Water in low-mass star-forming regions with Herschel

HIFI spectroscopy of NGC 1333**

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ABSTRACT

“Water In Star-forming regions with Herschel” (WISH) is a key programme dedicated to studying the role of water and related species during the star-formation process and constraining the physical and chemical properties of young stellar objects. The Heterodyne Instrument for the Far-Infrared (HIFI) on the Herschel Space Observatory observed three deeply embedded protostars in the low-mass star-forming region NGC 1333 in several H2O, H18O, and CO transitions. Line profiles are resolved for five H216O transitions in each source, revealing them to be surprisingly complex. The line profiles are decomposed into broad (>20 km s−1), medium-broad (~5−10 km s−1), and narrow (~5 km s−1) components. The H216O emission is only detected in broad 101 lines (>20 km s−1), indicating that its physical origin is the same as for the broad H218O component. In one of the sources, IRAS4A, an inverse P Cygni profile is observed, a clear sign of infall in the envelope. From the line profiles alone, it is clear that the bulk of emission arises from shocks, both on small (<1000 AU) and large scales along the outflow cavity walls (~10000 AU). The H2O line profiles are compared to CO line profiles to constrain the H2O abundance as a function of velocity within these shocked regions. The H2O/CO abundance ratios are measured to be in the range of ~0.1–1, corresponding to H2O abundances of ~10^−5−10^−4 with respect to H2. Approximately 5–10% of the gas is hot enough for all oxygen to be driven into water in warm post-shock gas, mostly at high velocities.

Key words. astrochemistry – stars: formation – ISM: molecules – ISM: jets and outflows – ISM: individual objects: NGC 1333

1. Introduction

In the deeply embedded phase of low-mass star formation, it is often only possible to trace the dynamics of gas in a young stellar object (YSO) by analysing resolved emission-line profiles. The various dynamical processes include infall from the surrounding envelope towards the central protostar, molecular outflows caused by jets ejected from the central object, and strong turbulence induced within the inner parts of the envelope by small-scale shocks (Arce et al. 2007; Jørgensen et al. 2007). One of the goals of the Water In Star-forming regions with Herschel (WISH) key programme is to use water as a probe of these processes and determine its abundance in the various components as a function of evolution (van Dishoeck et al., in prep.). Spectrally resolved observations of the H2O 101−101 line at 557 GHz with ODIN and SWAS towards low-mass star-forming regions have revealed it to be broad, ~20 km s−1, indicative of an origin in shocks (e.g., Bergin et al. 2003). Within the large beams (2′ and 4′), where both the envelope and the entire outflow are present, outflow emission most likely dominates. Observations and subsequent modelling of the more highly excited H2O lines with ISO-LWS were unable to distinguish between an origin in shocks or an infalling envelope (e.g., Ceccarelli et al. 1996; Nisini et al. 2002; Maret et al. 2002). Herschel/HIFI has a much higher sensitivity, higher spectral resolution, and smaller beam than previous space-based missions, thus is perfectly suited to addressing this question. Complementary CO data presented by Yıldız et al. (2010) are used to constrain the role of the envelope and determine outflow temperatures and densities.

NGC 1333 is a well-studied region of clustered, low-mass star formation at a distance of 235 pc (Hirota et al. 2008). In particular, the three deeply embedded, low-mass class 0 objects IRAS2A, IRAS4A, and IRAS4B have been observed extensively with ground-based submillimetre telescopes (e.g., Jørgensen et al. 2005; Maret et al. 2005) and interferometers (e.g., Di Francesco et al. 2001; Jørgensen et al. 2007). All sources have strong outflows extending over arcmin scales.
Table 1. H$_2$O and H$_2^{18}$O emission$^a$ in the NGC 1333 sources$^b$.

| Source | Transition | rms$^e$ (mK) | $T_{\text{mb}}$ (K) | $\int T_{\text{mb}}$ de (K km s$^{-1}$) | $T_{\text{mb}}$ (K) | $\int T_{\text{mb}}$ de (K km s$^{-1}$) |
|--------|------------|--------------|--------------------|-----------------|-----------------|-----------------|
| IRAS 2A | H$_2$O 110–000 | 23 | 0.36 | 4.5 | 0.35 | 13.5 |
|         | 201–100 | 21 | 0.14 | 0.8 | 0.43 | 14.0 |
|         | 31–210 | 100 | 0.07 | 0.4 | 0.32 | 13.6 |
|         | H$_2$O 111–010 | 3 | <0.01 | 0.02 | 0.43 |
|         | 111–020 | 23 | <0.06 | 0.01 |
|         | FWHM$^d$ (km s$^{-1}$) | 11.1 ± 2.3 | 37 ± 4 |
|         | $\Delta v_{\text{crit}}$ (km s$^{-1}$) | -0.6 ± 0.5 | +8.7 ± 1.0 |
| IRAS 4B | H$_2$O 110–000 | 28 | 0.10 | 0.40 | 0.10 |
|         | 201–100 | 20 | 0.14 | 0.8 | 0.43 | 14.0 |
|         | 31–210 | 150 | 0.32 | 1.3 | 0.76 | 17.5 |
|         | H$_2$O 111–010 | 3 | <0.01 | 0.02 | 0.43 |
|         | 111–020 | 23 | <0.06 | 0.01 |
|         | FWHM$^d$ (km s$^{-1}$) | 8.4 ± 0.5 | 24 ± 2 |
|         | $\Delta v_{\text{crit}}$ (km s$^{-1}$) | +8.1 ± 0.3 | +8.0 ± 0.5 |

Notes. $^a$ Obtained from Gaussian fits to each component. In the case of H$_2$O 11–000, this includes extrapolation over the absorption feature. $^b$ The coordinates used are for IRAS2A: 03:28:55.6, +31:14:37.1; IRAS4A: 03:29:10.5; +31:13:30.9; IRAS4B: +33:29:12.0; +31:13:08.1 (J2000). $^c$ Measured in 0.5 km s$^{-1}$ bins. $^d$ Intensity-weighted average of values determined from Gaussian fits of H$_2$O emission lines. $^e$ Uncertainties include statistical errors only.

(>15 000 AU). Both IRAS4A and 4B consist of multiple protostars (e.g., Choi 2005). Because of the similarities between the three sources in terms of luminosity (20, 5.8, and 3.8 $L_\odot$), envelope mass (1.0, 4.5, and 2.9 $M_\odot$; Jørgensen et al. 2009) and presumably also age, they provide ideal grounds for comparing YSOs in the same region.

2. Observations and results

Three sources in NGC 1333, IRAS2A, IRAS4A, and IRAS4B, were observed with HIPE (de Graauw et al. 2010) on Herschel (Pilbratt et al. 2010) on March 3–15, 2010 in dual beam switch mode in bands 1, 3, 4, and 5 with a nod of 3'. Observations detected several transitions of H$_2$O and H$_2^{18}$O in the range $E_u/k_B \approx 50$–250 K (Table 2). Diffraction-limited beam sizes were in the range 19–40'' (4500–9500 AU). In general, the calibration is expected to be accurate to $\sim$20% and the pointing to $\sim$2''. Data were reduced with HIPE 3.0. A main-beam efficiency of 0.74 was used throughout. Subsequent analysis was performed in CLASS. The rms was in the range 3–150 mK in 0.5 km s$^{-1}$ bins. Linear baselines were subtracted from all spectra, except around 750 GHz (corresponding to the H$_2$O 211–200 transition) where higher-order polynomials are required. A difference in rms was always seen between the H- and V-polarizations, with the rms in the H-polarization being lower. In cases where the difference exceeded 30% and qualitative differences appear in the line profile, the V-polarization was discarded, otherwise the spectra were averaged.

All targeted lines of H$_2^{18}$O are detected and are listed in Table 1 and Fig. 1. The 110–100 transition at 557 GHz was not observed before the sources moved out of visibility. The H$_2^{18}$O 101–101 line was detected in all sources (Fig. 2), although

The detection in IRAS2A was weak ($\sim$$\sigma$ = 0.13 K km s$^{-1}$). This line is superposed on the ground-state CH triplet at 536 GHz, observed in the lower sideband (Fig. 2). Neither the H$_2$O 111–011 nor the 202–111 line in IRAS4A is detected down to $\sigma$ < 0.06 K km s$^{-1}$.

The H$_2$O lines exhibit multiple components: a broad emission component (FWHM > 20 km s$^{-1}$) sometimes offset from the source velocity ($v_{\text{LSR}}$ = +7.2–7.7 K km s$^{-1}$); a medium-broad emission component (FWHM ∼ 5–10 km s$^{-1}$); and a deep, narrow absorption component (FWHM ∼ 2 km s$^{-1}$) seen at the source velocity. The individual components are all reproduced well by Gaussian functions. The absorption is only seen in the H$_2$O 111–011 line and is saturated in IRAS2A and IRAS4A. In IRAS4B, the absorption extends below the continuum level,
but is not saturated. Furthermore, the IRAS4A spectrum of the $^{2}O-1_{11}$ line exhibits an inverse P Cygni profile. The shape of the lines is the same within a source; only the relative contribution between the broad and medium components changes. For example, in IRAS2A the ratio of the peak intensities is $\sim 2$, independent of the line, whereas in IRAS4A it ranges from 1 to 2. The $H^{18}$O line profiles compare well to the broad component seen in $H_2O$, i.e., similar $FWHM > 20$ km s$^{-1}$ and velocity offset. The width is much larger than isotopologue emission of, e.g., $C^{18}O (\sim 1-2$ km s$^{-1}$) and is centered on the source velocity (Yıldız et al. 2010). The medium and narrow components are not seen in the $H^{18}$O $1_{10}-1_{10}$ spectra down to an rms of 2–3 mK in 0.5 km s$^{-1}$ bins.

The upper limits to the $H^{18}$O $1_{11}-0_{00}$ line are invaluable for estimating upper limits to the optical depth, $\tau$. In the following, the limit on $\tau$ is derived for the integrated intensity; in the line wings, $\tau$ is most likely lower (Yıldız et al. 2010). In the broad component, the limit ranges from 0.4 (IRAS4B) to 2 (IRAS2A), whereas it ranges from 1.1 (IRAS4B) to 2.7 (IRAS2A) for the medium component of the $H^{18}$O $1_{11}-0_{00}$ line. Performing the same analysis to the upper limit on the $H^{18}$O $2_{02}-1_{11}$ line observed in IRAS2A, infers an upper limit to the optical depth of $H^{18}$O $2_{02}-1_{11}$ of 1.5 for the medium component and 1.9 for the broad. Thus it is likely that neither the broad nor the medium components are very optically thick.

3. Discussion

Many physical components in a YSO are directly traced by the line profiles presented here, including the infalling envelope and shocks along the cavity walls. In the following, each component is discussed in detail, and the $H_2O$ abundance is estimated in the various physical components.

3.1. Line profiles

The most prominent feature of all the observed line profiles is their width. All line wings span a range of velocities of $\sim 40$–$70$ km s$^{-1}$ at their base. The width alone indicates that the bulk of the $H_2O$ emission originates in shocks along the cavity walls, also called shells, seen traditionally as the standard high-velocity component in CO outflow data, but with broader line-widths due to water enhancement at higher velocities (Sect. 3.2 Bachiller et al. 1990; Santiago-García et al. 2009). The shocks release water from the grains by means of sputtering and in high-temperature regions all free oxygen is driven into water. The shocked regions may be illuminated by FUV radiation originating in the star-disk boundary layer, thus further enhancing the water abundance by means of photodesorption. The broad emission seen in the $H^{18}$O $1_{10}-1_{01}$ line arises in the same shocks (see cartoon in Fig. 1).

The medium components ($FWHM \sim 5$–$10$ km s$^{-1}$) are most likely also caused by shocks, although presumably on a smaller spatial scale and in denser material than the shocks discussed above. For example, the medium component in IRAS2A is seen in other grain-product species such as $CH_3OH$ (Jørgensen et al. 2005; Maret et al. 2005, Fig. 3), where emission arises from a compact region ($<1''$, i.e., $<250$ AU) centred on the source (Jørgensen et al. 2007), and the same is likely true for the medium $H_2O$ component in that source. In interferometric observations of IRAS4A, a small ($\sim$few arcsec) blue-shifted outflow knot of similar width has been identified in, e.g., SiO and SO (Choi 2005; Jørgensen et al. 2007). Small-scale structures exist in the other sources as well, which may produce the medium components.
3.2. Abundances

3.2.1. Shocks: H$_2$O/CO

The observed broad components are compared directly with HIFI observations of CO 10–9 (Yıldız et al. 2010), because the width and position of the lines are similar and they were observed using approximately the same beamsize (22′′ versus 19′′). The exception is for IRAS2A, where the blue line wing is not observed. The advantage is that no detailed models are required to account for the H$_2$O/CO abundance, as long as the lines are optically thin, in particular the emission from the wings. The abundance ratio is estimated for various temperatures by using the RADEX escape probability code (van der Tak et al. 2007). The density is assumed to be 10$^5$ cm$^{-3}$, appropriate for the large-scale core. If the emission is optically thin, the abundance ratio scales linearly with density resulting in the same line ratio corresponding to a higher abundance ratio. There is little variation in the predicted ratio for $T > 150$ K, the typical temperature inferred by Yıldız et al. (2010). The line ratios and abundance ratios are listed as a function of velocity in Table 3.

The abundance ratio increases with increasing velocity from H$_2$O/CO of $\sim$0.2 near the line centre to H$_2$O/CO $\geq$ 1 in the line wings of all sources for velocity offsets larger than 15 km s$^{-1}$ with respect to that of the source (Fig. 3). Assuming that the CO abundance is $\sim$10$^{-4}$, the H$_2$O abundances are in the range of $\sim$10$^{-3}$–10$^{-4}$. Only at high velocities is the temperature high enough for oxygen to be driven into water by means of the neutral-neutral reaction $O + H_2 \rightarrow OH + H$; $OH + H \rightarrow H_2O$. The same result was found in the massive outflow in Orion-KL (Franklin et al. 2008), where less than 1% of the gas in the outflow experiences this high-temperature phase. The fraction of gas for which the H$_2$O/CO abundance is $\geq$1 is $\sim$5–10% for the sources observed here.

For IRAS2A, a deep spectrum of CO 6–5 obtained with CHAMP* on APEX simultaneously with observations of HDO 1$_1$–0$_0$ (Liu et al., in prep.) shows the same morphology in terms of a broad and medium component (Fig. 3). Furthermore, the velocity offset and FWHM are the same as for H$_2$O suggesting that the line profiles are not unique to H$_2$O, although the broad component is far more prominent in H$_2$O. The ratio of peak intensities for the two components is $\sim$2–3 in H$_2$O versus 10 in CO 6–5. Analysing the abundance ratio as a function of temperature shows that H$_2$O/CO $\sim$ 0.1–1 for $T > 150$ K (Table 3), consistent with what is found for CO 10–9.

3.2.2. Envelope

The simplest way to constrain the H$_2$O abundance in the outer envelope is with calculations using RADEX on the narrow absorption in the 1$_1$–0$_0$ line. The absorption is optically thick – in particular for IRAS2A and 4A, where the feature is saturated – which requires a para-H$_2$O column density of $>10^{13}$ cm$^{-2}$ if one assumes typical values for $T$ and $n$(H$_2$) of 15 K and $10^9$ cm$^{-3}$. With a pencil-beam H$_2$O column of $\sim$10$^{13}$ cm$^{-2}$ (Jørgensen et al. 2002), the total H$_2$O abundance in the outer envelope is $\geq$10$^{-10}$.

For IRAS2A and 4A, the H$_2$O abundance was further constrained using radiative transfer models. The setup is a spherical envelope with density and temperature profiles constrained from continuum data (Jørgensen et al. 2009), an infall velocity profile $v = (2$ km s$^{-1}$)$r/r_0^{-1/2}$, and a Doppler parameter $b = 0.8$ km s$^{-1}$. Line fluxes were computed with the new radiative transfer code LIME (Brinch & Hogerheijde, submitted). The models constrained the abundance of water in the outer envelope to be $\sim$10$^{-8}$. Lower values are insufficient to obtain saturated absorption in the 1$_1$–0$_0$ line, and $\sim$10$^{-8}$ is the highest abundance where the resulting narrow emission can be hidden in the observed higher-excitation H$_2$O lines. The models predict that the H$_2$O emission from the warm inner envelope ($r \leq 100$ AU) is optically thick, hence no constraints can be obtained from the H$_2$O spectra on the inner abundance. However, the lack of narrow H$_2$O emission infers an upper limit on the H$_2$O abundance of $\sim$10$^{-5}$ (Visser et al., in prep.).

4. Conclusions

These observations represent one of the first steps towards understanding the formation and excitation of water in low-mass star-forming regions by means of resolved line profiles. The three sources have remarkably similar line profiles. Both the H$_2$O and H$_2$O lines are very broad, indicating that the bulk of the emission originates in shocked gas. The broad emission also highlights that water is a far more reliable dynamical tracer than, e.g., CO. Comparing C$^{18}$O to H$_2$O emission and line profiles indicates that the H$_2$O/CO abundance is high in outflows and low in the envelope. Additional modelling of the emission, should be able to constrain the total amount of water in the envelope and outflowing gas, thus test the high-temperature gas-phase chemistry models for the origin of water. This will be performed for a total sample of the 29 low-mass YSOs to be observed within the WISH key programme.

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Table 2. Observed H$_2$O, H$_{18}$O and CH transitions$^a$.

| Transition | $\nu$ (GHz) | $\lambda$ (\(\mu\)m) | $E_u$ (K) | $A$ (10$^{-3}$ s$^{-1}$) | Beam $^b$ (\(^{''}\)) | $t_{int}$ (min.) |
|------------|-------------|-----------------|--------|-----------------|-------------------|---------------|
| H$_2$O 1$_{11}$–0$_{00}$ | 1113.34 | 269.27 | 53.4 | 18.42 | 19 | 43.5 |
| 2$_{02}$–1$_{11}$ | 987.93 | 303.46 | 100.8 | 5.84 | 22 | 23.3 |
| 2$_{11}$–2$_{02}$ | 752.03 | 398.64 | 136.9 | 7.06 | 29 | 18.4 |
| 3$_{12}$–3$_{03}$ | 1097.37 | 273.19 | 249.4 | 16.48 | 20 | 32.4 |
| 3$_{12}$–2$_{21}$ | 1153.13 | 259.98 | 249.4 | 2.63 | 19 | 13.0 |
| H$_{18}$O 1$_{10}$–1$_{01}$ | 547.68 | 547.39 | 60.5 | 3.59 | 39 | 64.3 |
| 1$_{11}$–0$_{00}$  | 1101.70 | 272.12 | 52.9 | 21.27 | 20 | 43.5 |
| 2$_{02}$–1$_{11}$ | 994.68 | 301.40 | 100.7 | 7.05 | 22 | 46.7 |
| 3$_{12}$–3$_{03}$  | 1095.16 | 273.74 | 289.7 | 22.12 | 20 | 32.4 |
| CH$^d$ 3/2, 2$^o$–1/2, 1$^+$ | 536.76 | 558.52 | 25.8 | 0.66 | 39 |
| 3/2, 1$^+$–1/2, 1$^+$ | 536.78 | 558.50 | 25.8 | 0.23 | 39 |
| 3/2, 1$^+$–1/2, 0$^+$ | 536.80 | 558.48 | 25.8 | 0.46 | 39 |

Notes. ($^a$) From the JPL database of molecular spectroscopy (Pickett et al. 1998); ($^b$) total on + off integration time; ($^c$) observed in the same setting as the main isotopologue; ($^d$) observed with H$_{18}$O 1$_{10}$–1$_{01}$.

Table 3. CO 6–5 and CO 10–9/H$_2$O 2$_{02}$–1$_{11}$ line ratios in 5 km s$^{-1}$ intervals and corresponding abundance ratio for $T > 150$ K and $n = 10^5$ cm$^{-3}$.

| $v_{LSR}$ (km s$^{-1}$) | IRAS2A | CO 6–5/ H$_2$O 2$_{02}$–1$_{11}$ | x(H$_2$O)/ x(CO) | IRAS4A | H$_2$O 10–9/ CO 2$_{02}$–1$_{11}$ | x(H$_2$O)/ x(CO) | IRAS4B | H$_2$O 10–9/ CO 2$_{02}$–1$_{11}$ | x(H$_2$O)/ x(CO) |
|----------------------|--------|-------------------------------|-----------------|--------|-------------------------------|-----------------|--------|-------------------------------|-----------------|
| -20– -15             | 5.0    | 0.34                          | ...             | 0.8    | 1.11                          | ...             | ...    | ...                           | ...             |
| -15– -10             | 3.8    | 0.45                          | ...             | 2.0    | 0.43                          | 0.9             | 1.00   |
| -10– -5              | 4.6    | 0.37                          | ...             | 2.8    | 0.31                          | 1.4             | 0.64   |
| -5–0                 | 9.3    | 0.18                          | ...             | 2.4    | 0.36                          | 1.7             | 0.50   |
| 0–5                  | 26.6   | 0.06                          | ...             | 2.9    | 0.29                          | 2.3             | 0.37   |
| 5–10                 | 17.0   | 0.10                          | 3.4             | 3.9    | 0.22                          | 2.9             | 0.29   |
| 10–15                | 11.1   | 0.15                          | 3.2             | 3.3    | 0.26                          | 2.1             | 0.42   |
| 15–20                | 3.5    | 0.48                          | 0.9             | 2.4    | 0.36                          | 1.6             | 0.53   |
| 20–25                | 1.4    | 1.25                          | 0.4             | 2.0    | 1.0                           | 0.83            | 1.1    |
| 25–30                | ...    | ...                           | ...             | 0.8    | 1.11                          | 0.5             | 1.67   |
| 30–35                | 0.9    | 2.00                          | ...             | ...    | ...                           | 0.9             | 1.00   |