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Water Depletion in the Disk Atmosphere of Herbig AeBe Stars

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WATER DEPLETION IN THE DISK ATMOSPHERE OF HERBIG AEBE STARS

D. Fedele1, I. Pascucci1,2, S. Brittain3, I. Kamp4, P. Woitke5,6,7, J. P. Williams8, W. R. F. Dent9, W.-F. Thi10

ABSTRACT

We present high resolution (R∼100,000) L-band spectroscopy of 11 Herbig AeBe stars with circumstellar disks. The observations were obtained with the VLT/CRIRES to detect hot water and hydroxyl radical emission lines previously detected in disks around T Tauri stars. OH emission lines are detected towards 4 disks. The OH 2Π_{3/2} P4.5 (1+,1-) doublet is spectrally resolved as well as the velocity profile of each component of the doublet. Its characteristic double-peak profile demonstrates that the gas is in Keplerian rotation and points to an emitting region extending out to ~15–30 AU. The OH emission correlates with disk geometry as it is mostly detected towards flaring disks. None of the Herbig stars analyzed here show evidence of hot water vapor at a sensitivity similar to that of the OH lines. The non-detection of hot water vapor emission indicates that the atmosphere of disks around Herbig AeBe stars are depleted of water molecules. Assuming LTE and optically thin emission we derive a lower limit to the OH/H2O column density ratio > 1 – 25 in contrast to T Tauri disks for which the column density ratio is 0.3 – 0.4.

Subject headings: astrochemistry – molecular processes – protoplanetary disks – stars: pre-main-sequence, Herbig AeBe

1. INTRODUCTION

Young pre-main-sequence stars are surrounded by gas-rich dust disks that are the left over from the collapse of the molecular cloud core. Sub-micron sized dust grains grow to larger sizes with time (e.g. Bouwman et al. 2001; Rodmann et al. 2006). This leads to the formation of planetesimals and eventually planets (e.g. Weidenschilling & Cuzzi 1993; Henning et al. 2006; Blum & Wurm 2008). The evolution of the infrared excess in pre-main-sequence stars (PMSs) suggests that most of the small dust grains in the disk disappear within 3–5 Myr from the collapse of the molecular cloud and very little amount of dust is found beyond 10 Myr (e.g. Haisch et al. 2001; Bouwman et al. 2006; Hernandez et al. 2007; Roccatagliata et al. 2009; Pascucci & Tachibana 2010). A similar timescale is found for the evolution of mass accretion rates in disks (e.g. Mohanty et al. 2005; Jayawardhana et al. 2006; Sicilia-Aguilar et al. 2008; Ingleby et al. 2009; Fedele et al. 2010). The energetic radiation field of a PMS star impinging onto the disk surface regulates the disk temperature, can ionize the gas, breaks molecular bonds and might lead to evaporation of the outer layers of the disk. An important role for the formation of a planetary system as well as for the origin of life on Earth is played by water. Compared to other volatiles (e.g. NH3, CO2, CH4) water has an higher condensation temperature. Thus, within a protoplanetary disk, water is the first volatile to condense as temperature decreases as a function of the radial distance from the star and vertical depth. In view of the cosmic abundance of hydrogen and oxygen, water is the most abundant ice. This sets a boundary (snow line) beyond which most of the molecular gas condenses onto ice. For a review on the snow line in the solar nebula and in protoplanetary disks see, e.g., Podolak (2010). Beyond the snow line the solid surface density, and perhaps even the total surface density of the disk, increases (Kennedy & Kenyon 2008). This, in turn, speeds up the formation of gas giant planets allowing them to form before the gas in the disk is dispersed.

Water and hydroxyl (OH) emission have been detected in a number of protoplanetary disks around young sun-like stars in the near-infrared (Carr et al. 2004, Thi & Bil 2003, Salvik et al. 2008, Mandell et al. 2008) as well as at mid-infrared wavelengths (10 – 40 μm) (Carr & Najita 2008, Salvik et al. 2008, Najita et al. 2010) and in the far-infrared with the Herschel Space Observatory (Sturm et al. 2010, van Kempen et al. 2010). Lines at different wavelengths trace different temperatures and hence different regions of the disk. While the near- to mid-infrared and high excitation far-infrared lines probe the molecular gas from the warm surface layers of the disk, the low excitation far-infrared lines are sensitive to colder gas (a few 100 K) located closer to the disk midplane (e.g. Woitke et al. 2009).

Mandell et al. (2008) performed high resolution
(R \sim 27,000) L-band spectroscopy towards two Herbig AeBe stars (AB Aur and MWC 758). They did not find evidence of hot water vapor emission in these two disks. Pontoppidan et al. (2010) searched for colder molecular emission in the mid-infrared the Spitzer Space Telescope. In contrast to T Tauri stars, the mid-infrared spectrum of Herbig AeBe stars is poor in molecular emission and they find only tentative H$_2$O and OH emission lines towards some Herbig AeBe stars.

The different molecular emission between T Tauri and Herbig AeBe stars might be due to photochemistry which controls the excitation and dissociation of molecules. Aiming to test this hypothesis, we performed a deep search for hot water and hydroxyl radical vapor emission in Herbig AeBe stars with circumstellar disks. We performed ultra high resolution (R \sim 100,000, \Delta \nu \sim 3 \text{ km s}^{-1}) L-band spectroscopy of 11 Herbig AeBe stars with CRIRES at the VLT. This spectral resolution allows us to resolve the velocity profile of the molecular emission lines and thus determine the radii over which the emission arises.

Observations and data reduction procedures are presented in Sec. 2. In Sec. 3 we describe the immediate results of the survey: the detection of the OH \Pi\(1^+1^-\) rovibrational line and the non-detection of water rovibrational lines. In Sec. 4 we present the analysis of the OH lines and discuss the implications of our findings in Sec. 5. Finally, we summarize our results in Sec. 6.

### 2. OBSERVATIONS AND DATA REDUCTION

High resolution L-band spectroscopy was obtained on the nights of 4, 5 and 6 December 2008 with the ESO’s VLT cryogenic high-resolution infrared echelle spectrograph (CRIRES, Kauff et al. 2004) at the Paranal observatory in Chile. A slit width of 0.2 arcsec was adopted. In order to center the target inside the narrow slit we used the adaptive optics system and the targets themselves as reference stars. This procedure reduces slit losses resulting in a higher signal-to-noise ratio and higher spectral resolution. Unresolved sky emission lines can be used to determine the actual spectral resolution. The full-width-half-maximum (FWHM) of the OH sky lines measured in the raw frames is \sim 3 \text{ km s}^{-1} (or R \sim 100,000) as expected from the nominal resolution. The spectra were recorded by nodding the telescope along the direction perpendicular to the slit (oriented along the parallactic angle) with a nodding throw of 10\". The spectra cover the wavelength range between 2861 – 2936 nm (order 19, \lambda_{\text{ref}} = 2909.6 \text{ nm}) thus covering several ro-vibrational lines of H$_2$O detected in comets (e.g. Dello Russo et al. 2004; Dello Russo et al. 2007) and in protoplanetary disks (Salvy et al. 2008) as well as ro-vibrational lines of OH detected in disks by Mandell et al. (2008) and Salvy et al. (2008).

The data were reduced using the ESO CRIRES pipeline v.11.1 following a standard approach: first the CRIRES frames are corrected for flat field, dark and bad pixels; second the frames at a given nodding position are combined together and the two master frames (one for each nodding position) are then combined together after correcting for the spatial offsets (due to the nodding procedure); finally, the spectrum is extracted using a rectangular mask. The sky emission lines are used to determine the wavelength dispersion solution. To properly correct for atmospheric telluric absorptions the spectra were bracketed with observations of standard stars of early spectral type (see Table 1). These spectra are divided by the stellar atmosphere models of Kurucz (1979) to determine the instrument response function and atmospheric transmission curve. The optical depth of the telluric lines is scaled to the depth of the science target. Finally, each science spectrum is divided by the response function. The spectral regions heavily absorbed (atmospheric transmission < 0.5) are not used in the rest of the analysis. For the flux calibration we scaled the CRIRES spectra to the observed L-band magnitude measured by de Winter et al. (2001); V380 Ori, HD 76534, UX Ori, HD 250550, HD 259431, HD 45677, BF Ori, HD 98922, HD 41753, HD 74195, HD 74280, HD 28873, HD 98718, HD 39764.

<table>
<thead>
<tr>
<th>Star</th>
<th>RA (J2000)</th>
<th>DEC (J2000)</th>
<th>Date observation</th>
<th>Exposure (s)</th>
<th>Airmass</th>
<th>Calibrator</th>
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<tbody>
<tr>
<td>UX Ori</td>
<td>05:04:29.9</td>
<td>-03:47:11.1</td>
<td>2008-12-06; 02:50:50</td>
<td>1440</td>
<td>1.2</td>
<td>HD 36512</td>
</tr>
<tr>
<td>HD 34282</td>
<td>05:16:00.5</td>
<td>-09:48:31.2</td>
<td>2008-12-06; 01:47:50</td>
<td>1440</td>
<td>1.1</td>
<td>HD 40494</td>
</tr>
<tr>
<td>CO Ori</td>
<td>05:27:37.8</td>
<td>+11:25:33.3</td>
<td>2008-12-07; 04:32:54</td>
<td>720</td>
<td>1.2</td>
<td>HD 64503</td>
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<tr>
<td>V380 Ori</td>
<td>05:36:25.0</td>
<td>-06:43:00.3</td>
<td>2008-12-05; 02:36:08</td>
<td>720</td>
<td>1.4</td>
<td>HD 23466</td>
</tr>
<tr>
<td>BF Ori</td>
<td>05:37:12.9</td>
<td>-06:35:07.5</td>
<td>2008-12-07; 05:15:18</td>
<td>2400</td>
<td>1.1</td>
<td>HD 64503</td>
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<tr>
<td>HD 250550</td>
<td>06:01:59.5</td>
<td>+16:30:50.7</td>
<td>2008-12-06; 05:34:49</td>
<td>1080</td>
<td>1.3</td>
<td>HD 41753</td>
</tr>
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<td>HD 45677</td>
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<td>-13:03:18.2</td>
<td>2008-12-06; 07:31:57</td>
<td>1080</td>
<td>1.1</td>
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</tr>
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<td>HD 259431</td>
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<td>+10:19:16.6</td>
<td>2008-12-06; 06:22:57</td>
<td>1080</td>
<td>1.2</td>
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<td>HD 76534</td>
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<td>2008-12-06; 08:22:59</td>
<td>480</td>
<td>1.3</td>
<td>HD 98718</td>
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</table>

3. IMMEDIATE RESULTS

http://www.eso.org/sci/data-processing/software/pipelines/index.html
Water depletion in Herbig AeBe disks

Table 2

Properties of the program stars

<table>
<thead>
<tr>
<th>Star</th>
<th>Sp.Type</th>
<th>Age [Myr]</th>
<th>A_V [mag]</th>
<th>D [pc]</th>
<th>L_{UV}^* [L_⊙]</th>
<th>M_{acc} [10^{-7} M_⊙ yr^{-1}]</th>
<th>Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>UX Ori</td>
<td>A3</td>
<td>4.5^a</td>
<td>0.8^c</td>
<td>460^b</td>
<td>2.4</td>
<td>0.66^i</td>
<td>II</td>
</tr>
<tr>
<td>HD 34282</td>
<td>A0</td>
<td>7^b</td>
<td>0.6^c</td>
<td>160^c</td>
<td>&lt;2.1^c</td>
<td>0.26^c</td>
<td>I</td>
</tr>
<tr>
<td>CO Ori</td>
<td>F7</td>
<td>&lt;0.12^c</td>
<td>2.2^c</td>
<td>460^h</td>
<td>2.9^i</td>
<td>0.9^g</td>
<td>II</td>
</tr>
<tr>
<td>V380 Ori</td>
<td>A1</td>
<td>&lt;0.01^c</td>
<td>1.43^c</td>
<td>430^c</td>
<td>18.8</td>
<td>25^i</td>
<td>I</td>
</tr>
<tr>
<td>BF Ori</td>
<td>A5</td>
<td>3.2^a</td>
<td>0.37^i-0.7^c</td>
<td>460^h</td>
<td>0.6-1.3</td>
<td>0.87^i</td>
<td>II</td>
</tr>
<tr>
<td>HD 250550</td>
<td>B7</td>
<td>0.25^c</td>
<td>1.17^c</td>
<td>700^h</td>
<td>160</td>
<td>0.16^i</td>
<td>I</td>
</tr>
<tr>
<td>HD 45677</td>
<td>B2</td>
<td>–</td>
<td>&gt;500^k</td>
<td>&gt;65</td>
<td></td>
<td></td>
<td>II</td>
</tr>
<tr>
<td>HD 259431</td>
<td>B5</td>
<td>&lt;0.01^c</td>
<td>0.63^l-1.62^e</td>
<td>800^g</td>
<td>225-2200</td>
<td>7.8^i</td>
<td>I</td>
</tr>
<tr>
<td>HD 76534</td>
<td>B2</td>
<td>&gt;0.5^d</td>
<td>0.80^f</td>
<td>870^g</td>
<td>1020^*</td>
<td></td>
<td>I</td>
</tr>
<tr>
<td>HD 85567</td>
<td>B5</td>
<td>&lt;0.01^c</td>
<td>2.23^c</td>
<td>1500^g</td>
<td>–</td>
<td></td>
<td>II</td>
</tr>
<tr>
<td>HD 98922</td>
<td>B9</td>
<td>&lt;0.01^c</td>
<td>0.54^f</td>
<td>1000^g</td>
<td>545</td>
<td>17.4^l</td>
<td>II</td>
</tr>
</tbody>
</table>

* Integrated between 1100 - 2430 Å, (IUE spectrum, Valenti et al. 2003) and multiplied by a factor 10^{0.4 A_{1770}}. Where A_{1770} is the extinction at λ = 1770 Å measured from A_V using the R = 3.1 extinction relation of Cardelli et al. (1989).

** Missing short wavelength IUE spectrum, integrated between 1850 - 2430 Å.

*** Missing long wavelength IUE spectrum, integrated between 1150 - 2000 Å.

We have searched for H₂O and OH rovibrational lines previously detected in protoplanetary disks around sunlike stars, comets, as well as transitions that are not yet detected but reported in recent synthetic molecular line lists. In the following section we summarize the main findings for H₂O and OH.

3.1. Detection of OH lines

The rovibrational OH 2Π_{3/2} P.4.5 (1+,1-) at 2.9345μm transition is detected towards 4 disks (V380 Ori, HD 250550, HD 259431 and HD 85567, Fig. 1). The high spectral resolution of CRIRES allows us to resolve not only the doublet but also the velocity profile of each transition. Modeling of the line profiles and estimates of the radii traced by this emission are presented in Sec. 4. The profile of the 2Π_{3/2} P.4.5 (1+,1-) line varies from object to object (Figs. 2-3). In the case of V380 Ori each line shows a characteristic double-peak profile as one would expect if the gas is in Keplerian rotation. In the case of HD 250550 the lines are narrower reflecting the lower inclination of the disk (Table 3). Finally, the OH line in HD 259431 and HD 85567 is very broad and the two transitions of the doublet are blended even at the high resolution of CRIRES. In the case of HD 259431, multiple peaks are visible hinting to multiple velocity components. Two peaks are detected (above 3σ) at the sides of the line at 2.9340 μm and 2.9352 μm respectively. The position of these peaks is symmetric to the center of the emission and correspond to a velocity of ± 47 km s^{-1}. The OH emission is very broad (FWHM = 90 km s^{-1}) and the sides of the emission might be contaminated by the strong telluric absorptions at 2.9335 μm and 2.9355 μm.

We used different telluric standard stars (taken at different airmass) to check the reliability of the line profile. In all cases we found the two high velocity wings above the 3σ level. Further confirmation of the presence of these wings comes from a posteriori analysis of the line profile (Sec. 4.2): if the OH emission is made of a single velocity component, the central part of the emission would be stronger than the sides due to the blending of the line (see e.g. dotted-dashed line in Fig. 3). The analysis of the line profile confirms the presence of multiple velocity components and the reliability of the high velocity peaks. At higher velocity, where the atmospheric transmission function drops below 70%, the emission is heavily corrupted by telluric absorption hence we excluded these regions from the analysis of the line.

Within the spectral range covered by our observations there are other two transitions of the OH 2Π_{3/2} P branch (J = 2.5, 3.5) as well as two transitions of the OH 2Π_{3/2} P branch (J = 2.5, 3.5). Unfortunately all four transitions fail either in highly saturated telluric absorption regions or inside the inter-chips gaps hence we cannot compute stringent line flux upper limits.

3.1.1. OH column density

The energy level of the ro-vibrational transitions of OH might be populated either thermally or radiatively (fluorescence). In the first case the collisions with atoms and molecules are the dominant excitation mechanism and the emission is only dependent on the temperature and density of the gas as we will show below (LTE case). In the case of fluorescent emission the ro-vibrational levels are populated by absorption of near-infrared photons.

...
Portion of the CRIRES spectra for V380 Ori, HD 250550, HD 259431 and HD 85567. In each panel the upper line (red) is the extracted target spectrum along with the atmospheric transmission curve (blue line). The lower plot of each frame is the spectrum cleaned by the telluric absorption lines multiplied by a factor of 10. The dashed line shows the 3σ detection level. For each star the OH P4.5 (1+,1-) doublet is detected and spectrally resolved. The vertical lines show the positions of some of the strongest H$_2$O rovibrational lines. The dotted line indicates the expected line height of the H$_2$O (001–000) [1166 – 1267] transition in the case of OH/H$_2$O column density ratio equal to unity.

OH P4.5 doublet towards V380 Ori. The red line is the best fit model (Sec. 4.2, Table 3) assuming Keplerian rotation. The asymmetry of the line profile indicates a deviation from the Keplerian motion of the gas (see Appendix).

\( \chi^2 \) contours in the \( \alpha - R_o \) parameter space for V380 Ori assuming \( i = 30^\circ \) and \( R_i = 2 \text{AU} \). The best fit value is shown as a black dot.

In the electronic ground state) or absorption of UV photons which excite the electronic states with following cascade in the electronic ground state. UV fluorescent pumping in protoplanetary disks has been investigated for the first time by\cite{Brittain2003, Brittain2007} to explain the CO emission from the disk around the HAeBe stars HD 141569 A and AB Aur.\cite{Mandell2008} implemented UV and IR fluorescent pumping for the OH rovibrational lines detected in the disk around AB Aur and MWC 758. They find that a fluorescent model can explain the observed OH line intensities as well as OH ther-
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\[ I(OH) = N_n(OH)h\tilde{\nu}cA_{nm} \]  

(1)

Figure 4. Same as Figure 2 for HD 250550

Figure 5. Same as Fig. 2 for HD 259431. The dashed and dot-dashed lines are the the optically thick and disk’s atmosphere components respectively.

normal emission. The difference between thermal and fluorescent emission is in the inferred OH column densities, which are higher in the LTE case. Since our observations do not allow us to discriminate between LTE and fluorescent emission, we assume in the following analysis that the OH gas is in LTE, the emission is optically thin, and compute the total number of OH molecules from the measured line flux. For the gas temperature we take a value of 700 K as estimated by Mandell et al. (2008) for the Herbig AeBe stars AB Aur and MWC 758. With these assumptions the OH line intensity is

\[ N_n(OH) = g_J \exp(-E_n/kT) Q(T) \]  

(2)

where \( g_J = 2J+1 \) is the degeneracy of the state, \( E_n \) the energy of the upper state, \( k \) the Boltzmann constant and \( Q(T) \) the partition sum. Substituting \( N_n \) from Eq. 2 in Eq. 1 we have

Figure 6. \( \tilde{\chi}^2 \) contours in the \( \alpha_2 - R_{2,0} \) parameter space for HD 259431 assuming \( i = 50^\circ \), \( \alpha_1 = 0 \), \( R_{1,1} = 0.9 \) AU and \( R_{1,0} = R_{2,1} = 1.4 \) AU. The best fit value is shown as a black dot.

Figure 7. OH P4.5 doublet towards HD 85567.
The transition parameters and the partition sum are taken from HITRAN \cite{Rothman2003}. The total number of molecules can be converted into a vertical column density ($N_{\text{col}}$) by dividing it by the area of the OH emitting region, $\pi (R_{i}^{2} - R_{o}^{2})$, with $R_{i}$ and $R_{o}$ being inner and outer radius of the OH emitting region (see Sec. 3.2). When the OH P4.5 doublet is not detected and the emitting region is not known we assume $R_{i} = 0.4$ AU and $R_{o} = 10$ AU and a line width of 30 km s$^{-1}$ (based on our results of the OH line detections). The values of $N$ and $N_{\text{col}}$ are listed in Table 4. We note that increasing the temperature to $T(\text{OH}) = 1000$ K decreases $N$ (hence $N_{\text{col}}$) almost by an order of magnitude.

3.2. Non-detection of H$_{2}$O lines

In order to search for faint water vapor emission we first created a line list using the water line list catalog of Barber et al. (2006). The latter is the most complete and accurate water line list in the literature. We used their $B$-T2 code to produce the synthetic spectrum and adopted the same temperature as that for the OH gas (700 K). Some of the strongest water lines detected by Salvik et al. (2008) in the T Tauri stars AS 205 A and DR Tau lie around 2930 nm close to the OH 2Π$_{3/2}$ P4.5 doublet we have detected in 4 disks and hence in a clean part of the spectrum. For comparison Fig. 1 shows the positions of the strongest water emission lines from Salvik et al. (2008). None of the 11 Herbig AeBe stars observed with CRIRES show evidence of hot water vapor emission in the L-band spectra.

We compute the 3-$\sigma$ upper limit of the line flux for the line H$_{2}$O (001–000) [11$_{66}$ – 12$_{67}$] at 2.931 $\mu$m detected in T Tauri stars. The upper limit is measured as the product $3 \times \sigma \times \Delta \lambda$, where $\sigma$ is the standard deviation of the spectrum and $\Delta \lambda$ is a charateristic line width of 30 km s$^{-1}$ or $2.9 \times 10^{-4}$ $\mu$m (of the same order of the OH line width). The line flux upper limits for the program stars are given in Table 4. Typical upper limits are of the order of $10^{-16} – 10^{-15}$ erg cm$^{-2}$ s$^{-1}$. The water lines detected by Salvik et al. (2008) have fluxes of the order of $10^{-15} – 10^{-14}$ erg cm$^{-2}$ s$^{-1}$.

3.2.1. H$_{2}$O column density

With the same assumptions of Sec. 3.1.1 (optically thin emission, LTE, T = 700 K) we can estimate the upper limit to the total number of molecules and column density of H$_{2}$O. In the case of water, Eq. 3 must be modified to take into account an additional degeneracy associated with the nuclear spin ($g_{J} = 3$ for J odd and $g_{J} = 1$ for J even). We compute the upper limits of $N(\text{H}_{2}\text{O})$ and $N_{\text{col}}(\text{H}_{2}\text{O})$ using the line flux upper limits of the (001–000) [11$_{66}$ – 12$_{67}$] transition. The results are listed in Table 4. We note that also in this case the number of molecules decreases by almost an order of magnitude by increasing the temperature to $T(\text{H}_{2}\text{O}) = 1000$ K.

\begin{equation}
N(\text{OH}) = \frac{I(\text{OH}) Q(T) \exp(F_{n}/kT)}{hc\nu A_{nm}(2J + 1)}
\end{equation}

\[N(\text{OH}) = \frac{I(\text{OH}) Q(T) \exp(F_{n}/kT)}{hc\nu A_{nm}(2J + 1)}
\]

\text{TABLE 3}

<table>
<thead>
<tr>
<th>Stellar and disk parameters</th>
</tr>
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<tbody>
<tr>
<td>V380 Ori</td>
</tr>
<tr>
<td>$M_{*}$ [M$_{\odot}$]</td>
</tr>
<tr>
<td>$i$ [°]</td>
</tr>
<tr>
<td>$a$</td>
</tr>
<tr>
<td>$R_{i}$ [AU]</td>
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<td>$R_{2,o}$ [AU]</td>
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<tr>
<td>$\chi^{2}$</td>
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</table>

In the case of HD 259431 the model is the sum of two velocity components. The subscript “2” refers to the second velocity component.

\[\text{3.3. OH/H$_{2}$O line ratio}\]

From the comparison of Fig. 1 with Fig. 2 of Salvik et al. (2008) it is evident that the OH/H$_{2}$O line ratio is higher in Herbig AeBe disks than in T Tauri disks. For the Herbig stars with detected OH emission lines, we have that the OH/H$_{2}$O line flux ratio is $\geq 1.5 – 3^{12}$. This translates into a lower limit to the OH/H$_{2}$O column density ratio of 1 – 25 (Table 4). For comparison we show in Fig. 1 the expected line height of the H$_{2}$O (001–000) [11$_{66}$ – 12$_{67}$] transition in the case of OH/H$_{2}$O column density ratio equal to unity (dotted line). The intensity of the OH P4.5 line for the four Herbig AeBe stars (Table 4) is of the order of $10^{-15} – 10^{-14}$ erg cm$^{-2}$ s$^{-1}$, similar to the OH and H$_{2}$O line flux measured in T Tauri disks (Salvik et al. 2008). However, in the case of T Tauri disks the OH/H$_{2}$O line flux ratio is $\sim 1$ and the column density ratio is 0.3 – 0.4, that is, the OH/H$_{2}$O column density ratio is $\sim 3$–25 times larger in Herbig AeBe disks than in T Tauri disks. This suggest that, in contrast to T Tauri disks, water vapor is less abundant than OH in the disk atmosphere of Herbig AeBe stars.

\[\text{4. ANALYSIS}\]

In order to understand the pattern of detections and non-detections we investigate whether there is any correlation between stellar and disk properties and the surveyed emission lines (Sec. 4.1). We also model the profiles of the resolved OH lines and provide estimates for the radial distances traced by the L-band OH emission in disks around Herbig AeBe stars (Sec. 4.2).

\[\text{4.1. OH lines and disk properties}\]

A noticeable distinction appears when detections are compared with the disk geometry: the majority of the sources with detection of OH emission appears to have a flared disk geometry. Meeus et al. (2001) have shown that the ratio of the far-infrared to the near-infrared flux is sensitive to the geometry of the disk. Far-infrared bright stars belonging to the group I of Meeus et al.

\[12\text{ Estimated from the Fig. 2 of Salvik et al. (2008)}\]

\[13\text{ We refer here to the total flux of the OH P4.5 doublet, i.e. twice the value listed in the fourth column of Table 4}\]
are thought to have a flared disk geometry, that is the disk scale height (\(H\)) and opening angle (\(\theta_h\)) of the disk increases with the distance from the star (\(R\)). Group II sources are thought to have a flat, self-shadowed geometry, due to the disk inner rim casting a shadow at larger disk radii (Dullemond & Dominik 2004). van Boekel et al. (2003) found that the two groups occupy two different regions in the IRAS \(m_{12} - m_{60}\) color versus \(L_{\text{NIR}}/L_{\text{IR}}\) diagram, where \(L_{\text{NIR}}\) is the integrated luminosity as measured by the J, H, K, L and \(M\) photometry and \(L_{\text{IR}}\) is the integrated luminosity measured by the IRAS 12, 25 and 60 \(\mu\)m fluxes. Following van Boekel et al. (2003) we provide in Table 2 the group of the program stars. Interestingly, three out of four stars for which \(OH\) emission is detected (V830 Ori, HD 250550, HD 259431) belong to group I while only one source showing \(OH\) emission (HD 85567) belongs to group II. We note that the other two \(HAE\)Be stars with detected \(OH\) emission in the literature (AU Aur and MWC 758 Mandell et al. 2008) also belong to group I. We discuss the origin of such a correlation in Sec. 5.5.

4.2. \(OH\) line profiles

In this section we present an analysis of the \(OH\) P4.5 (1+,1-) line profiles for V380 Ori, HD 250550, HD 259431 and HD 85567. Figs. 2-5 show the velocity profile of the doublet for the 4 stars from which we can estimate the radial distribution of the molecular gas. We assume that the line intensity follows a power-law distribution as a function of the radial distance from the star (e.g. Smak 1981; Carmona et al. 2007; van der Plas et al. 2009) of the form

\[
I_{\text{OH}}(R) = I_{\text{OH}}(R_0) \cdot \left(\frac{R}{R_0}\right)^{-\alpha} \tag{4}
\]

where \(R\) is the distance from the star and \(I_{\text{OH}}(R_0)\) is the intensity at the inner radius. We also assume that the \(OH\) line is optically thin. If the line is optically thick we should include in the analysis the continuum and line optical depths (e.g. Horne & Marsh 1986). Here, we are interested in determining the inner and outer radius of the \(OH\) emitting region and a complete analysis of the line emission properties is beyond the scope of this paper. The radial profile of the \(OH\) line is converted into a velocity profile assuming that the gas is in Keplerian rotation. In addition the model line is convolved with a velocity width \(v = \sqrt{v_{\text{in}}^2 + v_{\text{th}}^2}\) where \(v_{\text{in}}\) is the instrumental broadening (\(\sim 3\) km s\(^{-1}\)) and \(v_{\text{th}}\) (\(= \sqrt{2kT/m_{\text{OH}}}\)) is the thermal broadening of the line (where \(k\) is the Boltzmann constant, \(T\) is the gas temperature and \(m_{\text{OH}}\) is the mass of \(OH\)). We assume a temperature of 700 K as found by Mandell et al. (2008) which corresponds to \(v_{\text{th}}\sim 0.8\) km s\(^{-1}\). For the Keplerian rotation and line convolution we used the IDL codes “keprot” and “convolve” described in Acke et al. (2002).

With the assumption of Keplerian rotation and of the radial profile in Eq. 4 the velocity profile of the emission line is a function of 4 parameters: the power law intensity exponent (\(\alpha\)), the disk inclination (\(i\)), the inner and outer radii of the \(OH\) emitting region (\(R_0, R_o\)). The Keplerian velocity is \(v_{\text{kep}} = \sqrt{GM/R}\), hence the inner radius determines the maximum velocity in the line profile. Because the disk inclination is not known for our sources (apart from HD 259431) we fitted the \(OH\) P4.5 doublet by minimizing the reduced \(\chi^2\) between the observed and model velocity profile

\[
\chi^2 = \frac{1}{d} \sum \left(\frac{\text{model} - \text{observed}}{\sigma}\right)^2 \tag{5}
\]

with \(d\) degree of freedom. In our fitting procedure we leave free only three parameters: \(i\), \(R_0\) and \(R_o\) and repeat the model fitting for five different values of \(\alpha\) (0, 1.0, 1.5, 2, 2.5). The best fit parameters are listed in Table 3.

4.2.1. Determination of the outer disk (\(R_o\))

The measure of \(R_o\) requires further explanation. The contribution from the outer disk to the line intensity is reduced because of the power-law distribution (Eq.4). Moreover, the fit of the line profile might be degenerate if the parameters are not independent. As we saw above, \(R_i\) is uniquely determined by the maximum velocity of the line. In a Keplerian motion, the disk inclination and outer radius are responsible of the characteristic double-peak profile: for a given ring of gas at a distance \(R\) from the central star the two peaks of the line are separated by the quantity \(v_{\text{kep}} \cdot \sin(i) \propto R^{-1/2} \cdot \sin(i)\). If the disk inclination is known, it is possible to unambiguously determine \(R_o\). The power-law index (\(\alpha\)) controls how steeply the intensity intensity decreases with radius (hence velocity) and affects only slightly the peak-to-peak separation as shown in Fig. 1 of Smak (1981). To check the robustness of the fit we first determine the best fit parameters, then we fix the disk inclination and inner radius and compute the \(\chi^2\) surface on the \(\alpha = R_o\) parameter space.

Notes on individual targets:

V830 Ori. The \(OH\) emission extends from \(\sim 2\) AU to \(\sim 15\) from the central star (Fig 2) and we estimate a disk inclination of \(\sim 30^\circ\). Fig. 3 shows the \(\chi^2\) of the fit in the \(\alpha = R_o\) plane. The single peaked \(\chi^2\) distribution shows that the determination of \(R_o\) is robust. The \(OH\) P4.5 line profile is asymmetric with the blue peak stronger than the red peak. The model in Fig. 2 has been manually modified to account for the excess flux in the blue-shifted peak by multiplying the latter by a factor of 1.2. The origin of the asymmetric line profile is discussed in the Appendix.

HD 250550. In this case the line is top-flat and the two peaks are not visible. This is likely due to the low inclination of the disk in the plane of the sky (disk almost face-on). In this situation it is not possible to determine unambiguously \(R_o\) so we fix it to a value of 100 AU. The best fit is found for an inner radius of \(\sim 0.4\) AU and an inclination of \(10^\circ\).

HD 259431. The \(OH\) line profile in this case is more complicated and appears to have multiple components. We note that we were not able to fit the \(OH\) line profile with a model made of a single velocity component as in the previous cases. Multi-wavelength interferometric observations reveal the presence of optically thick gas within the dust sublimation radius (Kraus et al. 2008). In particular, the near-infrared continuum is dominated by optically thick gas that is accreting onto the star, while the mid-infrared continuum arises from the passively irradi
ated disk atmosphere at larger radii. Similarly, the analysis of the H$_2$ FUV lines (Bouret et al. 2003) suggests that the molecular hydrogen spectrum (seen in absorption) has multi-temperature components. In particular they find that an hot component (T $\sim$ 1300 K) comes from optically thick gas in the vicinity (> 0.5 AU) of the star. This is in good agreement with the detection of the high velocity wings in the OH line profile (Sec. 3). To account for the presence of optically thick gas inside the dust truncation radius we modify the standard model including a second component (see Fig. 5). Thus the free parameters of the fit are now 5: disk inclination, inner and outer radius of the optically thick component (R$_{1,i}$, R$_{1,o}$), inner and outer radius of the passively irradiated disk component (R$_{2,i}$, R$_{2,o}$). We adopt a disk inclination of 50$^\circ$ based on the results of Kraus et al. (2008). For the thermal broadening of the line we assume T$_1$=1300 K (= T(H$_2$)) and T$_2$ = 700 K (from Mandell et al. 2004) for the high and low velocity component respectively. Finally, we assume a constant radial dependence of the line intensity from the radius ($\alpha$ = 0 in Eq. 1) for the high velocity component. Our best model parameters are in good agreements with the results of the interferometric observations: the first component extends from $\sim$ 0.8 AU to $\sim$ 1.4 AU and the second components extends from $\sim$ 1.4 AU to $\sim$ 25 AU from the star. We note that our fitting routine tends to produce a low value of R$_{2,i}$ (lower than R$_{1,i}$), thus we constrain R$_{2,i}$ to be $\gtrsim$ R$_{1,o}$.

Fig. 6 shows the $\chi^2$ of the fit in the $\alpha$ – R$_{2,o}$ plane (after fixing all the other parameters). The value of R$_{2,o}$ is not degenerate with $\alpha$.

Recently Bagnoli et al. (2010) found a similar result for the [O I] line at 6300 Å. High spectral resolution observations revealed the presence of an high velocity component between $\sim$ 1 – 2 AU and a low velocity component peaking around 20 AU. Compared to the [O I] line profile, the OH high velocity component is clearly double-peaked and allows us to constrain better the outer radius of the high velocity component (R$_{1,o}$). Compared to the [O I] 6300 Å line, the OH emission detected here likely arises from deeper layers (higher A$_V$) in the disk.

**HD 85567.** The OH emission is broad (of the order of $\sim$ 100 km s$^{-1}$) and suggests the presence of high velocity molecular gas. As in the case of HD 259431, the high velocity OH emission might originate in an optically thick gas inside the dust sublimation radius. There are no estimates of the disk inclination in the literature and given the low signal-to-noise of the spectrum it is hard to estimate the radial extent of the OH emitting region. Further observations are needed to measure the properties of the OH emission from this disk.

## 5. DISCUSSION

The main findings of Sec. 3 & Sec. 4 are: i) the non-detection of water vapor emission lines, ii) the detection of OH emission lines from the disk atmosphere of Herbig AeBe stars and iii) the correlation between OH emission and disk flaring. In contrast, observations of T Tauri stars have shown that there exist a hot (500–1000 K) water layer in their disk atmosphere with densities similar to the OH layer we detect in Herbig AeBe stars (e.g. Carr & Najita 2008; Salvy et al. 2008). In this section we discuss the processes affecting the formation and destruction of water molecules in disks. The discussion is structured as follow: first we explain how water molecules form in the disk atmosphere (Sec. 5.1); then we address the water (and OH) destruction processes and outline the main differences between T Tauri and Herbig AeBe stars (Sec. 5.2). Finally we examine how non-stationary processes might affect the water content in different regions of the disk (Sec. 5.3 and 5.4) with a final discussion on the origin of the OH disk geometry correlation (Sec. 5.5).

### 5.1. Formation of water in disks

The formation of water molecules in the warm disk atmosphere is a three steps process

$$H + H + \text{dust} \rightarrow H_2 + \text{dust}$$ (6)

$$\phi + H_2 \rightarrow OH + H$$ (7)

$$OH + H_2 \rightarrow H_2O + H$$ (8)

The formation of H$_2$ on warm dust grains in the disk atmosphere (Eq. 6) is justified by the findings of Cazaux & Tielens (2002) who measure a moderate H$_2$ formation rate on warm (up to 900 K) dust grains. Further H$_2$ molecules might form through gas phase reactions (e.g. Glassgold et al. 2003)

$$H^- + H \rightarrow H_2 + e^-$$ (9)

The neutral-neutral reactions (Eqs. 7 & 8) require high temperature to occur (T $>$ 300 K). If H$_2$ is absent and hydrogen is mainly atomic, water may form through radiative association reactions (e.g. Kamp et al. submitted) such as

$$H + \phi \rightarrow OH + \nu$$ (10)

$$OH + H \rightarrow H_2O + \nu$$ (11)

In both cases (neutral-neutral or radiative association reactions) the gas phase formation of water in the disk atmosphere strongly depends on the gas density.

Recently a number of stationary disk chemical models have shown that water can be efficiently formed in the warm disk surface layer. Glassgold et al. (2009) (hereafter G09) investigated in situ water formation with a model based on X-ray (only) heating and ionization of the disk atmosphere which is most appropriate for T Tauri stars. Woitke et al. (2009) (hereafter ProDiMo model) compute the thermo-chemical structure of Herbig AeBe disks which generally have L$_X$/L$_{FUV}$ << 1 (Kamp et al. 2008) using only UV/optical irradiation. According to their model there exists a hot water layer at distances between 1 – 30 AU and relative height z/r $\lesssim$ 0.1 – 0.3 where water molecules are thermally decoupled from the dust (T(H$_2$O) $>$ T(dust)). In this model OH (and CO) are abundant within 30 AU from the star and above an A$_V$ of a few where water is not efficiently formed. Water is only found in deeper layers where it is shielded from photodissociation and densities/temperatures are high enough to form it through neutral-neutral gas-phase chemistry.

### 5.2. Destruction of water in disks


Pre-main-sequence stars emit strong ultraviolet radiation. For classical T Tauri stars UV photons are produced by three main components: the stellar photosphere, the enhanced chromospheric activity, and the magnetospheric accretion. In an X-ray irradiated T Tauri disk (as the one investigated by G09) water molecules are dissociated in the disk atmosphere through charge transfer reaction with H⁺. In the case of early spectral type stars (B and A) as the ones studied here, the stellar photosphere is the major source of FUV radiation and overwhelms any contribution from mass accretion or stellar activity. The UV radiation field impinging onto the surface of the circumstellar disk affects the physical properties (such as the gas and dust temperature) of the disk as well as its chemistry. In the case of the OH/H₂O chemistry, the strength of the UV field regulates the formation/destruction rate. Due to the strong soft UV radiation water can be easily photodissociated (e.g. [Woitke et al. 2009])

\[
\begin{align}
\text{H}_2\text{O} + h\nu &\rightarrow \text{OH} + \text{H} \quad (12) \\
&\rightarrow \phi + 2\text{H} \quad (13) \\
&\rightarrow \phi + \text{H}_2 \quad (14)
\end{align}
\]

Water can also be destroyed by charge transfer reactions as in the case of T Tauri stars (e.g. G09). However, given the intense ultraviolet radiation, UV photodissociation is likely to be the major dissociation mechanism in the atmosphere of an Herbig Ae/Be star as we will show next.

The minimum energy required to dissociate water molecules is 5.1 eV (e.g. [Harich et al. 2000]) which corresponds to a radiation of \( \lambda = 2430 \) Å. The photodissociation cross section \( (k_{pd}) \) of water varies with the color impinging radiation field. As an example, the cross section for an incoming radiation of a 10,000 K blackbody is nearly 4 times larger that for a 4,000 K blackbody (van Dishoeck et al. 2008). This is due to the stronger soft UV radiation (relevant for the photodissociation of water molecules) of Herbig AeBe stars compared to T Tauri stars. Column 4 of Table 2 lists the UV luminosity \( L_{UV} \) of the program stars integrated between 1100 Å and 2430 Å. The integrated luminosity is multiplied by a factor of \( 10^{0.4 A_{1770}} \) to correct for interstellar extinction. The quantity \( A_{1770} \) is the extinction at \( \lambda = 1770 \) Å and it is measured from \( A_V \) using the R = 3.1 extinction relation of Cardelli et al. (1989). The UV luminosity of the program stars ranges between \( \approx 1 - 10^5 L_\odot \). In the case of a classical T Tauri star, the UV luminosity ranges between \( \approx 0.01 - 1 L_\odot \). In particular, for the two stars in Salvik et al. (2008) (AS 205A, DR Tau) \( L_{UV} \) is \( \approx 0.1 - 1 L_\odot \). Thus, the UV radiation emitted by the Herbig AeBe stars in this sample is up to 4 orders of magnitude larger than that in the T Tauri stars studied by Salvik et al. (2008). Photodissociation is a plausible mechanism to explain the lack of hot water vapor lines in Herbig AeBe disks.

A way to further test this scenario would be to detect OH rotational lines in the mid-infrared at high J rotational levels. In fact OH molecules formed by the photodissociation of water (eq. [12]) are vibrationally and rotationally excited (e.g. Dutuit et al. 1983; van Harrevelt & van Hemert 2000; Harich et al. 2000). As a consequence, the high rotational levels of OH are easily populated (e.g. Carrington 1964; Harich et al. 2000; Bonev & Mumma 2006) and mid-infrared spectra could be able to detect the high J-value transitions such as found in the outflow of HH 211 (Tappe et al. 2009) and in TW Hya (Najita et al. 2010). A few high J OH lines have been detected in the mid-infrared towards Herbig AeBe stars with disks (Sturm, private communication). We note however that, depending on the density of the environment, the OH molecules might be thermallyized very fast. This might prevent us from detecting any trace of water photodissociation. In this regard, the rotational diagram of L-band OH lines in the two stars studied by Mandell et al. (2008) is characterized by a single rotational temperature.

In addition to photodissociation there are effects that could prevent us from detecting water vapor emission from the atmosphere of Herbig AeBe disks. The first effect to consider is the temperature difference between OH and H₂O lines detected here and in Salvik et al. (2008). The lower energy state of the OH P4.5 doublet is \( \approx 500 \) K while the energy state of H₂O transitions covered by our observations are \( \gtrsim 1000 \) K. Thus the OH emission potentially traces colder gas than the H₂O emission. One might speculate whether the H₂O non-detections are due to the different temperature layers probed in the disk. We find this possibility unlikely given that the OH transitions detected by Mandell et al. (2008) in AB Aur and MWC 758 have energies up to \( \approx 2360 \) K (OH P9.5), similar to the H₂O detected by Salvik et al. (2008). Thus the high OH/H₂O line flux ratio in Herbig AeBe stars is a signature of water depletion in the disk atmosphere rather than of transitions tracing different temperatures.

Another argument that is often used to explain the paucity of molecular emission lines in Herbig AeBe disks is that the strong infrared excess might be able to veil the faint emission of molecular lines in the infrared (e.g. Pontoppidan et al. 2010). In this case the molecular emission lines are veiled by the dust continuum. In this regard we note that the we detect OH emission at similar wavelengths and similar sensitivity of the H₂O vibrational transitions detected in T Tauri disks. Thus, if water vapor is present, it must be located deeper in the disk (at higher \( A_V \)) where is colder than the OH detected here and/or thermally coupled with the dust (i.e. \( T(H_2O) = T(dust) \)).

5.2.1. OH photodissociation

The most probable photodissociation channel of water is the one that produces an OH molecule (\( \approx 80\% - 90\% \), e.g. Crovisier 1989; Combi et al. 2004; Harich et al. 2000) that is followed by

\[
\text{OH} + h\nu \rightarrow \text{O} + \text{H} \quad (15)
\]

The photodissociation cross section of H₂O is only twice as large as that of the OH for an incoming blackbody radiation of 10,000 K which is representative for an Herbig Ae star (van Dishoeck et al. 2008). In addition, the minimum energy needed to break the OH bound is 4.47 eV which corresponds to a radiation of 2616 Å (van Dishoeck & Dalgarno 1983), very similar to that of water. This suggests that OH molecules...
should also photodissociate as is seen in comets (e.g. Combi et al. 2004). The dissociation of OH by UV photons (Eq. 15) is thought to be the main reservoir of the excited Oxygen (\(^1\text{D}\)) atoms which produce the 6300 Å transition often in solar system comets and in Herbig AeBe stars (e.g. van Dishoeck & Dalgarno 1984; Storzer & Hollenbach 1998; Morgenthaler et al. 2001; Acke et al. 2005). The similar radial distributions of OH and \([\text{O}\,\text{I}]\) in HD 259431 (Sec. 4 and Bagnoli et al. 2010) might be a direct evidence of the formation of O(\(^1\text{D}\)) atoms via OH photodissociation.

The previous discussion suggests that the atmosphere of Herbig AeBe disks is depleted in water vapor. The detection of OH emission and the column density ratio \(\text{OH}/\text{H}_2\text{O} \gtrsim 1\) suggests that OH molecules are produced again in situ (Eq. 15).

5.3. Transport of water in disks

Non-stationary processes might affect the content of water in disks. Within a protoplanetary disk gas and solid particles can migrate either inwards or outwards (for a review see Ciesla & Cuzzi 2006) or mixed by e.g. turbulent motions. Outwards migration was suggested, e.g., by Stevenson & Lunine (1988) to explain the formation of Jupiter. Inward migration was studied by Ciesla & Cuzzi (2000) with the aim at addressing the abundance of hot water vapor found in some T Tauri stars. Water can efficiently form in the disk interior on the surface of dust grains. If water-rich bodies such as icy planetesimals migrate inward and pass the snow line, the water ice evaporates from their surface and enrich the inner disk of water vapor. For such a process to happen however, the migration of planetesimals must be very fast and occur on a timescale shorter than the disk lifetime. Testing this hypothesis is important to probe the initial conditions of planetary systems. In this regards, two parameters are important: 1) the abundance of deuterated water and 2) the ortho-para ratio of water (e.g. Encrenaz 2008). Both these parameters are sensitive to the temperature formation and hence to the region where water forms in the disk (atmosphere or disk interior). We invite the interested reader to look into the recent work of Thi et al. (2010) for a detailed theoretical treatment of the formation of deuterated water. The case studied by Ciesla & Cuzzi (2006) is appropriate for T Tauri stars and does not include photodissociation. In the case of Herbig AeBe stars however, the transport and/or mixing of volatiles might induce the depletion of water in the disk interior by dredging up molecules to the surface layers where molecules are photodissociated. Two timescales are important in this regard: 1) the chemical relaxation timescale (\(\tau_{\text{chem}}\)) which regulates how fast chemical reactions occur, hence the formation of water and 2) the mixing timescale. If the vertical mixing is faster than the chemical relaxation, the disk interior can be depleted of water. Estimates of \(\tau_{\text{chem}}\) for an Herbig Ae disk computed with ProDiMo are \(\lesssim 10^2\) yr. The simulations of the transport processes in disks by Ilgner et al. (e.g. 2004) suggest that vertical mixing is slower and does not affect the global chemical evolution of the disk. In this regard, ProDiMo predicts very different chemical structures between T Tauri and Herbig AeBe disks: T Tauri disks are colder and \(\tau_{\text{chem}}\) may be as long as \(10^5\) yr in the dense mid-plane where water is condensed in ice. Disks around Herbig AeBe stars instead have hotter and more (chemically) active environment and there is only very little amount of icy water in the mid-plane.

5.4. Gas-dust decoupling and dust settling

An important parameter for the photochemistry of disks is the physical decoupling of gas and dust in the disk atmosphere (e.g. Meijerink et al. 2009). Direct observational evidence of gas and dust physical decoupling was found for the Herbig Ae stars HD 101412 (Fedele et al. 2008) and HD 95881 (Verhoeff et al. 2010). In the case of physical decoupling, the disk atmosphere is depleted in large dust grains (which settle into the midplane) and water molecules are unshielded from the UV radiation. In such a case the molecular content in the disk atmosphere might be easily reduced by UV photodissociation. The situation changes dramatically if water and \textit{OH self shielding} is taken into account as in Bethell & Bergin (2009). According to their model, in a dust-depleted disk atmosphere water and OH molecules become the major source of UV opacity and are able to block the photodissociative radiation from penetrating further into the disk. As a consequence, the abundance of water is enhanced even in the presence of a moderate FUV radiation (\(L_{\text{FUV}} = 10 L_{\odot}\)). One problem of the water self-shielding model of Bethell & Bergin (2009) is that it assumes the presence of \(\text{H}_2\) in the dust-depleted disk atmosphere. Without dust however, \(\text{H}_2\) form via the \(\text{H}^-\) route which produces an overall lower abundance of molecular hydrogen. On the other hands, the model of Meijerink et al. (2009) as well as G09 and ProDiMo do not include water self-shielding. This makes difficult to compare the observations with predictions from different models at this stage.

We do not have direct evidence of physical decoupling in the systems studied here but we do have evidence for thermal decoupling. If we assume a gas temperature of \(T \sim 700\) K as found by Mandell et al. (2008) for AB Aur and MWC 758, the gas is hotter than the dust (\(T_{\text{dust}} \lesssim 300\) K, e.g. Kamp & Dullemond 2004) at a spatial scale of \(\sim 1 - 20\) AU, the size of the OH emitting region (Sec. 4). Thus, the OH vapor detected here is likely thermally decoupled from the dust.

5.5. OH emission and disk geometry

In Sec. 4.1 we found that the presence of OH ro-vibrational lines correlates with the geometry of the disk: OH emission is mainly detected towards flaring disks (group I). As we saw in Sec. 3.1, the excitation of the OH ro-vibrational transitions depends on the temperature and density of the gas in the case of thermal emission and on the intensity of the UV and near-infrared radiation field in the case of fluorescence. In the case of Herbig AeBe stars the disk temperature is regulated by the UV output of the star as well as the near-infrared continuum emitted by the disk. Thus the intensity of OH ro-vibrational lines depends on the UV radiation field impinging into the disk surface regardless of the excitation
mechanism. In a flaring disk geometry, the disk surface area that is illuminated by the central star is much larger than in a self-shadowed geometry. In the latter case OH might still be excited but the emitting area is small (and the emission weak) and confined to the inner part of the disk. A trend is also found between CO fundamental ro-vibrational emission at 4.7μm and disk flaring (van der Plas et al. in preparation). CO emission originates from a larger disk area in flaring disks compared to flat disks. A larger sample of Herbig AeBe disks and more OH transitions are necessary to pin down the OH line excitation mechanism.

6. CONCLUSIONS

This paper presents high resolution L-band spectroscopic observations of Herbig AeBe stars with disks. Among the 11 stars analyzed here, four show hot OH emission which appears to correlate with the disk geometry and, in turn, with the UV irradiation impinging on the disk. The detection rate of OH emission is 70% for disks with a flared geometry (including the two systems analyzed by Mandell et al. 2008 and ~ 13% (1 out of 6) for self-shadowed disks. The OH ro-vibrational lines are spectrally resolved allowing us to measure an extension of ~ 10–30 AU for the OH emitting region. In contrast to T Tauri, Herbig AeBe stars do not show evidence of hot water vapor in their spectra. The detections of OH emission lines and the observed OH/H₂O column density ratio (> 1) indicate that the atmosphere of disks around Herbig AeBe stars is depleted in water molecules. Given the stronger UV radiation field of Herbig AeBe stars compared to T Tauri stars, a plausible explanation for the non-detection of water lines is that water in the disk atmosphere is dissociated by UV photons. The absence of hot water vapor in the disk atmosphere does not preclude the existence of colder water deeper in the disk (at lower temperature and higher AV). Far-infrared water lines have been detected with the Herschel Space Observatory towards the Herbig Ae star HD 100546 (Sturm et al. 2010) (although further confirmation is needed). This indicates the presence of warm water vapor in the disk.

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As we saw in Sec. 4.2, the OH line profile in V380 Ori is asymmetric, with the blue-shifted component brighter than the red-shifted one. A similar asymmetry was found towards other protoplanetary disks in the [OI] 6300 Å line for the Herbig Ae star HD 100546 (Acke & van den Ancker 2006) and in the CO fundamental rovibrational lines in EX Lupi (Goto et al. 2011). Such an asymmetry is either due to a deviation from the Keplerian motion of the gas or to a non homogeneous distribution of the emitting gas. The inner radius of the OH emitting region (∼ 2 AU) is too large to be coincident with the dust sublimation radius. Alecian et al. (2009) found evidence of a close low-mass star companion to V380 Ori. They determine a projected angular separation \( \sin(i) < 0.33 \) AU. Regardless of the inclination, the orbit of the companion is certainly within the inner rim of the OH emitting region. Circuminary disks have inner gap of the order of ∼ 2 – 3 times the binary separation (Artymowicz & Lubow 1994) which brings the truncation radius to ∼ 1 – 2 AU for V380 Ori (depending on the eccentricity, inclination and mass ratio of the binary). This is remarkably close to the OH inner radius estimated here. The companion might be also the source of the perturbation of the gas dynamics seen in the OH line profile. Recent simulation by Regaly et al. (2011) show that in the case of a circumbinary disk the velocity distribution of the gas differs from the circular Keplerian case. The disk may become eccentric (due to tidal interaction with the lower mass companion) and the velocity profile of the emerging lines is asymmetric in a fashion similar to Fig. 2.

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VLT, CRIRES.
**Table 4**

OH and H$_2$O lines parameters

<table>
<thead>
<tr>
<th>Star</th>
<th>OH FWHM [km s$^{-1}$]</th>
<th>OH</th>
<th>EW [$10^{-6}$µm]</th>
<th>L$_{OH}$</th>
<th>L$_{H_2O}$ @ 2.931 µm</th>
<th>log(N(OH)) [molecules]</th>
<th>log(N$_{col}$(OH)) [mol./cm$^{-2}$]</th>
<th>log(N(H$_2$O))</th>
<th>log(N$_{col}$(H$_2$O)) [molecules]</th>
<th>log(N$_{col}$(H$_2$O)) [mol./cm$^{-2}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>UX Ori</td>
<td>&lt; 3.0</td>
<td>8</td>
<td>8.4 (± 5.0)</td>
<td>&lt; 4.5</td>
<td>45.0</td>
<td>16.1</td>
<td>&lt; 44.5</td>
<td>&lt; 15.6</td>
<td>&lt; 15.5</td>
<td>15.6</td>
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<td>HD 34282</td>
<td>&lt; 2.0</td>
<td>&lt; 2.0</td>
<td>&lt; 43.8</td>
<td>43.9</td>
<td>&lt; 15.0</td>
<td>&lt; 44.5</td>
<td>&lt; 15.1</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>CO Ori</td>
<td>&lt; 1.0</td>
<td>&lt; 1.0</td>
<td>&lt; 43.8</td>
<td>43.9</td>
<td>&lt; 15.0</td>
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<tr>
<td>V380 Ori</td>
<td>27</td>
<td>8</td>
<td>8.4 (± 5.0)</td>
<td>&lt; 4.5</td>
<td>45.0</td>
<td>16.1</td>
<td>&lt; 44.5</td>
<td>&lt; 15.6</td>
<td>&lt; 15.5</td>
<td>15.6</td>
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<tr>
<td>BF Ori</td>
<td>27</td>
<td>8</td>
<td>8.4 (± 5.0)</td>
<td>&lt; 4.5</td>
<td>45.0</td>
<td>16.1</td>
<td>&lt; 44.5</td>
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<td>15.6</td>
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<tr>
<td>HD 259431</td>
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<td>12</td>
<td>14.5 (± 2)</td>
<td>&lt; 4.5</td>
<td>45.0</td>
<td>16.1</td>
<td>&lt; 44.5</td>
<td>&lt; 15.6</td>
<td>&lt; 15.5</td>
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<tr>
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<td>&lt; 44.6</td>
<td>&lt; 15.8</td>
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</table>

* Upper limits are computed as the product $3 \times \sigma \times \Delta \lambda$, with $\sigma$ standard deviation between 2.930 µm and 2.936 µm, and $\Delta \lambda = 30$ km s$^{-1}$. The OH line flux refers to the average flux of the two transitions of the $^2$H$_{1/2}$ P4.5 (1+,1-) doublet. The FWHM and EW are the mean of the FWHM and EW of the two transitions. Total and column densities are computed assuming optically thin emission, LTE and $T(OH) = T(H_2O) = 700$ K and $T(OH) = T(H_2O) = 1000$ K respectively.

** In this case the OH doublet is blended (Fig. 5 & 7). The FWHM and EW are computed as the half of the total doublet FWHM and EW.