Model simulation for periodic double-peak outbursts in blazar OJ 287: binary black hole plus lighthouse effect?

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Abstract The mechanism of formation of the double-peaked optical outbursts observed in blazar OJ 287 is studied. It is shown that they could be explained in terms of light-house effect for superluminal optical knots ejected from the center of the galaxy and move along helical magnetic fields. It is assumed that the orbital motion of the secondary hole of the supermassive binary black-hole system induces the 12-year quasi-periodicity of the occurrence of the major optical outbursts by the interaction with the disk around the primary hole. This interaction between the secondary hole and the disk of the primary hole (e.g. tidal effects or magnetic coupling) excites or injects plasmons (or relativistic plasmas plus magnetic field) into the jet which form superluminal knots. These knots are assumed to move along helical magnetic field lines to produce the optical double-peaked outbursts by light-house effect. The four double-peaked outbursts observed at 1972, 1983, 1995 and 2005 are model-simulated. It is shown that such light-house models are quite plausible and feasible to fit the double-flaring behavior of the outbursts. The main requirement may be that in OJ 287 there exists a rather long (~40–60 pc) highly collimated zone, where the light-house effect occurs.

Key words: optical continuum — galaxies: jets — galaxies: kinematics — galaxies: variability — galaxies: individual (blazar OJ 287)

1 INTRODUCTION

Research on blazars is an important extragalactic astrophysical field, in which extensive observations of their radiation from radio through to \( \gamma \)-ray are carried out, and the mechanisms of radiation (including polarization) are studied (recent progress, referring to, e.g., Marscher 2011; Marscher et al. 2011; Abdo et al. 2010; Raiteri et al. 2007, 2011; Schinzel et al. 2010, 2012; Vercellone et al. 2010; Marscher et al. 2012; Qian 2011, 2012, 2013; Qian et al. 2014). Through the studies of the spectral energy distribution (SED) and the variation of SED of blazar radiation (e.g, Ghisellini et al. 2009a,b,c, 2010; Ghisellini & Tavecchio 2010; Tavecchio et al. 2007, 2010; Joshi et al. 2012a,b; Jorstad et al. 2010, 2012; Aleksić et al. 2011), the radiation mechanisms have been determined to be synchrotron and inverse-Compton processes. The strong radiation and its rapid variation of blazars are closely related to their relativistic jets with bulk Lorentz factors of \( \sim 10–30 \), which direct towards us at small viewing angles, thus relativistic beaming and Doppler boosting dominate the blazar phenomena. Relativistic jets of blazars are believed to be produced in the supermassive black
hole-accretion disk system existing in the center of their host galaxies. Since Fermi satellite was launched in 2008 studies of blazars have achieved significant progress. Especially, based on the coordinated study of γ-ray and mm-outbursts and VLBI-monitoring, it is found that γ-rays can emitted from the regions of jet much beyond 1 pc, reaching 10–40 pc from the BH (e.g. Schinzel et al. 2010; Agudo et al. 2011a, 2012b).

OJ 287 (z = 0.306) is one of the most well studied prominent blazars. It is an optically violent variable BL Lac object (BLO) with large and rapid polarized outbursts and radiates across the entire electromagnetic spectrum from radio through optical and X-ray to γ-rays. Very strong variability is observed in all these wavebands with various timescales (hours/days to years). OJ 287 was one of the bright Fermi γ-ray sources (Nolan et al. 2012; Ackermann et al. 2011). Since Fermi satellite was launched in 2008 further investigations on OJ 287 have been carried out. Multifrequency observations, study of its SED and correlations between different wavebands have demonstrated important clues to the radiation mechanisms, especially for X-ray and γ-ray emission and their emission positions in the jet. Agudo et al. (2011b) showed that its γ-ray emission was produced at a distance >14 pc from the core. Marscher & Jorstad (2011) discover its large-scale (Mpc) X-ray jet.

OJ 287 is one of the well-studied blazars and has been monitored for long times through radio, IR, optical, UV, X-ray and γ-ray observations. (e.g., Agudo et al. 2011a,c; Villforth et al. 2010; Valtaoja et al. 2000; Sillanpaa et al. 1988; Marscher & Jorstad 2011; Valtonen & Sillanpää 2011; Valtonen et al. 2009; Ciprini et al. 2007; Agudo et al. 2011b, 2012b). It is highly variable in all these wavebands.

OJ 287 is also a well-studied superluminal source on parsec scales, having a core-jet structure and superluminal components are ejected from the core steadily. Jet position angle swings (both long-term and sharp changes) have been observed (e.g., Agudo et al. 2012a; Tateyama & Kingham 2004; Moór et al. 2011; Valtonen & Wiik 2012; Valtonen & Pihajoki 2013). Valtonen & Pihajoki explain the jump of optical polarization position angle in terms of the precession of the helical structure of the optical emission region.

In particular, its optical behavior is remarkable or exceptional. The most interesting features are the (quasi-) periodic outbursts observed in optical wavebands during a long period (∼120 yr). (Sillanpaa et al. 1988, 1996a,b; Lehto & Valtonen 1996; Sundelius et al. 1997; Valtonen 2007; Valtonen et al. 2009, 2011; Valtonen & Ciprini 2012; for a recent review see Villforth et al. 2010).

The record of optical observations since 1891 shows that the optical outbursts occurs in OJ 287 with a (quasi-) periodicity of ∼12-year. It also has a long-term optical variability of a (quasi-) periodicity of ∼60 yr. The range of variability reaches ∼4.5 magnitude (optical flux density ranges from ∼1 mJy to ∼60 mJy). Rapid variations of the optical emission occurs often on time scales less a few weeks with flux density fluctuations up to 1–3 magnitude. Exceptionally, some (may be each) of the observed optical outbursts actually constitutes of two flares separated by ∼1–2 yr. Up to now four outbursts with double-peaked flares occurred in 1972, 1983, 1995 and 2005 has been clearly recorded.

2 INTERPRETATIONS

The observational facts listed above put OJ 287 in an important position for studies of blazars, because such remarkable, clearly determined, long lasting (quasi-) periodicities have never been observed in other blazars. These quasi-periodicities have been assumed to be related to the regular behavior of the binary black hole-accretion disk system in the center of its host galaxy.

Sillanpaa et al. (1988) firstly suggested that the regularly appearing optical outbursts were produced by a close binary black hole system in which the pericenter passage of the secondary black hole induces tidal disturbances in the accretion disk of the primary. The orbital period of the binary black hole was assumed to be 12 yr to explain the observed 12-year cyclic optical outbursts.
Lehto & Valtonen (1996) further developed this model and suggested that the orbit of the secondary black hole is highly eccentric and during each orbit the secondary black hole twice impacts the disk of the primary, causing the outbursts constituting double-peaked flares separated by time interval of 1–2 yr: that is, the two flares are produced during the two crossings of the secondary black hole through the accretion disk of the primary. Particularly, both the flares are assumed to be produced by bremsstrahlung process (i.e., thermal flares). The profiles of the double flares are interpreted in terms of the rate of inflow particles in the accretion disk of the primary hole, not related to the relativistic jet (Sundelius et al. 1997; Valtonen et al. 2009). As Sillanpaa et al. (1996b) commented, this model could explain the periodicity and the double peak structure, but it has problems in explaining the fact that the two flares had same colour (extremely stable colour during the outbursts e.g., observed in the 1995 outburst), because the energy production mechanism changed for the flares produced at different impact locations. In order to predict the exact times of the future optical outbursts and double-peaked flares, this binary black hole model (Lehto/Valtonen model) has been continually improved by taking into account of general relativity effect (orbital precession) and the interaction mechanisms between the secondary black hole and the disk of the primary (Valtonen 2007; Valtonen et al. 2009, 2011; Valtonen & Sillanpää 2011; Valtonen & Wiik 2012; Valtonen & Pihajoki 2013). When both the gravitational precession and gravitational radiation were included, Valtonen (2007) accurately predicted the second flare of the occurrence of the 2007 outburst. Since this model is based on orbit dynamical theory of the binary black hole, it may have strong ability to predict the exact times of the occurrence of the outbursts. Moreover, it has the ability to derive the masses of both the primary and secondary black holes, even to measure the spin of the primary black hole, (Valtonen et al. 2010a,b), helping testing general relativity.

Other authors have suggested alternative models for the periodic optical outbursts in OJ 287, also based on the assumption that OJ 287 hosts a binary black hole, but pay more attention on the relativistic beaming and Doppler boosting effects of the relativistic jet of this object. (a) Katz (1997) suggested that the 12-year cyclic optical outbursts was produced by the precession of the jet of the primary black hole. Since the jet is anchored in the accretion disk of the primary hole and the orbital motion of the companion (secondary) drives the precession of the accretion disk, the jet follows this precession and sweeps through the line of sight regularly with the period of precession (~12 yr), causing periodic optical outbursts due to enhanced radiation through relativistic beaming and Doppler boosting. According to Katz’s suggestion, the double-peak structure of the optical outbursts was caused by the nodding of the jet (Katz et al. 1982). In this driven-precessing disk model, the orbital period was only ~2.7–3 yr. Interestingly, Valtonen & Wiik (2012) recently followed Katz’s model, suggesting that the precession of the jet of the primary hole caused the 120 or 60-year variability (so called Kozai period) and the 12-year cyclic outbursts was due to the nodding effect. The double flares separated by time of 1–2 yr remained to be caused by the impact-crossing of the secondary hole through the accretion disk of the primary.

Alternatively, Villata et al. (1998) suggested a double-jet scenario, in which both primary and secondary black hole produced a jet and the two jets swept through the line of sight on intervals of ~1–2 yr causing optical outbursts constituting double-peaked flares. Villata et al. ascribed the 12-year periodic occurrence of the outbursts to the orbital motion of the binary (not due to precession). This model needed a very special geometry of the relative positions of the jets. The radiation mechanism for the optical outbursts invoked in this model, like in the Katz’s disk-driven precession model, is synchrotron, which is in agreement with general theoretical results for the radiation mechanisms (synchrotron and inverse-Compton) of generic blazars (including astrophysics for VLBI-phenomena of radio galaxies and quasars).

Valtaoja et al. (2000) suggested different radiation mechanism for the two flares of the outbursts: the first flare was caused by the impact-crossing of the second hole through the accretion disk of the primary and thus was a thermal flare without correlated mm/radio counterpart. The second flare was produced in the jet by a relativistic shock (thus a synchrotron flare) with a polarized mm/radio out-
burst followed. This scenario seems not able to explain why the first flares and the second flares having so similar properties observed (in variations of flux density, polarization, profile, timescale of spikes and spectrum), because the first flares and the second flares are produced by completely different mechanism: bremsstrahlung and synchrotron. Valtaoya et al. also argued against lighthouse effect as the mechanism producing the optical outbursts, based on the observational fact that the optical variability during the outbursts and during the quiet periods had similar timescales. However this argument seems not so compelling because the quiet-jet and the shocked-jet could have similar variability timescales: e.g., during quiet state the variability timescales represent variations in the optical core or turbulent plasma flows crossing ‘standing shocks’, while during burst state the variability timescales represent the variations of the optical knots propagating through the turbulent jet\(^1\) (Qian et al. 1991; Quirrenbach et al. 1989; Standke et al. 1996; Marscher et al. 1992; Marscher & Jorstad 2010). Both could have similar Doppler time-shortening effect.

Although binary black hole system is clearly the most obvious approach to explain the 12yr-periodicity, but Villforth et al. (2010) indicated that for the case of OJ 287 the properties of certain outbursts suggest the jet as a source for variations (e.g. Marscher & Marchenko 1997). Thus Villforth et al. (2010) suggested a magnetic breathing model. That is a resonance mechanism of magnetic fieldlines in the accretion disk. In this case the periodicity and double peak structure could be caused by resonance occurred in the accretion disk and/or jet. Specifically, the outbursts could be related to accretion of magnetic fieldlines. The regularly appearing flares are signs that the the accretion of the magnetic field happened in avalanches. Massive accretion of magnetic field causes strong disturbances in the magnetic field of the accretion disk. These disturbances cause a resonance in the accretion disk (e.g. Ouyed et al. 1997; Ouyed & Pudritz 1997a,b) \(^2\), a ‘magnetic breathing’ of the disk. The resonance causes regularly appearing avalanche accretion of magnetic field. Each double-peaked outburst represents a phase of massive magnetic field accretion. Villforth et al. argued that polarization observation support this resonance model. The biggest caveat of this approach is the fact that it could not naturally explain the double peak structure. Villforth et al. speculate that the first flare represents the accretion of magnetic field and the second flare represent accretion of matter: 1–2 yr time interval represents the delay of the matter accretion with respect to the field accretion. It does not explain the missing of the radio counterparts in some flares. It is not yet clear what decides if a disturbance in the jet will be observed in radio, therefore it is unclear if the magnetic breathing model can explain the radio behaviour. Gupta et al. (2012) suggested that the periodic variations in the accretion disk could translate to variations in the jet with the observed timescale shortened by a factor of \(\Gamma\) (jet Lorentz factor, also Valtonen & Pihajoki 2013). This ingredient should be taken into account when the relation between the thermal emission and synchrotron emission of the binary hole-accretion disk system is studied.

At present, arguments for the precessing binary hole model suggested by Lehto & Valtonen (1996) (and its variants) seem prevailing and it may be the most promising one to understand the phenomena of periodic double-peaked outbursts observed in OJ 287. If really so, based on this model, OJ 287 could become a test-bed for general relativity (e.g., orbital precession and gravitational waves). Although the binary black hole models (Sillanpaa et al. 1988; Lehto & Valtonen 1996; Sundelius et al. 1997) have achieved some success (remarkable in exact timing of the outbursts), there are still some aspects to be clarified and tested: for example, some issues about the estimation of the masses of the supermassive black-holes, the timescales of the disk-crossings of the secondary hole and the division/connection between the thermal emission and synchrotron, see Villforth et al. (2010). Here we would consider the radiation mechanisms of the double-peaked outbursts. Up to now four optical outbursts have been observed in OJ 287 at 1972, 1983, 1995 and

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\(^1\) Rapid radio variability could be explained in terms of shocks propagating through turbulent jet was firstly suggested by Qian et al. (1991) and this concept could also be used to interpret variability in other wavebands (Melrose 1994).

\(^2\) Strong magnetic disturbances could also be produced in the magnetosphere of the black hole due to instabilities, e.g. Tomimatsu et al. (2001)
2005, each of which consists of two flares separated in timescales of \( \sim 1–2 \) yr. The profiles of the optical flares showed usually some spikes with different intensities. As an example, the second flare of the 2005-outburst was closely observed during the period of September 2007–February 2008 (see Villforth et al. 2010). It contained several spikes of timescales \( \sim 1–2 \) weeks, the most prominent one occurred in late of November 2007. Interestingly, the observations of optical polarization showed that \( \sim 60 \% \) data points had polarization degree larger than 15\% and \( \sim 20 \% \) data points had polarization degree less than 10\%. If assuming that the emission with low polarization degrees was due to thermal bremsstrahlung and the emission with high polarization degrees was due to jet-synchrotron, then the ‘alternative occurrence’ of the low- and high-polarization degrees during the period of September 2007–February 2009 would imply the ‘alternative functioning’ of the two mechanisms: thermal bremsstrahlung and jet-synchrotron. However, this is impossible, because the impact crossing of the secondary hole could only produce the thermal emission of the first spike (with a timescale of \( \sim 1–2 \) weeks). Moreover, the thermal spikes and the jet-synchrotron spikes have very different properties: the observed flux density (or radiative energy) of the jet-synchrotron spikes are augmented by Doppler-boosting (by a factor of \( \sim 10^{3–4} \)) with timescales shortened by relativistic effects (by a factor of \( \sim 10 \)), but those of the thermal spikes are not. Therefore, the optical light curves observed in OJ 287 could not be directly compared with those predicted by the accretion flow of particles due to impact-crossing of the secondary black hole, and the effects of time-delay, Doppler beaming and time-shortening should be taken into account. We also note that the behaviour of the outbursts observed in OJ 287 are very similar to those in generic blazars (flux, polarization, variability and timescales). Thus we would ascribe all the spikes of this flare to jet-synchrotron.

3 The flares of other outbursts might have similar behaviour. Therefore, in the following we will discuss the possibility: if light house effect could explain the double-flaring behaviour of the optical outbursts observed in OJ 287.

### 3 A NEW SCENARIO

We will propose a new scenario (binary hole system plus light-house effect) for interpreting the optical phenomena observed in OJ 287. We assume that the optical light curve observed in OJ 287 is formed from five processes.

1. **OJ 287 hosts a binary black hole system and the orbit of the secondary hole has a modest eccentricity and an orbital period of 12 yr.** The orbital motion of the secondary black hole around the primary induces large amplitude disturbances near the pericenter passage in the accretion disk (accretion flow) of the primary and in the injection of plasma/magnetic field into the jet of the primary black hole, causing the 12 yr quasi-periodicity of optical outbursts. This assumption is similar to that originally suggested firstly by Sillanpaa et al. (1988). We do not assume an extreme eccentricity for the disk-crossing process to explain the double-peaked flares of time-interval of 1–2-year. The 60-year cyclic variability is assumed to be caused by the precession of the jet droved by the orbital motion of the secondary hole, as suggested by Valtonen & Wiik (2012);

2. **We assume that The double-peaks of the outbursts with time-interval of \( \sim 1–2 \) yr are caused by lighthouse effect.** Lighthouse effect has been suggested to interpret the (quasi-) periodic optical flares in some prominent blazars (e.g., Camenzind & Krockenberger 1992, 3C 273; Schramm et al. 1993, 3C 345; Wagner et al. 1995, PKS0420–140). This phenomenon occurs when superluminal optical knots move along helical magnetic fieldlines in relativistic jets and periodically sweep through the line of sight, producing cyclic optical flares. In the case of OJ 287, the helical

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3 We assume that the low polarization degrees of the spikes observed during the outbursts could be due to the random magnetic fields (turbulent fields) within the optical knots or the cancellation of the polarization from multi-components (e.g. optical core, optical knots and the extended optical jet).
structure in its jet could be very stable during a long-term period of (e.g.) over $\sim 100$ yr. Thus lighthouse effect could help to explain the double-peak structure of the outbursts observed in OJ 287 and its reoccurrence during the past tens of years. Helical motion has also been suggested to interpret VLBI observations, e.g., Qian et al. (1992); Steffen et al. (1995); Ostorero et al. (2004); Perucho et al. (2012a,b, 2013); Valtonen & Pihajoki (2013).

(3) The formation and evolution of the optical knots causing the outbursts should also be included in the interpretation of the optical light curve, since the radiation lifetimes of the optical knots could have similar timescales as observed in the light curve.

(4) There is also a thermal component produced by the accretion disk of the primary hole through bremsstrahlung. And the synchrotron emission of the ‘quiet optical core’ of the jet should also be taken into account. For simplification, we assume that both components are constant during the outbursts, but having different levels for different outbursts.

(5) In blazars, especially in BLO-blazars, very rapid variations in brightness have been often observed. In the case of OJ 287 the optical flux density can vary by (e.g.) a factor of ten in about 1–3 weeks (see light curves given below). This short-time variability could be related to the variability in the optical core of the jet and the optical knots propagating along the turbulent jet with large-amplitude fluctuations of plasma density and field strength. However, in this paper we do not intend to include this short timescale variability, concentrating on the study of some ‘mean’ profiles of the flares. Of course, appropriately dealing with the rapid flux (and polarization) variations would improve our understanding of the optical phenomena observed in OJ 287. However, in this paper we only deal with the three processes (2) to (4).

Our main purpose is to make model simulation to look for the explanation of the double-peak structure of the optical outbursts observed in OJ 287 through the lighthouse effect. Specifically, we look for appropriate helical motion of the optical knots and appropriate parameters to describe their evolution. we will model-simulate the profiles of the double flares for the 1972, 1983, 1995 and 2005 outbursts observed in OJ 287.

In this paper, we will adopt the concordant cosmological model ($\Lambda$CDM model) with $\Omega_m = 0.27$, $\Omega_\Lambda = 0.73$ and Hubble constant $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$ (Spergel et al. 2003). Thus for OJ 287, ($z = 0.306$), its luminosity distance is $D_L = 1.58$ Gpc (Hogg 1999; Pen 1999) and angular diameter distance $D_A = 0.9257$ Gpc. The angular scale 1 mas = 4.487 pc, and the proper motion of 1 mas yr$^{-1}$ is equivalent to an apparent velocity of $19.1c$ ($c$ is the speed of light).

4 FORMALISM OF MODEL SIMULATION

In order to study the formation of double-peak structure of the optical outbursts observed in blazar OJ 287, we will consider the lighthouse effect caused by optical knots moving along magnetic fieldlines of the jet. We will apply the formalism given by Qian et al. (1992), which has been used to study the kinematics of radio superluminal knots on parsec scales in blazars, e.g., 3C 345, 3C 279 and 3C 454.3 (Qian et al. (2009); Qian (2011). Qian (2012, 2013); Qian et al. (2014)).

The geometry of the model for helical motion is shown in Figure 1. Three coordinate frames are shown: $(X, Y, Z)$, $(X_p, Y_p, Z_p)$ and $(X_n, Y_n, Z_n)$. $Y_n$ axis directs towards the observer and $(X_n, Z_n)$ defines the plane of the sky with $X_n$-axis directing the negative right ascension and $Z_n$-axis the north pole. $Z$-axis represents the jet-axis defined by parameters $(\epsilon, \psi)$. $\Phi$ represents the phase of the optical knot. The trajectory of a superluminal knot is described in cylinder coordinates $(Z, A(Z), \Phi(Z))$: $Z$—distance from the origin along the jet axis. $A(Z)$ represents the amplitude of the knot’s path; $\Phi(Z)$ is the azimuthal angle or the phase of the knot. $Z$ and $A(Z)$ are measured in units of milliarcsecond (mas) and $\Phi$ is measured in units of radian. For the helical motion of a knot along magnetic fieldlines the trajectory (or orbital) phase of the knot can be defined as:

$$\Phi(Z) = \Phi_0 + R_\phi(Z) \times Z,$$
where $R_φ$ is the rotation rate (rad mas$^{-1}$) and $Φ_0$ is the initial phase of the knot at $Z = 0$. When functions $A(Z)$, $Φ(Z)$ (or $R_φ(Z)$) are given and parameters $ε$, $ψ$, $Φ_0$ and $Γ$ (bulk Lorentz factor of the knot) are set, the kinematics of the knot (projected trajectory, apparent velocity and Doppler factor, viewing angle as functions of time) can then be calculated. The formulas are listed as follows.

\begin{align*}
X(Z, Φ) &= A(Z)\cos Φ(Z), \quad (2) \\
Y(Z, Φ) &= A(Z)\sin Φ(Z). \quad (3)
\end{align*}

The projected trajectory on the plane of the sky is represented by

\begin{align*}
X_n(Z, Φ) &= X(Z, Φ)\cos ψ - \left[Z\sin ε - Y(Z, Φ)\cos ε\right]\sin ψ, \quad (4) \\
Z_n(Z, Φ) &= X(Z, Φ)\sin ψ + \left[Z\sin ε - Y(Z, Φ)\cos ε\right]\cos ψ. \quad (5)
\end{align*}

Introducing the following functions:

\begin{align*}
Δ &= \arctan\left[\frac{dX}{dZ}^2 + \frac{dY}{dZ}^2\right]^{\frac{1}{2}}, \quad (6) \\
Δ_p &= \arctan\left[\frac{dY}{dZ}\right], \quad (7) \\
Δ_s &= \arccos\left[1 + \left(\frac{dX}{dZ}\right)^2 + \left(\frac{dY}{dZ}\right)^2\right]^{-\frac{1}{2}}, \quad (8)
\end{align*}

We then can calculate the elapsed time $T_0$ (at which the knot reaches axial distance $Z$), apparent velocity $β_a$, Doppler factor $δ$, and viewing angle $θ$ of the knot

\begin{align*}
T_0 &= \int_0^Z \frac{1 + z}{Γc\cos Δ_s}dz, \quad (9) \\
θ &= \arccos[\cos ε(\cos Δ + \sin ε\tan Δ_p)], \quad (10) \\
δ &= \frac{1}{Γ(1 - β\cos θ)}, \quad (11) \\
β_a &= \frac{β\sin θ}{Γ - β\sin θ}, \quad (12)
\end{align*}

where $β = v/c$ (v–speed of the knot) and $Γ = (1 - β^2)^{-\frac{1}{2}}$. 

Fig. 1 Geometry for the model simulation of the four double-peaked optical outbursts.
5 MODEL SIMULATION

In the following we will make models to simulate the light curves of the four optical outbursts with double peaks occurred in blazar OJ 287: 1972-, 1983-, 1995- and 2005-outbursts given in Valtaoja et al. (2000) and Villforth et al. (2010).

As indicated in the introduction, it is assumed in the proposed model that the optical light curves contain different physical processes (see Fig. 2): (1) the radiation from the accretion disk of the primary black hole, produced by bremsstrahlung; (2) the injection of magnetized plasma into the jet, which is modulated by the orbital motion of the secondary black hole (through tidal effect, as suggested by Sillanpää et al. 1998). The interaction between the accretion disk of the primary black hole and the companion black hole is very complex. We assume that the optical outbursts are excited by the pericenter passage of the companion black hole. Thus an orbital period of ~12 yr is assumed to causes the periodic optical outbursts. The precession of the jet-axis derived by the orbital motion (~60 or 120 yr) could be the cause for the long-term quasi-periodic optical variability; (3) the formation and evolution (including emission and kinematic properties) of the superluminal optical knots which are responsible for the optical radiation through synchrotron mechanism; (4) the superluminal motion of the optical knots along the helical magnetic fieldlines of the jet causes lighthouse effect through relativistic beaming of radiation. Thus there are many physical parameters involved which can be adjusted to explain the light curves of the outbursts. On the other hand, for superluminal optical knots no data on their kinematics can be obtained. (this is different from radio superluminal knots for which VLBI-data can provide important information). Thus in the following we would not attempt to make detailed “purely physical” models (e.g. Camenzind & Krockenberger 1992; Schramm et al. 1993) to interpret the double-peak outbursts of OJ 287. Instead, we will only propose a “formal” model (tentative and qualitative) and use very simple numerical simulations to show the possibility of our model to explain the formation of the double-peaked optical outbursts (flare profiles and time-interval of the double flares). The four double-peaked outbursts will be treated individually.

Since the model contains many parameters and functions we will make a few assumptions to simplify the description of the model as follows.

1. We assume that $\epsilon = 3^\circ$ and $\psi = 0$, which define the direction of the jet axis;
2. assume $\Gamma = 10$ which defines the bulk Lorentz factor of the all (four) optical knots;
3. We will not consider detailed physical models for the formation and evolution of the emission of the knots which involve the acceleration of relativistic electrons and field magnification by (e.g.) magnetic turbulence, but only assume that the flux density of the knot is described by

$$F(\nu_{\text{obs}}, Z) = F_s(\nu_{\text{obs}}, Z) \times \delta^{3+\alpha} + F_0(\nu_{\text{obs}}),$$

where $F_s(\nu_{\text{obs}}, Z)$ is the comoving flux density of the knot. The factor $\delta^{3+\alpha}$ describes the Doppler boosting (Blandford & Königl 1979). The variation in Doppler factor $\delta$ caused by the helical motion of the superluminal optical knot produces the lighthouse effect. $\alpha$ is the spectral index ($F_\nu \propto \nu^{-\alpha}$). $F_0(\nu_{\text{obs}}) = F_d(\nu_{\text{obs}}) + F_c(\nu_{\text{obs}})$ describes the emission from the accretion disk of the primary hole and the ‘quiet optical core’ of the jet. We assume $F_0 = \text{constant}$ during the period of the outbursts. But actually they are variable and inclusion of these variations would improve the simulations of the light curves of the flares, especially for the periods between the two flares.
Optical spectral index $\alpha$ has been measured for the outbursts in OJ 287 (Villforth et al. 2010; Hagen-Thorn et al. 1998). It depends on the brightness of OJ 287, varying between $\sim1.6$ to $1.1$. We take $\alpha = 1.0$ here.

(4) Since we do not apply a physical model to describe the relation between the functions $A(Z)$ and $R_\phi$ defining the helical trajectory, and the evolution the optical knot radiation ($F_\nu(Z)$), we will use step-functions of irregular lengths to describe the functions $A(Z)$, $\Phi(Z)$, $R_\phi(Z)$ and $F_\nu(Z)$, separately. But a few conditions are set as follows.

(5) The amplitude function $A(Z)$ should contain three regions with initial opening and then collimation and expansion. Collimation region is the region in which double flares with similar intensity could be produced through lighthouse effect. As Schramm et al. (1993) indicate that the jet must be perfectly collimated at the base in agreement with expectations for self-collimated current-carrying jets (Appl & Camenzind 1993). Thus we assume that the jet becomes collimated at axial distance $Z < \sim 0.1$ mas (0.45 pc). The amplitude of the trajectory $A(Z) \sim 0.02 - 0.03$ mas in the collimation region. In the expansion regions the optical knots evolve into radio knots and radio counterparts appear following the second optical flare.

(6) Rotation rate $R_\phi(Z)$ in the collimation region should be large enough to produce helical rotation of the optical knots, causing double flares. Generally, $R_\phi(Z)$ should conform to the amplitude $A(Z)$: when $A(Z)$ increases, $R_\phi(Z)$ decreases. Only two values of $R_\phi$ are taken for each of the four outbursts;

(7) The evolution of the synchrotron radiation of the optical knot should contain three stages: an initial rapid increase, a plateau and a decreasing stage (or correspondingly, Compton-, synchrotron- and adiabatic stage). This requirement is consistent with the normal evolution of superluminal knot (Marscher & Gear 1985). Due to pressure effects and dissipation the jet would expand sideways when it emerges beyond $\sim10$ mas-scale. Driven by this expansion the knot spectrum moves to lower frequencies so that the optical synchrotron flux decays. We would not specifically set the properties of the optical knots (e.g. density and energy spectrum of the relativistic electrons, magnetic field strength, knot size, etc.) and only choose some type of flux variations for making simulations. E.g. within the collimated regions of the jet the optical flux of the knots remain stable to assure the production of quasi-equal intensity double flares through the lighthouse effect (Schramm et al. 1993). The expansion of the jet leads to the optical knots evolving into radio knots and producing mm/radio outbursts.

(8) we will not consider the rapid and short-term variations (on timescales of weeks) of the optical knots. In the case of OJ 287 these variations make the profiles of the double-peaked outbursts difficult to determine; And we only simulate the 'average' (smoothed) profiles of the optical outbursts. The rapid variations in flux density on timescales of weeks could be due to the propagation of the relativistic shocks (optical knots superluminally moving through the very turbulent jet, e.g., Qian et al. 1991; Standke et al. 1996; Marscher et al. 1992; Marscher & Jorstad 2010).

(9) We include the optical emission from the disk of the primary hole ($F_\delta$, bremsstrahlung) and that from the optical core of the jet ($F_c$). In the numerical simulation we assume that both components are stable (non-variable: $F_0 = F_\delta + F_c$ = constant) during the outbursts in the following numerical simulations. Actually, $F_0$ is rapidly variable on short time scales of weeks (especially for the jet core, the flux from which is Doppler-boosted) and inclusion of this component would help better to explain the optical variations during the periods between the double flares.

These conditions are required for assuring obtaining an explanation of the double-peak flares.

Although our model simulation is qualitative, the projected trajectory and time-scale obtained in the following are similar to those obtained by Schramm et al. (1993) for the optical knot of blazar 3C 345 in their lighthouse effect model (see below).
Fig. 3 Model simulation for 1972 outburst. Upper four panels for amplitude $A(t)$, orbital phase $\Phi(t)$, rotation rate $R_\phi(t)$ and comoving flux density $F_\ast(t)$. Lower four panels (for the kinematic properties of optical knot): bulk Lorentz factor $\Gamma(t)$, apparent velocity $\beta_a(t)$, Doppler factor $\delta(t)$ and viewing angle $\theta(t)$. Epoch zero corresponds to 1970.58.
5.1 Model simulation of the 1972-flare

The parameters \((A(Z), \Phi(Z), R_\phi(Z))\) for model simulation are given as follows:

1. \(Z(\text{mas}) \leq 0.1: A(Z)(\text{mas}) = 0.0278(Z/0.1); \Phi(Z) (\text{rad}) = 1.552 + R_\phi(Z) \times Z; R_\phi(Z) (\text{rad mas}^{-1}) = 0.7.\)
2. \(Z(\text{mas}) = 0.1 - 14: A(Z)(\text{mas}) = 0.0278; \Phi(Z) (\text{rad}) = 1.622 + R_\phi \times (Z - 0.1); R_\phi(Z) (\text{rad mas}^{-1}) = 0.7.\)
3. \(Z(\text{mas}) = 14 - 24: A(Z)(\text{mas}) = 0.0278; \Phi(Z) = 11.352 + R_\phi(Z) \times (Z - 14); R_\phi(Z) (\text{rad mas}^{-1}) = 0.7.\)
4. \(Z(\text{mas}) > 24: A(Z)(\text{mas}) = 0.0278 \times [1+0.5(Z-18)]; \Phi(Z)(\text{rad}) = 18.352 + R_\phi \times (Z - 24); R_\phi(Z) (\text{rad mas}^{-1}) = 0.3.\)

The flux density from the quiet background component (accretion disk of the primary black hole plus the quiet core of the jet) is assumed to be \(F_0 = 5.5 \text{ mJy}.\)
It should be noted that the position \((Z, A) = (0, 0)\) is only a ‘mathematical origin’, does not represent the location of the central supermassive black hole, or the location of the optical core either. A reasonable choose may be that the location of the first peak produced by the superluminal knot is regarded as the site of the optical core of the jet and the black hole is located a bit inwards.

The comoving flux densities are given as follows:

1. \(Z(\text{mas}) \leq 0.1: F_c(Z)\text{(mJy)} = 5.10 \times 10^{-4}Z/0.1\).
2. \(Z(\text{mas}) = 0.1 - 12: F_c(Z)\text{(mJy)} = 5.10 \times 10^{-4}[1 - 0.0196(Z - 0.1)]\).
3. \(Z(\text{mas}) = 12 - 20: F_c(Z)\text{(mJy)} = 3.91 \times 10^{-4}[1 - 0.125(Z - 12)]\).
4. \(Z(\text{mas}) > 20: F_c(Z)\text{(mJy)} = 0\).

The results of the model simulation are shown in Figure 3–5. It can be seen that the double-peaked optical outburst of OJ 287 observed in 1971–1972 is well simulated by our simple numerical model, including the peak flux densities, the widths of the flare profiles, the time interval between the two flares and the radiation level of the quiet background component. The model simulation for this outburst is a very typical example: Both the double flares of the outburst are simulated to occur within the collimated region of the jet and with uniform rotation rate of 0.7 rad mas\(^{-1}\). The radial distances of the two peaks occur at 6.7 mas and 15.2 mas from the origin \((Z = 0)\). If the first flare peak is approximately regarded as occurring near the core of the optical jet, then the second flare is emitted at \(\sim 8.5\) mas (38 pc) from the core. The width of the jet at both positions of peaks are \(\sim 0.0278\) mas, (\(= 0.13\) pc).

### 5.2 Model simulation of the 1983-flare

The parameters \(A(Z), \Phi(Z)\) and \(R_\phi(Z)\) for the model simulation are given as follows:

1. \(Z \leq 0.1: A(Z)\text{(mas)} = 0.0278(Z/0.1); \Phi(Z)\text{(rad)} = 1.552 + R_\phi(Z) \times Z; R_\phi(Z)\text{(rad mas}\(^{-1}\)) = 0.7.
2. \(Z(\text{mas}) = 0.1 - 15: A(Z)\text{(mas)} = 0.0278; \Phi(Z)\text{(rad)} = 1.622 + R_\phi(Z) \times (Z - 0.1); R_\phi(Z)\text{(rad mas}\(^{-1}\)) = 0.7.
3. \(Z(\text{mas}) = 15 - 24: A(Z)\text{(mas)} = 0.0278; \Phi(Z)\text{(rad)} = 12.052 + R_\phi(Z) \times (Z - 15); R_\phi(Z)\text{(rad mas}\(^{-1}\)) = 0.7.
4. \(Z(\text{mas}) > 24: A(Z)\text{(mas)} = 0.0278[1 + 0.5(Z - 18)]; \Phi(\text{rad}) = 18.352 + R_\phi(Z) \times (Z - 24); R_\phi(Z)\text{(rad mas}\(^{-1}\)) = 0.4.

The flux density of the quiet background component is a constant, \(F_0 = F_d + F_c = 4.0\) mJy.

The comoving flux density of the optical knot is given as follows:

1. \(Z(\text{mas}) \leq 3: F_c(Z)\text{(mJy)} = 7.15 \times 10^{-6} \times Z/3\).
2. \(Z(\text{mas}) = 3 - 6: F_c(Z)\text{(mJy)} = 7.15 \times 10^{-6}[1 + 9.67(Z - 3)]\).
3. \(Z(\text{mas}) = 6 - 13: F_c(Z)\text{(mJy)} = 2.15 \times 10^{-4}\).
4. \(Z(\text{mas}) = 13 - 16: F_c(Z)\text{(mJy)} = 2.15 \times 10^{-4}[1 - 0.2(Z - 13)]\).
5. \(Z(\text{mas}) = 16 - 18: F_c(Z)\text{(mJy)} = 8.58 \times 10^{-5}[1 - 0.3(Z - 16)]\).
6. \(Z(\text{mas}) = 18 - 20: F_c(Z)\text{(mJy)} = 3.43 \times 10^{-5}[1 - 0.5(Z - 18)]\).
7. \(Z(\text{mas}) > 20: F_c(Z)\text{(mJy)} = 0\).

The model simulation results are shown in Figure 6–8. 666777888 Like 1972 outburst, the 1983-outburst is also a typical example of lighthouse effect: Both the double flares of the outburst were simulated to occur within the collimated region and with an uniform rotation rate \(R_\phi = 0.7\) rad mas\(^{-1}\). The radial distances of the peaks occur at 6.8 mas and at 14.8 mas. If the first flare is assumed to occur near the core of the optical jet (or the optical polarization core defined by Villforth et al. 2010), then the second flare occur at radial distance \(\sim 8\) mas (\(~ 40\) pc) from the core. (Actually, we don’t know how far the optical core locates from the black hole). The jet width at these sites is \(0.0278\) mas (\(~ 0.125\) pc).
Fig. 6 Model simulation for the 1983-flare. Upper four panels show the amplitude $A(t)$, orbital phase $\Phi(t)$, rotation rate $R_\phi(t)$ and comoving flux density $\mathcal{F}_*(t)$. Lower four panels shows the kinematic properties of the optical knot: bulk Lorentz factor $\Gamma(t)$, apparent velocity $\beta_a(t)$, Doppler factor $\delta(t)$ and viewing angle $\theta(t)$. Epoch zero corresponding to 1982.58.
Fig. 7 1983 outburst: model simulation of the light curve of the optical double-peaked outburst. Right panel shows the simulation of its first flare on an expanded timescale. Epoch zero = 1982.58.

5.3 Model simulation for the 1995-outburst

For the model simulation the parameters $A(Z)$, $\Phi(Z)$ and $R_\phi(Z)$ are given as follows:

1. $Z(\text{mas}) \leq 0.1$:
   \[ A(Z)(\text{mas}) = 0.0325(Z/0.1); \quad \Phi(Z)(\text{rad}) = 1.552 + R_\phi \times Z; \quad R_\phi (\text{rad mas}^{-1}) = 1.30. \]
2. $Z(\text{mas}) = 0.1 - 5$:
   \[ A(Z)(\text{mas}) = 0.0325; \quad \Phi(Z)(\text{rad}) = 1.682 + R_\phi(Z - 0.1); \quad R_\phi(Z) (\text{rad mas}^{-1}) = 1.3. \]
3. $Z(\text{mas}) = 5 - 6$:
   \[ A(Z)(\text{mas}) = 0.0325; \quad \Phi(Z)(\text{rad}) = 8.052 + R_\phi \times (Z - 5); \quad R_\phi (\text{rad mas}^{-1}) = 0.6. \]
4. $Z(\text{mas}) > 6$:
   \[ A(Z)(\text{mas}) = 0.0325[1+0.1(Z-6)]; \quad \Phi(Z)(\text{rad}) = 8.652+R_\phi(Z-6); \quad R_\phi (\text{rad mas}^{-1}) = 0.6. \]

The flux density emitted by the quiet background component (accretion disk of the primary black hole plus the quiet optical core) is taken as a constant, $F_0 = F_d + F_c = 2.5$ mJy.

The comoving flux density of the optical knot is set as follows:

1. $Z(\text{mas}) \leq 2$: $F_\ast(Z)(\text{mJy}) = 5.42 \times 10^{-5} \times Z/2$.
2. $Z(\text{mas}) = 2 - 15$: $F_\ast(Z)(\text{mJy}) = 5.42 \times 10^{-5}[1 - 0.01(Z - 2)]$. 
Fig. 8 Simulation of the projected trajectory of the optical knot of the 1983 outburst. The ‘circles’ indicate the positions where the double flares are emitted.

(3) \( Z(\text{mas}) = 15 - 17: F_{\ast}(Z) (\text{mJy}) = 4.72 \times 10^{-5}[1 - 0.5(Z - 15)]. \)
(4) \( Z(\text{mas}) > 17: F_{\ast}(Z) (\text{mJy}) = 0. \)

The results of model simulation for the 1995- outburst are shown in Figure 9–11. It can be seen that the double peak structure of the outburst is well fitted. The double flares of this outburst had narrower profiles than those of the 1972- and 1983-outbursts. Thus a larger rotation rate was needed for the first flare (\( R_{\phi} = 1.3 \text{ rad mas}^{-1} \), in comparison with \( R_{\phi} = 0.7 \text{ rad mas}^{-1} \) for the 1972- and 1983- outbursts). The second flare has to be simulated to occur in the expansion region of the jet with \( R_{\phi} = 0.6! \text{rad mas}^{-1} \). The radial distances of the two flares are 3.6 mas and 13 mas from the origin \( Z = 0 \). If we define the location of the first flare peak as the core of the optical jet, then the second flare occur at radial distance of 9.4 mas (\( \sim 42 \text{ pc} \)). The jet width at the sites are simulated to be 0.033 mas and 0.053 mas, larger than those for the 1972- and 1983 outbursts (0.028 mas).

5.4 Model simulation of the 2005-outburst

For model simulation of the 2005-outburst the parameters \( A(Z), \Phi(Z) \) and \( R_{\phi}(Z) \) are set as follows.

(1) \( Z \leq 0.1 \text{ mas}: \)
\[ A(Z) (\text{mas}) = 0.0278 \times (Z/0.1); \quad \Phi(Z) (\text{rad}) = 0.7520 + R_{\phi} \times Z; \quad R_{\phi}(Z) (\text{rad mas}^{-1}) = 0.7. \]
(2) \( Z(\text{mas}) = 0.1 - 14: \)
\[ A(Z) (\text{mas}) = 0.0278; \quad \Phi(Z) (\text{rad}) = 0.822 + R_{\phi}(Z - 0.1); \quad R_{\phi} (\text{rad mas}^{-1}) = 0.7. \]
(3) \( Z(\text{mas}) > 14: \)
\[ A(z) (\text{mas}) = 0.0278[1 + 0.40(Z - 14)]; \quad \Phi(Z) (\text{rad mas}^{-1}) = 10.552 + R_{\phi}(Z - 14); \]
\[ R_{\phi}(\text{rad mas}^{-1}) = 0.23; \quad \text{At } Z > 14 \text{ mas rotation rate } R_{\phi} \text{ has a small value is for obtaining a larger time interval between the two flare peaks (\( \sim 2 \text{ yr} \)).} \]

The flux density emitted by the accretion disk of the primary black hole and the quiet optical core is taken as a constant, \( F_{d} = F_{d} + F_{e} = 2.5 \text{ mJy} \). The comoving flux density of the optical knot is set as follows:
Fig. 9 Model simulation for the 1995-outburst. Upper four panels: amplitude $A(t)$, orbital phase $\Phi(t)$, rotation rate $R_\phi(t)$ and comoving flux density $F_\ast(t)$. Lower four panels (for kinematic properties of the superluminal motion of the optical knot): bulk Lorentz factor $\Gamma(t)$, apparent velocity $\beta_a(t)$, Doppler factor $\delta$ and viewing angle $\theta(t)$. Zero epoch =1994.50
The results of the model simulation are shown in Figure 12–14. It can be seen that the double peak structure of the 2006-outburst is reasonably well simulated. In this case the time-interval between the two flare peaks is \( \sim 2 \) yr, two times longer compared with those in the cases of 1972-, 1983 and 1995-outbursts. Thus the second flare is simulated to occur in the expansion region with rotation rate \( R_\Phi = 0.23 \) rad mas\(^{-1}\), while the first flare in the collimated region with \( R_\Phi = 0.7 \) rad mas\(^{-1}\). similar to the case for the 1972- and 1983- outbursts. The intensity evolution of the optical knot shows some different behavior from those in the cases of 1972- and 1983-outbursts, that is, its rest-frame flux density always slowly decreases from collimated region to expansion region without a plateau stage. In this case, the two intensity peaks are simulated to be at radial distances 7.8 mas and 24 mas. If we define the location of the first flare peak occurring at the core of the optical jet, then the second flare occurred at a separation of \( \sim 16.2 \) mas (73 pc) from the core. This seems imply that very efficient acceleration mechanism of relativistic particles exists in the jet at \( \sim 100 \) pc from the
central supermassive black hole, constructing a Compton/synchrotron loss zone to produce $\gamma$-rays and optical emission.

The width of the jet at these sites are 0.028 mas and 0.13 mas, separately, and the projected separation of the second flare from the core is about 0.8 mas (3.6 pc).

The projected location ($X_n$, $Z_n$) = (1.2 mas, 0.13 mas) obtained for the second flare here are similar to that obtained for the fourth peak of the light curve for blazar 3C 345 by Schramm et al. (1993) in their lighthouse model. (Note: in the case of 3C 345, the viewing angle of the jet is set as $0.95^\circ$, thus the deprojected factor is larger than that in our model by a factor of $\sim 3$).

6 SUMMARY AND DISCUSSION

We have made model simulations for the light curves of the four double-peaked optical flares consistently. Since we only chose certain set of parameters and functions, these simulation results can only be regarded as particular solutions or examples, because different sets of parameters and functions would lead to different results (for example, for different jet orientation, bulk Lorentz factor, helical pattern of trajectory etc.). In the simulations we have considered three emission components: emission from the superluminal optical knot and the ‘quiet core’ of the optical jet (both synchrotron) and emission from the accretion disk of the primary hole (bremsstrahlung). Here we summarize the main ideas and assumptions involved in the simulations and the main results.

Orbital motion of the secondary black hole round the primary black hole strongly disturbs the accretion disk of the primary black hole and induces enhanced injection of plasmas and magnetic fields into the jet by tidal and electromagnetic effects near pericenter passage. An adequate eccentricity and 12 yr orbital period are required. Thus superluminal knots are created (formed) periodically per 12 yr. The superluminal knots move along helical magnetic fieldlines and produce the double-peaked optical outbursts (optical light curves) through light-house effect, due to the jet axis directing towards the observer with a small angle of $\sim 3^\circ$ and bulk Lorentz factor $\Gamma \sim 10$ (Doppler factor $\sim 12$–18). These values are similar to those obtained by other researchers, e.g. (Tavecchio et al. 2010; Hovatta et al. 2009; Pihajoki et al. 2013; Ciprini et al. 2007). In the lighthouse model, the optical
Fig. 12 Parameters used for the model simulation of the 2005-outburst. Upper four panels: amplitude $A(t)$, orbital phase $\Phi(t)$, rotation rate $R_{\phi}(t)$ and rest-frame flux $F_{\ast}(t)$ of the optical knot; Lower four panels (for the kinematic properties of the superluminal motion of the optical knot): bulk Lorentz factor $\Gamma(t)$, apparent velocity $\beta_{a}(t)$, Doppler factor $\delta(t)$ and viewing angle $\theta(t)$. Zero epoch= 2005.60.
radiation is Doppler boosted by a factor of $\sim 10^4$, thus the comoving (rest-frame) radiation energy is lower with respect to the bremsstrahlung energy (in binary black hole model with disk-crossings) by the same factor. And significant energy is contained in the kinetic energy of the bulk relativistic motion of the optical knots. Moreover, if we assume that the disturbed magnetized plasma flow injected into the jet of the primary hole lasts about 3–4 yr (one third or fourth of the orbital period) near the pericenter passage of the secondary hole, then the emission observed from the disturbed flow in the jet would correspondingly last about 0.3–0.4 yr (shortened by a factor of $\sim 10$). This is just consistent with the timescales of the profile width of the double flares observed (see fig. 3 in Sillanpaa et al. 1988). Thus the model simulations show that the binary black hole plus light-house effect scenario may be useful to simplifying the excitation mechanism of the optical/radio outbursts, only through gravitationally tidal effects and electromagnetic interaction during the pericenter passage of the second black hole.

The four optical double-peak outbursts occurred in blazar OJ 287 in 1972, 1983, 1995 and 2005 are reasonably well simulated, including their peak intensity, profiles, and the time-interval between the two peaks. In the region where the double peak outbursts occurred, the amplitude $A \simeq 0.03$ —
Table 1

<table>
<thead>
<tr>
<th>Outburst</th>
<th>First flare</th>
<th>Second flare</th>
<th>Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>$R_\phi$</td>
<td>A</td>
<td>$R_\phi$</td>
</tr>
<tr>
<td>1972</td>
<td>0.028</td>
<td>0.70</td>
<td>0.028</td>
</tr>
<tr>
<td>1983</td>
<td>0.028</td>
<td>0.70</td>
<td>0.028</td>
</tr>
<tr>
<td>1995</td>
<td>0.033</td>
<td>1.30</td>
<td>0.053</td>
</tr>
<tr>
<td>2005</td>
<td>0.028</td>
<td>0.70</td>
<td>0.13</td>
</tr>
</tbody>
</table>

0.05 mas (i.e., width of the collimated jet region) and the rotation rate $R_\phi$ is $\sim 0.7 - 1.3 \text{ rad mas}^{-1}$. The time-intervals between the two peaks obtained in the model simulations are 1.08, 1.02, 1.17 and 2.03 yr for the four outbursts separately. If the locations of the first flares are defined as the site of the core of the optical jet, then the second flares occur at axial separations of 38, 36, 32, and 73 pc for the four outbursts separately. The simulations show that the parameters used for the four double-peaked flares are quite similar, as shown in Table 1 where a comparison of the parameters used for the modulations are given. This may indicate that the helical magnetic field structure of the jet in OJ 287 has been rather stable during a very long time period (e.g. $\sim 100$ yr). This is possible because this helical field is anchored in the innermost region of the accretion disk of the primary black hole, whose gravitational effect keeps the helical field structure in the jet solid and stable.

In the simulations the location of the first flares of the four double peaked outbursts is defined as the core of the optical jet of OJ 287 and the second flares occur at projected separations $\sim 0.4$ mas (for 1972-, 1983- and 1995- outbursts) from the core (see Figs. 5, 8 and 11). These three outbursts have time intervals of the double-peaks of about 1–2 yr. The projected trajectories and timescales obtained by our model simulations are quite similar to those obtained by Schramm et al. (1993) for model fitting to the periodic flares in blazar 3C 345 by applying a physical model of lighthouse effect. We should point out that in our model simulations the functions describing the helical trajectory ($A(Z)$, $R_\phi(Z)$) and knot flux density evolution $F_\ast(Z)$ are given independently, thus our model could not be fully physically coherent. But for searching the possibility for explaining the double-peak structure of the outbursts by lighthouse effect, our simulation have obtained meaningful results, interpreting the basic properties and required conditions for the lighthouse effect mechanism applying to the optical behaviour observed in blazar OJ 287.

Based on our scenario, the three basic properties of OJ 287 (as Sillanpaa et al. 1996b suggested) could be explained consistently: (a) The 12-year cyclic optical outburst behaviour and (b) the double-peak structure of the cyclic outbursts (as described above) and (c) the extremely stable colour (observed during the 1995-outburst with both the flares having same colour, Sillanpaa et al. 1996b). Lighthouse effect is an achromatic effect (purely geometric effect). The optical outbursts are solely produced by the change in the Doppler boosting when the optical knots rotate along the helical trajectories. Villforth et al. (2010) found spectral changes during the 2005-outburst (May 2005–June 2009): OJ 287 was bluer when it was brighter. This flattening of the optical spectrum could be interpreted in terms of injection of higher-energy electrons into the optical knot. Thus both stable colour and spectral change could be explained in our scenario, as for outbursts occurred in generic blazars.

Since in the highly collimated zone the optical knots do not experience expansion losses and the efficient acceleration of particles could keep the optical knots emitting in optical wavebands. Therefore the optical knots could not evolve into radio knots and the optical knots themselves are optically thick in the mm/radio wavebands. This explains why the first flares of the double-peaked outbursts observed in OJ 287 were not accompanied by strong radio counterparts. Only when the optical knots evolve into mm/radio knots by expansion and due to lack of acceleration of particles
strong mm/radio outbursts could appear. And this could occur when the optical knots have moved out of the collimated region into expanding region of the jet. This explains why the second flares of the double-peaked outbursts observed in OJ 287 had mm/radio counterparts.

The optical outbursts observed in OJ 287 have short timescale spikes of (~a few weeks) with fluctuations in intensity of ~30% – 40% both during quiet-phase and burst-phase. Valtaoja et al. (2000) argued against lighthouse model based on this behaviour. Although in this paper we did not take into account this ingredient, this behaviour (short timescale variations) could be explained in our scenario. For example, the short timescale variations during the burst phase could be due to the shocks (optical knots) propagating through the very turbulent jet and those during quiet phase due to turbulent plasma flow passing through a standing shock or the optical core. Therefore they could have similar timescales, because they could have similar Doppler boosting and similar time-shortening by relativistic effects (Qian et al. 1991; Standke et al. 1996; Quirrenbach et al. 1989; Marscher & Jorstad 2010).

The key point (or assumption) of our model simulations is that there may exist a highly collimation zone in the jet of OJ 287, where expansion losses are negligible and efficient acceleration of electrons could compensate the radiation losses through Compton/synchrotron processes to keep the optical knots emitting in γ-ray and optical wavebands. Thus the rotation of the optical knots along the helical trajectories could produce double-peaked outbursts with similar intensities.

Figures 4, 7, 10 and 13 illustrate such good examples. The significant decay of radiation of the optical knots could only occur after the optical knots move out of the collimated zone. This explanation is consistent with the results obtained by Schramm et al. (1993) for the periodic optical flares observed in blazar 3C 345; the first three optical flares with almost equal-intensity and equal time-width fitted by their light-house model occurred in the highly collimated region (initial opening angle of the jet was 0.05 degrees), and the fourth (predicted) flare occurred in the jet expanding region with decayed intensity. Therefore, in principle, if there exists a highly collimated zone in the jet, light-house effect could play its role to explain the occurrence of double-peaked outbursts.

However, in this case the highly collimated region should have a rather long-length. This has been regarded as a problem for lighthouse effect model (e.g. Sillanpaa et al. 1996b). However, recent γ-ray observations seem to provide some evidence for this requirement. Schinzel et al. (2010, 2012) report that the gamma-rays of blazar 3C 345 are produced in a region of the jet of up to 23 pc (de-projected) and suggest the synchrotron self-Compton process as the most likely mechanism for the production of gamma-rays and question the entire class of models that place the gamma-ray emission site within 1 pc from the central engine of AGN. Through mm/gamma-ray connection study Agudo et al. (2011b, 2012b) argued that in blazars OJ 287 and AO0235+164, gamma-ray flares were produced at sites larger than 1 pc and 12 pc from the mm-core, respectively. These observational facts strongly support the possibility of existence of highly collimated zone in the jets of blazars having length of a few ten parsecs, which is a key requirement of the lighthouse effect model.

These observations show that optical knots, optical photons of which as seed-photon source of the self-Compton process, can propagate to tens of parsec, implying this region of the jet could be highly collimated and the optical knots have not been diminished by expansion and radiative losses, constructing a stable Compton/synchrotron loss zone to produce γ-ray and optical emission up to ~100 pc. This is just what the lighthouse model requires. Within the collimated regions (without adiabatic losses due to sideways expansion), efficient particle acceleration by shocks and magnetic turbulences (e.g. turbulent cell model proposed by Marscher & Jorstad 2010) would keep the optical knots emitting in SSC-gamma-rays and synchrotron optical wavebands. This would be the cause

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5 A large scale of about a few ten parsecs, e.g., for the 1972 outburst of OJ 287, the second flare occur at location of ~40 pc from the core in the model simulation of this paper.
6 This distance depends on the viewing angle chosen. If a smaller viewing angle 2.7° (Jorstad et al. 2005, instead of 5.2°, Schinzel et al. 2010) is used, this distance would be 40 pc.
for the long length of the Compton loss zone found by Schinzel et al. (2010). Qian et al. (2010) also suggested the existence of a highly collimated region in the jet of blazar BL Lacertae (a BLO-blazar like OJ 287) through the study of the evolution of its mm/cm outbursts in terms of 3-stage evolutional model (Compton-synchrotron-adiabatic stage) in order to explain the lack of spectral flattening from the transit of Compton stage to adiabatic stage. Thus both the observational results and the theoretical results (Camenzind & Krockenberger 1992; Schramm et al. 1993; Wagner et al. 1995) are consistent to support the idea: in blazars highly collimated zone (Compton-synchrotron loss zone) could exist up to radial distances in the range of ∼40–80 pc from the core.

We point out that the proposed model do not require extraordinary physical conditions (e.g. crossing of the secondary black hole into the accretion disk of the primary black hole) and seems very feasible (flexible). The results obtained by this numerical simulation demonstrate the plausibility (or possibility) to understand the double-peaked outbursts in terms of jet phenomenon. The parameters and functions chosen in our model simulation are only examples, not unique. Different sets of parameters and functions could be chosen for the simulation. However, such type of model simulation could not be able to make accurate timing of the future double peaking events and other properties, because in this model the occurrence of the radiation processes mentioned in section-3 can not be accurately predicted. (This is contrast to the binary hole scenario of Lehto & Valtonen (1996) with twice crossing of the secondary hole into the accretion disk of the primary black hole). The most caveat is how to find a set of helical motion (A and \(R_\phi\)) and evolution of optical knots which allowed by theoretical arguments based on jet formation and radiation theory. The numerical simulations does not take into account the physical connection between helical trajectory and rest-frame intensity, thus not necessarily appropriate, and might be inconsistent with each other in some aspects: for example, the expanding helical trajectory and the evolution of the knots' emission. Of course, the model simulation of the profiles, interval-lengths, peak intensity and peak-ratio should be based on consistent theoretical models.

Although losing ability of the timing prediction of the second flares, the proposed scenario has the advatage to accomodate the explanations for the double peak outbursts, including time-interval between the two peaks, flare profile width, peak intensity ratio, etc. And this scenario seems more consistent with the results of theoretical studies of optical flares in generic blazars (synchrotron plus relativistic beaming).

Although we did not give the physical details (models) for the four processes, it seems not difficult to describe these processes individually in the framework of astrophysics for blazars. Based on the results of this model, a detailed theoretical model of relativistic jet for the double-peaked outbursts could be established. Specifically, in the case of OJ 287 a detailed physical model should contain several theoretical aspects. For example, (1) The interaction between the secondary black hole and the accretion disk of the primary black hole should be detailed, and the enhanced injection of the magnetized plasma flow into the jet and the formation of the superluminally moving optical knot (including the calculation of the time delays between the pericenter passage of the secondary black hole and the first optical flare) (Sillanpaa et al. 1988; Valtonen & Wiik 2012); (2) The helical field structure should be described by continuous functions. The amplitude function \(A(Z)\) should conform to the rotation rate function \(R_\phi(Z)\) through the rule of conservation of angular momentum. (Camenzind & Kronkenberg 1993). (3) The connection between the disk bremsstrahlung and the synchrotron of the superluminal knot should be detailed; (4)Further investigations in correlation between mm/radio and optical outbursts and that between the optical and \(\gamma\)-ray outbursts, including optical polarization and SED should be carried out, which would help to clarify the nature of the optical emission and determine the physical parameters for the three processes.Future observations

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7 Similar phenomenon could occur in blazar 3C 273 and 3C 345 (Qian et al. 2010; Stevens et al. 1996, 1998).

8 Our model simulation did not include the variation of the optical emission on timescales less than ∼1 month. These short-term variations could be due to variable conditions within the optical knots (e.g. acceleration of relativistic electrons by magnetic turbulences), while the shocks propagate through the turbulent jet, experiencing relativistic time shortening.
of double-peaked optical flares would test the model. Since we ascribe the double flares of the outbursts to synchrotron of the optical knots in the jet, there are plenty of theoretical results for generic blazars can be applied for OJ 287; for example, magnetohydrodynamics theory for relativistic jets and accretion disk flow and radiation theory for outbursts in blazars.

The proposed model, obviously, is oversimplified and just a preliminary, tentative and semi-qualitative. Our aim is to find some alternative clues for explain the formation of the double-peaked optical outbursts observed in blazar OJ 287. Future observation would test these ideas. Obviously, if lighthouse effect model is an appropriate model to interpret the double peaked outbursts of OJ 287, then theoretical and physical models (like Camenzind & Krockenberger 1992; Schramm et al. 1993; Wagner et al. 1995) should be constructed to establish the physical connections between the helical motion, evolution of the knot, interaction of the disk disturbances and plasma/field injection of the jet, bulk Lorentz factor etc.

References

Joshi, M., Marscher, A., Jorstad, S., et al. 2011, in AAS/High Energy Astrophysics Division, vol. 12, #07.03
Marscher, A. P. 2011-a, in AAS/High Energy Astrophysics Division, vol. 12, #07.06
Qian, S.-J., Krichbaum, T. P., Witzel, A., et al. 2010, RAA (Research in Astronomy and Astrophysics), 10, 47
Qian, S.-J. 2011, RAA (Research in Astronomy and Astrophysics), 11, 43
Qian, S.-J. 2012, RAA (Research in Astronomy and Astrophysics), 12, 46
Qian, S.-J. 2013, RAA (Research in Astronomy and Astrophysics), 13, 783
Qian, S.-J., Britzen, S., Witzel, A., et al. 2014, RAA (Research in Astronomy and Astrophysics), 14, 249
Tomimatsu, A., Matsuoka, T., & Takahashi, M. 2001, Phys. Rev. D, 64, 123003