Emission Lines in 3C 445

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ABSTRACT
We extract the multiple-epoch Balmer-line profiles of the heavily obscured quasar 3C 445 from the spectral curves in the literature, and analyze the emission-line profiles of the Hα and Hβ lines and the profile variability in the Hα line in the large time interval of more than three decades. The profile comparison between the Hα and Hβ lines shows that both Balmer lines share the profile with the same form, while the blue system of the Hβ line is seriously weaker than that of the Hα line. Moreover, the blue system of the Hα line suddenly disappeared completely and then did not appear again, however the other two components did not exhibit significant variation in the velocity or the amplitude. These findings suggest that the blue system of 3C 445, as with SDSS J153636.22+044127.0 and its analogs, is probable the result of the shock-heated outflowing gases. The observation angle of almost edge-on which the previous studies suggested can easily produce the high-speed and high-temperature shock in the collision between the massive outflow and the inner surface of the dusty torus.

Key words: galaxies: active – quasars: emission lines – quasars: individual (3C 445)

1 INTRODUCTION
The emission-line system of quasars provides an effective way to understand the structure and gas properties of active galactic nuclei (AGNs). It has been traditional view that the broad-line emission originates in inner high-density clouds orbiting the central ionizing radiation source, and the origin of narrow-line is the extended low-density materials at larger scales, which are called the broad-line region (BLR) and the narrow-line region (NLR), respectively, in the unified model (Antonucci 1993). Moreover, with the increase in spectral observation data and the deepening of research on emission-line profiles, researchers have been cognizant of that other mechanisms, such as the accretion disk (e.g., Collin-Souffrin et al. 1980; Chen et al. 1989; Oke 1987; Halpern 1990), the outflowing of gas at the different scales (e.g., Leighly 2004; Wang et al. 2011; Marziani et al. 2013; Liu et al. 2016; Zhang et al. 2017a), and even the dusty torus (e.g., Li et al. 2015, 2016), can seriously affect the broad-line profile and produce some unique emission-line profiles.

To investigate the origins of the unique emission-line profiles, follow-up observations and other high-/low-ionization lines extending to the infrared (or/and ultraviolet) bands, assisted by kinetic and photoionization simulations, can effectively diagnose the true source of the anomalous emission-line system. For example, it was once considered that in SDSS J153636.22+044127.0 and its analogs, the blue system of the double-peaked hydrogen Balmer lines arises from the broad-line region of a secondary supermassive black hole (Boroson & Lauer 2009; Tang & Grindlay 2009); however, new evidences from the follow-up optical/near-infrared spectral observations, i.e., the profile invariance in the time interval of 10 years and the absence of the blue system in the He I 410830 emission-line profile, suggests that these peculiar emission-line profiles are is probably related to the shock-heated outflowing gases (Zhang et al. 2019).

3C 445 (z = 0.0562; Osterbrock et al. 1976) is also a widely studied broad-line radio galaxy with double-peaked Balmer emission lines, in which irregular, non-symmetric profiles were suggested to result from mass motions of the ionized gas in a relatively small number of “clouds” or “streams” at one time (Osterbrock et al. 1976). Indeed, the Balmer lines in 3C 445 are more complex than most ordinary double-peaked emitters (see the samples in Eracleous & Halpern 2003 and Strateva et al. 2003, 2004). In the following three decades, there have been several spectral observations of its emission-line profiles (e.g., Crenshaw et al. 1988; Eracleous & Halpern 1993; Corbett et al. 1998; Buttiglione et al. 2009). These spectral archives would provide an ap-
proach to exploring the origins of the emission-line components of the Balmer lines with the unique flux ratios and different variations.

2 SPECTRAL DATA OF THE BALMER LINES

As a famous double-peaked broad-line source, there are many spectral observations of 3C 445 in the literature. In this work, we choose only five optical spectral observations in the large time interval of more than three decades, which all provide high-quality emission-line profiles of the Hα line that can be used to check the possible evolution of the broad emission lines.

Two scans of 3C 445, 64 minutes in blue and 48 minutes in red spectral regions, respectively, were firstly taken with the 120 inch telescope at Lick Observatory on 1974 July 22nd and September 9th, and the summed scans were compared with the other three broad-line radio galaxies in Figure 1 of Osterbrock et al. (1976). In Figure 6 of Osterbrock et al. (1976), the emission-line profiles of Balmer lines, with the blended [N II], [S II], and [O III] lines removed, are displayed. We extract the relative intensities of the Hα and Hβ lines from the curves in the figure using a semiautomated tool called “WebPlotDigitizer”.

The first follow-up spectrum of 3C 445 has already presented the large-amplitude variability in the Hα line within the velocity range of the blue system. It was obtained with the Ohio State University Image Dissector Scanner (IDS) on the 1.8 m Perkins reflector at Lowell Observatory on 1986 November 5th. An exposure of 5400 seconds was taken in the red region and the 600 lines mm⁻¹ grating provide a wavelength range of 2000 Å centered on approximately 6800 Å. The new Hα-line profile is extracted from the curve in the last panel of Figure 1 of Crenshaw et al. (1988).

Five years later, two observations (with exposure times of 2200 and 2400 seconds) were carried out using the 2.1 m telescope and GoldCam CCD spectrograph at the Kitt Peak National Observatory on 1991 June 20th and 21st. The spectral range was 6330 ~ 7440 Å to include Hα and its broad wings with a spectral resolution of 3.7 Å. Two Hα-line profiles are extracted from the curves in Figure 1-(g) of Era- cleous & Halpern (1993), and there is no evidence for profile variability on the time scale of a few days. Thus we combine two Hα-line profiles for the following analysis.

The third follow-up spectrum is taken from the spectropolarimetric observations on 1995 June 6th and 7th. Three polarization spectra were obtained on the red arm of the ISIS dual-beam spectrograph on the 4.2 m William Herschel Telescope at the Observatorio del Roque de los Muchachos with exposure times of 2000, 2000 and 500 seconds. A 316 line mm⁻¹ grating gave a wavelength range of 1500 Å and a dispersion of approximately 1.5 Å pixel⁻¹. Since the last observation has a significantly different continuum polarization position angle from those of the first two observations (which are consistent), an average spectrum was created by combining the first two observations, as shown in Figure 1-(c) of Corbett et al. (1998). We extract the total flux spectrum.

The fourth follow-up spectrum is obtained with the 3.58 m optical/infrared Telescopio Nazionale Galileo (TNG) with the DOLORES spectrograph on 2007 August 6th (Buttiglione et al. 2009). The chosen long-slit width is 2 arcsec. An exposure of 500 seconds was taken with the VHR-R (6100~7800 Å) grism with a resolution of ~ 5 Å. The Hα-line spectrum is downloaded from the NASA/IPAC Extragalactic Database (NED). For the third and the fourth follow-ups, the local continua were subtracted from the observed spectra to obtain the Hα-line profiles. The local continuum of the Hα regime is estimated from two continuum windows ([6200, 6250] Å and [6800, 6850] Å) in the form of a linear function.

3 PROFILE ANALYSIS

3.1 Profile Comparison of the Balmer Lines and Unusual Blue System

In the left panel of Figure 1, we compare the emission-line profiles of the Hα and Hβ lines. As Osterbrock et al. reported, the observed emission-line profile of the Hβ line has the same form as the Hα-line profile within the observational accuracy. However, intriguingly, the blue peak of the Hβ-line profile at ~ −1600 km s⁻¹ is significantly weaker than that of the Hα-line profile. It is more likely that the Balmer profiles in 3C 445 are more complex than most ordinary double-peaked emitters, which is explained as a relativistic accretion disk plus one set of AGN’s broad/narrow emission lines at the zero velocity (e.g., Halpern 1990; Eracleous & Halpern1994).

Carefully analyzing the emission-line profiles of the Hα and Hβ lines, we found that the profiles can be decomposed into a double-peaked baseline plus two emission-line systems, which are shown by the green dash-dotted line and marked as the “blue system” and the “red system” in the right panel of Figure 1, respectively. In particular, the double-peaked baseline is modeled using an axisymmetric Keplerian disk-line model from Chen & Halpern (1989), the disk inclination is i ~ 48°, the inner/outer radii are r1 ~ 1400 rG and r2 ~ 13,000 rG, the velocity dispersion is σ = 600 km s⁻¹, and the index of the surface emissivity power law is q = 2.5. We should know that the first three parameters in the disk model, i.e., the inclination angle and the inner and outer radii, are degenerate to some degree, and the larger inclination angle would lead to the larger inner radius (see Figure 3 of Tang & Grindlay 2009), therefore, the bestfit parameters are only good as a rough estimate. In the right panel of Figure 1, the shoulder-like peak is obscured by the blue system, plus, there is a blue wing component which cannot be fit well by an axisymmetric Keplerian disk model, as shown obviously in the Hα profile, which was also found in SDSS J153636.22+044127.0 (Tang & Grindlay 2009). Moreover, the blue and red systems are portrayed by one single Gaussian (blue dashed line), and two Gaussians (red dashed lines), and the velocity shifts of the blue system and the broad and narrow components of the red system are ~1588, 0, and 95 km s⁻¹, and their full width at half maximum (FWHM) values are 1132, 2051, and 825 km s⁻¹, respectively.

Indeed, the Balmer profile properties (the whole

1 https://automeris.io/WebPlotDigitizer/
Figure 1. Left: Balmer-line profile comparison of 3C 445 (scanned in 1974). Two Balmer lines share the same profile within the observational accuracy except the blue peak. Intriguingly, the blue peak of the Hβ-line profile at ~1600 km s\(^{-1}\) is significantly lower than that of Hα. The emitting gases of the blue peak are probable with different intrinsic gas/dust properties from the other emission-line components. Right: Hα-line profile and its decomposition of 3C 445. The black line is the continuum-removed spectrum from Osterbrock et al. (1976), the green dash-dotted line is the best-fit disk-line model, the left blue dashed line is the Gaussian fit to the blue peak (marked as the “blue system”), the central red dashed lines are the two Gaussians fit to the red peak (marked as the “red system”).

emission-line profile includes the blue/red systems with large velocity offset and a double-peak baseline, and the flux ratio of the blue system is significant different from those of other two emission-line components) of 3C 445 are very similar to those of SDSS J153636.22+044127.0 and its analogs reported by Zhang et al. (2019). The two significant differences are that the emission strength of the blue system of 3C 445 is weaker, and the velocity offset between the blue and red systems of 3C 445 is also smaller than those of these analogs. Generally, the double-peak baseline is the disk-line component of the accretion disk around the black hole, the red system is the emission component originating from the normal emission-line regions. In Zhang et al. (2019), the blue system is considered to be probably related to the shock-heated outflowing gases. Similarly for 3C 445, large disagreement between the Hα and Hβ blue systems and rough consistency at other velocities imply that the emitting gases of the blue system are probable with different intrinsic gas/dust properties (e.g., the abnormal intrinsic Hα/Hβ ratio, and extra extinction) in the nuclear region from the other two emission-line components.

3.2 Blue System Variability in the Hα Line

In Figure 2, we present the Hα-line profiles of 3C 445 in the literature in the velocity space. Each follow-up profile of the Hα line is multiplied by a factor to match the red peak of the earliest profile. The narrow lines blended in the Hα-line profile do not interfere in the comparison of broad-line profiles; thus the [N II] and [S II] lines are not removed (in the profile of 1974 observation these lines have been removed by Osterbrock et al. 1976), and we mark these narrow lines with dotted lines in the figure. Through the comparison of the emission-line profiles, the blue system of the Hα line sud-

Figure 2. Hα-line profile comparison of 3C 445 from 1974 to 2007. The Hα lines in the literature share the same profile within the observational accuracy except the blue system. The blue system of Hα suddenly disappeared between 1974 and 1986, and did not appear again in the next two decades. The different variations in the three emission-line components are probable to be related to the origins of the complex Balmer-line profile. The blue system disappeared completely between 1974 and 1986, but in the next two decades after 1986, the profile of the Hα line has no significant variation in the velocity or the amplitude. In detail, the three components contained in the Balmer-line profiles exhibit different variations, i.e., the absent blue system, and other two emission components without significant
variation. We also checked other emission-line profiles of the Hα line in the literature (e.g., Cohen et al. 1999; Keel et al. 2005; Jones et al. 2009). These spectra are observed in the 1990s and beyond, and they have low spectral resolution or their observed times are very close to one of the spectra we have presented in Figure 2. As we expected, the blue system is also absent in these Hα profiles. These differences in the variability of the three emission-line components are probable to be related to the origins of the complex Balmer-line profile suggested in the last section. Of course, there are also people who think that the disappearance of the Hα blue system may be the profile change of the double-peaked disk line, which generally represents the variations of relatively large-scale accretion disks in AGNs (e.g., Lewis et al. 2010 and references therein). In this situation, the Hα blue system in the 1974 observation is part (i.e., the blue shoulder) of the disk-line component. However, that cannot explain the profile difference of the Balmer lines, the maximum relative intensity of the Hβ blue peak is only ∼ 70% of the Hα blue peak. Moreover, the disk-line model needs the extremely small inclination angle to match the high blue peak of the Hα line, and the broad extended wings of the Hα-line profile cannot be explained at all.

4 SUMMARY AND DISCUSSION

In this work, we extract the multiple-epoch Balmer-line profiles of 3C 445 from the curves in the literature, and analyze the emission-line profiles of the Hα and Hβ lines and the profile variability in the Hα line in the large time interval of more than three decades. The comparison between the Hα and Hβ profiles in the first observation shows that both lines share the emission-line profile with the same form, while the blue system of the Hβ line with a blueshifted velocity of ∼ 1600 km s\(^{-1}\) is much lower than that of the Hα line. Intriguingly, in the next three decades following Osterbrock et al.'s spectral observation, the double-peaked baseline and the red system (at the zero velocity) of the Hα line in 3C 445 have no significant variation in the velocity or the amplitude, however, the Hα blue system suddenly disappeared completely and then did not appear again. The differences in the flux ratio and the profile variability between the three emission-line components suggest that the origin of the unique Balmer-line profile of 3C 445 is complex and that the three components emit from the different gas clouds in the nuclear region of 3C 445.

Generally, the double-peaked baseline is thought to be the disk-line component of the accretion disk around the black hole, and the red system is the emission component originating from the normal emission-line regions. In previous studies, the extra blue system in the broad emission lines had been considered to be coming from the BLR around the secondary black hole in a binary black hole system (e.g., Boroson & Lauer 2009; Tang & Grindlay 2009; Decarli et al. 2010), or those are closely related to the outflowing gases (e.g., Leighly 2004; Liu et al. 2016; Zhang et al. 2017b, 2019). In the binary black hole model, the periodic changes in the velocity offset between the blue and red systems and flux amplitude of the blue system are expected, obviously, this binary hypothesis is not entirely consistent with the observed facts of 3C 445. The blue system of the Hα-line profile disappeared suddenly in the 12 years after the first spectral observations, and then never appeared as scheduled in the next two decades.

In Table 2 of Osterbrock et al. (1976), the combined intensities of the Hα and Hβ lines measured from the first spectrum were listed. The rough Balmer decrement of 3C 445 (Hα/Hβ = 47.2/4.97) is much steeper than the recombination decrement. In Veilleux & Osterbrock (1987), they adopted Hα/Hβ = 3.1 for active galaxies and 2.85 for H II region galaxies (e.g., Ferland & Netzer 1983; Gaskell 1984; Gaskell & Ferland 1984), and the large sample statistics suggested that the intrinsic value of broad-line Hα/Hβ is 3.06 with a standard deviation of 0.03 dex (Dong et al. 2008). The steep Balmer decrement of 3C 445 suggests that 3C 445 is reddened, i.e., E(B − V) = 1.23 mag if the SMC extinction law is employed, which was confirmed by the large Fαz/Hβ ratio (5.6; Rudy & Tokunaga 1982). Furthermore, the Balmer decrement without the blue system contribution is Hα/Hβ ∼ 8.0 (Crenshaw et al. 1988), which predicts a slightly small reddening with E(B − V) ∼ 1.05 mag. Indeed, it does not really matter what the value of the extinction exactly is, and the fact itself that the nuclear region of 3C 445 is heavily obscured is unquestionable. In such a situation, the Lyα emission from the nuclear region would be completely absorbed, and it is not plausible in view of the detection of the Lyα line by Crenshaw et al. (1988). However, we find that the Lyα line is narrow and the profile of which is similar to those of [O III] \(λ\lambda 4959,5007\) (see Fig. 1 in Crenshaw et al. 1988). The origin of the Lyα line is probable the star-forming in the host galaxy. In order to check this guess, the broadband spectral energy distribution (SED) of 3C 445 taken with the SDSS (York et al. 2000), 2MASS (Skrutskie et al. 2006), and WISE (Wright et al. 2010) surveys are presented in Figure 3. Following the method of Zhang et al. (2017b), the broadband SED from the optical out to the middle-infrared can be modeled with

![Figure 3. Broadband SED of 3C 445 from optical to middle-infrared by orange squares. The reddened quasar composite, the `cst_54Gyr_z008' galaxy template and their sum are shown by pink, green, and black curves.](image-url)
the combination of a scaled and reddened quasar composite with \( E(B - V) = 1.1 \) mag and a scaled \( c_{\text{H}10}\text{Gyr} = 0.08 \) template \( (z = 6 \text{ Gyr}, Z = 0.008, \) and undergoing continuous star formation; Brzual 2009) in the BC03 SSP library. These all are consistent with the Balmer decrement measurements.

3C 445 was identified as a FR II radio source (Kronberg et al. 1986) with a round elliptical galaxy (Madrid et al. 2006) and a very bright unresolved Seyfert 1.5 nucleus (Vérón-Cetty & Vérón 2010). 3C 445 is clearly lobe-dominated with a steep radio spectrum between 2.7 and 4.8 GHz \( (\alpha_{2.7}^{4.8} = 0.7) \) and a core-to-lobe intensity ratio of \( R = 0.039 \) (Morganti et al. 1993). From the projected sizes of the supergalactic-scale biconical lobes, Eracleous & Halpern (1998) inferred an inclination of \( i > 60^\circ \). Moreover, Sambruna et al. (2007) derived an upper limit of the inclination angle \( i < 71^\circ \) using the ratio of the radio fluxes of the approaching and receding jets \( (= 7.7; \) Leahy et al. 1997). These radio results suggest that 3C 445 is viewed at a very large observation angle \( (60^\circ < i < 71^\circ) \), which is consistent with the suggestion from the reddening properties. 3C 445 appears to host an obscured AGN. Indeed, the extremely red spectral energy distribution (Elvis et al. 1984; Crenshaw et al. 1988; Kotilainen et al. 1992), the large offsets of the hydrogen Balmer and Paschen lines relative to theoretical values (Osterbrock et al. 1976; Crenshaw et al. 1988; Rudy & Tokunaga 1982), and the X-ray continuums from the XMM-Newton, ROSAT and ASCA observations (Sambruna et al. 1998, 2007), consistently imply the nuclear region of 3C 445 obscured by the circumnuclear dust. Moreover, the polarization of the continuum (Brindle et al. 1990) with a trend of decreasing polarization degree with increasing wavelength (Rudy et al. 1983) also provides solid evidence for the presence of the dust in 3C 445. Furthermore, only the obscuring assembly in the AGN unified model, i.e., the dusty torus, can provide such a large amount of dust. The observer’s line of sight to 3C 445 would pass through the dusty torus. Based on the above properties, it can be concluded that 3C 445 is seen almost edge-on.

We suspect that the observation angle of view may be the key to solving the mystery of the unique Balmer-line profiles in 3C 445. It is viewed at a large inclination angle that is actually conducive to the production of the double-peaked hydrogen Balmer and Paschen lines relative to theoretical values (the result of the outflow) in 3C 445 is irregular, and the appearance/disappearance of the blue system (the inner region under the stable supply of the disk winds, but it is possible that the outflow in 3C 445 is discontinuous. In this case, the appearance/disappearance of the blue system (the result of the outflow) in 3C 445 is irregular, and the spectral archives just happened to catch the profile variability.

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