Water and OH Emission from the Inner Disk of a Herbig Ae/Be Star

Steven C. Adams1, Máte Ádámkovics1, John S. Carr2, Joan R. Najita3, and Sean D. Brittain1,3

1 Department of Physics and Astronomy, 118 Kinard Laboratory, Clemson University, Clemson, SC 29634-0978, USA
2 Naval Research Laboratory, Code 7211, Washington, DC 20375, USA
3 National Optical Astronomy Observatory, 950 North Cherry Avenue, Tucson, AZ 85719, USA; sbritt@clemson.edu

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Abstract

We report the detection of hot H2O and OH emission from the Herbig Ae/Be star HD 101412 using the Cryogenic Infrared Echelle Spectrograph on the Very Large Telescope. Previous studies of Herbig Ae/Be stars have shown the presence of OH around some of these sources, but H2O has proven more elusive. While marginal water emission has been reported in the mid-infrared, and a few Herbig Ae/Be stars show water emission in the far-infrared, water emission near 2.9 μm has not been previously detected. We apply slab models to the rovibrational OH, H2O, and CO spectra of this source and show that the molecules are consistent with being coplanar. We discuss the possibility that the detection of the CO overtone bandhead emission, detection of water emission, and the large line to continuum contrast of the OH lines may be connected to its high inclination and the Boö nature of this star. If the low abundance of refractories results from the selective accretion of gas relative to dust, the inner disk of HD 101412 should be strongly dust-depleted, allowing us to probe deeper columns of molecular gas in the disk, enhancing its molecular emission. Our detection of C- and O-bearing molecules from the inner disk of HD 101412 is consistent with the expected presence, in this scenario, of abundant volatiles in the accreting gas.

Key words: circumstellar matter – molecular processes – protoplanetary disks – stars: individual (HD 101412) – stars: pre-main sequence

1. Introduction

High-resolution spectroscopic studies of Herbig Ae/Be (HAeBe) stars indicate that their circumstellar environments are commonly home to hot CO (Blake & Boogert 2004; Brittain et al. 2007; Salyk et al. 2011a, 2011b; Brown et al. 2013; Banzatti & Pontoppidan 2015; van der Plas et al. 2015) and, less frequently, OH gas (Mandell et al. 2008; Fedele et al. 2011; Brittain et al. 2016), but they have yet to yield a detection of the H2O emission from 2 to 4 μm that has been observed in lower-mass pre-main-sequence T Tauri systems (Carr et al. 2004; Salyk et al. 2008; Doppmann et al. 2011; Fedele et al. 2011; Mandell et al. 2012; Banzatti et al. 2017). Likewise, mid- and far-infrared studies have yielded few detections of H2O emission from cooler gas in disks around HAeBes. In a study of 25 HAeBes using Spitzer, there were marginal detections of H2O emission reported for 12 of 25 systems (Pontoppidan et al. 2010). These detections were reported based on inspection by eye and were not determined to be above the 3.5σ detection threshold defined in the study. In contrast, similar surveys of T Tauri stars yield a much higher detection rate for H2O emission in the mid-infrared (22 of 48 exhibited a significant detection of H2O emission; Pontoppidan et al. 2010). Statistics compiled by Banzatti et al. (2017) showed that between 63% and 85% of 64 stars with a stellar mass less than 1.5 M⊙ exhibit mid-infrared H2O emission. In searches for H2O in the far-infrared, only 3 sources were detected out of 25 HAeBes observed (Fedele et al. 2012, 2013; Meeus et al. 2012). These results suggest that the abundance of H2O gas in the optically thin upper atmosphere around HAeBes is low.

One possible explanation for the dearth of near-infrared (NIR) water detections among HAeBes compared to T Tauri stars is that the high far-ultraviolet (FUV) luminosity of HAeBe stars causes a larger column of water to be dissociated to produce OH (e.g., Ádámkovics et al. 2016; Najita & Ádámkovics 2017). As the water falls below the dust photosphere, emission from the water becomes impossible to detect. Here we report what appears to be an exception to this picture—the first detection of NIR H2O emission from the HAeBe star HD 101412.

HD 101412 is a B9.5Ve star (Valenti et al. 2003) located at a distance of 411±3 pc (Gaia Collaboration et al. 2016, 2018). As part of an X-Shooter survey of 92 HAeBes, Fairlamb et al. (2015) determined the stellar parameters of their sample self-consistently. They find that $T_{\text{eff}} = 9750 \pm 250$ K and $\log(L/L_{\odot}) = 1.36 \pm 0.23$, adopting $d = 301$ pc. We adopt the Gaia distance and use Siess pre-main-sequence models to recalculate the stellar mass, radius, and luminosity (Siess et al. 2000). The updated values are $M = 2.5 M_{\odot}$, $R = 2.3 R_{\odot}$, and $\log(L/L_{\odot}) = 1.63$.

The inner disk surrounding HD 101412 is nearly edge-on. Fitting a uniform ring model to $N$-band visibilities acquired with the MID-Infrared Interferometric Instrument (MIDI) on the Very Large Telescope (VLT) indicates that the disk is inclined 80° ± 7° (Fedele et al. 2008). No (sub)mm observations have been made of this source so there is no observational estimate of the extent or mass of the disk. The mid-infrared spectral energy distribution (SED) of the star indicates that it is a self-shadowed disk (Group II; Fedele et al. 2008). Fairlamb et al. (2017) report the flux of H2 for this source and provide a relationship between the accretion luminosity and the luminosity of the H2 line. Adapting the stellar parameters above, we find that the accretion rate is $1.6 \times 10^{-7} M_{\odot}$ yr⁻¹. The accretion rate indicates that HD 101412 still harbors a large gaseous reservoir.

The disk of HD 101412 reveals a rich molecular spectrum. Both the rovibrational CO overtone (Cowley et al. 2012; Ilee et al. 2014; van der Plas et al. 2015) and fundamental (van der Plas et al. 2015) emission lines have been observed. Modeling of the profile of these lines indicates that the emitting region is narrow (0.8–1.2 au; van der Plas et al. 2015). Mid-infrared
Data reduction was performed using software based on algorithms developed for the reduction of Phoenix and Near-InfraRed echelle SPEctrograph (NIRSPEC) data (described in Brittain et al. 2007). Flats and darks were taken in order to remove systematic variation in the pixel gain. Sequential AB observations were combined (A - B) and then divided by the normalized flat field image. Median values of the combined images were used to identify and remove hot and bad pixels, as well as cosmic-ray hits. Pixel values that differ by 6σ were rejected. Spectra were then extracted using a rectangular extraction method. Wavelength calibration was performed using the telluric absorption features observed in the spectrum, A Sky Synthesis Program (SSP) model atmosphere (Kunde & Maguire 1974), which accesses the 2003 High-resolution TRANsmission molecular absorption database (Rothman et al. 2003), was computed based on the airmass of the observations. Standard star observations of λ Cen were taken immediately after the observations of HD 101412. The telluric standard was reduced following the same process as HD 101412. The normalized spectrum of HD 101412 was divided by the normalized spectrum of λ Cen to correct for atmospheric absorption lines. Regions of the spectrum where the atmospheric transmittance was below 50% were excluded. Final reduced L-band spectra and ratios are presented in Figure 1.

We also reduced archival data for the CO bandhead emission previously reported for HD 101412 (Cowley et al. 2012; Ilee et al. 2014). The data were obtained based on observations made with CRIRES on the VLT under program ID 087.C-0124 (A). The CO data were re-reduced using the same method as the OH and H₂O observations. The CO data were then modeled in order to determine self-consistently the CO-emitting region, temperature, and column density.

The flux densities adopted for the continua of the K- and L-band spectra were obtained using values from Johnson-K and Johnson-L filter photometry measurements found using the VizieR Photometry Viewer (Ochsenbein et al. 2000). The flux density at 2.94 μm was estimated at a value between the flux density at these filters by a linear fit to the two data points. A continuum flux of 3.20 × 10⁻¹⁰ erg s⁻¹ cm⁻² μm⁻¹ was used for the L band (OH), and 4.21 × 10⁻¹⁰ erg s⁻¹ cm⁻² μm⁻¹ was used for the K band (CO).

### 3. Results

The fully reduced L-band spectrum has a spectral resolution of R ≈ 90,000 and a signal-to-noise ratio of ~200. We detect the OH P4.5 and OH P5.5 doublets with the peak in the normalized line flux relative to the continuum of 9% (Figure 2, panel (A) and (C), respectively). Gaps in the profile of the P5.5 doublet are due to telluric absorption greater than 50%. We also detect H₂O emission near 2.93 μm (Figure 4). Another H₂O feature between 2.9074 and 2.9110 μm is also observed (Figure 5). Table 2 gives transition parameters for the individual transitions that we propose comprise the most prominent emission features. Errors for equivalent widths (EWs) are determined by adding the noise across each pixel in the emission feature in quadrature.

#### 3.1. OH Emission

The P4.5 doublet transition is spectrally resolved; however, the doublet itself is blended. The emission feature is bracketed by strong telluric absorption features. The EW is calculated over the entire range of the doublet between the absorption features and divided by 2 due to the blending. The EW is 4.3 ± 0.2 × 10⁻³ μm that, when factoring in the distance and L-band flux density, corresponds to a line luminosity of 7.2 ± 0.3 × 10⁻³ Lₖ. The line to continuum contrast of the P4.5 OH doublet is 9% (Figure 2), which is more than three times the line to continuum contrast typically observed for this doublet in previous observations of HAeB stars (Mandell et al. 2008; Fedele et al. 2011; Brittain et al. 2016).

The P5.5 emission feature is partially obscured by atmospheric absorption. The profile of the P5.5 doublet and P4.5 doublet differ slightly in the blue portion due to different separations of the doublet transition energies. Thus, the individual peaks in the blue portion of the P5.5 feature show each doublet’s peak as being further apart. This broadens the overall line width; however, the inner peak separation between
the blue portion of the (1−) line and red portion of the (1+) line is reduced. Due to the atmospheric absorption, an EW cannot be determined from the data. Based on the model fits obtained from fitting the full P4.5 doublet, we determine the P5.5 EW to be $3.7 \pm 0.1 \times 10^{-5}$ μm, which corresponds to a line luminosity of $6.2 \pm 0.3 \times 10^{-5} L_\odot$.

We observe a Doppler shift of 24.4 km s$^{-1}$. This implies a heliocentric radial velocity of 16.9 km s$^{-1}$ based on the date the observations were made. Hubrig et al. (2010) observe Fe lines in the spectrum of HD 101412 and report an average heliocentric radial velocity of 16.65 km s$^{-1}$, which is consistent with our determined radial velocity.

Brittain et al. (2016) find a power-law relationship between the luminosity of rovibrational CO ($\nu = 1 \rightarrow 0$ P30) and OH ($\nu = 1 \rightarrow 0$ P4.5) emission from HAeBes and find that the ratio of their luminosities is $11.0 \pm 0.2$. We compare the relative luminosity of the OH and CO emission for HD 101412 (Figure 3). Because the lines are so broad, there is significant line blending. We take the most isolated CO line ($\nu = 1 \rightarrow 0$ P26 transition; Troutman 2010) and determine the luminosity of the P30 line, assuming the gas is 1300 K (see Section 4). Because of the line blending, we take the CO luminosity to be an upper limit and find that $L(\text{CO})/L(\text{OH}) < 1.24$. Thus the relative flux of the OH emission is an order of magnitude larger than the previous HAeBes studied.

### 3.2. H$_2$O Emission

One prominent H$_2$O emission feature is observed at 2.929 μm (Figure 4). This feature is partially obscured by telluric absorption. The emission is due to a blend of multiple
Another $H_2O$ emission feature is observed between 2.9074 and 2.9078 $\mu$m (Figure 5), with some regions obscured by atmospheric absorption. This feature is also a blend of multiple transitions. In both instances, the $H_2O$ transitions observed all require high temperatures to reach the upper levels, thus making it unlikely that the $H_2O$ emission observed is residual from telluric correction.

### 3.3. CO Observations

In order to determine self-consistently the column densities of $CO$, $OH$, and $H_2O$, we also present $K$-band observations of HD 101412. We reproduce the results of Cowley et al. (2012) and Lee et al. (2014) in that we detect both the $CO\;\nu = 2 \rightarrow 0$ and $\nu = 3 \rightarrow 1$ bandheads. We determine the signal to noise of the chips containing the $CO\;\nu = 2 \rightarrow 0$ bandhead and isolated emission features (Chips 2 and 3) to be $\sim$290, while Chip 4,

![Figure 2](image_url)

**Figure 2.** (A) P4.5 (1+, 1−) OH emission doublet. The normalized fluxes of the OH doublets are plotted vs. wavelength. The upper $x$-axis shows the relative velocity of the emission features. The zero velocity is centered at the laboratory rest wavelength of the P4.5 (1+) line (2.93428 $\mu$m). The green tick marks indicate the wavelength of each doublet feature in the rest frame of the star. The Doppler shift inferred from the molecular emission indicates that the heliocentric radial velocity is 16.9 km s$^{-1}$, which is consistent with the heliocentric radial velocity inferred from the measurement of photospheric lines (16.5 km s$^{-1}$; Hubrig et al. 2010). The best-fit model is plotted in red. (B) Model line profile of each doublet feature, scaled to match the P4.5 intensity. (C) P5.5 (1+, 1−) OH emission feature. The emission feature is partially obscured by telluric absorption. The green tick marks indicate the location of each doublet feature in the rest frame of the star. The zero velocity bin is centered at 2.96997 $\mu$m, which is the laboratory rest wavelength of the P5.5 (1+) lines.

| Wavelength ($\mu$m) | Transition | $A_{\text{rot}}$ (s$^{-1}$) | $\delta_0$ | $E_N$ (K) |
|---------------------|------------|-----------------------------|------------|-----------|
| 2.97040             | 3/2 P5.5f  | 12.67                       | 20         | 5627.64   |
| 2.96997             | 3/2 P5.5e  | 12.67                       | 20         | 5626.56   |
| 2.93461             | 3/2 P4.5f  | 11.68                       | 16         | 5414.92   |
| 2.93428             | 3/2 P4.5e  | 11.68                       | 16         | 5414.31   |

**Table 2**

Molecular Line Properties

Note. Parameters for some transitions that comprise observed emission features in HD 101412 $L$-band observations. Line groups are presented in the order that the emission feature is discussed in the text. All data were acquired using the HITRAN database (Rothman et al. 2013).
consistent with the OH lines.

The upper x-axis gives the velocity space information and shows a Doppler shift of 24.4 km s\(^{-1}\), consistent with the OH lines.

Figure 4. The 2.93 \(\mu\)m H\(_2\)O emission lines. The blue tick marks indicate the positions of the dominant transitions contributing to the emission feature. The zero velocity bin is centered at 2.92909 \(\mu\)m, the transition with the shortest wavelength of the list in Table 2 found in this spectral region. The upper x-axis gives the velocity space information and shows a Doppler shift of 24.4 km s\(^{-1}\).

containing the \(\nu = 3 \rightarrow 1\) bandhead emission, has a signal to noise of \(\sim 120\). Figure 6 shows the isolated CO \(\nu = 2 \rightarrow 0\) emission lines (Chip 3), while Figure 7 show the CO \(\nu = 2 \rightarrow 0\) (left) and \(\nu = 3 \rightarrow 1\) (right) bandhead emission. A discussion of the modeling is presented in Section 4.

4. Modeling

To determine the spatial location, column density, and temperature of the CO, OH, and H\(_2\)O emission, we fit the spectra using a slab model (Carr et al. 2004). The disk models assume Local Thermodynamic Equilibrium (LTE) and Keplerian rotation. Because we find that the emission originates in a fairly narrow annulus, the gas temperature and the column density for each species are taken to be constant over the emitting region.

We start by fitting the velocity profile of the CO \(\nu = 2 \rightarrow 0\) lines, because the CO spectrum covers the greatest range of energy levels and has the highest signal to noise. The CO lines near 2.31 \(\mu\)m (Figure 6) are separated from other lines and give a clean measure of the line profile. A composite profile is formed using the four lines least affected by telluric absorption.

A Keplerian disk emission model is fit to the profile using \(\chi^2\) minimization, which gives 50.5 km s\(^{-1}\) for the projected velocity at the inner radius of the emitting region and 42.1 km s\(^{-1}\) at the outer radius (or equivalently, \(R_{\text{out}}/R_{\text{in}} = 1.44\)). A third fit parameter is the exponent of a power law for the radial intensity, \(I \propto r^\alpha\); however, the result is insensitive to this parameter, due to the small radial extent of the emission, and the exponent is set to a fixed value of \(\alpha = -2\).

Having set the kinematics of the CO emission, the CO \(\nu = 2 \rightarrow 0\) bandhead and isolated lines are fit with a disk emission model. Given the narrow radial extent of the emission, the CO column density, \(N(\text{CO})\), and temperature, \(T\), are taken to be constant with the radius. The main parameters that determine the bandhead shape and relative line intensities are \(T\) and \(N(\text{CO})\). If you hold \(T\) constant, increasing \(N(\text{CO})\) will increase the luminosity of the emission lines. For a given \(T\) and \(N(\text{CO})\), matching the CO emission flux gives the projected emitting area, which is characterized by the radius of an equivalent circular area. The shape of the bandhead is also affected to a lesser degree by the local line broadening; the local line width was initially set to the CO thermal width. We find that the model fits to the CO \(\nu = 2 \rightarrow 0\) bandhead have a large degeneracy between \(T\) and \(N(\text{CO})\). Acceptable fit temperatures range from 1000 to 2500 K, and we rule out emission for temperatures above 3000 or below 800 K. When the CO \(\nu = 3 \rightarrow 1\) bandhead is included in the fit, the relative flux of the \(\nu = 3 \rightarrow 1\) and \(\nu = 2 \rightarrow 0\) emission restricts the range in \(T\) and \(N(\text{CO})\), removing the degeneracy from fitting the CO \(\nu = 2 \rightarrow 0\) alone (Figure 7).

The best-fit parameters for the CO overtone emission are \(T = 1300^{+300}_{-200}\) K and \(N(\text{CO}) = 7.0^{+6.9}_{-1.3} \times 10^{20}\) cm\(^{-2}\), and the projected emitting area, \(\pi R_e^2\), has a radius of \(R_e = 0.156\) au. This model is overplotted in red on the CO \(\nu = 2 \rightarrow 0\) and \(\nu = 3 \rightarrow 1\) bandheads in Figure 7, along with models for higher and lower temperatures.
Once we have the emitting column and projected area, we can break the degeneracy between disk inclination and the radius by finding the inclination that is consistent with both the projected velocity and the projected emitting area. For the above solution, this inclination is $i = 86^\circ$. The inner and outer radii for the CO emission are then $R_{\text{in}} = 0.88$ and $R_{\text{out}} = 1.27$ au.

We also investigate the impact of nonthermal broadening (turbulence). The thermal width of CO at 1300 K is 1.5 km s$^{-1}$ (FWHM). Different amounts of extra broadening are added to the thermal width and the CO composite profile is refit. Then, the fits to the $\nu = 2 \rightarrow 0$ bandhead are repeated. A change in the local line width alters the overlap of the closely spaced transitions at the bandhead. Because the CO lines are optically thick, the amount of overlap affects the relative distribution of flux with the wavelength and hence the shape of the bandhead. As the turbulence becomes larger, the fit to the shape at the bandhead becomes progressively worse. Based on this, we rule out $v_{\text{turb}}$ (FWHM) $\geq 3.5$ km s$^{-1}$ (Figure 8).

In modeling the OH, we first determine the radial extent of the OH emission by modeling the profile of the blended OH P4.5 doublet feature, using the same procedure used for the CO profile. Using the same inclination angle ($86^\circ$) from the CO modeling, the OH emitting region extends from $R_{\text{in}} = 0.81$ to $R_{\text{out}} = 1.46$ au. Figure 2 panel (A) shows the model fit to the P4.5 doublet. The model includes nonthermal line broadening (FWHM) of 6.7 km s$^{-1}$, which improves the appearance of the fit at the peaks of the OH emission; however, the statistical significance versus thermal broadening is small, and its inclusion does not change the derived radii for the emission. The same best-fit velocity profile is consistent with the P5.5 emission feature, as shown in Figure 2 panel (C).

The OH and CO emission originate from similar radii, but the radial extent (and area) of the OH emission is somewhat larger than that found for the CO emission. Given that the CO and OH spectra were obtained 2 yr apart, it is not clear whether the OH and CO line profiles point to an intrinsic difference in their respective radial distributions or reflect the variability of the emitting size.

In order to derive a column density for the OH emission, we adopt the temperature of 1300 K found for CO, since the OH features give no constraint on the gas temperature. Using the projected area for the OH emission, the column density is adjusted to match the flux in the OH P4.5 doublet. We find that $N(\text{OH}) = 2.8^{+1.2}_{-0.8} \times 10^{18}$ cm$^{-2}$, which yields a ratio of $N(\text{OH})/N(\text{CO}) = 4.0^{+3.5}_{-0.8} \times 10^{-3}$.

Modeling of the H$_2$O emission is more complicated. We originally confirmed our identification of these features as water by comparison to emission from LTE slab models. Due to the lower signal to noise of the H$_2$O emission, we find that it is not possible to determine uniquely the temperature and column density of water from the spectrum, although it is clearly hot, in the range of 1000–3000 K. In addition, the velocity line profile cannot be constrained to the accuracy that is possible for CO and OH. Hence, the OH velocity profile and emitting area are used for H$_2$O, along with the same 1300 K.
temperature. The column density required to match the H$_2$O flux is $N$(H$_2$O) = 5.8$^{+0.6}_{-0.8} \times 10^{17}$ cm$^{-2}$. This model is compared to the H$_2$O emission features in Figure 9. Other features, outside of those mentioned in Section 3.2, are consistent with the H$_2$O emission model. The adopted parameters are consistent with the relative fluxes and velocity widths in the H$_2$O spectrum. The derived water column density yields ratios of $N$(H$_2$O)/$N$(OH) = 0.21$^{+0.11}_{-0.06}$ and $N$(H$_2$O)/$N$(CO) = 8.3$^{+4.1}_{-3.0}$ $\times 10^{-4}$.

### 5. Comparison to Young Stellar Objects

To contextualize our detection of water in the inner disk around HD 101412, we compare the column densities of CO, OH, and H$_2$O among seven other young stars for which water has been detected (HD 259431 does not have a detection of NIR water emission, just an upper limit on the water column density; Table 3). SVS 13 is a 3 $M_\odot$ (Hirota et al. 2008) young stellar object on the Class 0/Class I boundary (Chen et al. 2009) from which the CO $\nu = 2 \rightarrow 0$ bandhead and H$_2$O emission lines near 2.2935 $\mu$m have been observed (Carr et al. 2004). AS 205A, DR Tau, and RU Lup are all classical T Tauri stars (CTTS; spectral type K0, K5, and G5, respectively) around which CO, OH, and H$_2$O emission has been observed (Salyk et al. 2008; Mandell et al. 2012). V1331 Cyg is a 2.8 $M_\odot$ intermediate mass T Tauri star (IMTTS; spectral type G7-K0; Petrov et al. 2014). Dopmann et al. (2011) observed OH and H$_2$O emission in the L band from this star. 08576nr292 is a massive young stellar object (MYSO; $\sim$6 $M_\odot$; B5 star) from which H$_2$O and CO bandhead emission have also been detected (Thi & Bik 2005).

For four of the sources (HD 101412, SVS 13, V1331 Cyg, and 08576nr292) in Table 3, the CO column density is comparable (0.7–6 $\times 10^{24}$ molecules cm$^{-2}$). Three other sources (AS 205A, DR Tau, and HD 259431) have much lower CO column densities reported, ranging from 0.6 to 1.6 $\times 10^{19}$ molecules cm$^{-2}$ (RU Lup only has column density ratios reported in Mandell et al. 2012). However, even with the range in column densities, the ratios between molecules show similar trends when comparing similar sources. Lower-mass T Tauri stars have $N$(OH)/$N$(CO) of a 2–3.3 $\times 10^{-2}$ and $N$(H$_2$O)/$N$(CO) of 0.6–3.0 $\times 10^{-4}$. As you move to more massive sources, this trend changes. $N$(OH)/$N$(CO) is now

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**Table 3**

| Star          | SpT | $M_*$ ($M_\odot$) | Class | $N$(CO) (cm$^{-2}$) | $N$(OH) (cm$^{-2}$) | $N$(H$_2$O) (cm$^{-2}$) | $N$(OH)/$N$(CO) | $N$(H$_2$O)/$N$(CO) |
|---------------|-----|------------------|-------|-------------------|-------------------|---------------------|----------------|------------------|
| SVS 13 (1)    | ... | 3.0              | Class 0/1 | 1.2 $\times 10^{21}$ | ...              | 1.8 $\times 10^{21}$ | ...             | 1.5              |
| DR Tau (2)    | K5  | 0.8              | CTTS    | 7.0 $\times 10^{18}$ | 2.0 $\times 10^{17}$ | 8.0 $\times 10^{17}$ | 2.9 $\times 10^{-2}$ | 1.1 $\times 10^{-1}$ |
| AS 205A (2)   | K0  | 1.2              | CTTS    | 6.0 $\times 10^{18}$ | 2.0 $\times 10^{17}$ | 6.0 $\times 10^{17}$ | 3.3 $\times 10^{-2}$ | 1.0 $\times 10^{-1}$ |
| V1331 Cyg (3) | G7-K0 | 2.8            | IMTTS  | 6.0 $\times 10^{21}$ | 1.0 $\times 10^{21}$ | 2.0 $\times 10^{21}$ | 2.0 $\times 10^{-2}$ | 3.0 $\times 10^{-1}$ |
| RU Lup (4)    | G5  | 0.7              | CTTS    | ...               | ...              | ...                | 1.6$-3.3$ $\times 10^{-2}$ | 5.5 $\times 10^{-2}$ |
| HD 101412     | B9.5 | 2.5             | HBe    | 7.0$^{+0.6}_{-1.3}$$\times 10^{10}$ | 2.8$^{+1.4}_{-0.7}$$\times 10^{18}$ | 5.8$^{+0.6}_{-0.8}$$\times 10^{17}$ | 4.0$^{+1.3}_{-0.5}$$\times 10^{-3}$ | 8.3$^{+0.0}_{-0.1}$$\times 10^{-4}$ |
| 08576nr292 (5) | B5  | 6.0              | MYSO   | 3.9 $\times 10^{21}$ | ...              | 2.5 $\times 10^{18}$ | $\sim1.0$$\times 10^{-3}$ | 6.4 $\times 10^{-4}$ |
| HD 259431 (6), (7) | B5  | 6.6              | HBe    | 1.6 $\times 10^{19}$ | 7.9 $\times 10^{15}$ | $<3.2$$\times 10^{14}$ | 4.9 $\times 10^{-4}$ | $<2.0$$\times 10^{-5}$ |

**Note.** Comparison of molecular column densities from previously reported observations of young stellar objects. Thi & Bik (2005) did not observe OH emission in 08576nr292. $N$(OH)/$N$(CO) for 08576nr292 is based off of chemical models. (1) Carr et al. (2004); (2) Salyk et al. (2008); (3) Dopppmann et al. (2011); (4) Mandell et al. (2012); (5) Thi & Bik (2005); (6) Ilee et al. (2014); (7) Fedele et al. (2011).
| Star     | SpT   | M \((M_\odot)\) | Class    | \(L_{\text{H}_2O} / L_\odot\) \((10^{-6} L_\odot)\) | \(L_{\text{OH}} / L_\odot\) \((10^{-5} L_\odot)\) |
|----------|-------|----------------|----------|---------------------------------|---------------------------------|
| AS 205A  | K0    | 1.2            | CTTS     | 3.76 ± 1.39                     | 1.06 ± 0.39                     |
| DF Tau A | K5    | 0.8            | CTTS     | 2.19 ± 0.28                     | 0.79 ± 0.10                     |
| DR Tau A | M3    | 0.5            | CTTS     | 3.41 ± 0.52                     | 0.96 ± 0.14                     |
| EX Lup08 | M0    | 0.8            | CTTS     | 6.79 ± 2.04                     | 3.03 ± 0.91                     |
| EX Lup14 | ...   | ...            | ...      | 0.25 ± 0.02                     | 0.09 ± 0.01                     |
| RU Lup   | K7-M0 | 0.7            | CTTS     | 3.42 ± 0.48                     | 1.28 ± 0.18                     |
| S Cra N  | G0    | 0.6            | CTTS     | 6.36 ± 1.97                     | 2.75 ± 0.85                     |
| T Tau N  | K1.5  | 2.4            | IMMTS    | 8.28 ± 6.63                     | 3.98 ± 3.18                     |
| VW Cha   | K7    | 0.6            | CTTS     | 2.39 ± 0.13                     | 1.52 ± 0.08                     |
| VZ Cha   | K7    | 0.8            | CTTS     | 0.85 ± 0.01                     | 0.30 ± 0.01                     |
| BF Ori   | A5    | 1.4            | HAe      | <0.16                           | <0.16                           |
| HD 34282 | A0    | 1.9            | HAe      | <0.20                           | <0.20                           |
| HD 76534 | B2    | 11.4           | HBie     | <1.51                           | <1.51                           |
| HD 85567 | B5    | 6              | HBie     | <3.32                           | 33.19 ± 9.96                    |
| HD 98922 | B9    | 5.2            | HBie     | <0.40                           | <0.40                           |
| HD 101412| B9.5  | 2.5            | HBie     | 3.96 ± 0.30                     | 7.18 ± 0.25                     |
| HD 250550| B7    | 3.6            | HBie     | <1.06                           | 2.23 ± 0.16                     |
| HD 259431| B5    | 6.6            | HBie     | <0.55                           | 23.86 ± 3.29                    |
| UX Ori   | A3    | 2.1            | HAe      | <0.33                           | <0.33                           |
| V380 Ori | A1    | 2.8            | HAe      | <1.13                           | 6.31 ± 3.75                     |

Note: Luminosity values from the literature used in Figure 10. T Tauri flux values are obtained from Banzatti et al. (2017), and HAeBe flux values and upper limits are from Fedele et al. (2011). HD 101412 flux values are from this work. Flux values are converted to luminosities using distances obtained from Gaia Collaboration et al. (2016). Upper limits have been converted to 1σ limits for consistency.

The infrared molecular emission from HD 101412 is unusual in several respects. First, we see the CO bandhead emission arising from a narrow annulus. To populate the CO bandheads, the gas must be hot \((T ≥ 2000\) K) and dense \((n_H ≥ 10^{10} \text{ cm}^{-3})\); Najita et al. (1996). The requisite conditions are ordinarily only met in systems with high accretion rates \((∼10^{-7}−10^{-6} M_\odot \text{ yr}^{-1})\); Ilee et al. (2014). CO bandhead emission is rarely observed in HAeBe systems, with a detection rate of 7% (Ilee et al. 2014).

In order to detect the large columns of CO gas observed in emission, all CO bandhead sources require strong suppression of the K-band opacity in the CO-emitting region. For HD 101412, the CO column density inferred from overtone bandhead emission \((7 × 10^{20} \text{ cm}^{-2})\); Table 3 corresponds to \(N_H = 1.4 × 10^{25} \text{ cm}^{-2}\), assuming a CO/H$_2$ of 1 × 10$^{-4}$ and an $A_K = 600$ if the dust were interstellar. Detecting a CO column as large as \(7 × 10^{20} \text{ cm}^{-2}\), therefore, requires a reduction in the K-band continuum opacity by a factor of \(∼600\), i.e., a factor of \(~6\) larger than the typical factor of \(∼100\) reduction in grain surface area that is found for T Tauri disks (Furlan et al. 2007).

Ilee et al. (2014) mention that CO emission is primarily observed around B-type stars, which makes sense due to the required temperatures to excite CO bandhead emission. Conditions around lower-mass stars may only reach requisite temperatures during episodic accretion events, thus resulting in variable CO bandhead emission. Also, due to the high gas density required, some disks may lack sufficient material to allow for CO bandhead emission. Ilee et al. (2014) also mention a possible connection to high disk inclinations with CO bandhead emission. Their sources with detections had a range of inclinations from 51° to 72°, based on model fits. A possible explanation for this inclination dependence would be the CO bandhead emission tracing the inner disk wall near the dust sublimation radius.

Second, whereas water emission is rare among HAeBe disks (Section 1), in HD 101412 we detect hot water emission with a luminosity comparable to the most luminous water emission from T Tauri disks. One possible explanation for the dearth of water emission from HAeBe disks compared to T Tauri disks is the relative UV luminosities to which the circumstellar disks are exposed; the strong FUV field of HAeBe stars can readily dissociate water in their disk atmospheres. This may not be apparent from the Walsh et al. (2015) chemical model of a disk around an HAe star, which finds a water-rich disk atmosphere with water column densities much larger than is consistent with observations. As they note, one reason for the discrepancy between the observed and predicted water columns may be their assumption of interstellar grains (gas-to-dust ratio and grain size distribution), which limits the penetration depth of the UV photons and their effect on disk molecular abundances.

The T Tauri disk models of Ádámkovics et al. (2014, their Figure 4; see also Ádámkovics et al. 2016; Najita & Ádámkovics 2017) support this perspective. Assuming grain...
growth at the level inferred for observed sources (e.g., Furlan et al. 2007), these models find that increasing the FUV radiation from T Tauri stars does, in fact, push the molecular layer deeper into the disk and dissociates H$_2$O to produce more extensive OH. Models of HAeBe disks that assume a comparable level of grain growth would likely find a similar reduction in the water column density in the disk atmosphere, which is more consistent with the general lack of water emission detected from HAeBe stars (Figure 10). In principle, water emission could be detected in HAeBe disks if the dust opacity in the disk atmosphere was low enough that the dust photosphere was located below the transition from OH to H$_2$O.

There are reasons to expect a low dust opacity in the inner disk of HD 101412. The stellar photosphere of HD 101412 is a λ Boö star (Folsom et al. 2012). Kama et al. (2015) hypothesize that the depletion of heavy elements in the photosphere of the star is a consequence of selective accretion of gas relative to dust, which is the accreting material has a gas-to-dust ratio of $\sim$600, i.e., a reduction in refractories by a factor of $\sim$6, similar to the extra factor of 6 reduction needed in the K-band continuum opacity to expose the entire CO bandhead-emitting column to view.

What is the source of the depletion of refractory material in the disk? If a giant planet (with mass from 0.1 $M_\oplus$ to 10 $M_\oplus$) is present in the disk, the pressure bumps it creates (e.g., at the edge of a gap) could preferentially reduce the accretion of solids relative to gas through the disk by aerodynamic drag (Rice et al. 2006; Zhu et al. 2012). Due to the lack of a convective outer layer in early-type stars, the refractory depleted material that accretes onto the star would reside on the surface, giving rise to the λ Boö abundance pattern (Figure 11).

The detection of C- and O-bearing molecules (CO, OH, and H$_2$O) from the inner region of the HD 101412 disk and the detection of CO$_2$ with Spitzer (Pontoppidan et al. 2010), which presumably will eventually accrete onto the star, is consistent with the high abundance of volatile elements in the stellar atmosphere of HD 101412. The presence of oxygen-bearing molecules, such as H$_2$O and CO$_2$, in the gas phase implies that if a planet-induced gap is responsible for filtering out the solids from the inwardly accreting material (Kama et al. 2015), the planet would likely be located well inward of the snow line (which we estimate is located at $\sim$25 au, adopting the distance at which a blackbody is 150 K, but must lie beyond 5 au; Figure 11). If the planet were located near or beyond the snow line, dust filtering would remove water ice (and oxygen) as well from the accreting material, creating a more carbon-rich composition, in which molecules like H$_2$O and CO$_2$ are unlikely to be abundant (Figure 11).

The NIR molecular emission from HD 101412 overlaps the [OI] emission from the source and is roughly coincident spatially with the inner edge of the dust disk seen in the mid-infrared. The mid-infrared dust emission arises from 1.1 to 5.2 au when taking into consideration the new distance from Gaia (Figure 12; Fedele et al. 2008; van der Plas et al. 2008). The structure shown in Figure 12 is analogous to a miniature photodissociation region with the inner emission arising from [OI], then molecular emission, followed by dust emission. The [OI] emission probes the tenuous atomic layer of the disk that is depleted of dust and molecules. It is not clear what the radial extent of the disk is as there are presently no far-infrared or submillimeter observations that would probe the cooler dust arising from beyond 5 au.

Given the high inclination of the system ($i = 86^{\circ}$; Section 4), the hot molecular emission we see may be coming from the inner wall of the far side of the disk. A viewing angle of 4° edge-on appears large enough to obtain an unobstructed view of the bright molecular emission from the far side of the inner disk. Given the temperature of the molecular emission (1300 K; Section 4) and the stellar mass (2.5 $M_\odot$; Section 1), the disk scale height at the radius of the molecular emission (1 au) is 0.05 au if the gas is in hydrostatic equilibrium; thus the height of the molecular emitting gas on the near side of the disk may rise $\sim$1.5 au above the midplane when viewed from the far side of the disk 2 au away.

There are two observational approaches to test our hypothesis that the luminosity of the water emission and CO bandhead emission are enhanced by the depletion of dust in the inner disk (by a factor of 6 or more; Kama et al. 2015). First, one can compare the EW of the molecular emission to the gas-to-dust ratio of the accreting material as inferred from photospheric abundances of the star. Larger molecular emission EWs are expected for systems with larger gas-to-dust ratios. Second, one can test the role of the disk inclination by observing additional edge-on systems and comparing these to more inclined systems. The emission from the edge-on systems will be dominated by the inner wall of the disk and should probe denser gas than the more face-on systems where the emission is dominated by less dense gas from the disk surface.
Figure 11. Above schematic presents one possible scenario, discussed in detail in the text, to explain the NIR observations of HD 101412. Based on the stellar luminosity for HD 101412, we determine the dust sublimation radius to be at 0.25 au. The molecular emission arises from a narrow annulus (∼0.8–1.4 au). Refractory elements are observed to be below solar abundances based on photospheric observations, while C and O are found to be at solar abundances (Folsom et al. 2012). This indicates that large dust grains are filtered out, leading to a depletion of refractory elements in the inner disk. If a planetary body was forming within the snow line (>5 au), this would allow for C- and O-containing molecules to reside in the inner disk, eventually accreting onto the central star, and giving rise to the observed photospheric abundance pattern. This figure is not to scale.

Figure 12. Updated Figure 8 from Fedele et al. (2008) showing locations of [O I] emission, dust emission, and molecular emission from HD 101412. The orange region indicates the location of OH, H2O, and CO gas presented from our analysis. The blue region indicates the dust emission based on MIDI observations, updated to account for the Gaia Collaboration et al. (2016) distance. The light brown region is the overlap of the two regions, with the [O I] emission (in green) remaining unchanged due to the use of similar stellar masses between the studies.

The feasibility of this scenario can also be tested through thermochemical modeling of the inner disk. One possible concern is that if grains are too underabundant, it is difficult to synthesize H2 on grains, which is a critical first step in the gas phase synthesis of molecules, such as OH, CO, and water. Severe dust depletion may make it difficult to counteract photodestruction of molecules and to sustain a substantial reservoir of molecular gas. Self-consistently fitting the infrared portion of the SED and molecular column density in the disk atmosphere will inform the feasibility of our hypothesis.

7. Conclusions

We present the first detection of water emission at 2.9 μm in a Herbig Ae/Be star system, along with a new detection of OH rovibrational emission. The OH emission observed represents the strongest ever observed in an HAeBe disk in terms of a line-to-continuum ratio. The observed line profiles for both OH and H2O indicate that the emitting region for both molecules is narrow and ∼1 au from the star.

The bright molecular emission from HD 101412 may be related to its photospheric abundance pattern, i.e., its nature as a λ Boö star, and the disk’s large inclination angle. If the low abundance of refractory elements is a result of selective accretion of gas relative to dust, as has been previously hypothesized, the inner disk from which HD 101412 accretes should be strongly dust-depleted and its continuum should be more optically thin. This situation would tend to produce strong molecular emission from the inner disk, as is observed. Our detection of C- and O-bearing molecules from the inner disk is consistent with the expected presence in this scenario of abundant volatiles in the accreting material.

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ORCID iDs

Máté Ádámkovics @ https://orcid.org/0000-0003-1869-0938
John S. Carr @ https://orcid.org/0000-0002-6695-3977
Sean D. Brittain @ https://orcid.org/0000-0001-5638-1330

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