al. 2007, 2008; Ostorero et al. 2004). We will continue to argue for this possibility below, especially based on the connection between the radio and optical outbursts.

2.3. Similarity between 2015 and 2016 outbursts

In the following sections, we will perform model simulation of the multi-wavelength (NIR-optical-UV) light curves of the December/2015 and March/2016 outbursts (Kushwaha et al. 2018; Gupta et al. 2016) and show that the temporary and spectral variations of the December/2015 outburst are very similar to those of the March/2016 outburst, although the March/2016 outburst occurred ∼90 days later, but was as strong as the December/2015 outburst and had high polarization degrees. They have similar multi-wavelength light curves in the NIR-optical-UV bands having symmetric profiles with very similar rising and declining timescales. While the December/2015 outburst has been claimed to be an “impact thermal outburst", occurring at a location ∼18,000 AU away from the primary black hole and originating from an evolving gas-bubble torn out from the accretion disk of the primary hole (Lehto & Valtonen 1996; Valtonen et al. 2016), the March/2016 outburst is definitely a non-thermal flare, originating from synchrotron process in the jet. It is rather difficult to understand why the December/2015 thermal outburst could have its temporary and spectral variability behavior so resembling to that of the March/2016 synchrotron outburst. Our model simulation of their light-curves indicates that the March/2016 and December/2015 outbursts could be interpreted in terms of the lighthouse effect due to helical motion of one superluminal optical knot in a perfect collimation zone of the jet via two helical revolutions. Thus the resemblance in the temporary and spectral variations observed in December/2015 and March/2016 outbursts may imply that both December/2015 and March/2016 outbursts originate from a common radiation mechanism and they are non-thermal (synchrotron) flares produced in the jet. The two outbursts may be combined into “one flaring event" and their observational data-points are superposed to analyze the common properties of their temporary and spectral variations. For the R-band light curves, the data-points measured by Valtonen et al. (2016) are also incorporated in the analysis, providing sufficiently complete temporal coverage for the simulation of the multi-wavelength light curves.

2.4. Nature of 2015 outburst: γ-ray observations

The nature of the radiation of the outburst in December/2015 (peaking at 2457360) is still a debatable issue: whether it is a synchrotron flare or a bremsstrahlung-dominated one. We argue that the December/2015 optical outburst may be a synchrotron flare. According to Valtonen et al. (2016), the December/2015 outburst is composed of two components: one bremsstrahlung component and one synchrotron component, and it is bremsstrahlung-dominated. In order to explain its observed polarization degree of ∼6%, the non-thermal component is assumed to be highly polarized with a polarization degree of 40%. In this case the thermal component is much stronger than the non-thermal component, making ∼68% and ∼17% contributions to the total flux of the outburst, respectively. However, the relationship between the thermal component and the non-thermal component was not clarified: (1) where this highly-polarized component is produced: in the jet of the primary hole or in the jet of the secondary hole? (2) How could the flux variation of the non-thermal component be simultaneous with that of the thermal component, because the two emission components appeared at different locations (not co-spatial): the thermal flare occurred at ∼0.1 pc away from the primary hole and its jet? (3) How could the variable non-thermal component (with a constant polarization degree) be possible to closely match the behavior of the thermal component, because they originate from different emission mechanisms: bremsstrahlung from an evolving gas-bubble and synchrotron emission from a shock in the jet, having different evolution behaviors with different timescales.

It is worth noticing that the December/2015 outburst emits γ-rays and the variations in the γ-ray bands are simultaneous with the variations in the NIR-optical-UV bands without time lags (Kushwaha et al. 2018), having similar variability time scales. Obviously, this γ-ray flare should be associated with the synchrotron flare component and both emitting regions must be co-spatial within the relativistic jet. Thus the simultaneity in the variations and the similarity in the variability behavior between the γ-ray flare and the bremsstrahlung-dominated outburst seems unlikely, because the bremsstrahlung flare is believed to be produced by an evolving gas-bubble torn off the primary hole accretion disk by the second black hole penetrating into the primary disk (Lehto & Valtonen 1996; Valtonen et al. 2016), while the synchrotron component flare and its associated γ-ray flare are produced in the jet of the primary black hole: they occur at different locations (not co-spatial) through different mechanisms. The only plausible interpretation for the

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5 The data-points of the March/2016 outbursts need to be shifted backward in time by 89.4 days.

6 Here we do not consider the case that the base-level makes a 10% contribution to the polarization degree.

7 The base-level emission makes a steady ∼15% contribution to the total flux density.
simultaneous variations in the γ-ray and optical bands may be that the December/2015 optical outburst is originated from the jet through synchrotron process. This may be the most persuasive argument for the December/2015 outburst being a non-thermal flare.

2.5. Spectral energy distribution of December/2015 outburst

As typically observed in generic blazars, the spectral energy distribution of the December/2015 outburst consists of two bumps: one in the NIR-optical-UV bands and the other one in the γ-ray bands (Kushwaha et al. 2013). These two bumps are normally interpreted in terms of synchrotron and inverse-Compton processes, respectively. In the one-zone scenario (e.g., Qian et al. 1998a, 1998b, Ghisellini et al. 2007, Vercellone et al. 2010, 2012), the simultaneity of the NIR-optical-UV and γ-ray variations and their similar variability time scales (rising and declining timescales) would suggest that the NIR-optical-UV emitting region and the γ-ray emitting region are co-spatial in the jet of the primary hole. It seems difficult to understand that the γ-ray flare could be simultaneous with the NIR-optical-UV variations in a bremsstrahlung-dominated outburst. Moreover, under the bremsstrahlung-dominated assumption for the December/2015 outburst, the low-frequency bump of its SED has to be decomposed into two parts (Kushwaha et al. 2013): one thermal and one non-thermal. The peak frequency of the non-thermal part has to be shifted to the far-infrared regime and its optical-UV power has to be lowered to only a half of the observed optical-UV power, reaching the power levels during the quiescent states in OJ287 (e.g., Seta et al. 2009, Kushwaha et al. 2013, Kushwaha et al. 2015). This seems inconsistent with the normal behavior observed in γ-ray blazars: the synchrotron bump moves to higher frequency with higher peak power ($\nu F_\nu$) during γ-ray flaring states, when the high-energy bump shifts to higher energy γ-ray bands. Therefore, it seems more likely that the low-frequency bump of the December/2015 outburst may be entirely synchrotron in origin.

2.6. Broken power-law spectrum

The spectral break detected in the optical–UV wavebands for the December/2015 outburst (Kushwaha et al. 2013) has been interpreted as due to the thermal emission of the accretion disk surrounding the primary black hole with a mass of $1.8\times10^{10}M_\odot$. It is noted that the March/2016 outburst has a similar spectral break, which may not originate from the primary disk and due to the superposition of the synchrotron emission from different jet regions. Moreover, both outbursts has no color variations, as Gupta et al. (2016) observed. Thus in the following simulations of the multi-wavelength light curves of the two outbursts, a common broken power-law spectrum will be assumed with a spectral break of $\Delta\nu=5\times10^{15}\nu^{-0.8}\nu$ in the $K$- to $V$-bands $S_\nu\propto\nu^{-\alpha}$ with $\alpha=0.8$, and in the $V$- to $\gamma$-bands $S_\nu\propto\nu^{-\alpha}$ with $\alpha=1.3$. The spectrum is sketchily shown in Figure 2 (left panel). This kind of broken power-law spectrum can be resulted from local continuous injection or re-acceleration of relativistic electrons in the superluminal optical knots under synchrotron/IC radiative losses (Kardashev 1962, Pacholczyk 1970, Qian 1978, 1996a, 1996b, 1997) and Sahayanathan et al. (1998). The synchrotron spectrum assumed here is essentially different from the bubble-emitting bremsstrahlung spectrum produced by the disk-impacting process. It is noted that the thermal spectrum predicted by the disk-impact model was much flatter at optical-UV wavelengths. According to Valtonen & Ciprini (2012) and Valtonen et al. (2012), the thermal spectrum of the 2005 outburst was derived from the observed spectrum by correcting the host galaxy extinction with a hydrogen column density of $6.3\times10^{20}/\text{cm}^2$. However, if correction of extinction in the host galaxy were needed, the synchrotron spectrum of the March/2016 outburst would also be converted into a thermal spectrum. This seems unlikely. Thus the host galaxy extinction will not be included here and we suggest that both the December/2015 and March/2016 have similar non-thermal spectra.

2.7. Spectral variability

As explained in Sect.2.1, the spectral energy distribution of the December/2015 outburst (peaking at 2457360) in the NIR-optical-UV bands exhibits two distinct features: the offset between the NIR and optical portions and the transition from the rather steep optical spectrum to a flatter spectrum in the UV portion. If this NIR-optical-UV spectrum could be interpreted as composed of two constituents: a thermal spectrum emitted from the accretion disk of the primary black hole (with a mass of $\sim2\times10^{10}M_\odot$) dominating the optical-UV emission and a synchrotron spectrum emitted from a shock in the jet dominating the IR-radio emission, one would have to explain why the two emitting sources could vary simultaneously. Moreover, the March/2016 outburst (peaking at 2457450) has its spectrum and spectral variations very similar to those of the December/2015 outburst and both outbursts exhibit no color changes (Gupta et al. 2016). As the March/2016 outburst is a highly-polarized synchrotron one, its spectral variations should not be related to the thermal emission from the primary disk and its color stability must be a characteristic feature of the synchrotron source itself. The color stability commonly observed in both December/2015 and March/2016 outbursts may be a significant signature demonstrating the nature of their emission. Thus the similarity in the spectral variations between the December/2015 and March/2016 outbursts may imply that the December/2015 outburst also originate from the jet. In fact, according to the disk-impact model, the December/2015 outburst is caused by the evolving gas-bubble torn off the primary disk by the secondary hole impacting. The thermal emission from an evolving gas-bubble during its adiabatic expansion and cooling (from $\sim10^5$K to lower temperatures) would be color-changeable, inconsistent with the observations.

2.8. Symmetry in light curve profiles

As Sillanpää et al. (1996a) pointed out that during the OJ-94 project period (1993.8–1996.1) the two major outbursts
had a strong symmetry. Through detailed inspection, we recognized that the two major outbursts could be decomposed into a number of subbursts, each having symmetric light curves with similar rising and declining timescales. A few isolated moderate outbursts also have symmetric light curves. Most Interestingly, the December/2015 outburst peaking at JD2457360 (Valtonen et al. 2016) does not exhibit the “standard light curve” expected for “impact outbursts” (Valtonen et al. 2011), but showing a symmetric profile. During the period of September/2015–May/2017, a number of rather isolated moderate bursts (e.g., peaking at JD-2457379,-2457450,-2457759 and -2457885; Valtonen et al. 2017) were observed to exhibit symmetric profiles. As discussed in Sect.4 below, the five periodic outbursts (in 1983.00, 1984.10, 1994.75, 2005.76 and 2007.70) could be decomposed into a number of subbursts with each sub-flare (or “elementary flare”) having a symmetric light curve. This can be clearly seen in Figures 10–12 and 14–15. Since symmetry in the light curves is a common characteristic feature, the periodic and non-periodic outbursts in OJ287 should originate from similar mechanisms. However, both the evolving gas-bubble emitting mechanism (Lehto & Valtonen 1996) and the shock-in-jet models (e.g., Marscher & Gear 1985, Qian 2010), could not produce outbursts with symmetric light-curves. In this work, we would suggest that the symmetric light-curves observed in OJ287 are produced by lighthouse effect due to the helical motion of superluminal optical knots in the jet (Qian 2015).

2.9. Connection between radio and optical flares

Investigations of the connection between the radio and optical variations may provide important clues for the entire phenomena in OJ287 and help to understand the nature of its multi-waveband emissions. Centimeter radio bursts (e.g., at 8 GHz) are typically observed to be delayed with respect to the optical outbursts by a month or so. The bump-like structure in the radio light curves are connected with the spike-like structure in the optical light-curves (Britzen et al. 2018, Tateyama et al. 1999, Qian 2018). This kind of radio-optical connection can be understood as a result of the evolution of the superluminal optical knots (shocks or blobs) combined with the opacity effects at radio frequencies (Qian 2010). However, simultaneous flares have been observed in OJ287 at millimeter and optical wavelengths. For example, Sillanpää (1996a) observed a simultaneous behavior at the beginning of the year 1992 (JD2448610–JD2448670); the variations at optical V-band and at 37 GHz were not only simultaneous but also had very similar profiles. According to Valtaoja et al. (2000), during the period 1990.5–1994.0, the 37 GHz variations were mostly simultaneous with the optical variations with no measurable time delays. In addition, the major 37 GHz outburst (peaking in 1996.61) has an approximately symmetric profile with its declining phase closely tracking the optical flare. Most interestingly, the two major optical flares of the double-peaked outbursts during 1994.7–1996.1 had different connections between the millimeter flares and the optical flares. For the first optical flare (1994.8–1995.3) there was no simultaneous 37 GHz counterpart observed (Sillanpää et al. 1996a). But for the second optical flare (1995.90–1996.10) simultaneous 37 GHz and optical variations were observed. According to Valtaoja et al. (2000)

| $t$ | $\Gamma$ | $\delta_{\text{max}}$ | ratio | $S_{\text{int}}$ (mJy) | FWHM |
|-----|---------|-----------------|------|----------------|-----|
| 360 | 9.5     | 18.88           | 4.11 | $1.16 \times 10^{-1}$ | 5.9 |
| 450 | 9.5     | 18.88           | 4.11 | $1.16 \times 10^{-1}$ | 5.9 |

Fig.8 therein), both the optical and millimeter flares have complex multi-component structures. The millimeter and the optical variations are not only simultaneous but also have very similar envelopes. Thus both the optical and radio/mm light curves could be decomposed into a number of subflares (or elementary flares) with symmetric profiles and interpreted in terms of the helical motion model. Obviously, the close connection between the millimeter and optical variations observed in the 1995.9 periodic outburst seems important, implying that: (1) The optical and radio flares should be produced in co-spatial emitting regions and originate from a common synchrotron process in the relativistic jet; (2) The simultaneity in the millimeter and optical variations may disfavor shock-in-jet models, because optical shocks typically evolve through three stages (Compton - synchrotron - adiabatic stages), resulting in different optical-radio relationships (Qian et al. 2011, Qian 1996a, 1996b, 1997, Marscher & Gear 1985, Valtaoja et al. 1988, 1992, Litchfield et al. 1995). Thus shock-in-jet models seem not to produce simultaneous mm-radio and optical variations with very similar symmetric light curves. We would suggest that lighthouse effect due to helical motion of superluminal optical knots (shocks or blobs) may be the most plausible mechanism to interpret the simultaneity and symmetry observed in the mm-radio and optical variations observed in OJ287. The proposed helical motion model seems working well, as described in Sect. 3 and 4. We point out that helical motion of radio superluminal knots might also exist. For example, model-simulation of the kinematics of the superluminal components C10 and C11 of OJ287 in terms of helical models has been tried in Qian (2013), which are shown in Figure 3. These helical trajectories have very small pitch angles and could not be easily discovered. It should be noted that in the precessing jet-nozzle models (Qian et al. 2019) the flux density curves of the optical and radio knots can be explained in terms of lighthouse effect caused by their helical motions, but different knots may move along different helical trajectories. This is different from the Doppler boosting and beaming effects caused by the precession of the whole jet (with a ~12 yr period) which do not contribute to the radio and optical flaring activities with timescales of ten days or so.

9 Here “co-spatial” would mean some special structure (or emission distribution) of the optical-millimeter source in the direction perpendicular to its motion.

10 This does not exclude the possibility that the superluminal components are steady shocks on time-scales of ten days or so.
Fig. 3. Model simulation of the superluminal motion of knot C10 (left panel) and knot C11 (right panel). The black thin dashed lines denote the precessing common trajectories. The black thick dashed lines represent the model trajectories with outer curvatures. The red dashed lines indicate the helical trajectory fits. The helical motions of both knots have very small pitch angles on parsec scales (Qian 2018).

Fig. 4. Left panel: model simulation of the R-band light-curves for the outburst in December/2015 observed by Kushwaha et al. (2018) labeled by “TR” and observed by Valtonen et al. (2016) labeled by “TVal-R”). Right panel: model simulation of the R-band light curves for the combination of December/2015 outburst and March/2016 outburst (Kushwaha et al. 2018 labeled by “SR”). The light curve of the March/2016 outburst has been shifted in time backward by 89.4 days. The combination of the light-curves provides a sufficient time coverage to clearly exhibit the symmetric profiles with similar rising and declining time scales.

Fig. 5. Model simulation of the K-band light curves for the outbursts in December/2015 (labeled by “TK”) and in March/2016 (labeled by “SK”). In the right panel the observing time of the March/2016 outburst has been shifted backward by 89.4 days. The light curves are very well simulated for both outbursts by the lighthouse model.
2.10. Lighthouse effect and Doppler boosting

We will explain the multi-wavelength light curves of the optical outbursts in terms of lighthouse effect. For simplicity, it is assumed that the superluminal optical knots move along helical trajectories around the rectilinear jet axis which precesses around the precession axis, as sketchily shown in Figure 1 (left panel). In this case the lighthouse effect results in a symmetric light curve via Doppler boosting per revolution. In addition, we assume that the observed flux density $S_{\text{obs}}$ of the optical outbursts at any frequency consists of two constituents: a steady base-level ($S_b$) and the flaring part $S(t)$:

$$S_{\text{obs}}(t) = S(t) + S_b$$  \hspace{1cm} (1)

Using relativistic jet models, the evolution of the flux density of superluminal optical knots can be written as:

$$S(t)=S_{\text{int}} \times \delta(t)^{p+\alpha}.$$  \hspace{1cm} $S_{\text{int}}$ is the intrinsic flux density (in the comoving frame of the optical knots). For moving optical knots $p=3$ (Blandford & Königl 1979) and $\alpha$ is the spectral index. In our model simulation $S_{\text{int}}$ is assumed to be constant and the spectral index in V-band equals to 1.0. The broken power-law spectrum in the NIR-optical-UV bands is assumed as: $\alpha=0.8$ in the NIR – optical (V) bands and $\alpha=1.3$ in the optical (V) – UV bands. The steady base-level spectrum $S_b(\nu)$ is listed in Table 3 and shown in Figure 2 (middle panel). The modeled intrinsic flux densities $S_{\text{int}}(\nu)$ for the optical knot are shown in Figure 2 (right panel) for I-, V- and U-bands as a demonstrating example. The multi-wavelength light curves of the optical knot are only determined by the Doppler boosting.

In the simulation of the outburst light curves the modeled flux density of the outbursts (at V-band) will vary in the range from $S_{\text{int}}\delta_{\text{min}}$ to $S_{\text{int}}\delta_{\text{max}}$, while the total flux density in the range from $S_b+S_{\text{int}}\delta_{\text{min}}$ to $S_b+S_{\text{int}}\delta_{\text{max}}$. Because the base-level flux $S_b$ does not vary during the outbursts, the variability amplitude of the total flux will be smaller than that of the flaring components. This shows the characteristic feature of our precessing nozzle model distinct from the precessing jet models usually used in literature, where the precession of the entire jets will also cause the variations in the base-level flux density.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|}
\hline
$\nu$ (\text{GHz}) & $\nu^\alpha$ & $S_b(\nu)$ (\text{mJy}) \\
\hline
100 & 0.5 & 10 \text{ mJy} \\
150 & 0.6 & 5 \text{ mJy} \\
200 & 0.7 & 2 \text{ mJy} \\
\hline
\end{tabular}
\caption{Observed light curves for the outbursts in December/2015 (labeled by “TJ” and “TI”) and in March/2016 (labeled by “SJ” and “SI”). In the right panels the observing time of the March/2016 outburst has been shifted backward by 89.4 days. The observed I-band light curves are very well fitted by the helical motion model. The peak of the model light curve for the J-band is much higher than the observed one, because the assumed model spectral index at J-band $\alpha=0.8$ is larger than the observed one.

\textbf{Fig. 6.} Model simulation of the J-band (top panels) and I-band (bottom panels) light curves for the outbursts in December/2015 (labeled by “TJ” and “TI”) and in March/2016 (labeled by “SJ” and “SI”). In the right panels the observing time of the March/2016 outburst has been shifted backward by 89.4 days. The observed I-band light curves are very well fitted by the helical motion model. The peak of the model light curve for the J-band is much higher than the observed one, because the assumed model spectral index at J-band $\alpha=0.8$ is larger than the observed one.

\textbf{9}
2.11. Selection of parameters for simulation

In this work we shall use simple approaches to make model simulation of the observed light curves for all the outbursts concerned, that is, all the model parameters listed in Table 1 are assumed to be constant. The parameters describing the spectral features of the outbursts (the broken power-law spectra) are also taken to be constant. Notwithstanding this simplification, the variability behaviors of all the outbursts (both periodic and non-periodic) can be well interpreted in terms of our lighthouse scenario. At the same time, there remains a wide scope for choosing the model parameters to improve the simulation for any individual outburst. For example, an adoption of a different value for \( \omega \) can consider the helical motion (and lighthouse effect) at a different precession phase. Changes in parameters \( A_0 \) and \( \frac{d\phi(z)}{dz} \) can be used to investigate various patterns of helical motion of the superluminal optical knots. Specifically, a local slight change of the spectral index at J-band could result in a better fit to the J-band flux densities observed in the December/2015 and March/2016 outbursts (see Fig.6, upper panels). In addition, intraday variations (IDV) could also be included for explaining the rapid variations, which might be due to interstellar scintillation or turbulent fluctuations in the emitting sources (Qian et al. 1991, Melrose 1994, Marscher et al. 2008, Marscher 2014). It is found from the light curve simulations that intraday spectral variations might be an important ingredient, which could result in the data-points deviating from the model light curves. Therefore through adjusting the model parameters, the model-fits to the light curves of all the outbursts discussed in this paper could be further improved.

2.12. Relevant MHD theories

Most astrophysicists believe that relativistic jets are formed by rotating magnetic fields in the magnetospheres of the black-hole/accretion-disk systems, as the magnetohydrodynamic (MHD) theories of jet formation indicate (Blandford & Znajek 1977, Blandford & Payne 1982, Camenzind 1990, Beskin 2010, Meier 2001, Vlahakis & Königl 2004). However, few observations have provided direct and compelling evidence for helical magnetic fields and helical motions on parsec scales (e.g., Gabuzda et al. 2004, Marscher 2014). Now, as demonstrated in this work, the prevailing symmetric properties of the light curves of the optical outbursts observed in OJ287 may be recognized as a favorable evidence of helical motion of its superluminal optical knots along helical magnetic fields in the relativistic jet. This would
Fig. 8. Model simulation of the B-band (top panels) and U-band (bottom panels) light curves for the outbursts in December/2015 and in March/2016. In the right panels the observing time of the March/2016 outburst has been shifted backward by 89.4 days. The good fits of the combined light curves in both bands demonstrate the applicability of the helical-motion model in the high-frequency region, revealing the December/2015 outburst has a variability behavior very similar to that of the synchrotron outburst in March/2016.

also help to investigate the helical motion of superluminal knots in other blazars. However, for OJ287, the interpretation of the quasi-periodicity in its variability behavior and the timing of the double-peaked outbursts remains to be a challenge.

2.13. A brief summary

For understanding the phenomena observed in blazar OJ287, comparison of the emission properties of the periodic outbursts (so claimed “disk-impact outbursts”) and the non-periodic optical outbursts (normal synchrotron outbursts) may be an appropriate approach. Based on the above assumptions we will be able to model simulate the multi-wavelength light curves of both the December/2015 and March/2016 using a very simple model, which only involves a superluminal optical knot (with a steady broken power-law synchrotron spectrum) moving along a steady helical trajectory. As shown by the model simulation results given in the next section, this simplified model is already sufficient to explain the most of the basic properties of the temporal and spectral variations of the two optical outbursts, showing their very similar variability behaviors and the nature of their optical/UV emission. Both the optical outbursts in December/2015 and March/2016 can be well interpreted as produced by the lighthouse effect due to one superluminal optical knot moving along a helical trajectory through two helical revolutions: the lighthouse effect firstly produces the December/2015 outburst and then the March/2016 outburst 90-days later. This would imply, as suggested in Qian (2015), that there may exist a stable and perfect collimation/acceleration zone (with strong magnetic fields) in OJ287, providing the necessary physical conditions (injection of relativistic electrons and helical motion) to cause such a behavior of optical outbursts for long times, although in most cases only one outburst is caused by one helical revolution due to the opening of the jet or intrinsic dimming of the optical knots in the outer parts of the jet.

We will also model simulate the light-curves of other five periodic optical outbursts in 1983.00, 1984.10, 1994.75, 1994.75, 2005.76, and 2007.70, and for a few isolated moderate outbursts (in 1993.93, 1994.17 and at JD2457380), showing the common properties of these outbursts and their common mechanism for optical radiation production. All the data on the light curves of the optical outbursts used in this work were collected from: Valtonen et al. (2016, 2017, 2008), Kushwaha et al. (2018), Valtaoja et al. (2000), and Sillanpää et al. (1996a, 1996b) and private communication.
In this work, we adopt a $\Lambda$CDM cosmological model with the parameters as: $\Omega_m = 0.27$, $\Omega_{\Lambda} = 0.73$ and $H_0=71\text{km s}^{-1}\text{Mpc}^{-1}$ (Spergel et al. 2003, Komatsu et al. 2009). 1 mas = 4.5 pc (Hogg, 1999).

3. Simulation results of multi-wavelength light curves

The model simulation results of the multi-wavelength light curves (in NIR-optical-UV bands) for the periodic optical outburst in December/2015 (peaking at JD2457360) and the non-periodic synchrotron outburst in March/2016 (peaking at JD2457450) are shown in Figures 4–9. The relevant model parameters are listed in Table 4.

Firstly, in Figure 4 (left panel), we display the model simulation of the R-band light curves of the December/2015 outburst observed by Valtonen et al. (2016) labeled by “TVal-R” and by Kushwaha et al. (2018) labeled by “TR”). It can be seen that the combination of the data-points from Valtonen et al. (during the rising phase) and Kushwaha et al. (during the decaying phase) constructs a well-defined profile simulated by the modeled symmetric light curve. The right panel of Figure 4, the R-band light curve of the March/2016 outburst (labeled by “SR”) observed by Kushwaha et al. has been incorporated in the simulation with its time-axis being shifted backward by 89.4 days. It can be seen that the R-light curves of both the December/2015 and March/2016 outbursts can be well simulated in terms of a common symmetric profile. Since the March/2016 outburst is definitely a non-thermal (synchrotron) flare with high optical polarization degrees, the strong similarity between the variability behaviors of the December/2015 and March/2016 outbursts leads us to recognize that the December/2015 outburst is also a synchrotron flare generated in the relativistic jet. Thus both outbursts can be interpreted in terms of lighthouse effect due to the helical motion of one superluminal optical component during two helical revolutions.

Now we present the simulation results of the multi-wavelength light curves for each waveband individually.

- The model simulation results of the K-band light curves for both outbursts in December/2015 and March/2016 are shown in Figure 5. Here two panels are presented: the left panel displays the simulation of the two light curves in time sequence and the right panel shows the simulation of the combined light curve. It can be seen that the K-band light curves of both outbursts are well fitted by the helical motion model, implying that the outburst in December/2015 has its variability behavior very similar to that of the synchrotron outburst in March/2016.

- The model simulation results of the J-band and I-band light curves for the outbursts in December/2015 and March/2016 are shown in Figure 6. The upper panels show that the observed J-band peak is much lower than the model light curve. This result should have been expected, because the assumed model spectral index at J-band $\alpha = 0.8$ is larger than the observed one (Kushwaha et al. 2018). The observed I-band light curves for both outbursts are well fitted by the helical motion model.

- The December/2015 outburst peaking at JD2457360 was identified as the periodic “impact thermal flare” in the disk-impact model.

- The model simulation results of the R-band light curves for both outbursts in December/2015 and in March/2016 are shown in Figure 7 (top panels). The left panel displays the simulation of the light curves for both outbursts in time sequence and the right panel shows the simulation of the three light curves (labeled by “TR”, “SR” and “TVal-R”) in a combined form. It can be seen that the R-band light curve of the outburst in December/2015 has its variability behavior very similar to that of the synchrotron outburst in March/2016: both are well fitted by the helical motion model with symmetric profiles having similar rising and decaying time-scales.

Similarly, the model simulation results of the V-band light curves for the outbursts in December/2015 and in March/2016 are displayed in Figure 7 (bottom panels). It can be seen that both the observed V-band light curves (whether presented in time sequence or in combined form) are very well fitted by the helical motion model. Thus at both R- and V-bands the outburst in December 2015 has its variability behavior very similar to that of the synchrotron outburst in March/2016, implying that their emission may originate from a similar mechanism. In this work we suggest that both outbursts are produced by the helical motion of one superluminal optical knot via lighthouse effect through two helical revolutions, although we cannot exclude the possibility that they might be independent flares with very similar temporary and spectral variations.

- The model simulation results of the B-band and U-band light curves for the outbursts in December/2015 and in March/2016 are shown in Figure 8. It can be seen that the observed light curves for both outbursts are well fitted by the helical motion model, showing that even in high frequency regions (B- and U-bands) the outburst in December/2015 has a variability behavior similar to that of the synchrotron outburst in March/2016. The symmetry of the outburst profiles characteristic in the low frequency region (K-band to V-band, modeled spectral index $\alpha = 0.8$) persists in the high frequency region (modeled spectral index $\alpha = 1.3$).

- The model simulation results of the UVW1-, UVW2- and UVM2-band light curves for the outbursts in December/2015 and in March/2016 are shown in Figure 9. It can be seen that the light curves observed at the three bands for both outbursts were well fitted by the helical motion model. Thus the outburst in December/2015 has its variability behavior very similar to that of the synchrotron outburst in March/2016 in the UV-bands. But it should be noticed that rapid (intraday) variability due to interstellar scintillation (or extinction) or turbulent fluctuations in optical knots (Qian et al. 1991b, Marscher et al. 2008, Marscher 2014) might cause scattering of the observational data-points.

Based on the model simulation of the multi-wavelength light curves for the periodic outburst in December/2015 and the non-periodic synchrotron outburst in March/2016 as shown in Figure 4–9, we come to the conclusion that the December/2015 outburst, which was claimed to be a bremsstrahlung flare, has its variability behavior (both temporary and spectral) very similar to the synchrotron flare in March/2016: both have similar peaking flux densities and spectral features, and their flux density curves having sym-
Fig. 9. Model simulation of the UVW1-band (top panels), UVW2-band (middle panels) and UVM2-band (bottom panels) light curves for the outburst in December/2015 and in March/2016. For the UVW2-band the data-points observed by Valtonen et al. (2016) are also incorporated (labeled by TVal-UVW2 in green). In the right panels the observing time of the March/2016 outburst has been shifted backward by 89.4 days. The good fits of the combined UV-band light curves (right panels) indicate the applicability of the lighthouse model in the UV-bands and the December/2015 outburst still has its variability behavior similar to that of the synchrotron outburst in March/2016.

As argued in the previous section, the symmetry in the optical light curves and the similarity between the periodic and non-periodic optical outbursts may be important for understanding the optical variations in OJ287. In order to further investigate this behavior and clarify the nature of the phenomena in OJ287, we will make model simulation of periodic optical outbursts.
the light curves for the five periodic optical outbursts observed in 1983.00, 1984.10, 1994.75, 2005.76 and 2007.70, and show that their light curves can be decomposed into a number of subflares (or elementary flares) with symmetric profiles. In addition, we will make model simulation for some well-resolved (or isolated) non-periodic optical bursts to reveal the similarity in optical variations between the periodic outbursts (claimed as thermal flares) and non-periodic outbursts (recognized as synchrotron flares). In combination with the results presented in Sect.3 for the December/2015 and March/2016 outbursts, it can be seen that the consistency in the variability behavior of all these outbursts provides important clues for understanding the nature of their emission, affording persuasive evidence that the entire phenomena observed in blazar OJ287 may be caused by lighthouse effect due to the helical motion of superluminal optical knots (plasmons or shocks) within the relativistic jet.

For simplicity and easy comparison, we will apply the same approaches as used in Sect.3 to make model simulation of the light curves for the five periodic outbursts. The outbursts are assumed to be composed of two components: the

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**Fig. 10.** Model simulation of the light curve for the 1983.00 periodic optical outburst, which has been decomposed into three subbursts with symmetric profiles. The violet line denotes the model-fit of the total flux density curve. The origin of the time-axis is 1983.00. Data are taken from Valtonen et al. (2008).

**Fig. 11.** Model simulation of the light curve for the 1984.10 periodic optical outburst, which has been decomposed into two subbursts with symmetric profiles. The magenta line represents the model-fit of the total flux density curve. The dashed lines denote the model-fits of the two subbursts, respectively. The origin of the time-axis is 1984.05. Data are taken from Valtaoja et al. (2000).
Fig. 12. Model simulation of the light curve for the 1994.75 periodic optical outburst which has been decomposed into five subbursts with symmetric profiles. The violet line denotes the model-fit of the total flux density curve. Data are taken from Sillanpää et al. (1996a) OJ-94 project.

Fig. 13. Model simulation of the light curves for two isolated moderate outbursts (in 1993.93 and 1994.17) with each having a symmetric profile. Data are taken from Sillanpää et al. (1996a) OJ-94 project.

Table 5. Base-level flux densities (V-band) for the six periodic optical outbursts.

| Flare  | $S_b$ (mJy) |
|--------|-------------|
| 1983.00| 5.0         |
| 1984.10| 2.8         |
| 1994.75| 1.0         |
| 2005.76| 2.0         |
| 2007.70| 5.5         |
| 2015.87| 3.5         |

underlying jet emission (or base-level component) and the flaring component. The base-level component can be taken to be constant during individual outbursts, but may change on longer time-scales due to the jet precession and intrinsic variations in the underlying jet (jet-parameters and bulk Lorentz factor). For the six periodic outbursts simulated, the base-level flux densities (at V-band) are listed in Table 5.

4.1. Periodic optical outburst in 1983.00

The outburst in 1983.00 is the first optical flare of the 1983–1984 double-peaked outbursts. The simulation results for the 1983.00 periodic outburst are shown in Figure 10. Its total flux density curve has been decomposed into three subflares. The first flare was identified as the “impact (thermal) outburst”. Obviously, its light curve does not have the “standard shape” expected for impact outbursts. It looks like a single elementary flare and its light-curve can be very well fitted with a symmetric profile in terms of the helical motion (or lighthouse) model. Similarly, the light-curves of the other two subflares can also be well fitted. The model parameters for the three subflares are given in Table 6.
4.2. Periodic optical outburst in 1984.10

Interestingly, the second optical flare of the 1983–1984 double-peaked outbursts (during 1984.1–1984.3; see Fig.6 in Valtaoja et al. [2000] clearly exhibits its structure consisting of two rather separated outbursts peaking at 1984.18 and 1984.23, respectively. As like the 1983.00 outburst the major flare (peaking at 1984.18 with peak flux=\(~20\) mJy at V-band) is a single elementary one and its flux density curve can be very well simulated by a symmetric profile and is displayed in Figure 11. The relevant model parameters for the two subflares are listed in Table 7. Thus for the 1983–1984 double-peaked outbursts, both the major flares exhibit the symmetry in their light curves. As discussed below, the major flares of the outbursts in 2007.70 and 2015.87 (Figs.15 and 16) also reveal this characteristic feature. Symmetry in the optical outburst light curves can not be explained in terms of the disk-impact scenario, where the flux density curves of “impact outbursts” emitted from evolving gas-bubbles would have a non-symmetric pattern with a rapid rising and slower decaying phases.
4.3. Periodic optical outburst in 1994.75

The 1994–1996 periodic double-peaked outbursts were intensively monitored via international cooperation of the “OJ-94 project” (Takalo 1996a, Takalo et al. 1996b), starting at 1994.75 and 1995.84, respectively. During this period the optical flares may be related to the ejection of superluminal radio (15 GHz) components C1, C2, C3 and C4 (Britzen et al. 2018; Qian 2018; Tateyama et al. 1999). The simulation results for the first outburst in 1994.75 are shown in Figure 12. The observational data are taken from Sillanpää et al. (1996a, OJ-94 project; private communication). Its total flux density curve has been decomposed into five subflares simulated with symmetric profiles. Two rather isolated moderate outbursts peaking at JD2449326 and 2449415 were also model simulated and the results are shown in Figure 13. The relevant model parameters are described in Table 8. The successful simulation of the light curve for the 1994.75 outburst might have demonstrated that any complex outburst observed in OJ287 can be decomposed into a few elementary flares and explained in terms of the proposed helical motion (or light-house) model.

4.4. Periodic optical outburst in 1995.84

The outburst starting at 1995.84 was the second one of the 1994–1996 double-peaked outbursts. Its light curve exhibits a complex structure, showing some distinct features which may be meaningful for understanding the phenomena in OJ287 (Valtaoja et al. 2000).

Firstly, the “impact flare” (during 1995.84–1995.90) identified by the disk-impact model (Dey et al. 2018) was a small one with its peak flux density ≃5 mJy, much weaker than the follow-up flares with peak flux of ≃12 mJy (Valtaoja et al. 2000). This would pose a problem: why a strong disk impact could only produce a small “thermal” optical flare, but resulted in the production of strong follow-up synchrotron flares. Obviously, it seems that some other physical processes would have played their roles.

Secondly, it is noticed that the 1995.84 flaring event (during 1995.84–1995.90) had its light curve very similar to that of the 1994.75 outburst and could also be decomposed into a number of subflares simulated with symmetric profiles.

In Lehto & Valtonen (1996) and Valtonen & Lehto (1997) this outburst was identified as the “disk-impact thermal outburst”. Recently Dey et al. (2018) suggested that its starting time should be changed to 1994.60 and the corresponding “impact outburst” was missed due to lack of monitoring observations.

13 According to the disk-impact model (Dey et al. 2018), the 1995.84 outburst occurred at a distance of ~3800 AU from the primary hole and should be produced by a strong impact of the secondary hole onto the primary disk.
The symmetry of this double-peaked outburst was firstly discovered by Sillanpää et al. (1996), which essentially reflects the symmetry existing in the light curves of their subbursts with similar rising and declining time-scales. Thus both the double-peaked outbursts during 1994 – 1996 period can be interpreted in terms of our helical motion (lighthouse) model. 15

Thirdly, the most interesting feature of the 1995.84 outburst may be the close connection between the radio and optical variations. According to Valtaoja et al. (2008) Fig.8 therein, its radio variations at 22/37 GHz were very similar to the V-band optical variations: both variations are not only simultaneous but also have similar envelopes. Even a few radio emission peaks can be recognized to be concurrent with the optical peaks. This strict simultaneity of the radio and optical variability seems important and may have provided some significant clues to the physical processes producing the radio/optical outbursts in OJ287. Unfortunately, this radio-optical connection has not been explained since its discovery. In combination with the model simulation of the light curves for the December/2015 and March/2016 outbursts in Sect.3, we would come to the conclusion that this close connection between the radio and optical variability can no longer be explained in terms of disk-impact scenario and shock-in-jet models, and can only be explained in terms of lighthouse effect due to the helical motion of superluminal knots, but requiring some special structure of the emitting source.

4.5. Periodic optical outburst in 2005.76

The double-peaked outbursts during the period of 2005–2007 were extensively observed by Valtonen et al. (2005) and Villforth et al. (2010). The ejection of superluminal radio components C11, C12, C13L, C13U and C14 (Qian et al. 2016) may be connected with these optical flaring events. The simulation results for the light curve of the first outburst starting in 2005.76 are shown in Figure 14. Its total flux density curve has been decomposed into five subbursts, which are well simulated with symmetric profiles in terms of the lighthouse model with symmetric profiles. 16

| T  | τ  | δmax | ratio | Sint | FWHM |
|----|----|------|-------|------|------|
| 20 | 5.0| 13.90| 2.68  | 1.81×10^{-4} | 14.9 |
| 37 | 7.0| 13.90| 2.68  | 1.73×10^{-4} | 14.9 |
| 58 | 7.0| 13.90| 2.68  | 1.63×10^{-4} | 14.9 |
| 90 | 5.5| 10.89| 2.03  | 4.18×10^{-4} | 31.7 |
| 182| 6.0| 11.90| 2.23  | 1.76×10^{-4} | 25.8 |

15 Due to lack of relevant data the 1995.84 outburst was not simulated in this work.
16 It was identified as the “impact (bremsstrahlung) flare” by Valtonen et al. (2008).

4.6. Periodic optical outburst in 2007.70

The outburst starting at 2007.70 is the second flare of the double-peaked outbursts during 2005–2007 period. The model simulation results for this periodic optical outburst are shown in Figure 15(17). Its total flux density curve has been decomposed into three subbursts which are all well simulated with symmetric profiles in terms of the lighthouse model. The model parameters are given in Table 9. Although the declining part of the major outburst is mixed with the rising part of the secondary burst, its rising-peaking part still clearly demonstrates the trend of its symmetric profile.

In combination with the results given in Sect. 4.5, we found that the total flux density curves of both periodic outbursts (in 2005.76 and 2007.70) can be well interpreted in terms of the lighthouse model with symmetric profiles. It can be seen from Figures 14 and 15 (also see Tables 9 and 10) that the subflares of 2005.76 outburst all have timescales much longer than those for the subflares of 2007.70 outburst, this might be related to their different impact distances as expected by the disk-impact model: the 2005.76 outburst occurred at ∼12,000 AU and the 2007.70 outburst at only ∼3,000 AU. However, the peak flux den-

Table 8. Model parameters for the simulation of the 1994.75 periodic optical outburst and two isolated moderate bursts (at V-band). S0=1.0 mJy, t = flare time = day–1994.75. Bursts at JD2449325 and JD2449415 are isolated moderate flares. The major periodic outburst has been decomposed into five subbursts. Explanation of the parameters and units as in Table 6.

Table 9. Model simulation results for the 2005.76 outburst. Its total flux density curve was decomposed into five sub-flares with symmetric profiles. S0=2.0 mJy, t = flare time = day–2005.76. Explanation of the parameters and units as in Table 6.
Table 10. Model simulation results for the 2007.70 outburst. Its total flux density curve is decomposed into three subbursts with symmetric profiles. $S_{\text{int}}=5.5\,\text{mJy}$. \( t = \) flare time = day–2007.70. Explanation of the parameters and units as in Table 6.

| $t$ (day) | $\Gamma$ | $\delta_{\text{max}}$ | Ratio | $S_{\text{int}}$ (mJy) | FWHM |
|----------|----------|--------------------------|--------|------------------------|-------|
| 5        | 11.4     | 22.64                    | 5.49   | $2.22\times10^{-4}$    | 3.4   |
| 6        | 12.0     | 23.82                    | 5.97   | $9.00\times10^{-6}$    | 3.0   |
| 10       | 11.4     | 22.64                    | 5.49   | $1.21\times10^{-5}$    | 3.4   |

Table 11. Model simulation results for the non-periodic synchrotron outburst peaking at 2457380 and its comparison with that for the major periodic outburst in December/2015 (peaking at 2457360). $S_{\text{int}}=3.5\,\text{mJy}$. \( R=\text{R-band} \). \( t = \) flare time = day–2457000. Explanation of the parameters and units as in Table 6.

| $t$ (day) | $\Gamma$ | $\delta_{\text{max}}$ | Ratio | $S_{\text{int}}$ (mJy) | FWHM |
|----------|----------|--------------------------|--------|------------------------|-------|
| 360      | 9.5      | 18.88                    | 4.11   | $1.35\times10^{-4}$    | 5.9   |
| 380      | 13.5     | 26.77                    | 7.29   | $1.67\times10^{-5}$    | 2.2   |

5. Discussion

We have applied the precessing jet nozzle model previously proposed by Qian et al. (e.g., 1991, 2013, 2019) to investigate the optical variations observed in OJ287 and tried to clarify the nature of emission for the outbursts. It is found that the multi-wavelength variations (in NIR-optical-UV bands; Kushwaha et al. 2018) of the periodic major outburst in December/2015 (peaking at JD2457360) are very similar to those of the non-periodic highly-polarized synchrotron outburst in March/2016 (peaking at JD2457450). The multi-wavelength light curves of both the outbursts can be well simulated by symmetric profiles and interpreted in terms of lighthouse effect due to the helical motion of one superluminal optical knot through two helical revolutions. This result seems important, indicating that the December/2015 outburst may like the March/2016 outburst and also originate from synchrotron process. Its association with the simultaneous $\gamma$-ray flare supports this interpretation.

The five periodic outbursts observed in 1983.00, 1984.10, 1994.75, 2005.76 and 2007.70 (at V-band), and a few isolated non-periodic flares have also been simulated. We find that all the periodic outbursts can be decomposed into a number of subbursts (or “elementary flares”). The light curves of all these elementary flares can be simulated by symmetric profiles with similar rising and decaying time-scales and interpreted in terms of the lighthouse model. The isolated non-periodic flares show their variability behavior similar to these elementary flares.

In combination with the simulation results for the December/2015 and March/2016, we tentatively suggest that the periodic optical outbursts observed during 1983–2015 may all originate from synchrotron process in the relativistic jet and they may be produced by lighthouse effect due to the helical motion of superluminal optical knots (blobs or shocks). This interpretation is consistent with the requirement of “single mechanism”, which is derived from the color stability during the optical outbursts (Sillanpää et al. 1996a, Gupta et al. 2016). The low polarization of the first flares of the double-peaked outbursts can also be understood, because synchrotron flares can have a large range of polarization degree, as typically observed in OJ287 (from <2% to ~40% (Villforth et al. 2010, Kushwaha et al. 2018). The close connection between the radio/mm and optical variations (e.g., observed in the 1995.84 outburst) can also be explained.

We have shown that the entire optical variability in OJ287 could only be explained by invoking lighthouse effect due

18 This non-thermal flare appeared at JD2457380, only 20 days after the appearance of the December/2015 outburst.

19 The December/2105 outburst was identified as the “impact (bremsstrahlung) flare” according to the disk-impact model.
to the helical motion of superluminal optical knots. This result may have been expected, based on the magnetohydrodynamical (MHD) theories for jet formation in spinning black hole–accretion disk systems, in which relativistic jets are produced in the rotating magnetospheres with strong toroidal magnetic fields and strong helical fields should be permeated in the jets near the black holes (e.g., Blandford & Znajek [1977], Blandford & Payne [1982], Camenzind [1990], Li et al. [1992], Beskin [2010], Valhakis & Königl [2004], Meier [2013, 2001]). It would be a natural phenomenon that superluminal optical knots move along helical trajectories, producing optical outbursts through light-house effect. Unfortunately, there seems only a few observational events revealing this phenomenon (e.g., Schramm et al. [1993], Dreissigacker [1996a], Dreissigacker & Camenzind [1996b], Camenzind & Kronberger [1992], Wagner et al. [1994], Qian [2015]). This work demonstrates that helical motion of superluminal optical components may be a general phenomenon in blazar OJ287 and thus provide some observational evidence for the existence of helical magnetic fields in the inner jet regions of blazars.

Under the binary black hole scenario, we have tentatively proposed a unified and plausible relativistic jet model for fully explaining the optical activities in OJ287 (including its periodic and non-periodic outbursts), invoking lighthouse effect due to the helical motion of superluminal optical components. The chain of the physical processes in this model may be: a succession of discrete accretion events (including the double-stream accretion flows; e.g., Tanaka [2013]) created by the pericenter passages of the secondary hole (moving in an eccentric orbit) results in a succession of ejection of superluminal optical components through the jet formation mechanism, producing a succession of the elementary optical flares which blend together to form major complex outbursts.

The relativistic jet model tentatively suggested in this work should be tested by the future multi-wavelength (from radio to γ-rays) observations. If this scenario is proved to be correct, the optical phenomena in OJ287 can be explained without needing to invoke the disk-impact mechanism, although this mechanism seems very attractive for testing the effects of general relativity (Einstein [1916, 1918]). However, the relativistic jet scenario only concentrates on the explanation of the nature and characteristics of the optical activities (temporal and spectral variations of the outbursts), the quasi-periodicity of its optical variability and the double-structure of the periodic outbursts remain to be interpreted. In principle, under the framework of binary black hole models, the quasi-periodicity can be related to the modulation of accretion rates via the pericenter passages of the companion black hole in an eccentric orbit. As Sillanpää et al. [1996a] originally suggested, the eccentric orbital motion of the secondary hole can cause quasi-periodically enhanced accretion flows onto the primary hole, which consequently result in ejections of superluminal optical knots via jet-formation mechanism(s), producing quasi-periodic optical outbursts. As regards the explanation of the double-structure of periodic optical outbursts, cavity-accretion models as suggested by Tanaka [2013] might be applicable. In the case of comparable-mass and eccentric binary systems, usually two gas streams are created per pericenter passage of the secondary hole in the circumbinary disk and flow toward the binary black holes, producing a double-peaked outbursts. The cavity-accretion processes

| t         | R_{imp}(AU) | v_{0}/c | S_{v, obs}(mJy) | S_{v}(mJy) |
|-----------|-------------|---------|-----------------|------------|
| 2007.70   | 3299        | 0.264   | 12.0            | 6.5        |
| 1995.84   | 3855        | 0.245   | 5.0             | 3.5        |
| 1983.05   | 4073        | 0.106   | 11.0            | 9.0        |
| 1994.75   | 7079        | 0.058   | 8.0             | 9.0        |
| 2005.76   | 12427       | 0.058   | 18.0            | 14.5       |

Table 12. Relation between the strength (S_{v}, peak flux density at V-band) of the impact outbursts, the impact distance (R_{imp}) and the secondary velocity v_{0}/c. t = flare time. The data are arranged in sequence of impact distance. S_{v, obs} = S_{v} + S_{b}.

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