A HIFI preview of warm molecular gas around \( \chi \) Cygni: first detection of \( H_2O \) emission toward an S-type AGB star

K. Justtanont\(^1\), L. Decin\(^{2,3}\), F. L. Schöier\(^1\), M. Maercker\(^{4,2,2}\), H. Olofsson\(^{1,5}\), V. Bujarrabal\(^6\), A. P. Marston\(^7\), D. Teyssier\(^7\), J. Alcolea\(^8\), J. Cernicharo\(^9\), C. Dominik\(^{3,10}\), A. de Koter\(^{3,11}\), G. Melnick\(^{12}\), K. Menten\(^{13}\), D. Neufeld\(^{14}\), F. Planesas\(^{6,15}\), M. Schmidt\(^{16}\), R. Szczerba\(^{16}\), R. Waters\(^{3,2}\), Th. de Graauw\(^{17}\), N. Whyborn\(^{17}\), T. Finn\(^{18}\), F. Helmich\(^{19}\), O. Siebert\(^{20}\), F. Schmütting\(^{20}\), V. Ossenkopf\(^{20}\), and R. Lai\(^{21}\)

(Affiliations are available on page 5 of the online edition)

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ABSTRACT

A set of new, sensitive, and spectrally resolved, sub-millimeter line observations are used to probe the warm circumstellar gas around an S-type AGB star \( \chi \) Cyg. The observed lines involve high rotational quantum numbers, which, combined with previously obtained lower-frequency data, make it possible to study in detail the chemical and physical properties of, essentially, the entire circumstellar envelope of \( \chi \) Cyg.

Water is an important molecule in CSEs as it is thought to be one of the main cooling agents in the wind. It is also expected to be a good probe of the inner regions of the CSE where the gas is accelerated. However, to fully explore the potential of \( H_2O \) lines as a probe of the circumstellar gas, a full radiative transfer analysis has to be performed. Owing to difficulties in calculating accurate collisional rates coupled with the very high optical depth of the \( H_2O \) lines in the inner region of the CSE, slow progress has been made. Nevertheless, calculations of the heating and cooling in the CSEs of O-rich stars suggest that \( H_2O \) dominates the cooling in most parts of the envelope until it is photodissociated by interstellar UV photons (Goldreich & Scoville 1976; Justtanont et al. 1994; Maercker et al. 2008, 2009; Decin et al. 2010a), and that some lines should come mainly from the acceleration zone. Eventually, spectrally resolved circumstellar \( H_2O \) lines were observed by two space missions dedicated to search for cosmic water line emission: SWAS and Odin. Both missions were able to detect the ground-state line of \( H_2O \) at 557 GHz in a number of AGB stars (Harwit & Bergin 2002; Melnick et al. 2001; Justtanont et al. 2005; Hasegawa et al. 2006; Maercker et al. 2009). It was shown that not only the line intensity, but also the line profile is crucial for interpreting the data correctly.

In 2009, the ESA-Herschel Space Observatory (Pilbratt et al. 2010) was launched with the Heterodyne Instrument for the Far-Infrared (HIFI, de Graauw et al. 2010), which aims to study \( H_2O \) line emission in different environments in our Galaxy and beyond.
Table 1. HIFI observations of χ Cyg.

<table>
<thead>
<tr>
<th>Molecule</th>
<th>Transition</th>
<th>ν (GHz)</th>
<th>$E_{\text{up}}$ (K)</th>
<th>$I^*$ (K km s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>$J = 6$–$5$</td>
<td>691.473</td>
<td>116</td>
<td>15.3</td>
</tr>
<tr>
<td>CO</td>
<td>$J = 10$–$9$</td>
<td>1151.985</td>
<td>304</td>
<td>13.6</td>
</tr>
<tr>
<td>CO</td>
<td>$J = 16$–$15$</td>
<td>1841.346</td>
<td>752</td>
<td>13.5</td>
</tr>
<tr>
<td>o-H$_2$O</td>
<td>$1^1_0$–$1^1_0$</td>
<td>556.936</td>
<td>61</td>
<td>3.0</td>
</tr>
<tr>
<td>p-H$_2$O</td>
<td>$2^2_1$–$2^2_0$</td>
<td>752.033</td>
<td>137</td>
<td>4.2</td>
</tr>
<tr>
<td>p-H$_2$O</td>
<td>$2^0_1$–$1^1_1$</td>
<td>987.927</td>
<td>101</td>
<td>7.5</td>
</tr>
<tr>
<td>p-H$_2$O</td>
<td>$1^1_0$–$0^0_0$</td>
<td>1113.343</td>
<td>53</td>
<td>8.0</td>
</tr>
<tr>
<td>o-H$_2$O</td>
<td>$3^2_1$–$2^2_1$</td>
<td>1153.127</td>
<td>249</td>
<td>7.5</td>
</tr>
<tr>
<td>o-H$_2$O</td>
<td>$3^2_1$–$3^2_2$</td>
<td>1162.912</td>
<td>305</td>
<td>1.5</td>
</tr>
<tr>
<td>o-H$_2$O</td>
<td>$3^2_0$–$2^2_1$</td>
<td>1716.770</td>
<td>197</td>
<td>18.1</td>
</tr>
</tbody>
</table>

Notes. (a) The absolute calibration accuracy is between 10% to 30% (see text).

Beyond HIFI offers the opportunity to study the warm molecular layers in CSEs of AGB stars in great detail, e.g., the high spectral resolution and wide spectral coverage allow a detailed study of the gas dynamics.

As part of the guaranteed time programme HIFISTARS (P.I.: V. Bujarrabal), the S-star (C/O = 1) χ Cyg was selected for study. Distance estimates range from 150 pc (Knapp et al. 2003) to 180 pc (van Leeuwen 2007). The star exhibits SiO masers (e.g., Olofsson et al. 1981; Schwartz et al. 1982; Alcolea & Bujarrabal 1992), but no H$_2$O maser emission has been found (Menten & Young 1995; Shintani et al. 2008). Being nearby and bright, χ Cyg has been observed using interferometric techniques in both the optical (Lacour et al. 2009) and the infrared (Tevoussian et al. 2004). In this Letter, we briefly describe the observations in Sect. 2, we discuss the modelling of the observed molecular emission in Sect. 3, and present our results and conclusions in Sect. 4.

2. Observations

The HIFI data were obtained using the dual-beam-switching mode (Roelfsema et al. 2010) with a throw of 3′ and slow (0.5–1 Hz) chopping in March–April 2010. A total of 8 frequency settings with a total of 10 lines detected are being reported in this paper. The targeted lines were selected to cover a wide range of excitation temperature, exploring different regions of the CSE. As backend, the wide band spectrometer (WBS) covering a region of 4 GHz with a resolution of 1.1 MHz was used. More details about these observations can be found in Bujarrabal et al. (2010). The data were calibrated using the standard pipeline for Herschel, HIPE version 2.8. Only the H-polarization data are presented here because the V-polarization data are noisier especially for the high frequency lines. We subtracted the baseline using a first or second order polynomial, except for the H$_2$O lines obtained from the Hitran database (Rothman et al. 2009) and the infrared (Tevoussian et al. 2004). This provides a circumstellar model, including a mass-loss-rate estimate based on the CO line modelling, which is used to model the H$_2$O line emission and its contribution to the cooling. The H$_2$O cooling is then used to recalculate the gas kinetic temperature in the CO model, and the process is iterated until good fits to the observed CO and H$_2$O lines are obtained.

3. Modelling HIFI lines

We started the analysis by fitting the spectral energy distribution of the CSE (assumed to be spherically symmetric) using Dusty (Ivezic & Elitzur 1997) to derive the dust mass-loss rate. Based on this, we solved the gas-dust drag equation, assuming that both are momentum coupled, to derive the velocity structure using the observed terminal gas velocity as a constraint, as shown in Fig. 1. This also provides a so-called dynamical mass-loss rate estimate, 4.9 × 10$^{-1}$ $M_\odot$ yr$^{-1}$ in the case of χ Cyg (see e.g., Ramstedt et al. 2008). The gas velocity law is fed into the CO radiative transfer model, where the line fluxes and shapes are computed and compared to the observations. At the same time, the heating by dust grains and the cooling by CO lines are calculated and the resulting temperature structure obtained (e.g., Justtanont et al. 1994; Crosas & Menten 1997; Decin et al. 2006; van der Tak et al. 2007; Ramstedt et al. 2008). This provides a circumstellar model, including a mass-loss-rate estimate based on the CO line modelling, which is used to model the H$_2$O line emission and its contribution to the cooling. The H$_2$O cooling is then used to recalculate the gas kinetic temperature in the CO model, and the process is iterated until good fits to the observed CO and H$_2$O lines are obtained.

3.1. Modelling of the CO lines

The Monte Carlo code developed by Schöier & Olofsson (2001) was used to model the observed CO lines. The molecular data were taken from the Hitran database (Rothman et al. 2009) and the collisional rate coefficients from Yang et al. (2010) for the 41 lowest rotational levels in the ν = 0 vibrational state. We fitted the line shapes and fluxes for the low-J lines obtained from ground-based observations, as well as the interferometric data for the J = 1–0 and 2–1 lines to more tightly constrain the size of the CO envelope (Schöier et al, in prep.). The parameters are listed in Table 2. The gas kinetic temperature distribution is shown in Fig. 1.

We assume a distance of 150 pc (Knapp et al. 2003), and the resulting mass-loss rate is 7 × 10$^{-7}$ $M_\odot$ yr$^{-1}$ using an adopted CO abundance of 6 × 10$^{-14}$ (relative to H$_2$, see Table 2), which provide the best fits to both the line profile and line intensities. The uncertainty in the mass-loss rate is of the order 50%. This mass-loss rate agrees well with the dynamical mass-loss rate (certainly to within the errors in the input parameters). A comparison of the model fits and the HIFI observations can be
Table 2. Parameters used in the modelling of the line emission.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance</td>
<td>150 pc</td>
</tr>
<tr>
<td>Stellar effective temperature ( (T_{\text{eff}}) )</td>
<td>2600 K</td>
</tr>
<tr>
<td>Stellar luminosity ( (L_*) )</td>
<td>( 7.5 \times 10^3 L_\odot )</td>
</tr>
<tr>
<td>Gas terminal velocity ( (v_{\text{exp}}) )</td>
<td>( 8.5 \text{ km s}^{-1} )</td>
</tr>
<tr>
<td>Inner radius of the shell ( (R_\text{in}) )</td>
<td>( 2 \times 10^{10} \text{ cm} )</td>
</tr>
<tr>
<td>Gas mass-loss rate ( (M) )</td>
<td>( 7 \times 10^{-7} M_\odot \text{ yr}^{-1} )</td>
</tr>
<tr>
<td>CO abundance ( (\text{CO}/H_2) )</td>
<td>( 6 \times 10^{-4} )</td>
</tr>
<tr>
<td>Ortho-H(_2)O abundance ( (\text{o-H}_2\text{O}/H_2) )</td>
<td>( 7.5 \times 10^{-6} )</td>
</tr>
<tr>
<td>Para-H(_2)O abundance ( (\text{p-H}_2\text{O}/H_2) )</td>
<td>( 3.6 \times 10^{-6} )</td>
</tr>
</tbody>
</table>

The observed HIFI lines are reliable probes of the inner CSE as the high-energy lines probe the wind in the acceleration zone. Both the velocity and density structures are tightly constrained using the HIFI lines. The abundance of CO used is \( 6 \times 10^{-4} \), intermediate to those usually adopted for O- and C-rich CSEs. The derived ortho- and para-H\(_2\)O abundances are significantly lower, \( (7.5 \pm 1.4) \times 10^{-6} \) and \( (3.6 \pm 0.5) \times 10^{-6} \) respectively (Table 2).

We used a higher order Chebyshev polynomial for the baseline subtraction (bottom right panel of Fig. 3).

Our results are consistent with the velocity structure of a dust-driven wind as can be seen in good fits to both the CO and H\(_2\)O line profiles (Figs. 2 and 3), respectively. Unlike the case for IK Tau (Decin et al. 2010a, b), no modification to the dynamical calculation is required.

4. Results and conclusions

The observed HIFI lines are reliable probes of the inner CSE as the high-energy lines probe the wind in the acceleration zone. Both the velocity and density structures are tightly constrained using the HIFI lines. The abundance of CO used is \( 6 \times 10^{-4} \), intermediate to those usually adopted for O- and C-rich CSEs. The derived ortho- and para-H\(_2\)O abundances are significantly lower, \( (7.5 \pm 1.4) \times 10^{-6} \) and \( (3.6 \pm 0.5) \times 10^{-6} \) respectively (Table 2).

These values are well below the limits for O-rich AGB stars of \( >10^{-4} \) (Justtanont et al. 2005; Maercker et al. 2008, 2009) consistent with \( \chi \) Cyg being an S-star of C/O very close to unity. From our modelling, assuming that all carbon is locked up in CO (i.e., C/H = 3 \times 10^{-4}) and the oxygen is locked up in both CO and H\(_2\)O (i.e., O/H = 3 \times 10^{-4} + 5.5 \times 10^{-5}), our derived C/O is \( \approx 0.98 \), given that a small fractional abundance of the oxygen is in dust grains. This value is slightly higher than that of 0.95, assumed by Duari & Hatchell (2000). A non-thermal equilibrium chemistry model for S-stars (C/O = 0.98) predicts an H\(_2\)O abundance of \( 10^{-4} \) at the stellar photosphere, falling off to a few \( 10^{-6} \) at \( 5 R_\odot \) (Cherchneff 2006), an order of magnitude lower than our value.

In the thermal equilibrium (TE) limit at high temperature, the expected ortho-to-para ratio is 3. Our derived ortho-to-para ratio is 2.1 \( \pm 0.6 \), close to the high-temperature TE value. The reported ortho-to-para ratio in CSEs of O-rich stars vary from 1 in W Hya with a large uncertainty (Barlow et al. 1996) to 3 in IK Tau (Decin et al. 2010b). Our result is consistent with H\(_2\)O molecules being formed under thermal equilibrium conditions in the warm and dense stellar photosphere.

Given the low total H\(_2\)O abundance of \( (1.1 \pm 0.2) \times 10^{-5} \), it is clear from our analysis that the dominating cooling agent in the CSE of \( \chi \) Cyg is CO (Fig. 4). Vibrationally excited H\(_2\) and rotationally excited H\(_2\)O contribute only in the innermost \( (r < 10^{15} \text{ cm}) \) part of the CSE while CO line cooling extends further out until CO is photodissociated by the external UV field. Adiabatic cooling dominates only in the outermost part of the CSE. The derived H\(_2\)O abundance, although much lower than in O-rich stars, is higher than that observed in C-stars, IRC+10216 (Melnick et al. 2001) and V Cyg (Neufeld et al. 2010), consistent with AGB stars of S-type being chemically intermediate between O-rich and C-rich AGB stars.
Fig. 3. The model fits (smooth lines) to the HIFI ortho- and para-H$_2$O lines (histogram). The scaling factor (used to scale the model result to fit the observed integrated intensity) is given for each line, showing the goodness of the fit. The pipeline-reduced data of the 3$_{03}$−2$_{12}$ line are plotted along with the fitted baseline at the bottom right. This line is affected by standing waves within HIFI.

Fig. 4. The cooling rates due to different processes: rotational cooling by H$_2$O (solid), CO (dashed) lines, vibrational cooling by H$_2$ (dotted) line, and adiabatic cooling (dot-dash).

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