Ultradense Gas at the Dusty Torus Scale in a Partially Obscured Quasar

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Abstract

We present detailed studies of the partially obscured quasar 2MASS J151653.23+190048.2 with continuous broadband spectrophotometry from near-infrared (NIR) through optical to ultraviolet (UV). The NIR and optical spectra show strong broad emission lines, while the UV spectrum is dominated by a set of rich intermediate-width emission lines (IELs). These IELs, unshifted with respect to the quasar systemic velocity measured by narrow emission lines, share a common profile, line-of-sight component and mass of the bulge (e.g., Magorrian et al. 1998; Gebhardt et al. 2000; Merritt & Ferrarese 2001; McLure & Dunlop 2002; Tremaine et al. 2002; Häring & Rix 2004; Ferrarese & Ford 2005; Aller & Richstone 2007; Gültekin et al. 2009; Woo et al. 2010). It is generally believed that the IELs are related to the ionized gas in the dusty torus that has strong ionizing radiation from the central source. The IELs can be detected in the optical and NIR regions, and they have been studied for decades (e.g., Wills et al. 1993; Netzer & Laor 1993; Brotherton et al. 1994; Mason et al. 1996; Crenshaw & Kraemer 2007; Hu et al. 2008; Crenshaw et al. 2009; Zhu et al. 2009; Li et al. 2015, 2016; Adhikari et al. 2016, 2018). They have been detected in the partially obscured quasars (e.g., Zhan et al. 2019a, 2019b). Studying these emission lines can be quite important for understanding the physics of AGN feedback.

1. Introduction

It is well established that massive galaxies generally contain supermassive black holes (SMBHs) in their centers. Observations over the past decades have revealed tight correlations between the SMBH mass and various properties of their host galaxy, such as the velocity dispersion, luminosity, and mass of the bulge (e.g., Magorrian et al. 1998; Gebhardt et al. 2000; Merritt & Ferrarese 2001; McLure & Dunlop 2002; Tremaine et al. 2002; Häring & Rix 2004; Ferrarese & Ford 2005; Aller & Richstone 2007; Gültekin et al. 2009; Woo et al. 2010). It is generally believed that the IELs are related to the ionized gas in the dusty torus that has strong ionizing radiation from the central source. The IELs can be detected in the optical and NIR regions, and they have been studied for decades (e.g., Wills et al. 1993; Netzer & Laor 1993; Brotherton et al. 1994; Mason et al. 1996; Crenshaw & Kraemer 2007; Hu et al. 2008; Crenshaw et al. 2009; Zhu et al. 2009; Li et al. 2015, 2016; Adhikari et al. 2016, 2018). They have been detected in the partially obscured quasars (e.g., Zhan et al. 2019a, 2019b). Studying these emission lines can be quite important for understanding the physics of AGN feedback.

The identification of IELs, however, has been very elusive due to the weakness and width of IELs in line profile decompositions and results in many debates (Mason et al. 1996; Sulentic & Marziani 1999; Hu et al. 2008; Zhu et al. 2009). Recently, Li et al. (2015) reported a clear detection of IELs in the partially obscured quasar OI 287 with the aid of high-resolution spectroscopy. The detection provides strong evidence for the existence of IELs and also introduces a novel method for detecting unambiguous IELs.

The high data quality of the UV spectrum is useful in using this method to identify the IELs, as the suppression of BELs can be more easily found in UV bands where the dust extinction is more significant. The HST Space Telescope Imaging Spectrograph (STIS), with a wide wavelength range starting from the far-UV (FUV) band of 1150 Å, provides a good opportunity to

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Table 1

| Band   | Value (mag) | Facility | Observed Date (UT) |
|--------|-------------|----------|-------------------|
| FUV    | 18.494 ± 0.078 | GALEX | 2007 Apr 13 |
| NUV    | 18.049 ± 0.036 | GALEX | 2007 Apr 13 |
| u      | 16.198 ± 0.015 | SDSS | 2005 Apr 9 |
| g      | 15.614 ± 0.015 | SDSS | 2005 Apr 9 |
| r      | 15.169 ± 0.014 | SDSS | 2005 Apr 9 |
| i      | 14.592 ± 0.014 | SDSS | 2005 Apr 9 |
| z      | 14.861 ± 0.019 | SDSS | 2005 Apr 9 |
| J      | 13.437 ± 0.022 | 2MASS | 1997 Jun 15 |
| H      | 12.613 ± 0.022 | 2MASS | 1997 Jun 15 |
| K      | 11.376 ± 0.018 | 2MASS | 1997 Jun 15 |
| W1     | 10.017 ± 0.022 | WISE | 2010 Jan 30 |
| W2     | 8.869 ± 0.020  | WISE | 2010 Jan 30 |
| W3     | 6.353 ± 0.015  | WISE | 2010 Jan 30 |
| W4     | 4.424 ± 0.026  | WISE | 2010 Jan 30 |

obtain more clear UV IELs in partially obscured quasars. In this paper, we report a partially obscured quasar, 2MASS J151653.23 +190048.2 (hereafter J1516+1900), which shows rich and clear IELs in the HST/STIS UV spectrum. Our detailed analyses of these observed IELs suggest a scenario of quasar energy feedback: the quasar outflow collides with the inner wall of the dusty torus and greatly enhances both its density and temperature, and in the meantime, “lights up” the shocked gas.

This paper is organized as follows. In Section 2, we describe the observations and data reduction; in Section 3, we analyze the observational properties of broadband spectral energy distributions (SEDs), emission-line spectra, and dust extinction; in Section 4, we propose two possible origins for the quasar IELs and discuss their probabilities; and finally, we give a brief summary and implication in Section 5. Throughout this paper, we use the cosmological parameters $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.3$, and $\Omega_L = 0.7$.

### 2. Observations and Data Reduction

#### 2.1. Photometric Data

We collected the broadband photometric data of J1516+1900 from the archives of various large sky surveys, which include the Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010), Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006), Sloan Digital Sky Survey (SDSS; York et al. 2000), Galaxy Evolution Explorer (GALEX; Morrissey et al. 2007), and Chandra X-ray Observatory (Wilkes et al. 2002). The details of the multiwavelength photometric data are presented in Table 1.

#### 2.2. Spectral Data

The spectral data of J1516+1900 cover the FUV to near-infrared (NIR). Table 2 summarizes these observations, and we describe the details below.

**HST UV spectroscopy.** The UV spectrophotometry of J1516+1900 was obtained on 2002 February 11 with the STIS on board the HST (PI: Paul Smith; program ID: 9161). Two spectral observations were taken using a long slit of 52" x 0.75", One was performed using the G140L grating for a 2857 s exposure, giving an FUV spectrum with wavelength coverage from 1150 to 1730 Å; the other was obtained using the G230L grating for a 2857 s exposure, producing a near-UV (NUV) spectrum from 1570 to 3180 Å. The data were reduced and calibrated with the HST STIS pipeline. We retrieved the spectra from Mikulski Archive for Space Telescopes (MAST).  

**Hale NIR spectroscopy.** On 2016 April 20, we performed follow-up NIR spectroscopic observations of J1516+1900 using TripleSpec (Wilson et al. 2004) on the Hale Telescope. The slit has a width of 1/1. Four 300 s exposures were taken in an A-B-B-A dithering mode with the primary configuration of the instrument. These settings yielded a spectrum with a wavelength range of $\lambda \sim 0.97–2.46 \mu$m. The data were reduced with the Triplespectool package, a modified version of Specxtool (Cushing et al. 2004).

**Shane/Hale optical spectroscopy.** To acquire an optical spectrum with higher quality, we performed two spectroscopic observations. We observed this object using the Kast Double Spectrograph on the Shane Telescope at the Lick Observatory on 2016 July 4. We selected gratings with 600 lines mm$^{-1}$ for both the blue and red sides. We set the blazing angles that result in wavelength coverage of 3433–5510 Å on the blue side and 5088–7841 Å on the red side. We chose a slit with a width of 1/5 to match the seeing. We took two exposures with a time of 600 s. We also observed this object using the DoubleSpec on the Hale Telescope at Palomar Observatory on 2017 January 9. We selected gratings with 600 lines mm$^{-1}$ for the blue side and 316 lines mm$^{-1}$ for the red side. We set the blazing angles so that the wavelength coverage on the blue side is 3000–5700 Å and that on the red side is 4800–10700 Å. We chose a slit with a width of 1/5. We took two exposures with a time of 600 s. For both observations, standard stars were observed quasi-simultaneously for flux calibration. Spectra of Fe/Ar and He/Ne/Ar lamps were taken for wavelength calibration for the blue and red sides, respectively. The data reduction was accomplished with standard procedures using IRAF.  

We stacked the SDSS, Lick, and P200 spectra to form one coadded spectrum with wavelength coverage of about 3000–10700 Å. Before conducting an analysis, all of the photometric and spectroscopic data have been corrected for a Galactic reddening of $E(B − V) = 0.040$ using the updated dust map of Schlafly & Finkbeiner (2011) and converted to the rest frame of the quasar using the redshift $z = 0.1893$ determined by the peak of the [O III] $\lambda5007$ emission line.

### 3. Data Analysis and Results

#### 3.1. Broadband SED

With the multiwavelength photometric and spectroscopic data of J1516+1900, we generate its broadband SED in the rest frame spanning the infrared to the X-ray (Figure 1). The spectroscopic data are well consistent with the photometric data, indicating that flux variation is not significant among different observation epochs. As monitored in the Catalina Sky Survey from 2005 July 6 to 2013 June 16, the V-band variations of J1516+1900 are within 0.07 mag, roughly consistent with the median measurement uncertainty of 0.06 mag. Therefore, the variability of J1516+1900 in the optical band is insignificant.

For comparison, we overplot the composite quasar spectrum (Shang et al. 2011) and normalize it to the SED of J1516+1900

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5 http://archive.stsci.edu/

6 IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

7 http://nsssi.cacr.caltech.edu/DataRelease/
at the WISE W3 band. In the long-wavelength range (λ > 1 μm), the SED of J1516+1900 is consistent with the composite quasar spectrum. In contrast, toward shorter wavelengths, the continuum flux level of J1516+1900 gradually decreases in the optical band and sharply decreases in the UV band. We zoom in on this wavelength range in the inset panel to make a better demonstration. We redden the quasar composite spectrum (red line) using the SMC extinction curve with an E(B − V) of 0.32 and find it can well match the observed SED of J1516+1900.

![Figure 1. Broadband SED of J1516+1900 in the rest frame spanning the infrared to the X-ray. The composite quasar spectrum (blue line) normalized at WISE W3 is overplotted for comparison. The observed SED of J1516+1900 is identical to the composite quasar spectrum in the longward portion (λ > 1 μm), while it decreases in the shortward portion. We zoom in on the short-wavelength region in the inset panel to make a better demonstration. We redden the quasar composite spectrum (red line) using the SMC extinction curve with an E(B − V) of 0.32 and find it can well match the observed SED of J1516+1900.](image)

Figure 1. Broadband SED of J1516+1900 in the rest frame spanning the infrared to the X-ray. The composite quasar spectrum (blue line) normalized at WISE W3 is overplotted for comparison. The observed SED of J1516+1900 is identical to the composite quasar spectrum in the longward portion (λ > 1 μm), while it decreases in the shortward portion. We zoom in on the short-wavelength region in the inset panel to make a better demonstration. We redden the quasar composite spectrum (red line) using the SMC extinction curve with an E(B − V) of 0.32 and find it can well match the observed SED of J1516+1900.

Table 2

| Wavelength Range (Å) | Slit Width (arcsec) | λ/Δλ | Exp. Time (s) | Instrument | Data (UT) |
|----------------------|---------------------|------|--------------|------------|-----------|
| 1150–3180            | 0.5                 | 1200, 755 | 2857, 2311   | HST/STIS   | 2002 Feb 11 |
| 3433–7841            | 1.5                 | 2195, 1385 | 600 × 2      | Shane/DoubleSpec | 2016 Jul 4 |
| 2500–10700           | 1.5                 | 800, 1700 | 600 × 2      | Hale/DoubleSpec | 2017 Jan 9 |
| 9720–24629           | 1.5                 | 3500   | 300 × 4      | Hale/TripleSpec | 2016 Apr 20 |

The SMC has a gas-to-dust ratio of N_H/E(B − V) = 3.7–5.2 × 10^{21} cm^{-2} mag^{-1} (Bouchet et al. 1985), which is larger than that for the Milky Way (5.0 × 10^{21} cm^{-2} mag^{-1}; Burstein & Heiles 1978) and the Large Magellanic Cloud (2 × 10^{21} cm^{-2} mag^{-1}; Koomen 1982).
are dominated by an intermediate-width component, while their broad components are almost completely absent. More interestingly, on the blue sides of the strongest UV lines of Ly$\alpha$, N V $\lambda 1240$, and C IV $\lambda 1549$, there is also a relatively weaker component, blueshifted by $\sim 2500$ km s$^{-1}$. The optical and NIR emission lines (such as H$\beta$, H$\alpha$, Pa$\beta$, and Pa$\alpha$) are dominated by their broad components.

We decompose the main emission lines of J1516+1900 into broad, narrow, and intermediate-width components to measure the strengths of different emission-line components. The method of line decomposition is similar to that described in detail in Li et al. (2015), with small modifications. A single Gaussian is performed to model the narrow and intermediate components, and two Gaussians are performed for the broad component. The same components in different lines are assumed to have the same redshift and line width. For the doublets of O VI $\lambda\lambda 1032, 1037$, N V $\lambda\lambda 1239, 1243$, Si IV $\lambda\lambda 1394, 1403$, C IV $\lambda\lambda 1548, 1551$, and Al III $\lambda\lambda 1855, 1863$, each doublet component is modeled separately with their relative intensity ratios fixed at 1:1, assuming that the emission is optically thick. The O IV $\lambda 1402$ is heavily blended with the Si IV $\lambda 1397$, together producing a broad $\lambda 1400$ feature. The O IV $\lambda 1402$ is a multiplet of five components with rest wavelengths of $\lambda 1397, \lambda 1400, \lambda 1401, \lambda 1405$, and $\lambda 1407$. As the shortest-wavelength O IV component is at 1397 Å, the left portion of the $\lambda 1400$ feature should be due to Si IV $\lambda 1394$ only (see Laor et al. 1997). The right portion of the $\lambda 1400$ feature is stronger than the left one. The excess flux should be contributed by O IV in the case of optically thick (Si IV $\lambda 1403$ is equal to Si IV $\lambda 1394$). Since here we are only interested in the total flux of the five O IV components, and reliably decomposing the seriously blended O IV is almost impossible, we use one Gaussian to roughly fit O IV. The forbidden lines [O III] $\lambda\lambda 4959, 5007$ are modeled with two components, one narrow component for the line core and one free Gaussian component for the blue wing. An additional
broad Gaussian is performed to eliminate the influence of the Hβ “red shell” (Meyers & Peterson 1985; Véron et al. 2002), a red wing extending underneath the [O III] doublet. Absorption lines and bad pixels are carefully masked during the fitting process. The best-fit results are shown in Figure 3, and the emission-line parameters are summarized in Table 3.

### 3.3. Extinction Analysis for Emission-line Regions

With the measurements of BELs, we first investigate the extinction for the BEL region (BELR) using the intensity ratios of BELs in J1516+1900 to those in the composite quasar spectra (Vanden Berk et al. 2001; Scott et al. 2004; Harris et al. 2016). Figure 4 presents the derived intensity ratios of J1516+1900 BELs to composite quasar BELs. The intensity ratios are normalized to unity at Paα. For those blended lines, we use the summed intensities (including Lyγ + C III λ977, Lyβ + O VI λ1035, Lyα + N V λ1240, Si IV λ1397 + O IV λ1402, and Si III] λ1892 + C III] λ1909) for both J1516+1900 and the composite spectrum to reduce the uncertainties of the line decompositions. In the shorter-wavelength range, the BELs (such as Lyγ, C III λ977, N III λ991, Lyβ, and O VI λ1035) are too weak to be reliably measured, but these lines can put strong constraints on estimating the BELR extinction. We use their 3σ upper limits to constrain the extinction. As shown in Figure 4, the intensity ratios gradually decrease toward shorter wavelengths, which can be well modeled by the SMC extinction curves with an $E(B-V)$ of 0.35 ± 0.04.

On the other hand, the prominent presence of UV IELs in the observed spectrum indicates that dust extinction is not significant for the IEL gas. We first investigate the IEL extinction through the intensity ratio of Lyα/Lyγ. Here we use Lyγ rather than Lyβ, since Lyγ is more sensitive to dust extinction and also more reliably measured than Lyβ. The observed Lyα/Lyγ in J1516+1900 IELs is 20.5 ± 4.16. The intrinsic intensity ratio of Lyα/Lyγ indicated by photoionization calculations is as large as a few $\sim 10^3$ in the low-density condition and in a range of $\sim 10^{-2}$ in the high-density condition. For the high-density case, and by assuming an SMC extinction curve, the extinction value of the IEL gas is roughly estimated to be $E(B-V) \lesssim 0.03$. We also estimate the extinction through the intensity ratio of Paα/Lyα. The observed Paα/Lyα value of 0.0364 ± 0.0127 and the intrinsic Paα/Lyα range of $\sim 0.005$–$0.01$ indicate an extinction value of $E(B-V) \sim 0.07$–$0.11$. It is relatively larger than the extinction value derived by Lyα/Lyγ. This might be due to the large

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**Table 3**

| Line     | BEL Flux (10^{-17} erg s^{-1} cm^{-2}) | IEL          | Blueshifted Line |
|----------|----------------------------------------|--------------|------------------|
| Lyγ      | <15.3                                  | 7.56 ± 0.931 × 10^3 |                  |
| C III λ977 | <21.7                                  | 1.39 ± 0.162 × 10^3 |                  |
| N III λ991 | <24.1                                  | 1.80 ± 0.182 × 10^3 |                  |
| Lyβ      | <63.6                                  | 1.07 ± 0.315 × 10^3 |                  |
| O VI λ1035 | <4.68 × 10^2                           | 1.34 ± 0.213 × 10^4 |                  |
| Lyα      | 4.12 ± 0.547 × 10^3                    | 1.55 ± 0.102 × 10^4 | 1.44 ± 0.221 × 10^3 |
| N V λ1240 | 1.53 ± 0.223 × 10^3                    | 1.57 ± 0.116 × 10^3 | 1.85 ± 0.304 × 10^3 |
| Si IV λ1397 | <9.03 × 10^2                         | 3.42 ± 0.448 × 10^3 |                  |
| O IV] λ1402 | <5.28 × 10^2                         | 1.08 ± 0.166 × 10^3 |                  |
| C IV λ1549 | 3.80 ± 0.602 × 10^3                    | 9.57 ± 0.823 × 10^3 | 8.71 ± 1.54 × 10^2 |
| Al III λ1860 | 1.73 ± 0.283 × 10^2                 | 4.63 ± 0.519 × 10^2 |                  |
| Si III] λ1892 | 3.39 ± 0.614 × 10^3                | 1.68 ± 0.207 × 10^2 |                  |
| C III] λ1909 | 6.33 ± 0.715 × 10^3                  | <10.9 |                  |
| Hβ       | 4.29 ± 0.287 × 10^4                    | 8.48 ± 1.45 × 10^2 |                  |
| Hα       | 1.97 ± 0.110 × 10^5                    | 7.61 ± 1.27 × 10^2 |                  |
| Paα      | 1.58 ± 0.141 × 10^4                    | 4.10 ± 0.78 × 10^2 |                  |
| Paβ      | 1.87 ± 0.146 × 10^4                    | 6.61 ± 1.23 × 10^2 |                  |

| –5.51±0.0517 × 10^2 | 61.9 ± 5.06 | –2.61±0.0332 × 10^3 |

| 6.33±0.116 × 10^3 | 1.92±0.106 × 10^3 | 2.37±0.651 × 10^3 |

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5 Previous research suggested that the red shell might be originated from (a) broad Hβ, (b) broad O III λλ 4959, 5007, (c) He I λλ 4922, 5016, or (d) Fe II. It is unlikely that this feature in J1516+1900 originates from Hβ emission, since it is absent in the Hα, Hγ, and Paschen lines. Detailed study of this feature is beyond the scope of this paper, and we simply use an additional broad Gaussian to phenomenologically describe this component.
uncertainty of measuring the Paα IEL component, since Paα is dominated by the BEL component. Although these estimations are somewhat rough, they suggest that the IELs of this quasar should be produced in a dense region without much dust extinction.

### 3.4. Optical Fe II Emission

The optical Fe II multiplet emission is prominent in the spectrum of J1516+1900. Its equivalent width for the Fe II λ4570 blend in the 4434–4684 Å region is about 86 Å. The relative strength of the optical Fe II emission is generally believed to be correlated with the accretion rate in AGNs (e.g., Dong et al. 2011). The accretion rate of AGNs is often quantified by the parameter of the dimensionless accretion rate ($\dot{M}/L_{\text{Edd}}$) or the Eddington ratio ($L_{\text{bol}}/L_{\text{Edd}}$), where $\dot{M}$ is the mass accretion rate, $L_{\text{bol}}$ is the bolometric luminosity, and $L_{\text{Edd}}$ is the Eddington luminosity. Du et al. (2016) found that the accretion rate can be roughly estimated using the combination of the intensity ratio of optical Fe II to broad Hβ ($R_{\text{Fe II}}$) and the profile of the broad Hβ line ($D_{\text{H}\beta} = \text{FWHM}/\sigma_{\text{Fe II}}$). According to this relation and using the observed values of $R_{\text{Fe II}} \approx 0.49$ and $D_{\text{H}\beta} \approx 1.68$ in this quasar, we found that J1516+1900 has a moderate accretion rate, $\dot{M} \approx 2.8$, and $L_{\text{bol}}/L_{\text{Edd}} \approx 0.21$.

### 4. Discussion

#### 4.1. AGN Ionization Model

With the measurements for the rich UV IELs in J1516+1900, we investigate the physical condition of the IEL gas by combining a photoionization simulation using the CLOUDY code (version 13.03; Ferland et al. 1998). We consider a slab-shaped gas that is illuminated by an AGN source with an AGN SED defined by Mathews & Ferland (1987, hereafter MF87). For simplicity, we assume that the gas has a unique density, and a homogeneous chemical composition of solar values. The total column density ($N_{\text{H}}$) of the gas increases with a grid of $10^{20}$, $10^{21}$, and $10^{22}$ cm$^{-2}$. For each $N_{\text{H}}$, we calculate a two-dimensional grid with a variable hydrogen number density ($n_{\text{H}}$) and ionization parameter ($U$). The IEL gas of this quasar may have a large gas density, as mentioned in Section 3.3. Besides, the N V λ1240 of this quasar is very strong compared with Lyα, which indicates that the emitting gas has a very high density (see Rees et al. 1989). Here we consider a wide $n_{\text{H}}$ range from $n_{\text{H}} = 10^9$ cm$^{-3}$ to a high value of $n_{\text{H}} = 10^{14}$ cm$^{-3}$. As there are high-ionization IELs in the observed spectra, such as O VI, N V, and C IV, the IEL gas may also have a relatively high ionization parameter. We restrict the range of $U$ to be from $U = 10^{-3}$ to 1. Both $n_{\text{H}}$ and $U$ vary with a step of 0.5 dex.

In total, there are three parameters, $n_{\text{H}}$, $U$, and $N_{\text{H}}$, in the simulation. We constrain these parameters using the observed IEL ratios measured in J1516+1900. As shown in Figure 5, for each $N_{\text{H}}$, we plot the contours of the line intensity ratios (including Lyα/Lyγ, C IV/λ1549/λ1551, N V/λ1240/λ1242, and Si iv/λ1400) as functions of $n_{\text{H}}$ and $U$ for $N_{\text{H}} = 10^{20}$, $10^{21}$, and $10^{22}$ cm$^{-2}$. The shaded areas represent 1σ observation ranges. The five groups of intensity ratios give a best solution of $n_{\text{H}} = 10^{20.9}$ cm$^{-3}$, $U = 10^{-1.8}$, when $N_{\text{H}} = 10^{21}$ cm$^{-2}$. The gray dashed lines represent the distance of the emission-line region to the ionizing source, calculated as $R = (Q(\text{H})/4\pi U n_{\text{H}})^{0.5}$. With the constrained $n_{\text{H}}$ and $U$, the distance of the IEL gas to the ionizing source is derived to be only $\sim 0.027$ pc.

With the above constrained $n_{\text{H}}$ and $U$, we estimate the distance of the IELR to the ionizing source ($R_{\text{IELR}}$). According to the definition of $U$, $R_{\text{IELR}}$ can be expressed as

$$R_{\text{IELR}} = \frac{Q(\text{H})}{4\pi U n_{\text{H}}} = \frac{\int_{0}^{\infty} L_{\nu}/h\nu d\nu}{4\pi U n_{\text{H}}},$$

where $Q(\text{H})$ is the number of photons emitted by the ionizing source per second that can ionize hydrogen, $L_{\nu}$ is the specific luminosity of the ionizing source, and the integral is over all hydrogen-ionizing photons. Using the dust extinction-corrected continuum and assuming an MF87 SED, we have $Q(\text{H}) \approx 3.5 \times 10^{50}$ photons s$^{-1}$. Once $U$ and $n_{\text{H}}$ are given, $R_{\text{IELR}}$ can be inferred from Equation (1). In Figure 5, we also plot the contours (dotted lines) of $R_{\text{IELR}}$ as functions of $n_{\text{H}}$ and $U$. With the above constrained $n_{\text{H}}$ and $U$, we found that $R_{\text{IELR}}$ has a small value of $\sim 0.027$ pc.

Such a small distance, however, is significantly smaller than the BELR radius ($R_{\text{BELR}}$) of J1516+1900. The BELR radius is suggested to scale with the continuum luminosity (the...
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$R_{\text{BELR}} - L$ relation) indicated by reverberation mapping studies (e.g., Kaspi et al. 2000, 2005; Peterson et al. 2004; Bentz et al. 2006, 2009). Adopting the empirical correlation between $R_{\text{BELR}}$ and the optical continuum luminosity at 5100 Å (Bentz et al. 2009), the BELR radius of J1516+1900 is estimated to be $R_{\text{BELR}} \approx 0.17$ pc. Negrete et al. (2013) proposed a photoionization method to determine the size of the BELR based on the product $n_{\text{H}}U$ by analyzing UV lines. This study indicated that the BELR is well stratified with two different solutions for $n_{\text{H}}U$: a high-density, low-ionization solution and a low-density, high-ionization solution. Only the high-density solution showed good agreement with the results from reverberation mapping, whereas the low-density case has a much larger radius. Thus, the estimation from the $R_{\text{BELR}} - L$ relation of Bentz et al. (2009) could correspond to the size of the BELR inner zone. Recent reverberation mapping campaigns (e.g., Du et al. 2018) refined the $R_{\text{BELR}} - L$ relation by taking into account the accretion rate. The new research suggested that the BELR size should be smaller than that estimated from the canonical $R_{\text{BELR}} - L$ relation for sources with high accretion rates ($\dot{M} > 3$). This might not seriously affect our estimations of $R_{\text{BELR}}$ for J1516+1900, since this quasar has a moderate accretion rate of $\dot{M} \sim 2.8$ (see Section 3.4). According to the new revised formula of estimating $R_{\text{BELR}}$ (Equation (6) of Du et al. 2018), the BELR radius of J1516+1900 is derived to be $R_{\text{BELR}} \sim 0.16$ pc, consistent with the value of 0.17 pc estimated from the relation of Bentz et al. (2009). In short, these estimations show that the BELR radius of J1516+1900 is significantly larger than $R_{\text{BELR}}$. It is very interesting and confusing that the IELR with a smaller radius is not obscured, while the BELR of this quasar is shown to be obscured by dust grains.

The “failed wind” model (e.g., Proga & Kallman 2004; Sim et al. 2010) is a possible mechanism that avoids materials located in the inner accretion disk to be obscured. In the inner region of the accretion disk, the material is launched from the disk plane driven by local disk UV line radiation but not accelerated to reach escape speed due to overionization by central X-ray radiation. The wind eventually falls back to the disk plane. This scenario results in a failed wind, which has quite a high density at large scale heights above the disk plane (Proga 2005). Besides, the magnetic field in the inner disk can help to stir the material up to even greater scale heights and result in a larger covering factor (Schurch & Done 2006). This model allows the failed wind to be directly observed, even though the disk UV—optical radiation region and the BELR are obscured in the observer’s line of sight. The failed wind blocks the central X-ray and extreme UV radiation and prevents the outer wind from being overionized, as well as being ionized itself, and can produce emission lines through photoionization processes. However, the velocity dispersion of the failed wind is expected to be very large, since the failed wind locates in the inner accretion disk. The rotation velocity in the radius of the IELR is estimated to be $\sim 10^4$ km s$^{-1}$, much larger than the observed IEL velocity. Therefore, it is unlikely to result in emission lines with intermediate widths through the failed wind model.

4.2. Shock Ionization Model
4.2.1. Extra Ionizing Source

A reasonable explanation for the IELs of this quasar may be that the ionizing source of the IELs is not the center accretion disk but rather an extra ionizing source located in an outer position, where gas cannot be obscured in the line of sight. In fact, the line widths (FWHM $\approx 1900$ km s$^{-1}$) of the IELs indicate that the emission lines should originate from somewhere located at the scale of the dusty torus. Assuming both the BELR and IELR are bounded by the gravity of the central black hole, the distance of the IELR to the central black hole is derived as

$$R_{\text{IELR}} = \left( \frac{f_b V_{\text{BELR}}}{f_i V_{\text{IELR}}} \right)^2 R_{\text{BELR}},$$

where $V_{\text{BELR}}$ and $V_{\text{IELR}}$ are the gas velocity distribution for the BELR and IELR, respectively. The scale factors ($f_b$, $f_i$) for the BELR and IELR depend on the structure, kinematics, and orientation of the gas emission regions. As a simplified estimation, we assume $f_b/f_i = 1$. With the observed line widths of FWHM(BELs) and FWHM(IELs) (see Table 3) in J1516+1900 and the estimation of $R_{\text{BELR}}$ (see Section 4.1), we derived a rough estimation of $R_{\text{IELR}} = (\text{FWHM(BELs)} / \text{FWHM(IELs)})^2 R_{\text{BELR}} \approx 1.8$ pc.

This approximates to the scale of the inner radius of the dusty torus ($R_{\text{in}}$). Usually, the inner edge of the dusty torus is determined by the boundary where dust grains are sublimated by the irradiation from the central ionizing source. According to the formula of Barvainis (1987), the inner radius of the dusty torus can be roughly estimated as

$$R_{\text{in}} = 1.3 \left( L_{\text{uv,146}} / T_{1500} \right)^{0.5},$$

where $L_{\text{uv,146}}$ is the UV luminosity of the central source in units of $10^{46}$ erg s$^{-1}$, and $T_{1500}$ is the grain sublimation temperature in units of 1500 K. For dust grains with a sublimation temperature of about 1500 K and the extinction-corrected UV continuum luminosity of J1516+1900, this quasar’s inner radius of the dusty torus is estimated to be $R_{\text{in}} \approx 1.0$ pc. The comparison between $R_{\text{in}}$ and $R_{\text{BELR}}$ implies that the IELs observed in J1516+1900 may arise from somewhere located at the inner edge of the dusty torus.

The inner part of the dusty torus, however, usually has a number density of $\sim 10^{25}$ cm$^{-3}$ (Netzer 2013). This is much lower compared with the IELR number density $n_{\text{H}} \sim 10^{13}$ cm$^{-3}$ estimated above. To produce such ultradense gas at the scale of the dusty torus, a very possible mechanism is shock. Figure 6 displays a cartoon to illustrate this shock scenario. The outflowing wind is launched from the inner accretion disk and accelerated by disk UV line radiation. When it arrives at the dusty torus scale, the outflowing gas accumulates high kinetic energy and collides with local materials. The collision rapidly compresses the gas and greatly enhances the gas density and temperature. The heated hot gas, as an extra ionizing source, ionizes the adjacent medium through emitting strong extreme UV and soft X-ray ionizing radiation. These ionizing photons can lead to significant photoionization effects for producing the UV and optical emission lines. Since the dusty torus is suggested to be very clumpy or filamentary (e.g., Krolik & Begelman), some isolated clouds may be distributed in surrounding areas. If the outflow collides with these isolated small clouds, a large fraction of its momentum could be retained during a slight collision process, and only a small fraction of its kinetic energy can be converted to radiation energy. This collision gives rise to the blueshifted emission lines. However, when the outflow collides with the main body of the huge dusty torus, more of its momentum will be lost through a violent collision process, and a larger fraction of its kinetic energy can be converted to radiation energy.
energy. In this case, the collision results in the unshifted IELs. The observer’s line of sight passes through the boundary of the dusty torus. The central accretion disk and BELR are obscured by the dusty grains, while the shock-induced photoionization region is not. This results in the reddened SED and BELs and clearly detected UV IELs in J1516+1900.

### 4.2.2. Simulation of Shock Photoionization Model

To check this supposition, we also perform a simulation for the shock model. The simulations of the shock-induced photoionization have been developed by previous studies (e.g., Sutherland et al. 1993; Allen et al. 2008). The MAPPINGS III code (Allen et al. 2008) provides a convenient tool to evaluate the radiation in both the radiative shock and its photoionized precursor. This simulation, however, is limited in the case of a low-density ($\lesssim 10^3$ cm$^{-3}$) and low-velocity ($\lesssim 1000$ km s$^{-1}$) shock due to previously focused phenomena, such as expansion of the H II region, outflows from young stellar objects, supernova blast waves and galaxies, and collisions of cloud–cloud or galaxy–galaxy. Recently, Zhang et al. (2019a) made a simplified model to estimate the radiation of high-density ($\gtrsim 10^{12}$ cm$^{-3}$) shock-induced photoionization. This study used the continuum radiation from the optically thin corona as the ionizing spectra, since the majority of the continuum radiation produced in the cooling zone of the photoionizing shock is thermal bremsstrahlung radiation, and the optically thin corona is also dominated by thermal bremsstrahlung radiation. The SED of the incident radiation in this model is generally consistent with the ionizing spectra evaluated by Sutherland et al. (1993). The ionizing spectra are characterized by the temperature $T$, and the photoionized medium is also described using the three parameters of the ionized gas, $U$, $n_H$, and $N_H$. Following the model of Zhang et al. (2019b), we performed a similar simulation using CLOUDY to investigate the properties of IELs in J1516+1900. We consider a possible temperate range of $10^3 K < T < 10^7 K$. The settings of $U$ ($10^{-3} - 10^9$), $n_H (10^9 - 10^{14}$ cm$^{-3}$), $N_H (10^{20} - 10^{22}$ cm$^{-2}$), and metallicity (solar) are the same as those in the above AGN photoionization model.

In Figure 7, we plot the SED profiles of the incident radiation in the left column. Unlike an AGN SED, these SED profiles peak at the extreme UV to soft X-ray band and fall rapidly at higher energy. In the right three columns of Figure 7, we show the contours of the line intensity ratios as functions of $n_H$ and $U$ for $N_H = 10^{20}, 10^{21},$ and $10^{22}$ cm$^{-2}$. In the case of $T = 10^6$ K and $N_H = 10^{22}$ cm$^{-2}$, the five groups of diagnostic ratios derive a best solution of $n_H \sim 10^{13.1}$ cm$^{-3}, U \sim 10^{-1.55}$.

Adopting the parameters derived above, we use the CLOUDY code to export the predicted intensities for all of the UV IELs (including Ly$\gamma$, C III $\lambda$977, N III $\lambda$991, Ly$\beta$, O VI $\lambda$1035, Ly$\alpha$, N V $\lambda$1240, Si IV $\lambda$1397, O IV $\lambda$1402, C IV $\lambda$1549, Al III $\lambda$1860, Si III $\lambda$1892, and C III $\lambda$1909) observed in J1516+1900. We thus compare these line intensities predicted by the shock model with those observed in
J1516+1900. The comparison results are shown in Figure 8. Both the model-predicted and the observed intensities are normalized to Lyα, and the observed IEL intensities are corrected for the slight dust extinction as analyzed in Section 3.3. As shown in Figure 8, the IEL intensities observed in J1516+1900 are generally consistent with those predicted by the shock model.

Among these IELs, there are some semiforbidden lines, including O IV λ1402, Si III λ1892, and C III λ1909. All of these semiforbidden lines are significantly suppressed at the high density of $10^{13}$ cm$^{-3}$. The faintness of these semiforbidden lines is a natural consequence of the high density. The suppression of O IV λ1402 and Si III λ1892 enhances the line ratios of O VI/O IV and Si IV/Si III and thus makes them sensitive diagnoses for high-density gases. The C III λ1909 is seriously suppressed due to its much lower critical density, $n_{\text{crit}} = 1.4 \times 10^{10}$ cm$^{-3}$. The IEL component in C III λ1909 is too weak to be reliably measured. Its upper limit, shown in Figure 8, is much weaker compared with other lines.

The preshock zone is also photoionized by the radiation of the shock front. However, the number density of the preshock zone ($n_H \sim 10^6-10^9$ cm$^{-3}$) is 4–7 orders of magnitude lower than that of the postshock zone ($n_H \sim 10^{13}$ cm$^{-3}$). The emissivity $j$ in both the preshock and postshock obeys the high-density limit relation of $j \propto n_H$. The observed IELs of this quasar should be almost contributed by the postshock zone. This is also consistent with the weakness of the semiforbidden C III λ1909 IEL component.

Figure 7. Photoionization simulations of gas illuminated by a shock-induced ionizing source with a temperature of $10^5$ (top), $10^6$ (middle), and $10^7$ K (bottom). For each temperature, the corresponding SED profile of the ionizing source is shown in the left column. In the right three columns, we plot the contours of the line intensity ratios as functions of $n_H$ and $U$ for $N_H = 10^{20}, 10^{21},$ and $10^{22}$ cm$^{-2}$. The shaded areas represent the observed ranges. When $T = 10^6$ K and $N_H = 10^{21}$ cm$^{-2}$, the five groups of intensity ratios give a best solution of $n_H \sim 10^{13}$ cm$^{-3}$, $U \sim 10^{-1.5}$.

Figure 8. Comparison between the shock model-predicted and observed line intensities for all of the UV IELs in J1516+1900. Both the model-predicted and observed line intensities are normalized by Lyα. The dashed line represents a 1:1 relationship.

4.2.3. Estimating Line Luminosity

The shock simulation shows that the relative intensity ratios of IELs are generally consistent with the shock photoionization model. It is worth further exploring whether the luminosity of
IELs is accounted for in this model. Estimating the line luminosity is extremely difficult, since most parameters have larger uncertainties than the currently limited information. However, it is meaningful to have an order-of-magnitude rough estimation for a comparison with the observation.

The collision between the outflow and the dusty torus converts the kinetic energy of the outflow into thermal energy and consequently increases the gas temperature. For an ideal case of completely inelastic collision, the kinetic energy of the outflow is totally transformed to thermal energy. Under this situation, the typical temperature of the collided gas is estimated to be

\[ T = \frac{1}{2} m_p v^2 / k, \]

where \( m_p \) is the proton mass, \( v \) is the outflow velocity, and \( k \) is the Boltzmann constant. The outflow velocity of the IEL component is unknown but may approximate to the blueshifted component, \( v \approx 2600 \) km s\(^{-1}\). With this approximation, the gas temperature is estimated to be \( T \approx 4.1 \times 10^4 \) K. It is 2 orders of magnitude higher than the shock temperature \( T_{\text{shock}} \approx 10^6 \) K inferred from the shock model simulation. This oversimplified calculation implies that only a small fraction of the outflow kinetic energy is eventually transformed to gas thermal energy. The conversion efficiency of kinetic energy to thermal energy is estimated to be

\[ \eta = \frac{k T_{\text{shock}}}{\frac{1}{2} m_p v^2} \approx 0.24\%. \]

Such a low value of conversion efficiency \( \eta \) may be due to the clumpy structure of the dusty torus (i.e., the volume filling factor of all clouds \( \phi \ll 1 \); Nenkova et al. 2008). In this situation, only a small part of the outflow kinetic energy can be captured by the dusty torus and transformed to the thermal energy of hot gas.

The mass outflow rate of the outflowing wind can be roughly estimated as (see Williams et al. 2017)

\[ M_{\text{out}} = n_c m_p \Omega r^2 v, \]

where \( n_c \) is the number density of outflowing clouds, \( f \) is the filling factor of outflowing clouds, \( \Omega \) is the solid opening angle of the outflow, and \( v \) is the velocity of the outflow at the distance \( r \). Both \( n_c \) and \( f \) are unknown; we adopt the typical values of a quasar BELR, \( n_c \sim 10^{11} \) cm\(^{-3}\), \( f \sim 10^{-3} \) (Peterson 1997), as order-of-magnitude approximations, since the outflow should be arising from the central region. The opening angle \( \Omega \) of the outflow is also unknown but might be roughly estimated with the statistical fraction of broad absorption line quasars (\( f_{\text{BALQSOs}} \approx 0.17 \); Knigge et al. 2008), \( \Omega \sim 4 \pi f_{\text{BALQSOs}} \approx 2.1 \) sr. By taking \( r \) as the inner radius of the dusty torus \( r \approx 1 \) pc and assuming \( v \approx 2600 \) km s\(^{-1}\) again, we derive a rough estimation of the mass outflow rate, \( M_{\text{out}} \approx 1.4 \times 10^4 M_\odot \) yr\(^{-1}\).

The kinetic power of the outflow is then given as

\[ P_{k,\text{out}} = \frac{1}{2} M_{\text{out}} v^2 \approx 3.0 \times 10^{46} \text{ erg s}^{-1}. \]

As demonstrated before, only a small fraction of the kinetic energy can be converted to thermal energy. Multiplying by the conversion efficiency \( \eta \) estimated above, the luminosity of the collided hot gas caused by the shock is calculated as

\[ L_{\text{shock}} = n f_{\text{r},\text{out}} \approx 7.3 \times 10^{43} \text{ erg s}^{-1}. \]

The thermal energy of the collided hot gas further converts to radiation energy, which ionizes the surrounding gas and produces emission lines. For optically thick pure hydrogen gas, every photoionization ultimately results in one Ly\(\alpha \) photon (Peterson 1997). If all of the ionizing photons are absorbed, the number of ionizing photons equals the number of Ly\(\alpha \) photons. Thus, the Ly\(\alpha \) line luminosity can be estimated as

\[ L(L_{\text{Ly}\alpha}) = Q(\text{H}) h v_\text{Ly}\alpha \]

\[ = \int_{v_0}^{\infty} L_{\nu} d\nu h v_\text{Ly}\alpha \]

\[ \approx 1.3 \times 10^{43} \text{ erg s}^{-1}, \]

where \( L_{\nu} \) is taken from the SED profile of the 10\(^6\) K shock ionizing source (see Figure 6) and calibrated as \( \int_{v_0}^{\infty} L_{\nu} d\nu = L_{\text{shock}} \). Here we have assumed that the ionizing source is totally covered by optically thick gas. This may lead to somewhat overestimating the covering factor but should not be very serious, since the collision process can compress the gas and increase the covering factor. The estimated line luminosity has the same order of magnitude as the observed Ly\(\alpha \) IEL luminosity of \( 1.58 \times 10^{43} \) erg s\(^{-1}\). It is necessary to recall that the estimation may have a large uncertainty, as some parameters cannot be well constrained.

5. Summary and Implications

We presented a detailed analysis of the partially obscured quasar J1516+1900 with its archived data and follow-up observations. Both its broadband SED and BELs are reddened, while its UV spectrum shows rich and clear IELs with a FWHM of about 1900 km s\(^{-1}\). With the aid of these observed IELs, we analyzed in detail two possible origins for the IELs in this quasar. By assuming that the IELs are photoionized by the central hot accretion disk, the distance from the IEL gas to the center is estimated to be only \( \sim 0.027 \) pc, which is even smaller than the BELR radius. The shock model suggests that the IELs are produced by the local ionizing source, which is induced by the collision of the outflowing gas with the dusty torus.

The shock model seems to be more reasonable for J1516+1900 but should not be the exclusive origin of the general IELs in AGNs. Previous research suggests that the IELs of AGNs are generally produced by gas located at the dusty torus scale and photoionized by the radiation from the central accretion disk. This might be a general physical picture of producing IELs in AGNs. These IELs are usually very weak and produced by dusty gas with a lower density of \( \sim 10^{6-9} \) cm\(^{-3}\) (e.g., Li et al. 2015). The weakness of these IELs is interpreted as emission suppression due to dust absorption (Netzer & Laor 1993). Recent studies demonstrated that these IELs can become prominent if the gas density at the sublimation radius increases to the order of \( \sim 10^{15} \) cm\(^{-3}\), where the dust suppression effect is negligible (Adhikari et al. 2016, 2018).

The study of this paper implies that the IELs might also be produced through the collision of the outflowing wind with the dusty torus. An important characteristic of this model is the ultradense (\( \sim 10^{13} \) cm\(^{-3}\)) ionized gas. The IELs of J1516+1900 are also very weak, which could not have
been detected if the BELR was not obscured. Within the frame of the shock model, this weakness should depend on the energy released during the collision of the outflowing wind with the dusty torus. Stronger IELs may also be expected in quasars with higher kinetic energy outflow. Since the energy carried by the IELs is transformed from the kinetic energy of the outflowing gas rather than the radiation energy from the central source, the IEL strength can be exploited as an effective kinetic energy estimator of outflow in future studies.

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