Double-peaked [O I] Profile: A Likely Signature of the Gaseous Ring around KH 15D

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Abstract

KH 15D is a well-known spectroscopic binary because of its unique and dramatic photometric variability. The variability is explained by a circumbinary dust ring, but the ring itself was never directly detected. We present a new interpretation of the double-peaked [O I] λ6300 profiles as originating from the hot disk surface of KH 15D. By modeling these profiles, we measure emitting radii between ~0.5 and 5 au, basically a gaseous ring very similar in radial extent to the dust ring inferred from modeling the system’s photometric variability. We also discuss the possibility that external photoevaporation driven by ultraviolet photons from the nearby massive star HD 47887 has truncated the outer edge of the disk to the observed value.

Key words: open clusters and associations: individual (NGC 2264) – protoplanetary disks – stars: individual (KH 15D) – stars: pre-main sequence

1. Introduction

KH 15D is a pre-main sequence (PMS) spectroscopic binary (A+B) with near-equal-mass components (0.715 M⊙ for Star A and 0.74 M⊙ for Star B), high eccentricity (e ≈ 0.6), a semimajor axis of ~0.25 au, and a period of 48.37 days (Johnson et al. 2004; Winn et al. 2006; Aronow et al. 2018). It is a member of the NGC 2264 cluster at ~750 pc, based on the members from Venuti et al. 2018 and Gaia Data Release 2 parallaxes, and the cluster is about ~2–6 Myr old (Naylor 2009; Lim et al. 2016). KH 15D exhibits unique and dramatic long- and short-term photometric variability (e.g., Capelo et al. 2012). From 2006 to 2009 Star B was fully occulted, while after 2010 Star A became occulted; currently, the entirety of Star B is visible at each apastron passage (Aronow et al. 2018). The short-term variability has the same period as the binary (Kears & Herbst 1998; Hamilton et al. 2001; Herbst et al. 2002; Johnson et al. 2004). However, the large depth (several magnitudes) and long duration (days to tens of days) of the eclipse, in combination with the time variability, cannot be solely attributed to the binary. Additional occultation by circumbinary matter must be invoked (Hamilton et al. 2001; Herbst et al. 2002).

A nearly edge-on, warped, and precessing circumbinary ring of dust (~1 to 5 au) is thought to occult the eccentric PMS binary and explain the available light curves (Chiang & Murray-Clay 2004; Winn et al. 2004). However, the circumbinary disk eluded detection. The system shows no infrared excess emission out to 8 μm (Arunlanathan et al. 2016), in line with the relatively large inner dust edge. In addition, the dust ring has not been detected at millimeter wavelengths with the Submillimeter Array (SMA) or the Atacama Large Millimeter/submillimeter Array (ALMA). The millimeter observations have yielded upper limits on the total (gas+dust) circumbinary disk mass of 1.7 MJup (Aronow et al. 2018), just a factor of ~2 lower than the mean protoplanetary disk mass in young (1–3 Myr) star-forming regions (e.g., Ansdell et al. 2016; Pascucci et al. 2016). Interestingly, the SMA CO J = 3 → 2 line reveals a bipolar collimated outflow, the northern lobe of which is spatially coincident with the H2 jet associated with KH 15D (Tokunaga et al. 2004; Aronow et al. 2018). Finally, the system presents broad H2 line profiles, indicative of active accretion (Hamilton et al. 2012), perhaps funneled from gas surrounding both stars (see the case of the spectroscopic binary DQ Tau; Muzerolle et al. 2019). The presence of a jet and ongoing accretion point to the presence of a gaseous disk.

Here, we interpret the double-peaked [O I] λ6300 profiles from KH 15D as originating from the surface of this gaseous disk (Section 2). Modeling of the line profiles reveals that the emitting gas is radially confined (Section 3). We discuss how external photoevaporation could have truncated the gaseous disk to the outer edge inferred from our [O I] λ6300 modeling (Section 4).

2. Double-peaked [O I] λ6300 Profiles

The spectroscopic data presented in this work were obtained from the Very Large Telescope (VLT)/Ultraviolet and Visual Echelle Spectrograph (UVES), European Southern Observatory (ESO) archive for three nights in 2001 and six nights in 2004 with a spectral resolution of ~42,000 and have been already published in Hamilton et al. (2003, 2012) and Mundt et al. (2010). We extracted the raw data from the ESO archive and reduced them with the ESO UVES pipelines under the ESO Recipe Flexible Execution Workbench environment (Freudling et al. 2013). We obtain 21 spectra that cover both [O I] λ6300 and H2 lines. The 2001 December 14 and 21 and the 2004 December 16–18 (UT) spectra were taken during Star A eclipse phase, the spectrum acquired on 2001 December 29 was out of eclipse, and the spectra obtained on 2004 December 13–15 were approaching Star A eclipse phase (Mundt et al. 2010; Hamilton et al. 2012).

We removed telluric absorption and subtracted photospheric features near the [O I] λ6300 and H2 lines using a K7 PMS template (see e.g., Fang et al. 2018 for details). We adopted a heliocentric radial velocity vhelio = 18.676 km s⁻¹ as the systemic velocity (Mundt et al. 2010; Hamilton et al. 2012).

5 Based on observations collected at the European Southern Observatory under ESO programmes 267.C-5736(A) and 074.C-0604(A).
This value is consistent with the error-weighted mean radial velocity (19.4 ± 0.1 km s⁻¹) of other NGC 2264 cluster members (Kounkel et al. 2016). We shifted the [O I] λ6300 lines to the systemic velocity and present the spectrum with the highest signal-to-noise ratio (S/N), the one obtained on 2001 December 21, in Figure 1. Individual Hα and [O I] λ6300 profiles are shown in Figures 2 and 5.

The [O I] λ6300 emission shows the same double-peaked profile at all observing epochs. Note that the sharp blueshifted spikes in some profiles are due to sky contamination: (1) they are truly spikes, i.e., their width is much narrower than the spectral resolution (∼7 km s⁻¹); (2) sky lines peak near these spikes and, as they get stronger, so do the spikes; (3) for four spectra taken in 2001 covering also the [O I] λ5577 line, we detect the same strong and sharp spikes we see in the [O I] λ6300 profiles. The background Hα line, produced mostly by the H II region (Cone Nebula) around KH 15D, is also present but the ratio of its intensity to the source emission is much smaller than the sky lines at the [O I] λ6300 emission. This explains why we do not see such spikes in the reduced Hα profiles (see Figure 2).

The [O I] λ6300 profiles for KH15D differ from those found in most accreting T Tauri stars (TTSs). In TTSs with higher accretion luminosity, the [O I] λ6300 profiles typically show both a high-velocity component (usually but not exclusively blueshifted) attributed to a jet and a low-velocity component (LVC), which is also often blueshifted (Hartigan et al. 1995). The LVC is found in a broader range of TTSs, including those with low accretion luminosity and transition disks, and itself can consist of both a broad and a narrow component, which have been attributed to slow disk winds from the inner or outer disk, respectively (Hartigan et al. 1995; Simon et al. 2016; Fang et al. 2018; Banzatti et al. 2019). In some cases, the LVC is centered on the stellar velocity, and may be bound material on the surface of the disk; see, e.g., Figure 24 in Simon et al. (2016). The LVCs are always single peaked and have line widths that correlate with disk inclination, indicative of broadening by Keplerian rotation.

The [O I] λ6300 profile in KH 15D is distinctive from other TTSs. The profile shows symmetric red and blue peaks at radial velocities of ±20 km s⁻¹ and looks similar over multiple epochs. While such low velocities are characteristic of TTS LVCs, no other LVCs to date have shown a double-peaked structure. A jet close to the plane of the sky can have low radial velocities, as can be inferred for some TTSs where line ratios for several forbidden lines reveal properties characteristic of shocked, rather than thermally excited, gas for a few sources that would be classified as LVC based on their kinematic properties (Fang et al. 2018). This is the interpretation proposed by Mundt et al. (2010), that the [O I] λ6300 profile from KH 15D arises in a pair of identical approaching and receding jets in the plane of the sky. However, in this interpretation we would expect to see variable profiles at different epochs as noticed in other TTSs (Simon et al. 2016). Therefore, we put forward an alternate possibility, informed by recent work on TTS forbidden lines, that the [O I] λ6300 traces the surface of a disk and is broadened by Keplerian rotation. Its double-peaked structure, unlike other LVCs in TTSs, would result from the fact that the disk is more like a ring, rather than extended beyond ~5 au, as required to fill in the central dip in most TTSs (Hartigan et al. 1995; Simon et al. 2016).

3. Hα Profiles

An extensive analysis of Hα profiles and associated emission variability is provided in Hamilton et al. (2012). The analyzed spectra covered five contiguous observing seasons (from 2001 to 2006) over which Star A was fully visible as well as partially occulted (in ingress and egress events) and fully occulted. Some of these spectra are the same from which we have extracted the [O I] λ6300 profiles and are presented in Figure 2 in order to emphasize the difference in the line profiles of Hα and [O I] λ6300.

The out-of-eclipse and ingress spectra (left panel) are characterized by an inverse P-Cygni-type profile with a strong redshifted absorption whose changes in centroid velocity can be explained by an accretion stream onto A (Hamilton et al. 2012). The eclipse and egress spectra (right panel) present a more symmetric profile with often more pronounced broad extended wings (up to several hundreds km s⁻¹), which are characteristic of actively accreting stars. Additional spectra in this phase can be seen in Figure 9 of Hamilton et al. (2012). Mundt et al. (2010) interpreted the eclipse profiles as tracing the same bipolar jet as [O I] λ6300 because Hα also shows red and blue peaks, although the blue/red intensity is quite variable and the velocities are somewhat higher than [O I] λ6300. Alternatively, we might still be seeing accretion onto A (and perhaps A+B) through reflected light from the back of the wall of the circumbinary disk. This could explain the similarity of some ingress and mid-eclipse Hα profiles and has been proposed by Hamilton et al. (2012) to explain the presence of the broad wings during these phases.

While a detailed analysis of the Hα profiles is beyond the scope of this work, we draw the reader’s attention to the difference between the Hα and [O I] λ6300 profiles. While the...
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simpler, because
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the surface of the gaseous circumbinary disk.
preferred explanation is that the two lines trace different
Hartigan et al. 2011, Simon et al. 2016
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stellar photons on the disk structure and the gas chemical
Meijerink et al. 2012
investigated the effect of high-energy
stellar photons on the disk structure and the gas chemical
composition by varying the X-ray radiation from 0 to
10^{32} erg s^{-1} and the far-ultraviolet (FUV) from
10^{20} to 10^{32} erg s^{-1}. Their calculations show that there exists a
radially extended hot (~5000 K) region on top of the disk
surface\(^8\) with hydrogen densities of \(10^{6}-10^{8}\) cm\(^{-3}\). The
[O I] \lambda 6300 line should be tracing this region.
Mundt et al. 2010 claimed that there is a slight blue
asymmetry (14\%) in the [O I] \lambda 6300 line profiles. For a system
like the KH 15D with a close binary, the [O I] emitting regions
can be distorted by the time varying potential of the binary
system (Thun et al. 2017), causing some variability and
asymmetry in the [O I] \lambda 6300 line profile as proposed by
Mundt et al. (2010). However, as discussed in Section 2, the
blue part of [O I] \lambda 6300 line profile is also contaminated by sky
lines, hence changes restricted to a narrow range of velocities
close to the sky lines should be interpreted with caution.

\(^8\) From \(z/r \sim 0.2\) at \(r \sim 0.6\) au to \(z/r \sim 0.5\) at \(r \sim 5\) au, where \(z\) is the(53,948),(1005,994)
Figure 3. Corner plot showing the posterior distributions from the MCMC fit of the [O I] 6300 line obtained on 2001 December 21 (see Figure 1). The vertical dashed lines are the 16 and 85 percentiles, respectively. The solid lines indicate the medians of the posterior distributions.

Excluding these, likely spurious, features we do not identify any asymmetry in the highest S/N [O I] 6300 profile.

5. Inner and Outer Truncation of the Disk

Several theoretical papers have shown that the inner region of a disk surrounding a close binary is quickly dissipated (e.g., Lin & Papaloizou 1993; Artymowicz & Lubow 1994). Recently, Pichardo et al. (2008) carried out numerous simulations, using the test particle approach, to derive a simple relation between the gap radius and binary semimajor axis (a), eccentricity (e), and primary/companion mass ratios (q): \( R_{\text{gap}} \approx 1.93e(1 + 1.01e^{0.33})q(1 - q)^{0.043} \). For the KH 15D system, \( a \sim 0.25 \text{ au}, e \sim 0.6, \) and \( q \sim 0.83–0.97 \) (Winn et al. 2006; Aronow et al. 2018), thus the disk inner radius is expected to be \( \sim 0.8 \text{ au} \) according to these simulations. However, as shown in the more detailed physical models of Muñoz & Lai (2016) and Muñoz et al. (2019), it is actually difficult to define the cavity radius for an eccentric binary, as gas from the circumbinary disk flows in generating complex and transit streams. Therefore, we consider our estimate of \( \sim 0.5 \text{ au} \) from modeling the [O I] 6300 line to be pretty close to the possible cavity radius.

Chiang & Murray-Clay (2004) argued that the disk of KH 15D cannot extend beyond \( \sim 5 \text{ au} \) to maintain rigid precession and explain the long-term photometric variability of the system (but see Lodato & Facchini 2013 for the possibility of the disk extending to 5–10 au). Recently, Arulanantham et al. (2016) confirmed the rigid precession of the ring and estimated a velocity (across the sky) of \( \sim 15 \text{ m s}^{-1} \) for the projected edge of the ring. Then, the precession rate of the ascending node of the ring can be estimated to be \( 0.18 \text{ yr}^{-1} / \bar{a} \), where \( \bar{a} \) is the mean radius of the circumbinary ring in astronomical units. Using the approximate expression relating the precession rate of ascending node of an inclined circumbinary ring to the mean ring radius from Chiang & Murray-Clay (2004), the masses (0.715 and 0.74 M\(_{\odot}\); Aronow et al. 2018), and the orbit (0.25 au; Winn et al. 2004) of the binary, the mean radius of the ring should be \( \sim 4 \text{ au} \). This value is also close to the characteristic [O I] 6300 emitting radius, see Section 4.

Preventing the outer boundary from viscous spreading may require some sort of outside confinement. Chiang & Murray-Clay (2004) proposed a planet exterior to the ring. Here, we explore external photoevaporation as an alternative. At a projected separation of \( \sim 37^\prime\prime \), southwest from KH 15D, there is a massive star HD 47887 (\( T_{\text{eff}} = 24,000 \pm 1000 \text{ K}, \) Fossati et al. 2014). Based on Gaia Data Release 2, KH 15D and HD 47887 have similar parallaxes (1.2691 ± 0.0751 mas versus 1.3272 ± 0.0751 mas). Thus, it is very likely that both of them belong to the NGC 2264 cluster. With a distance from us of \( \sim 750 \text{ pc} \), the projected distance between them is \( \sim 0.135 \text{ pc} \).

Taking this projected distance, the model atmosphere from Lanz & Hubeny (2007), and the broadband photometry from Kharchenko (2001), the UV field strength near KH 15D produced by HD 47887 is \( \sim 4470 G_0 \).\(^9\) Under such UV field

\(^9\) G0 is the Habing unit of UV radiation corresponding to the integrated flux \((1.6 \times 10^{-3} \text{ erg cm}^{-2} \text{s}^{-1}) \) over the wavelength range 912 A to 2400 A used in Haworth et al. (2018).
strength (4470 G0), we make a toy model to assess the timescale for dissipating the outer disk of KH 15D as close in as 5 au. In the models, the initial disk sizes are set to be 100, 150, or 200 au, disk masses are 0.0075 or 0.015 M\(_\odot\) (0.5% or 1% of the KH 15D system mass), and the inner disk radius is fixed to be 0.1 au. The disk material has a surface density \(\Sigma \propto r^{-1}\), and the central binary is simplified as one single star with a mass of 1.5 M\(_\odot\). Furthermore, we assume that the bulk of the mass loss due to external photoevaporation is driven from the disk outer edge, as in Haworth et al. (2018), and neglect the disk viscous evolution. We interpolate the disk mass-loss rates within the UV field strength of 4470 G0 during the disk dissipation using the FRIED grid of mass-loss rates for externally irradiated protoplanetary disks (see details in Haworth et al. 2018). The mass-loss rates range from \(\sim 10^{-6}\) to \(\sim 10^{-10} M_\odot\text{yr}^{-1}\) when disk size decreases from hundreds au to 5 au. The resulting disk sizes from our toy models are shown in Figure 4 as a function of age. Our calculations show that the size of a disk within the UV field strength of 4470 G0 can decrease to 5 au at the age of the cluster (2–6 Myr, Naylor 2009; Lim et al. 2016). Thus, photoevaporation can explain the outer truncation of the disk.

6. Conclusion

We provide a new interpretation to the double-peaked \([\text{O I}]\lambda 6300\) emission line as arising from the hot surface of the gaseous disk surrounding the spectroscopic binary KH 15D. Line profile modeling constrains the emission to a relatively narrow radial extent \(\sim 0.5–5\) au, similar to the extent of the dust ring inferred from modeling the source photometric variability. The relatively large inner edge is likely set by the binary dynamical interaction. We show that the small outer disk radius could be shaped by external photoevaporation driven by UV photons from the nearby massive star HD 47887. Newer, high \(S/N\) \([\text{O I}]\lambda 6300\) line profiles would be useful to further test our interpretation and detect any subtle changes that might arise from disk precession.

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Appendix

Comparison of Observed \([\text{O I}]\lambda 6300\) Line Profiles and the Model Line Profile

Figure 5 shows the comparison of the line profiles observed at different epochs (gray and red lines) with the best-fit model line profile (blue lines). The latter is obtained by fitting the 2001 December 21 profile (outermost right panel). We chose this line profile because (1) it has the highest \(S/N\), and (2) it shows the least contamination from sky lines. The best-fit parameters are: \(\alpha = -2.82\), \(r_{\text{in}} = 0.54\) au, and \(r_{\text{out}} = 5.0\) au, see also Section 4.
Figure 5. [O I] λ6300 line profiles (gray and red lines) obtained between 2001 and 2004, compared to our best-fit line profile (blue lines), see the Appendix for details. The red line shows the [O I] λ6300 line profile taken on 2001 December 21 and used for the fitting. For multiple observations during 2001 December 14 and 2004 December 13–16, we only show one spectrum per night as there are no detectable variations in [O I] λ6300 profiles. The zero velocity marked with the dashed line is that of the KH 15D rest frame. The gray filled region marks wavelength ranges where sky contamination is likely.

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