SDSS J153636.22+044127.0 and Its Analogs: Shocked Outflows, Not Active Binary Black Holes

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Abstract

The binary emission-line system, particularly the binary broad-line emission system, is considered the most effective indicator of the black hole binary. A plausible example of such a system, SDSS J153636.22+044127.0, was reported as the first known object with two hydrogen Balmer broad-line systems, which are interpreted to be the result of broad-line regions around a pair of black holes. Here, we show the follow-up optical and near-infrared spectral observations of SDSS J153636.22+044127.0 and its analogs. In these objects, the broad hydrogen Balmer and Paschen, He I, and Mg II lines share the same peculiar emission-line profile (including a blue system, a red system, and a double-peaked disk-line component); however, the invariance of the blue system in He I λ10830 profile, and the abnormally strong emission of the hydrogen Paβ/3 blue system oppose the binary proposal. We suggest that these unique broad lines arise from the active galactic nucleus emission-line region and the shock-heated outflowing gases rather than a binary system of two active black holes.

Key words: black hole physics – quasars: emission lines – quasars: individual (SDSS J153636.22+044127.0)

1. Introduction

The quasar SDSS J153636.33+044127.0 (hereafter SDSS J1536+0441) is reported with great expectation as a candidate host of sub-parsec binary supermassive black hole (SMBH) system (Boroson & Lauer 2009). This expectation comes from the fact that it is the first known case whose peculiar hydrogen Balmer profiles exhibit two broad-line emission systems separated by ∼3500 km s⁻¹ (referred to here as the “blue system” and “red system”) but only one narrow-line emission system associated with the red system. The multiple components were expected to have arisen from two broad-line emission regions (BLRs) around a pair of black holes with masses of 10⁷.3 and 10⁸.9 M☉ and with a rotation period of ∼100 yr.

After the publication of this work, follow-up imaging and spectroscopic observations gradually deepened doubts about the binary interpretation. Images from the Very Large Array at 8.5 GHz (Wrobleski & Laor 2009) and by the European VLBI Network at 5 GHz (Bondi & Pérez-Torres 2010) resolved two parsec-scale cores separated by 0″97 (5.1 kpc), leading to the possibility of a celestial body pair, which was also confirmed by Hubble Space Telescope WFPC2/PC images (Decarli et al. 2009) and ESO/Very Large Telescope high-resolution V−K images (Lauer & Boroson 2009). The radio luminosity (L R ∼ 10⁴⁶ erg s⁻¹) and the flat radio spectrum suggest that both radio nuclei are powered by their own active galactic nuclei (AGNs) rather than by a 0.1 pc black hole binary (Bondi & Pérez-Torres 2010). The third velocity components identified in the red wing of the red system Hα and Hβ lines suggest that SDSS J1536+0441 is a double-peaked emission-line quasar (Chornock et al. 2009).

The further reconstruction of the Hα and Hβ profiles (with a circular Keplerian disk-line component and multi-Gaussian components) suggests that the unusual emission system of SDSS J1536+0441 is both a double-peaked emitter and a binary SMBH system and that the extra fluxes in the blue peaks come from the region around the secondary black hole (Tang & Grindlay 2009). However, over the almost one year difference between the rest-frame epoch of the KPNO Mayall, Palomar Hale, Keck II, and SDSS spectroscopies, the lack of velocity evolution and amplitude variation in either broad-line system appears to be too unique among either class of double-peaked emitter and black hole binary (Lauer & Boroson 2009; Chornock et al. 2010). Whether SDSS J1536+0441 is a binary and the origin of the unique emission lines, particularly the blue system, are questions that remain unanswered. From 2015 May to 2017 March, we accumulated optical and near-infrared (NIR) spectra of SDSS J1536+0441 on the Palomar 200 inch Hale telescope that can likely unravel this mystery when analyzed using archives obtained 10 years ago.

2. Observations and Analysis

The archival optical spectra of SDSS J1536+0441 used in this work were obtained from the Sloan Digital Sky Survey (SDSS; York et al. 2000) spectroscopic database and the Keck Echellette Spectrograph and Imager (ESI; Sheinis et al. 2002) archive observed by Chornock et al. (2010). The SDSS spectrum was obtained by the SDSS 2.5 m telescope with an exposure time of 4806 s on 2008 March 7. The 1D spectrum was accessed from the SDSS Data Release Seven (DR7; Abazajian et al. 2009). The SDSS spectrographs provide spectra with a high signal-to-noise ratio at a resolution of R ∼ 1800 and a wavelength range from 3800 to 9200 Å (Stoughton et al. 2002). The Keck ESI spectrum was obtained from a pair of 600 s observations on the Keck II 10 m telescope on 2009 March 22. The 0.75 arcsec slit was used, giving a resolution of ∼45 km s⁻¹ over the range of 4000–10200 Å.

Our follow-up optical spectrum of SDSS J1536+0441 was obtained with the Double Spectrograph (DBSP; Oke & Gunn 1982) on the 200 inch Hale telescope at Palomar Observatory on 2017 March 19. Two exposures of 400 s each were performed, and a 1.5 arcsec slit was used during the night.
We chose a 600/4000 grating for the blue side and a 316/7500 grating for the red side, and a D55 dichroic was selected. The setting yielded a wavelength coverage of 2778–5818 and 5358–11652 Å with median resolutions of ~1200 for the blue side and ~2800 for the red side. The follow-up optical data were calibrated using the hot subdwarf star Feige 66. The DBSP spectroscopic data were reduced following the IRAF\(^3\) standard routine. Wavelength calibration was carried out using Fe–Ar and He–Ne–Ar lamps on the same night during the observations. The standard stars were observed for flux calibrations before or after the observations of SDSS J1536+0441.

The NIR spectra of SDSS J1536+0441 were performed with the Triple Spectrograph (TSpec; Wilson et al. 2004) spectrograph on the Palomar 200 inch Hale telescope on 2015 May 24, and 2017 March 13. For each observation, four exposures of 300 s each were taken in an A-B-B-A dithering model. The TSpec spectrograph provides simultaneous wavelength coverage from 0.9 to 2.46 μm at a resolution of 1.4–2.9 Å, with two gaps at approximately 1.35 and 1.85 μm owing to the telluric absorption bands. Slits with a width of 1.0 arcsec were used, and the spectral resolution is ~2200 in the H band, where the He I λ10830 emission line is located. The follow-up NIR data were calibrated using the A0V star HD139031. The raw data of two observations were processed using the Spextool software package (Vacca et al. 2003; Cushing et al. 2004).

In order to study the properties of the emission line, a simple spline fit to the continuum beneath each emission line was first subtracted following the method of Chornock et al. (2010). The continuum windows of [2580, 2670] Å and [2890, 2950] Å for Mg II, [4320, 4720] Å and [5080, 5300] Å for Hβ; [6150, 6250] Å and [6850, 6950] Å for Hα, [1.03, 1.06] μm and [1.10, 1.12] μm for He I λ10830, and [1.19, 1.24] μm for Paβ were chosen. After that, in Figure 1, the multi-epoch emission-line profiles of Hα, Hβ, Paβ, He I λ10830, and Mg II are displayed in the velocity space at z = 0.3889. The blue system and red system are also marked by the vertical dotted lines. Two early observations of this are selected from the SDSS and Keck ESI archives. The addition of the newest spectrum from the DBSP offers us an opportunity to effectively check the profile change in a long temporal baseline (ΔT ≈ 9 yr), as the binary system would have a velocity shift in the blue system of ~100 km s\(^{-1}\) in a single year based on the projection model (Boroson & Lauer 2009). Although the original SDSS spectrum did not cover the full Hα and Mg II lines, comparisons are sufficient to present an unmistakable conclusion: there is no visible velocity shift or amplitude change in the blue system and red system, even though they were found in previous works (Lauer & Boroson 2009; Chornock et al. 2010). This is obviously inconsistent with Boroson and Lauer’s prediction. However, intriguingly, two infrared spectroscopic observations show that the He I λ10830 emission line seems to have a similar disk-line component to other lines and only one emission-line peak with the same velocity as the red system (at ~0 km s\(^{-1}\)). On the contrary, the emission-line profile of hydrogen Paβ exhibits (almost 3 times) stronger emission for the blue system than for the red system. The deviant flux ratios of the blueshifted emission-line component would have a serious impact on the binary hypothesis in the following analysis.

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As described in Tang & Grindlay (2009), the complex emission-line profile is decomposed to a bottom double-peaked emitter (e.g., Eracleous et al. 1997) plus two extra emission-line systems. The former is the disk-line component from the
accretion disk around the primary black hole, and the latter was interpreted as a binary black hole system (Boroson & Lauer 2009). In this work, we follow the method of Tang & Grindlay (2009) to describe the emission-line profile: an axisymmetric Keplerian disk-line model from Chen & Halpern (1989) for the bottom double-peaked component, one Gaussian for the blue system, and two (broad and narrow) Gaussians for the red system. With the exception of the flux strengths, other parameters for each emission line, i.e., five disk-line model parameters, velocity shift, and the width of each system, are taken directly from Tang and Grindlay's best fit for Hα.4 In particular, the disk inclination is \( i \sim 47^\circ \), the inner/outer radii are \( r_1 \sim 1000 \, r_G \) and \( r_2 \sim 13,000 \, r_G \), the velocity dispersion is \( \sigma = 1200 \, \text{km s}^{-1} \), and the surface emissivity power law is \( q = -3 \). Furthermore, the velocity shifts of the blue system and the broad and narrow components of the red system are \(-3470, 420\), and \(0 \, \text{km s}^{-1}\), and their FWHM values are \(1340, 1690\), and \(573 \, \text{km s}^{-1}\), respectively. More details can be seen in Section 2 and Table 1 of Tang & Grindlay (2009). This set of parameters also applies to the measurements of Hβ, MgII, and HeI λ10830. The fitting results are overplotted in cyan in Figure 1 for each line with least \( \chi^2 \), and the emission flux for each component are listed in Table 1.

In Figure 2, we present the flux ratios of HeI λ10830, Hβ, and Hα lines of the disk-line component, blue system, and red system. Because the HeI λ10830 line is not visible to the naked eye in the blue system, its 3σ upper limit is estimated to be \(7.4 \times 10^{-17} \, \text{erg s}^{-1} \, \text{cm}^{-2} \) from the Hα emission-line width and the observed flux errors.5

In this work, the emission-line fluxes are estimated under the assumption that the emission-line component emitting from the same gas cloud will have the same profile. We also noticed that Tang & Grindlay (2009) showed the different widths for the disk-line bottom and the red system in Hα and Hβ lines (HJ is suggested to be broader than Hα). However, the larger width of the red system in Hβ is probably due to the underestimation of the disk-line bottom in Hβ at around \(0 \, \text{km s}^{-1}\). In fact, it is hard to really distinguish the disk-line models of Hα and Hβ with current data. If the best-fit disk model for Hα is used in Hβ profile fitting, the width of the red system in Hβ could be almost the same as that in Hα.

Table 1

| Line         | Disk Line   | Blue System | Red System | Red System |
|--------------|-------------|-------------|------------|------------|
|              | (10^{-17} erg s^{-1} cm^{-2}) | (10^{-17} erg s^{-1} cm^{-2}) | (10^{-17} erg s^{-1} cm^{-2}) | (10^{-17} erg s^{-1} cm^{-2}) |
| Hα 6564.02  | 10873 ± 159 | 1519 ± 68   | 1260 ± 75  | 263 ± 43   |
| Hβ 4862.02  | 2161 ± 97  | 453 ± 52    | 260 ± 42   | 73 ± 27    |
| Paβ 12821.6 | 959 ± 84   | 220 ± 18    | 95 ± 15    | ...        |
| HeI λ10833.2| 1683 ± 61  | 74³          | 523 ± 26   | 380 ± 23   |
| MgII 2796,2803 | 2370 ± 112 | 192 ± 34    | 401 ± 35   | ...        |

Note.
³ The 3σ upper limit for the blue system of HeI λ10830.
The observed 1σ uncertainty ranges are presented with density $n_H = 10^{12}$ cm$^{-3}$, temperature $T = 10^7$ K, and extinction $E(B - V) = 0.3$, 0.4, 0.5 and 0.6. The long and narrow overlapping regions in the panels are the possible parameter space for the blue system emission lines of SDSS J1536. The allowable parameter space of Pa$\beta$/H$\alpha$ moves sharply to the high ionized region, but that of the He Iλ10830/H$\alpha$ (upper limit) exhibits almost no change, and participation of H$\beta$/H$\alpha$ further compresses the overlapping regions and rules out the excessive extinction.

Figure 4. Photoionization models of the flux ratios (hydrogen Balmer and Paschen, and He Iλ10830 relative to H$\alpha$) illuminated by the high-temperature ($T = 10^7$ K) shock. The observed 1σ uncertainty ranges are presented with density $n_H = 10^{12}$ cm$^{-3}$, temperature $T = 10^7$ K, and extinction $E(B - V) = 0.3$, 0.4, 0.5 and 0.6. The long and narrow overlapping regions in the panels are the possible parameter space for the blue system emission lines of SDSS J1536. The allowable parameter space of Pa$\beta$/H$\alpha$ moves sharply to the high ionized region, but that of the He Iλ10830/H$\alpha$ (upper limit) exhibits almost no change, and participation of H$\beta$/H$\alpha$ further compresses the overlapping regions and rules out the excessive extinction.

3. Discussion

To investigate the emission-line properties in the blue system, we employed the photoionization code Cloudy (Version 17.01, Ferland et al. 2017) and applied the measured emission-line ratios to these models to simulate the possible physical conditions and processes in the medium. The simple model is a slab-shaped gas with a unique density and homogeneous chemical composition of solar values, irradiated directly by the central ionization continuum source. For the BLR around one of the hypothesized binary black holes, such primordial models can be simply described using parameters such as density $n_H$, hydrogen column density $N_H$, ionization parameter $U$, and spectral energy distribution (SED) of the incident radiation. A typical AGN ionization continuum is applied as the incident SED, which is a combination of a blackbody “Big Bump” and power laws. The component peaks at $\approx 1$ Ryd and is parameterized by $T_{BB} = 1.5 \times 10^5$ K. The slope of the X-ray component, the X-ray to UV ratio, and the low-energy slope are set as $\alpha_x = -2$ (beyond 100 keV) and $-1$ (between 1.36 eV and 100 keV), $\alpha_x = -1.4$, and $\alpha_{UV} = -0.5$, respectively. This UV-soft SED is regarded as more realistic for radio-quiet quasars than the other available SEDs provided by Cloudy (see the detailed discussion in Section 4.2 of Dunn et al. 2010). We calculated a series of photoionization models with different ionization parameters, densities, and hydrogen column densities. The ranges of these parameters are $-4.0 \leq \log_{10} U \leq 1.0$, $3.0 \leq \log_{10} n_H$ (cm$^{-3}$) $\leq 11.0$, and $19.0 \leq \log_{10} N_H$ (cm$^{-2}$) $\leq 24.0$, with a step of 0.2 dex, which could well cover the possible parameter space of the broad-line and narrow-line regions.

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6 See details in Hazy, a brief introduction to Cloudy; http://www.nublado.org.
Figure 3, the flux ratios of $\text{He}\lambda 10830/\text{H}\alpha$ are presented in the log $U$–log $N_H$ space for the five densities (log $n_H$ (cm$^{-3}$) = 3, 5, 7, 9, and 11). The extensive parameter space is almost enough to cover all the typical possibilities of the AGN “normal” emission-line regions. However, the typical BLR gases with $n_H \sim 10^5$–$10^{10}$ cm$^{-3}$, $N_H \sim 10^{22}$ cm$^{-2}$ and $U \sim 10^{-2}$–$10^{-1}$ present the relatively strong He$\lambda 10830$ emission. If the blue system of SDSS J1536+0441 is also compared, the observed ratio of He$\lambda 10830$/H$\alpha$6564 is at least larger than 0.1, which is two times the 3σ upper limit. Further extensive calculation in a larger parameter space suggests that a parameter combination range of $U n_H \approx 10^{1.5}$ cm$^{-3}$ with an exceedingly high density of $n_H \geq 10^{12}$ cm$^{-3}$ would reproduce the observed flux ratios of the hydrogen and helium lines. If the blue system emits from such a high-density medium, the size would be 50 times less than that of the red system BLR (based on the sub-parsec binary hypothesis, in which both BLRs are illuminated by the same ionizing flux), and the number ratios of ions in the blue system and red system would be only approximately five per thousand. Even accounting for the higher emission efficiency (within an order of magnitude), the high-density medium is not sufficient to emit blue system lines comparable to those of the red system.

In previous works, we accurately measured the blueshifted emission-line system in two quasars—SDSS J00610.67+121501.2 (Zhang et al. 2017) and SDSS J163459.82+204936.0 (Liu et al. 2016)—and those of IRAS 13224–3809 and 1H 0707–495 were reported by Leighly (2004). In general, the blueshifted lines in these cases are shifted approximately one to two thousand kilometers per second, but their emitting winds are also irradiated by the AGN ionization continuum; therefore, the blue system of SDSS J1536+0441 does meet the scenario of outflowing emission lines. However, the interaction of the outflowing winds with the peripheral expanding matter provides other possible ionizing sources. A probable candidate is the photoionizing shock originating in the collision between massive outflow and the inner surface of the dusty torus. The ionizing photons are produced in the postshock plasma when it cools and diffuses to ionize the adjacent medium. In this way, the kinetic energy would eventually be dissipated through radiation. Since the outflow can be accelerated to more than several thousand kilometers per second, the shock velocity $v_s$ must be very large. In such a fast shock, the ionizing flux diffusing upstream forms a photoionization front with a velocity exceeding $v_s$. The photoionization front would thus be driven into the preshock gas, expanding as a precursor H II region ahead of the shock. Additionally, emission lines from the precursor H II region could dominate the optical emission of the shock.

The theoretical study of photoionizing shock began with the cloud–cloud collision in BELR and later covered expansion of H II regions, stellar and AGN outflows, supernova blasts, and the collision of galaxies. Great efforts has gone into developing code to simulate these processes (Sutherland et al. 1993; Allen et al. 2008). The ionizing continuum itself and the emission lines in both the shock and precursor could be evaluated. Due to the nature of the problems being studied previously, the simulation mainly covers the case of low preshock density ($n_H \leq 10^3$ cm$^{-3}$) and low shock velocity ($v_s \leq 1000$ km s$^{-1}$). In the low-density shock, various optical forbidden lines, such as [Fe II] λλ5073, 9812,10132, λλ9965,9998, λλ10491,10502,10863,11126, and λλ12570,12791, are extensively used for the diagnosis of shocks. However, all these lines are absent in the blueshifted emission component in SDSS J1536+0441. Therefore, we hypothesize that the preshock density could be much higher, a component that the previous theoretical works did not explore.

Alternatively, we use a toy model to estimate the properties of the shock in SDSS J1536+0441. Since the majority of continuum radiation produced in the cooling zone of photoionizing shock is thermal bremsstrahlung radiation, we use the continuum radiation from optically thin corona as the ionizing spectra, which is also dominated by thermal bremsstrahlung radiation and characterized by the temperature $T$. The SED of incident radiation in our model is generally consistent with the ionizing spectra evaluated by Sutherland et al. (1993). Unlike the typical AGN continuum, for high temperatures of $10^6 < T < 10^8$ K, the ionizing spectrum peaks at EUV to the soft X-ray band (100–1 Å) and falls rapidly at higher or lower energies. The photoionized medium (precursor H II region) is also described using the three parameters of the ionized gases ($U$, $n_H$, and $N_H$). Furthermore, the intrinsic value of H$\alpha$/H$\beta$ was adopted to be 3.1 for active galaxies and 2.85 for H II region galaxies (Veilleux & Osterbrock 1987); the observed large flux ratio (H$\alpha$/H$\beta$) = 3.35 ± 0.41 for the blue system, and 4.85 ± 0.83 for the red system) suggests that both emitting gases are probably obscured by the dusty torus. Therefore, an extra parameter, the external dust extinction $E(B–V)$ under the SMC extinction law, is added to the simulation process.

As we expect in a quite dense medium, $n_H$ is set to be larger than $10^{12}$ cm$^{-3}$, while $4 \leq log U \leq 4$, $19 \leq log N_H$ (cm$^{-2}$) \leq 24, and $6 \leq log T(K) \leq 8$ for the ionizing radiation. Two unique and clean emission lines (He$\alpha 10830$ and Pa$\beta$) and the strongest emission line (H$\alpha$) are chosen to investigate the properties of the gas. Their flux ratios, i.e., Pa$\alpha 12821$/H$\alpha$6564 and He$\alpha 10830$/H$\alpha$6564 (upper limit), present critical criteria for the parameters, especially $n_H$ and $T$. Theoretical calculations suggest that only in the cases with high-density ($n_H \geq 10^{12}$ cm$^{-3}$) gas illuminated by a high-temperature ($T \approx 10^7$ K) shock could the observed values for the line ratios be reproduced. The observed flux ratios of Pa$\alpha$, He$\alpha 10830$, and H$\alpha$ are presented with $n_H = 10^{12}$ cm$^{-3}$, $T = 10^7$ K, and $E(B–V) = 0.3, 0.4, 0.5$, and 0.6 (Figure 4). They exhibit different variation properties in the log $U$–log $N_H$ space with the enhancement of extinction; i.e., the allowable parameter space of Pa$\alpha$ 12821/H$\alpha$6564 moves sharply to the highly ionized region, but that of the He$\alpha 10830$/H$\alpha$6564 (upper limit) exhibits almost no change. The long and narrow overlapping regions in the panels are the possible parameter space for the blue system emission lines of SDSS J1536+0441. Furthermore, participation of H$\alpha$ 3486/H$\alpha$6564 further compresses the above mentioned regions and rules out the probability of the extinction $E(B–V) \geq 0.6$.

For example, the simulation-predicted H$\alpha$ luminosity is $2.33 \times 10^{43}$ erg s$^{-1}$ cm$^{-2}$ for $T = 10^7$ K, $n_H = 10^{12}$ cm$^{-3}$, $U = 10^{-1.5}$, $N_H = 10^{11.5}$ cm$^{-2}$, and $E(B–V) = 0.4$. The observed H$\alpha$ luminosity of the blue system is $L_{H\alpha} = (1.11 \pm 0.05) \times 10^{43}$ erg s$^{-1}$, so the area of the precursor ionizing region is $(4.78 \pm 0.21) \times 10^{53}$ cm$^2$, approximately a square with dimensions of 0.22 pc. Supposing the nucleus continuum follows the red system broad-line extinction, the corrected bolometric luminosity, $L_{bol} = 2.14 \times 10^{46}$ erg s$^{-1}$, estimated from the monochromatic luminosity at 5100 Å (Runnoe et al. 2012), suggests that the theoretical sublimation radii of the dust grains would be $R_{sub} = 1.78$ pc (Kishimoto et al. 2011; Burtscher et al. 2013). If this value is thought of as the inner side of the dusty torus, the precursor ionizing region
we observed is only a small part of the surface of the torus. In the general picture of the AGN outflow, the outflowing gases are prevalent in each AGN’s structure with a covering factor (Elvis 2000). Thus the collision shock would often be produced on or in the the inner surface of the dusty torus. However, such cases, i.e., SDSS J1536+0441 and its analogs, are extremely rare, and this phenomenon therefore may require an extreme observation angle to see the emission from the inner surface of the dusty torus through the clearance of the clumpy torus.

4. Summary

In this work, SDSS J153636.22+044127.0 and its analogs show that the dual broad emission-line system is likely to be a false-positive indicator of the black hole binary. There are actually many physical mechanisms to produce the blueshifted broad emission-line system, which are more likely to be the result of the AGN-driven or shock-heated outflowing gases. Furthermore, experience has taught us that exploring the black hole binary from the emission-line profile at optical wavelengths is limiting. For this work, spectral observations are appropriately extended to infrared (and/or ultraviolet) bands, and detection of as many high- and low-ionization emission lines as possible can help us effectively identify the true source of the anomalous emission-line system. Moreover, since possible BLRs’ mutual revolution following the orbital motion of the binary system would predict a velocity change in the blue system, long-timescale monitoring of the emission-line profile variation can further confirm the truthfulness of the binary black holes.

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Appendix A
SDSS J132052.19+574737.3

As an analog of SDSS J1536+0441, the SDSS archive provides the optical spectrum of SDSS J132052.19+574737.3 (hereafter SDSS J1320+5747 for short), which was obtained with an exposure time of 4504 s on 2013 June 10. The SDSS archive shows two broad-line emission systems. The higher redshifted “red system” at $z = 0.4567$ shows typical broad (H$_\alpha$, H$_\beta$, H$_\gamma$, and Mg II) and narrow ([O II], [O III], and [Ne III]) lines. The lower redshifted “blue system” at $z = 0.4391$ shows broad Balmer and Mg II lines. The full SDSS spectrum is shown in the top panel of Figure 5. To check the emission-line profile of He I $\lambda$10830, we obtained its NIR spectrum with the Palomar TSpec spectrograph on 2018 January 21. Two runs of four exposures of 120 s each in an A-B-B-A dithering model were performed with a slit width of 1.0 arcsec. The follow-up data were calibrated using the A0V star HD116405. The underlying continua of H$_\alpha$, H$_\beta$, and He I $\lambda$10830 are subtracted using a simple spline fit to the continuum windows, and the emission-line profiles of SDSS J1320+5747 with the underlying continua removed are shown in the bottom panels of Figure 5. For a clearer comparison, the emission-line profile of He I $\lambda$10830 is multiplied by 7. H$_\beta$ has a similar profile to H$_\alpha$, but with a higher emission peak in the blue system. The same fitting process used by Tang & Grindlay (2009) was used for the emission-line decomposition for the H$_\alpha$ profile. For the disk-line model, the velocity dispersion is set to $\sigma = 1200 \text{ km s}^{-1}$, which is a typical value for double-peaked emitters (Strateva et al. 2003), and we fix $q = -3$, as predicted in photoionization calculations (Collin-Souffrin & Dumont 1989; Dumont & Collin-Souffrin 1990). The disk inclination is $i \sim 50^\circ$, the inner radius is $r_1 \sim 700 \, r_G$, and the outer radius is $r_2 \sim 10,000 \, r_G$. When we use the combination of one Gaussian for the blue system and two (broad and narrow) Gaussians for the red system to model the extra emission-line components, the velocity shifts of the blue system and the broad and narrow components of the red system are $-3620$, 0 and 0 km s$^{-1}$, and their FWHM values are 1345, 2170, and 354 km s$^{-1}$, respectively. In the left panel of Figure 5, the best-fit components and the sum of the H$_\alpha$ emission line are shown in cyan and red. Moreover, we also plot the disk-line component and the modeled profile of H$_\alpha$ in the He I $\lambda$10830 panel. Unfortunately, any evidence of broad emission line and disk-line components is undetectable in such a low-quality spectrum, which only catches the narrow He I $\lambda$10830 line.
Appendix B

SDSS J150718.10+312942.5

Optical and NIR spectroscopic observations of SDSS J150718.10+312942.5 (hereafter SDSS J1507+3129 for short and also named as F2M1507+3129), 1 of 17 highly reddened FIRST-2MASS quasars (Glikman et al. 2004), were carried out on the Keck II 10 m telescope using the ESI and at the NASA Infrared Telescope Facility using SpeX (Rayner et al. 2003), respectively. The combined optical/NIR spectrum presented by Glikman et al. provides the distinct double-peaked profiles of Hα and Hβ emission lines and the unresolved HeI λ10830 emission line. For the high-quality profile of HeI λ10830, we obtained an improved NIR spectrum with the Palomar TSpec spectrograph on 2015 May 25. Four exposures of 400 s each in an A-B-B-A dithering model were performed with a slit width of 1.0 arcsec. The follow-up data were calibrated using the A0V star HD145647. The combined archive spectrum shows two broad-line emission systems. The higher redshifted “red system” at z = 0.9880 shows typical broad (Hα, Hβ, Hγ, and Mg II) and narrow ([O II], [O III] and [Ne III]) lines. The lower redshifted “blue system” at z = 0.9575 shows broad Balmer lines. The combined archive spectrum and the high-quality Hα emission line are shown in the top panel of Figure 6. Furthermore, the new NIR spectrum also clearly shows a double-peaked broad HeI λ10830 emission line in the K-band. Similar to the emission-line analysis of SDSS J1320+5747, the emission-line profiles of SDSS J1507+3129 with the underlying continua removed are shown in the bottom panels of Figure 6. The emission-line profile of HeI λ10830 is multiplied by 7. Hβ presents almost the same profile as Hα. The same fitting process Tang & Grindlay (2009) used for the Hα profile was also used for SDSS J1507+3129. The best-fit disk-line parameters are as follows: i ∼ 50°, r1 ∼ 650 rG, r2 ∼ 10,000 rG, σ = 1200 km s⁻¹, and q = −3. The velocity shifts of the blue system and the broad and narrow components

Figure 5. Top: the observed spectrum from the SDSS archive of SDSS J132052.19+574737.3. The two redshifted systems are presented, and the identified features are marked. The red system, at z = 0.4567, shows typical broad and narrow lines seen in quasars, including the broad Balmer and Mg II lines and the strong forbidden lines of [O II], [O III], and [Ne III]. The blue system, at z = 0.4391, shows only broad Balmer and Mg II lines. Bottom: emission-line profiles of Hα and He I λ10830 (seven times larger) of SDSS J1536+0441. The black lines are the continuum-removed spectra, and the red lines are the sum of the following decomposition components for Hα. The solid cyan line is the best-fit disk-line component, the dashed–dotted and dashed cyan lines are the Gaussian fit to the broad blue system and red system, and the dotted line is the Gaussian fit of the narrow Hα. The vertical gray dotted lines are the centers of the blue system and red system.

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in the red system are $-4610, 0$ and $0$ km s$^{-1}$ with the FWHM widths of $2005, 2241,$ and $589$ km s$^{-1}$, respectively. In the left panel of Figure 6, the best-fit components and the sum of the H$\alpha$ emission line are shown in cyan and red. Moreover, we also plot the disk-line component and the modeled profile of H$\alpha$ in the He I $\lambda$10830 panel.

Figure 6. Top: the observed spectrum from the combined archive spectrum and the follow-up high-quality H$\alpha$ emission line of SDSS J150718.10+312942.5. The two redshifted systems are presented, and the identified features are marked. The red system, at $z = 0.9880$, shows typical broad and narrow lines seen in quasars, including the broad Balmer and Mg II lines and the strong forbidden lines of [O II], [O III], and [Ne III]. The blue system, at $z = 0.9575$, shows only broad Balmer lines. Bottom: the same as Figure 5.

in the red system are $-4610, 0$ and $0$ km s$^{-1}$ with the FWHM widths of $2005, 2241,$ and $589$ km s$^{-1}$, respectively. In the left panel of Figure 6, the best-fit components and the sum of the H$\alpha$ emission line are shown in cyan and red. Moreover, we also plot the disk-line component and the modeled profile of H$\alpha$ in the He I $\lambda$10830 panel.

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