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Detection of warm water vapour in Taurus protoplanetary discs by Herschel*

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ABSTRACT

Line spectra of 68 Taurus T Tauri stars were obtained with the Herschel-PACS (Photodetector Array Camera and Spectrometer) instrument as part of the GASPS (GAS evolution in Protoplanetary Systems) survey of protoplanetary discs. A careful examination of the linescans centred on the [OI] 63.18 μm fine-structure line unveiled a line at 63.32 μm in some of these spectra. We identify this line with the 8→7 transition of ortho-water. It is detected confidently (i.e., >3σr) in eight sources, i.e., ∼24% of the sub-sample with gas-rich discs. Several statistical tests were used to search for correlations with other disc and stellar parameters such as line fluxes of [OIII] 6300 Å and 63.18 μm, X-ray luminosity and continuum levels at 63 μm and 850 μm. Correlations are found between the water line fluxes and the [OI] 63.18 μm line luminosity, the dust continuum, and possibly with the stellar X-ray luminosity. This is the first time that this line of warm water vapour has been detected in protoplanetary discs. We discuss its origins, in particular whether it comes from the inner disc and/or disc surface or from shocks in outflows and jets. Our analysis favours a disc origin, with the observed water vapour line produced within 2–3 AU from the central stars, where the gas temperature is of the order of 500–600 K.

Key words. astrochemistry – stars: formation – protoplanetary disks – astrobiology – molecular data – line: identification

1. Introduction

Discs are natural by-products of star formation and the birthplaces of planets. One of the key questions intimately linked with planet formation and the concept of planet habitability is how much vapour and icy water is present in discs and how it is radially distributed. However, it is only recently that observations of water vapour in discs have become possible.

Carr & Najita (2008), using the Spitzer InfraRed Spectrograph (IRS), reported a rich molecular emission-line spectrum dominated by rotational transitions of hot water from the disc of AA Tau. They concluded that the molecular emission seen in the mid-IR has a most likely origin within the 2–3 AU inner regions of the disc. Salyk et al. (2008) detected water emission in the 10–20 μm region with Spitzer-IRS, as well as water and hydroxyl emission around 3 μm with NIRSPEC on Keck II, for both DR Tau and AS 205 A. The emission comes from the disc atmospheres of the objects and the excitation temperatures were found to be (∼1000 K), which is typical of terrestrial planet formation regions. Pontoppidan et al. (2010b) performed a survey for more protoplanetary discs in Ophiuchus, Lupus, and Chamaeleon, again with Spitzer-IRS, and concluded that the presence of mid-IR molecular emission lines, including those of water, is a common phenomenon in discs around Sun-like stars. Also, Pontoppidan et al. (2010a) presented a sample of ground-based observations of pure rotational lines of water vapour in the protoplanetary discs of AS 205 A and RNO 90 that was analysed to measure line widths of 30–60 km s⁻¹, which is consistent with an origin in a disc in Keplerian rotation at a radius of ∼1 AU, and gas temperatures in the range 500–600 K.

The Herschel Space Observatory (Pilbratt et al. 2010) has opened the far-IR window with unprecedented sensitivity, allowing astronomers to survey the atomic and molecular gas content of disc regions that are cooler than those probed by Spitzer and ground-based instruments. Predictions of the water lines detectable by Herschel can be found in Cernicharo et al. (2009) and Woitke et al. (2009b). Hogerheijde et al. (2011) presented the first detection of cold water in the disc of the ∼10 Myr old TW Hya, using Herschel-HIFI. The Herschel open time key program GASPS (GAS evolution in Protoplanetary Systems; Mathews et al. 2010) is conducting a survey to measure gas lines and continuum in ∼250 discs around low- and intermediate-mass stars with ages in the range 1–30 Myr with PACS, the...
measurements from T Tauri stars from the Taurus star forming region with spectral
This study is based on a sample of 68 classical and weak-line
Photodetector Array Camera and Spectrometer (Poglitsch et al. 2010).
In this Letter, we report the first detection of the o-H$_2$O line at 63.32 μm in a subsample of protoplanetary discs around T Tauri stars in the 1–3 Myr old Taurus star forming region.

2. Observations and data reduction
This study is based on a sample of 68 classical and weak-line T Tauri stars from the Taurus star forming region with spectral measurements from Herschel-PACS centred at the wavelength of the [O i] $^{3}P_1 \rightarrow ^3P_2$ 63.184 μm line. The Taurus star-forming region is one of the main targets for the study of protoplanetary systems, because it is among the nearest star-forming regions ($d = 140$ pc) with a well-known population of more than 300 young stars and brown dwarfs according to Kenyon et al. (2008), Luhman et al. (2010), and Rebull et al. (2010).

The observations described in this letter are part of the Herschel open time key programme GASPS [P.I. W. Dent], (see Mathews et al. 2010), a flux-limited survey devoted to the study of the gas and dust in circumstellar systems around young stars. The survey focuses on the detection of the [O i] emission at the 63.18 μm feature. For this study, we analyzed 68 stars with spectral types ranging from late F-early G to mid M. The PACS spectral observations were made in chop/nod pointed line mode. The observing times ranged from 1215 to 6628 s, depending on the number of nod cycles. The data were reduced using HIPE 7.0.1751. A modified version of the PACS pipeline was used, which included: saturated and bad pixel removal, chop subtraction, relative spectral response-function correction, and flat fielding. Many observations suffer from systematic pointing errors, in some cases as large as 8′′, and are always shifted to the East. This is due to a plate scale error in the star tracker, which is normally negligible except in areas where the tracked stars are asymmetrically distributed within the field, as in Taurus. The mis-pointing translates into systematic small shifts in the line

### Table 1. Line positions and fluxes from PACS spectra.

| Name   | Sp. type | $\lambda_{\text{O}i} - \lambda_{\text{O}i}$ [Å] | [O i] flux $10^{-17}$ W/m$^2$ | o-H$_2$O flux $10^{-17}$ W/m$^2$ |
|--------|----------|---------------------------------|-------------------------------|-------------------------------|
| AA Tau | K7       | 0.140                           | 2.2 ± 0.13                   | 0.80 ± 0.13                   |
| DL Tau | K7       | 0.141                           | 2.4 ± 0.15                   | 0.65 ± 0.14                   |
| FS Tau | M0       | 0.139                           | 37 ± 0.26                    | 2.00 ± 0.33                   |
| RK Tau | K1       | 0.139                           | 10 ± 0.42                    | 1.95 ± 0.38                   |
| T Tau  | K0       | 0.138                           | 830 ± 0.75                   | 278 ± 0.7                     |
| XZ Tau | M2       | 0.139                           | 32.2 ± 0.48                  | 2.11 ± 0.48                   |
| HL Tau | K7       | 0.142                           | 54.3 ± 0.71                  | 8.14 ± 0.80                   |
| UY Aur | M0       | 0.139                           | 33.6 ± 0.37                  | 1.90 ± 0.32                   |

Notes. All spectral types from the compilation of Luhman et al. (2010). centred position. When the star was well centred within a single spaxel, we extracted the flux from that spaxel and applied the proper aperture correction. When the flux was spread over more than one spaxel, we co-added the spaxels.

3. Results and discussion

Among the sample of 68 Taurus targets studied in this letter, 33 have discs that are rich in gas. These 33 all show the [O i] $^{3}P_1 \rightarrow ^3P_2$ line in emission at 63.18 μm (signal-to-noise ratio $>$3, with values ranging from 3 to 375). In 8 of these 33 targets ($\sim$24%), an additional fainter emission-line at 63.32 μm is detected (Fig. 1). We computed 63.32 μm line fluxes by fitting a Gaussian plus continuum curve to the spectrum using DIPSOL

1 To improve the line fitting, the noisier edges of the spectral range were removed (i.e., $\lambda < 63.0$ and $\lambda > 63.4$). The results are listed in Table 1, where we report the peak position of the feature with respect to the observed wavelength of the [O i] 63.18 μm line. According to these fits, the peak of the feature is at $\lambda_0 = 63.32$ μm. The FWHM is 0.020 μm, i.e., the instrumental FWHM for an unresolved line. We identify the feature as the ortho-H$_2$O 8$_{18} \rightarrow 7_0$ transition at 63.324 μm ($E_{\text{Upper Level}} = 1070.7$ K, Einstein A = 1.751 s$^{-1}$) since no

1 http://star-www.rl.ac.uk/docs/sun50.htm/sun50.html
other abundant species emit strongly at or close to the observed wavelength of the feature. This water feature was observed by Herczeg et al. (2012) in the outflow of NGC 1333 IRAS 4B. The o-H2O emission is only present in spectra with [O I] detections. The targets FS Tau, HL Tau, and T Tau display extended emission in the [O I] 63.18 μm line, but only T Tau show hints of extended emission in the 63.32 μm o-H2O line. T Tau is an exceptional object. It is a triple star system that drives at least two jets. It was the most line rich PMS star observed by ISO (Lorenzetti 2005) and resembles more a hot core than a PMS inner disc geometry and radiative transfer considerations. We compared the line intensity with several star and disc (jet) parameters. We computed survival analysis ranked statistics using the ASURV code (Feigelson & Nelson 1985; Isobe et al. 1986). Although the sample is too small to test this relationship conclusively, we note that while L_{[O I]} spans four orders of magnitude, the H2O luminosity spans only one order of magnitude. Finally, the survival analysis statistics points to a possible relationship with the X-ray luminosity L_x (Fig. 4). While the Spearman probability for the real sample is only one order of magnitude smaller than for the random sample, the Kendall probability is two orders of magnitude smaller. Inspection of Fig. 4 also shows that the o-H2O line flux is detected only for sources with X-ray luminosities higher than 10^{30} erg s^{-1}, which is consistent with photochemical disc models that show that far-IR line fluxes increase significantly above this X-ray luminosity threshold (Aresu et al. 2011). We note that log L_x = 10^{30} erg s^{-1} is above the median (mean) X-ray luminosity in Taurus (log L_x = 29.8 (29.75) erg s^{-1} respectively, Güdel et al. 2007). Interestingly, more than half of the sources with L_x > 10^{30} erg s^{-1} do not display the o-H2O line. This behaviour may stem from either (1) the different shape of the X-ray spectrum (hardness ratio), (2) the duty cycle of the flares responsible for the high levels of X-ray fluxes, and/or (3) that X-rays are not the only driver of H2O chemistry and excitation, let alone any inner disc geometry and radiative transfer considerations. We caution that the correlation with X-rays is significantly weaker when T Tau is removed from the analysis. All the stars detected in o-H2O are outflow/jet sources, although three of them AA Tau, DL Tau, and RY Tau do not show any excess in [OI], i.e. all the emission is consistent with coming from the disc (Howard et al., in prep.). Two of these

Table 2. Probabilities for correlations between o-H2O line intensity and stellar/disc parameters.

| Observable | Points n | Spearman’s prob. | Kendall’s prob. |
|------------|----------|-----------------|----------------|
| \( L_{[O I]} \) | 68       | 0.0009 (0.4506) | 0.0000 (0.196) |
| 63 μm flux | 64       | 0.0147 (0.2635) | 0.0002 (0.4567) |
| 850 μm flux | 57       | 0.0145 (0.2596) | 0.0131 (0.8496) |
| \( L_{o-H2O} \) | 65       | 0.1719 (0.1130) | 0.1980 (0.5535) |
| \( L_{H2O} \) | 65       | 0.0025 (0.9912) | 0.0087 (0.6012) |
| \( \alpha(2-8 \mu m) \) | 62       | 0.0264 (0.1547) | 0.0386 (0.3580) |

Notes. The values obtained for random populations are shown in brackets. Accurate only if \( N > 30 \). (2) 850 μm continuum fluxes from Andrews & Williams (2005). (3) Values from Güdel et al. (2007). (4) SED slope from Luhman et al. (2010).
H$_2$O line and the dust temperature close to the mid-plane is low.

The gas densities are high enough to excite the 63.32 $\mu$m line emission only in AA Tau and UY Aur. Pontoppidan et al. (2010b) reported H$_2$O detections toward three out of eight stars in their sample: DR Tau, AA Tau, and IQ Tau. We did not detect o-H$_2$O in IQ Tau. Salyk et al. (2008), Pontoppidan et al. (2009) and Meijerink et al. (2009) argued that the Spitzer hot H$_2$O emission comes from the 0.1 to 1.0 AU annular region of the disc.

Assuming the same temperature, column density, and emitting areas as Carr & Najita (2011), i.e., 1 AU, we computed the 63.32 $\mu$m LTE line flux in AA Tau and UY Aur. The model line emission is too optically thick to derive the H$_2$O mass reliably. The size of the emitting region is instead estimated. In both cases, the model flux is ten times lower than measured. To recover the measured fluxes, the radius of the emitting area has to be about three times larger than the value they quote, i.e., 3.0 AU for AA Tau and 3.5 AU for UY Aur, a result that is consistent with the lower excitation temperature of the line we observed.

A radiation thermo-chemical model of a typical T Tauri disc obtained with the PkDInMo code (Woitke et al. 2009a; Kamp et al. 2010; Thi et al. 2010; Aresu et al. 2011) predicts that the emission region of the 63.32 $\mu$m o-H$_2$O line is of the order of 3 AU, about five times larger than the Spitzer emission-line region (see Fig. B.1). One particular o-H$_2$O line at 15.738 $\mu$m was selected as a representative Spitzer mid-IR H$_2$O emission line. This model does not intend to fit any particular object. A large non-LTE H$_2$O ro-vibrational model calculation was included to consistently calculate the Spitzer as well as the Herschel H$_2$O emission lines by applying escape probability theory (Faure et al. 2004, 2007; Faure & Josselin 2008). At ~3 AU, the gas densities are high enough to excite the 63.32 $\mu$m o-H$_2$O line and the dust temperature close to the mid-plane is low enough for H$_2$O to freeze onto grains.

The 63.32 $\mu$m line could provide the missing link between the mid-IR Spitzer detections of hot H$_2$O vapour in T Tauri discs and the cold far-IR H$_2$O lines observed with Herschel. Searches for the lower excitation H$_2$O lines have proven to be less successful. To date, the only clear detection of cold H$_2$O from a disc is TW Hya using HIFI (Hogerheijde et al. 2011), and Kamp et al. (in prep.), using PACS. Possible reasons for the lower detection rate of cold H$_2$O might be the much lower H$_2$O abundances in the outer disc caused by the freeze-out of H$_2$O and/or significant (vertical) settling of icy grains (Bergin et al. 2010). Observing the same molecule in transitions with very different excitation temperatures may trace it through a broader range of different radial zones in protoplanetary discs.

4. Conclusions

We have detected o-H$_2$O emission at 63.32 $\mu$m in 8 T Tauri stars in a sub-sample of 8 stars located in Taurus. The detection rate is ~24% in the sub-sample with gas-rich discs. The H$_2$O emission appears to be correlated with the continuum luminosities, the [OI] 63.18 $\mu$m line fluxes, and the X-ray luminosities. The gas temperature (500–600 K) and density needed to excite the observed o-H$_2$O line suggest that the line is coming from the inner parts of the discs and from the upper layers of its atmosphere, where the disc is directly illuminated. The correlation with X-rays flux and the role of X-ray emission in heating the gas, in particular during flares, needs to be investigated further. The typical size of the emitting region is estimated to be r ~ 3 AU, which is consistent with the typical location of the snow line in these objects. More effort is needed to detect several H$_2$O lines simultaneously in more objects to understand the full radial distribution of H$_2$O vapour in planet-forming discs.

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Appendix A: Non detections

GASPS is a flux-limited survey. All sources have detection limits for the o-H$_2$O line at 63.32 $\mu$m around $10^{-17}$ W/m$^2$, with an uncertainty of a factor of two both ways. The list of non detections is given in Table A.1.

Table A.1. Source list, spectral types, and 63.32 $\mu$m o-H$_2$O line fluxes.

| Name       | SP Type | o-H$_2$O flux \(10^{-17} \text{ W/m}^2\) |
|------------|---------|--------------------------------------|
| Anon 1     | M0      | <1.17                                |
| BP Tau     | K7      | <0.94                                |
| CIDA2      | M5.5    | <0.89                                |
| CI Tau     | K7      | <0.92                                |
| CoKu Tau/4 | K3      | <1.37                                |
| CW Tau     | K3      | <1.26                                |
| CX Tau     | M2.5    | <0.94                                |
| CY Tau     | M1.5    | <1.41                                |
| DE Tau     | M1      | <1.23                                |
| DF Tau     | M2      | <1.26                                |
| DG Tau     | K6?     | <1.32                                |
| DG Tau B   | <K6     | <1.25                                |
| DH Tau     | M1      | <1.07                                |
| DK Tau     | K6      | <0.53                                |
| DL Tau     | K7      | <1.14                                |
| DM Tau     | M1      | <0.89                                |
| DN Tau     | M0      | <0.77                                |
| DO Tau     | M0      | <1.21                                |
| DP Tau     | M0.5    | <0.92                                |
| DQ Tau     | M0      | <0.98                                |
| DS Tau     | K5      | <0.58                                |
| FF Tau     | K7      | <1.11                                |
| FM Tau     | M0      | <1.24                                |
| FO Tau     | M3.5    | <0.96                                |
| FQ Tau     | M3      | <0.91                                |
| FT Tau     | –       | <1.25                                |
| FW Tau     | M5.5    | <1.08                                |
| FX Tau     | M1      | <1.82                                |
| GG Tau     | M5.5    | <1.24                                |
| GH Tau     | M2      | <0.84                                |
| GIK Tau    | K7      | <0.74                                |
| GM Aur     | M0      | <1.21                                |
| GO Tau     | M0      | <1.23                                |
| Haro 6-13  | M0      | <1.43                                |
| Haro 6-37  | M1      | <1.84                                |
| HBC 347    | K1      | <1.69                                |
| HBC 356    | K2\(^1\) | <0.94                             |
| HBC 358    | M3.5    | <1.29                                |
| HK Tau     | M0.5    | <0.90                                |
| HN Tau     | K5      | <0.64                                |
| HO Tau     | M0.5    | <1.46                                |
| HV Tau     | M1      | <0.72                                |
| IP Tau     | M0      | <0.83                                |
| IQ Tau     | M0.5    | <1.38                                |
| 04158+2805 | M5.25   | <1.06                                |
| LkCa 1     | M4      | <1.06                                |
| LkCa 3     | M1      | <0.94                                |
| LkCa 4     | K7      | <0.98                                |
| LkCa 5     | M2      | <1.16                                |
| LkCa 7     | M0      | <0.88                                |
| LkCa 15    | K5      | <0.52                                |
| SAO 76428  | F8?     | <1.58                                |
| SU Aur     | G2      | <0.72                                |
| UX Tau     | K5      | <0.99                                |
| UZ Tau     | M2      | <0.60                                |
| V710 Tau   | M0.5    | <1.17                                |
| V773 Tau   | K3      | <0.77                                |
| V819 Tau   | K7      | <1.21                                |
| W927 Tau   | M4.75   | <0.88                                |
| YY Tau     | M0      | <1.30                                |

Notes. Spectral types from the compilation by Luhman et al. (2010). (1) from Herbig & Bell (1988).

Appendix B: Location of emission for H$_2$O lines

Fig. B.1. Location of the H$_2$O emission for a typical disc model ($M_*=0.8$ $M_{{\odot}}$, $L_* = 0.7$ $L_{{\odot}}$, $T_{\text{eff}} = 4400$ K, UV excess $f_{\text{UV}} = 0.01$, X-ray luminosity $L_X = 10^{30}$ erg s$^{-1}$, $R_{\text{in}} = 0.1$ AU, $R_{\text{out}} = 300$ AU, $M_{\text{dust}} = 0.01 M_{{\odot}}$, dust/gas = 0.01, $\epsilon = -1$, scale height $H_z = 1$ AU at $r_0 = 10$ AU, flaring $\beta = 1.1$, astronomical silicate with uniform dust size distribution $a_{\text{min}} = 0.05 \mu$m, $a_{\text{max}} = 1$ mm, and index $= 3.5$). The 15.738 $\mu$m line is used as a typical H$_2$O line detected by Spitzer. We have marked the radii where the cumulative line flux reaches 15%, 49% and 85% of vertical lines, for the four selected H$_2$O lines. In addition, the horizontal lines mark the heights above the midplane where 15% and 85% of the line flux, from every vertical column, originate in. The encircled regions are hence responsible for 70% $\times$ 70% = 49% of the total line flux (for a pole-on disc).