Disk origin of broad optical emission lines of the TDE candidate PTF09djl

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ABSTRACT

An otherwise dormant supermassive black hole (SMBH) in a galactic nucleus flares up when it tidally disrupts a star passing by. Most of the tidal disruption events (TDEs) and candidates discovered in the optical/UV have broad optical emission lines with complex and diverse profiles of puzzling origin. In this Letter, we show that the double-peaked broad \( \alpha \) line of the TDE candidate PTF09djl can be well modelled with a relativistic elliptical accretion disk and the peculiar substructures with one peak at the line rest wavelength and the other redshifted to about \( 3.5 \times 10^4 \text{ km s}^{-1} \) are mainly due to the orbital motion of the emitting matter within the disk plane of large inclination \( 88^\circ \) and pericenter orientation nearly vertical to the observer. The accretion disk has an extreme eccentricity 0.966 and semimajor axis of 340 BH Schwarzschild radii. The viewing angle effects of large disk inclination lead to significant attenuation of He emission lines originally produced at large electron scattering optical depth and to the absence/weakness of He emission lines in the spectra of PTF09djl. Our results suggest that the diversities of line intensity ratios among the line species in optical TDEs are probably due to the differences of disk inclinations.

Key words: accretion disk – black hole physics – galaxies: active – line: profiles

1 INTRODUCTION

A star is tidally disrupted when it wanders closely by a supermassive black hole (SMBH) in galactic nuclei (Hills 1975; Rees 1988). About 30-60 stellar tidal disruption events (TDEs) and TDE candidates have been observed in the X-rays, UV and optical (Komossa & Zensus 2016; Auchettl et al. 2017, for recent reviews). Few TDEs discovered in X-ray show optical emission lines in spectra, but those discovered in the optical have strong broad optical emission lines (Komossa et al. 2008; Gezari et al. 2012; Wang et al. 2012; Holoien et al. 2014). The broad emission lines of the optical/UV TDEs and candidates are complex, asymmetric and of puzzling origin (Gezari et al. 2012; Gaskell & Rojas Lobos 2014; Guillen et al. 2014; Strubbe & Murray 2015; Kochanek 2016; Roth et al. 2016) and the peculiar spectral characteristics raise skepticism on the identification of the optical/UV transients as TDEs (Saxton et al. 2017).

The optical spectra of the TDE candidate PTF09djl have strong and double-peaked \( \alpha \) emission line with one peak at the rest wavelength of the line and the other redshifted by about \( 3.5 \times 10^4 \text{ km s}^{-1} \) (Arcavi et al. 2014, see also Fig. 1). The line structure is reminiscent of the double-peaked line profiles in active galactic nuclei (AGNs) which are usually explained with disk models (Chen et al. 1989; Eracleous et al. 1995). When a circular disk model was applied to the double-peaked \( \alpha \) profiles, a bulk motion of velocity about \( 1.5 \times 10^4 \text{ km s}^{-1} \) has to be included to shift the model profiles to the red from their original position to fit it to the observed spectra (Arcavi et al. 2014). A post-merged BH can obtain a recoiling velocity up to 5000 km s\(^{-1}\) at coalescence of two black holes because of gravitational radiations (Lousto & Zlochower 2011). A SMBH may have a bulk velocity \( 1.5 \times 10^4 \text{ km s}^{-1} \), if it is a component of a BH binary of separation \( \leq 200r_S \) with \( r_S \) the BH Schwarzschild radius (Liu et al. 2014), smaller than the required disk size (Arcavi et al. 2014). A BH binary of mass \( 10^6-3M_\odot \) (with \( M_\odot \) the solar mass) and separation \( \leq 200r_S \) has an orbital period less than 6 d. Dramatic variations of the bulk velocity would be expected during the 60-d spectral observational campaign of PTF09djl, inconsistent with the observations. It was suggested that the geometry of the broad-line region may be more complex than a circular disk (Arcavi et al. 2014).

Hydrodynamic simulations of stellar tidal disruptions show that the circularization of bound stellar debris is due to the self-interaction of debris streams because of the relativistic apsidal precession, and that the accretion disk would have a large eccentricity except for cases with orbital pericenter of star about the BH radius (Evans & Kochanek 1989; Shiokawa et al. 2015; Bonnerot et al. 2016; Hayasaki & Loeb 2016). Broad emission lines originating in highly eccentric disk would have distinctive profiles.
In this Letter, we suggest that the broad emission lines of the spectra of PTF09djl originate in an eccentric accretion disk as expected from hydrodynamic models for TDEs. We show that the peculiar broad double-peaked profiles of the Hα emission line can be well reproduced with a relativistic elliptical disk model of semimajor axis 340r⊙ and eccentricity 0.966. The disk plane inclines by an angle 88° and has pericenter orientation nearly vertical to the observer.

2 THE SPECTRAL DATA OF PTF09djl

The TDE candidate PTF09djl was discovered in a redshift z = 0.184 E+A galaxy in the Palomar Transient Factory (PTF) survey on 2009 July 24, and follow-up optical spectra were obtained with the Low Resolution Imaging Spectrometer (LRIS) mounted on the Keck 110 m telescope for the transient on 2009 August 25, September 23 and October 24, and for the host galaxy on 2013 May 9† (Arcavi et al. 2014). We corrected the spectra for a Galactic extinction of A_V = 0.049mag and R_V = 3.1 (Cardelli et al. 1989; Schlafly & Finkbeiner 2011). The three spectra of PTF09djl and the spectrum of the host galaxy are shown in Fig. 1. The Balmer lines are extremely broad and prominent and the transient event can be regarded as the H-dominated in the sequence of He- to H-rich TDEs (Arcavi et al. 2014).

We globally model the continuum of the TDE using a third-order polynomial by fitting to several line-free regions of the TDE spectrum, plus a scaled spectrum of the host galaxy. The scale factor of the host spectrum is determined by matching regions with strong stellar features and without emission lines. Fig. 1 gives our spectral decomposition procedure for the three spectra and the residual emission-line spectra of PTF09djl after Galactic extinction correction and subtraction of the continuum and host galaxy starlight. Hα is strong and double-peaked with the blue peak at the rest wavelength of the line and the red one redshifted by about 3.5 × 10^3 km s⁻¹ at all epochs. Hβ line is also prominent. He emission lines are weak or absent from the spectra.

3 MODELING THE BROAD EMISSION LINES

3.1 Accretion disk in TDEs

The bound debris after disruption of star is circularized due to the interaction of the outflowing and inflowing streams because of the relativistic apsidal precession and the location of the interaction is

\[ r_{cr} \approx \frac{(1 + e_{mb})r_p}{1 - e_{mb} \cos(\Omega/2)} \approx \frac{2\pi r_p r_s}{\delta + 2\sin^2(\Omega/4)} \]  

(Dai et al. 2015), where \( r_p = x_p r_s \) with \( x_p \lesssim 23.54r_c m_s^{1/3} M_6^{-2/3} \) is the orbital pericenter of the bound stream, \( e_{mb} = 1 - \delta \) with \( \delta \approx 8.49 \times 10^{-4} e_{cr}^{-1} m_s^{1/3} M_6^{-1/3} x_p \) is the eccentricity of the most-bound stellar debris (with \( M_{BH} = 10^8 M_6 \) the mass of the BH; \( R_c = r_c R_s \) and \( M_s = m_s R_s^3 \), respectively, the star’s radius and mass; \( R_s \) the radius of the Sun) and \( \Omega \) is the instantaneous de Sitter precession at periapse of the most-bound stellar debris after tidal disruption, \( \Omega = 3\pi r_s / (r_p [1 + e_{mb}]) \approx 3\pi / (2x_p) \).

The size and orientation of the elliptical accretion disk are determined by the location of the self-interaction of streams. Provided that the collision is completely inelastic and the outgoing and incoming streams have similar mass, the circularized stellar debris forms an accretion disk of semimajor axis

\[ r_{ad} \approx \frac{r_{cr}}{2\sin^2(\theta_e/2)} \left( 1 + r_{cr} / (2d_{mb}) \right) \cos^2(\theta_e/2) \]  

(Dai et al. 2015), where \( d_{mb} \approx r_c^2 / 2r_c \) with \( r_c = R_c (M_{BH}/M_\odot)^{1/3} \) the stelllar tidal disruption radius (Guillochon & Ramirez-Ruiz 2013; Hayasaki et al. 2013) is the orbital semimajor axis of the most bound stellar debris, and \( \theta_e \) is the stream-stream intersection angle

\[ \cos(\theta_e) = \frac{1 - 2\cos(\Omega/2)e_{mb} + \cos(\Omega)e_{mb}^2}{1 - 2\cos(\Omega/2)r_{mb} + r_{mb}^2} \]  

or

\[ \sin(\theta_e/2) \approx \frac{2\sin(\Omega/4)}{\sqrt{\delta^2 + 4\sin^2(\Omega/4)}} \cos(\Omega/4) \approx \cos(\Omega/4). \]  

Equation (2) together with Equations (1) and (4) gives

\[ e_d \approx \left( \frac{1 - (1 + e_{em})r_p}{a_d} \right)^{1/2} \approx \left[ \cos^2 \left( \frac{\Omega}{2} \right) - 2\delta \right]^{1/2} \]  

3.2 A disk model for broad emission lines in TDEs

We assume that the broad emission lines in TDEs originate in the elliptical disk given in Sec. 3.1. No observation in hard X-rays was made for PTF09djl, but the survey of TDE candidates in the archive of Swift Burst Alert Telescope (BAT) shows that hard X-ray emissions should be ubiquitous in un-beamed TDE candidates (Hryniewicz & Walter 2016). Because the coronal hard X-ray source originates due to the magnetic reconnection in the poloidal field lines anchored to the ionized accretion disk, the coronal materials should move nearly radially along with the disk material and become radially extended. The configuration of coronal X-ray source in TDEs is different from that in AGNs, which is compact.

The calculations of radiative transfer indicate that an ionized optically thick accretion disk irradiated by hard X-ray source will produce strong optical emission lines when the ionization parameter is low to intermediate (Garcia et al. 2013). The reflection line emissivity of accretion disk at frequency \( \nu_e \) in the frame of the emitter irradiated by X-ray source of finite radial extent \( r_{eh} \) is a broken power law in radius \( r \) except for the regions near BH horizon

\[ I_{\nu_e} = \left\{ \begin{array}{ll} \frac{e_c}{2\pi(2\pi)^{1/2}} (\frac{\xi}{\xi_0})^{-\alpha_1} \exp \left[ \frac{(\nu_e - \nu_0)^2}{2\sigma_0^2} \right] & \text{for } \xi \leq \xi_0 \\
\frac{e_c}{2\pi(2\pi)^{1/2}} (\frac{\xi}{\xi_0})^{-\alpha_2} \exp \left[ \frac{(\nu_e - \nu_0)^2}{2\sigma_0^2} \right] & \text{for } \xi > \xi_0 \end{array} \right. \]  

with \( \alpha_1 \sim 0 \) for corona of constant radial distribution and \( \alpha_2 \simeq 3 \) for \( \xi > \xi_0 \) (Wilkins & Fabian 2012; Gonzalez et al. 2017), where \( \xi = 1 \)
The motion of particles on the energies of the emitted photons \((1 + e_v)\) with the least-squares method \((\chi^2)\). The break radius \(\xi_{br}\) might be less than the inner radius \(\xi_1\) of the emission line region but cannot be constrained observationally. Therefore, the calculations are limited to \(\xi_{br} \geq \xi_1\).

### 3.3 Fitting the double-peaked H\(\alpha\) profiles of PTF09djl

Provided pericenter \(x_p\), the size \((a_d/\xi_1)\) and eccentricity \((e_d)\) of debris accretion disk are computed with Equations (5) and (6), respectively. An inner disk edge 2\(R_g\) is adopted because the accretion disk has an extreme eccentricity \((e_d \approx 0.966)\); see Section 4) and the orbits of disk fluid elements are nearly parabolic, for which the marginal stable orbit for Schwarzschild black hole is about the marginal bound orbit 2\(R_g\) and fluid elements passing through 2\(R_g\) fall freely on to the BH. The line-emitting region lies between radii \(\xi_1\) and \(\xi_2 = (1 + e_d)a_d/\xi_1\). We calculate the model line profiles for a large parameter space (i.e. \(0 < \xi_d \leq \xi_1\), \(0 < \xi_0 < 2\xi_1\), \(1 < \xi_d \leq 50\), \(2 < \xi_1 \leq 70\), \(\xi_1 \leq \xi_{br} \leq \xi_2\) and \(10^3\) km s\(^{-1}\) \(\sigma \leq 2 \times 10^2\) km s\(^{-1}\)) and jointly fit the observed profiles of the first two spectra with shared paralipse \((x_p)\) and velocity dispersion \((\sigma)\) with the least-squares method \((\chi^2)\). The break radius \(\xi_{br}\) might be less than the inner radius \(\xi_1\) of the emission line region but cannot be constrained observationally. Therefore, the calculations are limited to \(\xi_{br} \geq \xi_1\).
Because the third spectrum has a low signal-to-noise ratio, the line profile is fitted with the averages $\chi_\lambda$, $\sigma$, $\phi_\lambda$ and $\lambda_\delta$ obtained with the first two spectra.

They are calculated with the dimensionless radii ($\xi$, $\zeta$ and $\xi_{\text{H}_\alpha}$), orbital pericenter $x_\alpha$, and disk semimajor axis $a_\alpha$, but Equations (5) and (6) show that the model line profiles depend explicitly and weakly on the BH mass (but nearly independent of the mass of star). The BH mass is $M_{\text{BH}}$ estimated with the $M_{\text{BH}}$-$M_{\text{bulge}}$ relation (Arcavi et al. 2014) and $\log(M_{\text{BH}}/M_\odot) = 5.82 \pm 0.56$ with the $M_{\text{BH}}-\sigma$ relation between the bulge of the host galaxy and the mass of the SMBH (Wevers et al. 2017). Both masses are consistent with each other within the uncertainties and we adopted the average $M_{\text{BH}} \approx 2.1 \times 10^6 M_\odot$ in this Letter. A similar BH mass with quite large uncertainties is obtained by fitting the H$\alpha$ line profiles.

4 RESULTS

The best-fitting models of the three H$\alpha$ spectra are shown in Fig. 3, and the best-fitting values of the model parameters and their associated errors are given in Table 1. Table 1 also gives the reduced $\chi^2$ of the best fits, which is calculated with respect to the averaged noises over the closest regions of the emission lines after subtraction of the spectral feature. The uncertainties of the fitting parameters at 90% confidence level are obtained with the Markov chain Monte Carlo (MCMC) methods.

The modelling of the three H$\alpha$ spectra of PTF09djl shows that the double-peaked H$\alpha$ line profiles with one peak at the line rest wavelength and the other extending to redshift about $3.5 \times 10^4$ km s$^{-1}$ can be well fitted with a relativistic elliptical disk model without bulk motion. Table 1 shows that the accretion disk has a semimajor $a_\alpha \approx 339.7 r_\odot$ and eccentricity $e_\alpha \approx 0.966$, following circularization of streams with orbital pericenter $r_\alpha \approx 11.38 r_\odot$. During the spectral observations, the radial extent of the hard X-ray source or corona slightly increases from $r_\alpha \approx 29.5 r_\odot$ to $32.9 r_\odot$. The contributions of the inner disk regions covered with the extended corona to the H$\alpha$ line flux is negligible as the effective size of the regions is $\Delta r = (\xi_\alpha - \xi_{\text{H}_\alpha}) r_\odot \sim 0$. The accretion disk is highly inclined with nearly constant inclination angle $i_\alpha \approx 88^\circ$. The pericenter of the accretion disk is orientated with nearly constant angle $\phi_\lambda \approx 72^\circ$ relative to the observer. An elliptical disk of high inclination and pericenter orientation nearly vertical to the observer leads to the formation of the broad (with full width at half-maximum, FWHM $\approx 4 \times 10^4$ km s$^{-1}$) and asymmetric double-peaked H$\alpha$ emission line with one peak at the line rest wavelength and the other redshifted to about $3.5 \times 10^4$ km s$^{-1}$.

5 DISCUSSION AND CONCLUSIONS

We analysed the three optical spectra of the TDE candidate PTF09djl, after careful treatment of the TDE featureless continuum and host galaxy starlight. The double-peaked H$\alpha$ line profiles are well reproduced with an elliptical disk of semimajor about 339.7 $r_\odot$ (apocenter 667.9 $r_\odot$) and eccentricity 0.966. The peculiar line substructures with one peak at the line rest wavelength and the other redshifted to $\sim 3.5 \times 10^4$ km s$^{-1}$ are due to the large disk inclination $88^\circ$ and pericenter orientation nearly vertical the observer.

For an accretion disk with $e_\alpha \approx 0.966$, the conversion efficiency of matter into radiation is $\eta \approx 4.2 \times 10^{-2}$. For typical stellar tidal disruptions with $\beta = n_l/\gamma_p \approx 1.48 m_\odot (\xi^2/2)_{\gamma_p}^{1/3} M_\odot^{2/3} \approx 1$, the peak accretion rate is $M_\alpha \approx A_{5/3}(M_{\text{BH}}/10^6 M_\odot)^{-1/2} M_\odot/yr$ with $A_{5/3} \approx 1.2$ (Guillochon & Ramirez-Ruiz 2013). For a BH of mass $M_{\text{BH}} \approx 2.1 \times 10^6 M_\odot$, PTF09djl has a peak accretion rate $M_\alpha \approx 0.83 M_\odot/yr$ and luminosity $L_\alpha = \eta M_\alpha c^2 \approx 2 \times 10^{42} \text{erg s}^{-1} \approx 0.75 L_{\text{Edd}}$, where $L_{\text{Edd}}$ is the Eddington luminosity. Accretion disk of sub-Eddington accretion rate is expected to be optically thick and geometrically thin.

The calculations of radiative transfer show that optical emission lines are prominent in the reflected spectra from an ionized, optically thick accretion disk irradiated by X-rays when the ionization parameter is in the range $1 \leq \zeta (\text{erg cm s}^{-1}) \lesssim 500$ (García et al. 2013), where $\zeta = 4 \pi F_\odot n_e/\gamma_p$ with $F_\odot$ the integrated flux in the energy range 0.1 $-$ 300 keV and $n_e$ the electron number den-
The accretion disk of semimajor axis $a_d \simeq 339.7 r_s$ and eccentricity $e_d \simeq 0.966$ has a typical peak temperature, $T_p \simeq 4.5 \times 10^4$ K, and is ionized. No hard X-ray observation was made for PTF09djl, but the survey of TDE candidates in the Swift BAT archive show that hard X-ray emission in TDE candidates should be ubiquitous with luminosity $L_x = (0.3 - 3) \times 10^{44}$ erg s$^{-1}$ in the energy range 20–195 keV (Hryniewicz & Walter 2016). Provided a typical X-ray luminosity $L_x \sim 10^{44}$ erg s$^{-1}$ from extended X-ray source corotating with disk below, the ionization parameter of PTF09djl is $\xi \sim 6 \pi L_x (m_p/1.2 M_\odot)^{1/2} (1 + e_d) a_d (H/r_0) [1 + (H/r_0)^2]^{-1} \sim 54$ erg cm s$^{-1}$ for $M_d \sim M_\odot$ and disk opening angle $H/r_0 \sim 0.1$, where $m_p$ is the mass of proton and the typical disk mass at peak $M_d \sim M_\odot/3$ is assumed.

Because electron scattering will increase the effective optical depths of emission lines, the ionized disk atmosphere becomes effectively thick to H and He II emission lines at different electron scattering depths (Roth et al. 2016). Strong He emission lines are expected because they are produced in a region of electron scattering depth a few times larger than that for H lines (Roth et al. 2016). He emission lines are absent/weak in the optical spectra of PTF09djl. It is probably due to the viewing angle effects that the effective optical depth changes with disk inclination angle $\tau_{\text{eff}} = \tau_{\odot} / \cos(i_d)$ (García et al. 2014). The accretion disk of PTF09djl is highly inclined with $i_d \simeq 88^\circ$, and the He emission lines originally formed at large $\xi_d$ is much more attenuated than H emission lines formed near the disk surface. Our results suggest that the broad optical emission lines in optical TDEs may originate in the ionized elliptical accretion disk and the diversity of line intensity ratios of the species among the optical TDEs is probably due to the different disk inclinations.

In conclusion, we have successfully modelled the peculiar double-peaked Hα profiles of the TDE candidate PTF09djl with a relativistic elliptical disk, without the need to invoke bulk motion, like BH recoil. Our results show that modelling the complex and asymmetric line profiles of TDEs provides a powerful tool to probe the structure of their transient accretion disk and potential kinematic signatures of SMBH binaries or recoiling SMBHs.

ACKNOWLEDGEMENTS

We are grateful to Iair Arcavi for providing us the electronic data of the spectra. This work is supported by the National Natural Science Foundation of China (NSFC11473003) and the Strategic Priority Research Program of the Chinese Academy of Sciences (grant no. XDB23010200 and no. XDB23040000). LCH was supported by the National Key R&D Program of China (2016YFA0400702) and the National Science Foundation of China (11473002, 11721303).

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