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A HIFI preview of warm molecular gas around $\chi$ Cygni: first detection of $\text{H}_2\text{O}$ emission toward an S-type AGB star


(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 the 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.

Methods. The data were obtained using the HIFI instrument aboard Herschel, whose high spectral resolution provides valuable information about the line profiles. Detailed, non-LTE, radiative transfer modelling, including dust radiative transfer coupled with a dynamical model, has been performed to derive the temperature, density, and velocity structure of the circumstellar envelope.

Results. We report the first detection of circumstellar $\text{H}_2\text{O}$ rotational emission lines in an S-star. Using the high-J CO lines to derive the parameters for the circumstellar envelope, we modulated both the ortho- and para-$\text{H}_2\text{O}$ lines. Our modelling results are consistent with the velocity structure of the line profiles. Detailed, non-LTE, radiative transfer modelling, including dust radiative transfer coupled with a dynamical model, has been performed to derive the temperature, density, and velocity structure of the circumstellar envelope.

Key words. stars: AGB and post-AGB – circumstellar matter – stars: kinematics and dynamics – stars: individual: $\chi$ Cyg – stars: late-type – stars: mass-loss

1. Introduction

Observations of the dust and gas components in the circumstellar envelopes (CSEs) around asymptotic giant branch (AGB) stars have been carried out at different wavelengths. Observations in the infrared trace the dust as well as the warm molecular layer close to the stellar photosphere (e.g., Justtanont et al. 1996; Aoki et al. 1999; Schöier et al. 2002). Submillimeter and radio observations of trace molecules have been used to study the cooler outer parts of the CSEs (e.g., Knapp & Morris 1985; Schöier & Olofsson 2000; Kemper et al. 2003). To bridge this gap, the ISO was used to observe a large number of AGB stars up to almost 200 $\mu$m, and in O-rich stars, a number of $\text{H}_2\text{O}$ emission lines were detected (Barlow et al. 1996; Neufeld et al. 1996). However, the circumstellar far-infrared lines were unresolved. Hence, crucial information about the line profiles remained unknown.

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 $\text{H}_2\text{O}$ lines as a probe of the circumstellar gas, a full radiative transfer has to be performed. Owing to difficulties in calculating accurate collisional rates coupled with the very high optical depth of the $\text{H}_2\text{O}$ 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 $\text{H}_2\text{O}$ 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 $\text{H}_2\text{O}$ 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 $\text{H}_2\text{O}$ 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 $\text{H}_2\text{O}$ line emission in different environments in our Galaxy and in other galaxies.

Herschel has been designed and built by a consortium of institutes and university departments from across Europe, Canada, and the United States under the leadership of SRON Netherlands Institute for Space Research, Groningen, The Netherlands and with major contributions from Germany, France and the US. Consortium members are: Canada: CSA, U. Waterloo; France: CESR, LAB, LERMA, IRAM; Germany: KOSMA, MPIfR, MPS; Ireland, NUI Maynooth; Italy: ASI, IFSI-INAF, Osservatorio Astrofisico di Arcetri – INAF; Netherlands: SRON, TUD; Poland: CAMK, CBK; Spain: Observatorio Astronómico Nacional (IGN), Centro de Astrobiología (CSIC-INTA). Sweden: Chalmers University of Technology – MC2; RSS & GARD; Onsala Space Observatory; Swedish National Space Board, Stockholm University – Stockholm Observatory; Switzerland: ETH Zurich, FHNW; USA: Caltech, JPL, NHSC.
Table 1. HIFI observations of \( \chi \) Cyg.

<table>
<thead>
<tr>
<th>Molecule</th>
<th>Transition</th>
<th>( \nu ) (GHz)</th>
<th>( E_a ) (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_2O )</td>
<td>( 1_{10}-1_{01} )</td>
<td>556.936</td>
<td>61</td>
<td>3.0</td>
</tr>
<tr>
<td>( p-H_2O )</td>
<td>( 2_{11}-2_{02} )</td>
<td>752.033</td>
<td>137</td>
<td>4.2</td>
</tr>
<tr>
<td>( p-H_2O )</td>
<td>( 2_{02}-1_{11} )</td>
<td>987.927</td>
<td>101</td>
<td>7.5</td>
</tr>
<tr>
<td>( p-H_2O )</td>
<td>( 1_{11}-0_{00} )</td>
<td>1113.343</td>
<td>53</td>
<td>8.0</td>
</tr>
<tr>
<td>( o-H_2O )</td>
<td>( 3_{21}-2_{22} )</td>
<td>1153.127</td>
<td>249</td>
<td>7.5</td>
</tr>
<tr>
<td>( o-H_2O )</td>
<td>( 3_{22}-3_{21} )</td>
<td>1162.912</td>
<td>305</td>
<td>1.5</td>
</tr>
<tr>
<td>( o-H_2O )</td>
<td>( 3_{30}-2_{21} )</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 \( \approx 1 \)) \( \chi \) Cyg was selected for study. Distance estimates range from 150 pc \( \text{(Knapp et al. 2003)} \) to 180 pc \( \text{(van Leeuwen 2007)} \). The star exhibits SiO masers (e.g., Olofsson et al. 1981; Schwartz et al. 1982; Alcolea & Bujarrabal 1992), but no \( H_2O \) maser emission has been found (Young 1995; Shintani et al. 2008). Being nearby and bright, \( \chi \) 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 \( \text{(Roelfsema et al. 2010)} \) with a throw of 3 arcsec 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 \( \text{Herschel}, \text{HIPE version 2.8)} \). 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 \( H_2O \) lines obtained from Bujarrabal et al. (2010), which used an adopted \( C/\text{O} = 6 \times 10^{-7} \) (relative to \( H_2 \), see Table 2), 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.

3. Modelling HIFI lines

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 HITEMP database (Rothman et al. 2009) and the collisional rate coefficients from Yang et al. (2010) for the 41 lowest rotational levels in the \( \nu = 0 \) 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 \( \text{(Knapp et al. 2003)} \), and the resulting mass-loss rate is \( 7 \times 10^{-7} M_\odot \text{yr}^{-1} \) using an adopted CO abundance of \( 6 \times 10^{-4} \) (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 estimate, certainly to within the errors in the input parameters. A comparison of the model fits and the HIFI observations can be
seen in Fig. 2. The models have been scaled to match the line intensities and the scaling factor (given in each panel of the figure) is a measure of the goodness of fit. The high rotational line at $J = 16–15$ is noticeably narrower than the lower-level lines observed with HIFI and ground-based instruments (e.g., Knapp et al. 1998), indicating that this line originates in a region where the gas is still being accelerated. The estimated outer CO radius from Rothman et al. (2009) and the collisional cross-sections used by Standing waves inside HIFI. For this line, 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 x 10^{-6}), our derived C/O is $\leq 0.98$, 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 $R_\ast$ (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 ($r < 10^{15}$ 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.

### 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</td>
<td>2600 K</td>
</tr>
<tr>
<td>Stellar luminosity</td>
<td>7.5 x 10^3 L$_\odot$</td>
</tr>
<tr>
<td>Gas terminal velocity</td>
<td>8.5 km s$^{-1}$</td>
</tr>
<tr>
<td>Inner radius of the shell</td>
<td>2 x 10^16 cm</td>
</tr>
<tr>
<td>Gas mass-loss rate</td>
<td>7 x 10^{-7} M$_\odot$ yr$^{-1}$</td>
</tr>
<tr>
<td>CO abundance</td>
<td>6 x 10^{-4}</td>
</tr>
<tr>
<td>ortho-H$_2$O abundance</td>
<td>7.5 x 10^{-6}</td>
</tr>
<tr>
<td>para-H$_2$O abundance</td>
<td>3.6 x 10^{-6}</td>
</tr>
</tbody>
</table>
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 process: 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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