Herschel observations in the ultracompact H II region Mon R2

Water in dense photon-dominated regions (PDRs)*,***


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ABSTRACT

Context. Monoceros R2, a distance of 830 pc, is the only ultracompact H II region (UC H II) where the photon-dominated region (PDR) between the ionized gas and the molecular cloud can be resolved with Herschel. Therefore, it is an excellent laboratory to study the chemistry in extreme PDRs (G0 > 105 in units of Habing field, n > 106 cm−3).

Aims. Our ultimate goal is to probe the physical and chemical conditions in the PDR around the UC H II Mon R2.

Methods. HIFI observations of the abundant compounds 13CO, C18O, o-H316O, HCO+, CS, CH, and NH have been used to derive the physical and chemical conditions in the PDR, in particular the water abundance. The modeling of the lines has been done with the Meudon PDR code and the non-local radiative transfer model described by Cernicharo et al.

Results. The 13CO, C18O, o-H316O, HCO+ and CS observations are well described assuming that the emission is coming from a dense (n = 5 × 106 cm−3, N(H2) > 1022 cm−2) layer of molecular gas around the H II region. Based on our o-H316O observations, we estimate an o-H2O abundance of ≈2 × 10−4. This is the average ortho-water abundance in the PDR. Additional H316O and/or water lines are required to derive the water abundance profile. A lower density envelope (n ∼ 105 cm−3, N(H2) = 2–5 × 1021 cm−2) is responsible for the absorption in the NH 1→0 line. The emission of the CH ground state triplet is coming from both regions with a complex and self-absorbed profile in the main component. The radiative transfer modeling shows that the 13CO and HCO+ line profiles are consistent with an expansion of the molecular gas with a velocity of 15 km s−1, although the expansion velocity is poorly constrained by the observations presented here.

Conclusions. We determine an ortho-water abundance of ≈2 × 10−4 in Mon R2. Because shocks are unimportant in this region and our estimate is based on H316O observations that avoids opacity problems, this is probably the most accurate estimate of the water abundance in PDRs thus far.

Key words. ISM: structure – ISM: kinematics and dynamics – ISM: molecules – H II regions – submillimeter: ISM

1. Introduction

Ultracompact (UC) H II regions constitute one of the earliest phases in the formation of a massive star and are characterized by extreme physical and chemical conditions (G0 > 105 in units of Habing field and n > 106 cm−3). Their understanding is important for distinguishing the different processes in the massive star formation process and because they can be used as a template for other extreme photon-dominated regions (PDRs) such as the surface layers of circumstellar disks and/or the nuclei of starburst galaxies. The UC H II Mon R2 is the only one that can be resolved with Herschel.

Mon R2 is a nearby (d = 830 pc; Herbst & Racine 1976) complex star forming region. It hosts a UC H II region near its center, powered by the infrared source Mon R2 IRS1 (Wood & Churchwell 1989). The molecular content of this region has been the subject of several observational studies. The huge CO bipolar outflow (Meyers-Rice & Lada 1991), ∼15′ long (≈3.6 pc) is a relic of the formation of the B0V star associated to IRS1 (Massi et al. 1985; Henning et al. 1992) and strong shocks are currently not at work in this region (Berné et al. 2009). Previous molecular observations (Giannakopoulou et al. 1997; Tafalla et al. 1997; Choi et al. 2000; Rizzo et al. 2003, 2005) showed that the UC H II region is located inside a cavity and bound by a dense molecular ridge. The peak of this molecular ridge (hereafter, MP) is located at an offset (+10′′, −10′′) relative to the peak of the ionized gas (hereafter, IF). The molecular hydrogen column density toward the MP is 2–6 × 1022 cm−2. The detection of the reactive ions CO+ and HOC+ showed a dense photon-dominated region (PDR) surrounding the UC H II region (Rizzo et al. 2003, 2005). Recent Spitzer observations probed the thin molecular gas layer (n = 4×105 cm−3, N(H2) = 1×1021 cm−2) with Tk = 574±20 K in between the ionized gas and the dense molecular gas traced by

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** Figures 1 and 4 (page 5) are only available in electronic form at http://www.aanda.org
We detected the CH 1 → 0, HCO+ 6 → 5, CS 11 → 10, o–H$_2$^{16}O 10 → 1, C$^{13}$O 5 → 4, C$^{15}$O 5 → 4, and NH 1 → 0 lines in the MP (see Fig. 2). We stress that this is the first detection of the rarer water isotopologue o–H$_2$^{15}O toward a spatially resolved PDR. All the lines except NH 1 → 0 were detected in emission. Gaussian fits are shown in Table 1 and Fig. 2. We fitted the three components of the CH 1 → 0 line assuming the same excitation temperature and estimated that the opacity of the main component is >3. In this case, the central velocity is not well determined because of the self-absorption and the flattened profiles produced by the large opacities. The NH 1 → 0 line was tentatively detected (~3σ) in absorption. This line is composed of 10 components and we fitted all of them assuming the same excitation temperature. Our fit shows that the NH line is optically thin. Because the individual components are not resolved with a linewidth of ~4 km s$^{-1}$, the individual line parameters are uncertain. This detection needs to be confirmed.

3.1. Line profiles

Different velocity components can be distinguished in this region. The ambient cloud is centered at $V_{lsr} = 10.5 \pm 1$ km s$^{-1}$. A large scale molecular outflow is associated with IRS 1 (Meyers-Rice et al. 1991; Tafalla et al. 1997). The wings observed in the emission profiles of the HCO$^+$ 1 → 0 and 3 → 2 lines and in the C$^{13}$O 2 → 1 line (velocity ranges [0,6] km s$^{-1}$ and [4,14] km s$^{-1}$) are associated with the molecular outflow. The HCO$^+$ 6 → 5, C$^{13}$O 5 → 4 and C$^{15}$O 5 → 4 lines are centered at a velocity of ~10.4 km s$^{-1}$. In Fig. 3 we compare the HIFI lines with the low rotational lines of the same species observed with the IRAM 30m telescope. The angular resolution of the IRAM data was degraded to match those of Herschel. The line profiles of the low rotational lines of HCO$^+$ and C$^{13}$O are self-absorbed at redshifted velocities. For C$^{15}$O, there is a perfect match between the profiles of the J = 5 → 4 and J = 2 → 1 lines. The profiles of the CS J = 2 → 1 and J = 11 → 10 lines also match perfectly.

The HCO$^+$ 6 → 5, CS 11 → 10, C$^{13}$O 5 → 4 and C$^{15}$O 5 → 4 lines have characteristic linewidths of 2–3 km s$^{-1}$. The largest linewidths observed in the NH 1 → 0 and CH lines (~5 km s$^{-1}$) indicate that these lines are tracing a different, probably more diffuse component. As argued in Sect. 4.1, the NH absorption is very likely caused by the cold and lower density envelope surrounding the UC H II region. The CH 1 → 0 line is seen in absorption and emission suggesting that CH is present in the low density envelope and the dense PDR.

3.2. Molecular column densities

In Table 2 we present the estimated molecular column densities. We used the rotational diagram technique to estimate the rotation temperature and the column density of the CO isotopologues and CS. This technique gives an average rotation temperature and total column density providing that the emission is optically thin.

Table 1. Summary of HIFI observations.

<table>
<thead>
<tr>
<th>Line</th>
<th>Freq. (GHz)</th>
<th>$T_A \times r$ (K)</th>
<th>$\Delta v$ (km s$^{-1}$)</th>
<th>$\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH</td>
<td>536.961</td>
<td>1.83(0.2)</td>
<td>10.4(1)</td>
<td>3.60(0.6)</td>
</tr>
<tr>
<td>NH</td>
<td>974.478</td>
<td>-0.24(0.07)</td>
<td>9.0(0.4)</td>
<td>4.9(0.8) 0.10(0.7)</td>
</tr>
</tbody>
</table>

Fig. 2. HIFI spectra toward the MP in Mon R2. Note that the $^{13}$CO 5 → 4 and HCO$^+$ 6 → 5 lines appear close in velocity. This is an artifact of the DSB observations. The HCO$^+$ 6–5 line is observed in the LSB and the $^{13}$CO 5 → 4 line, in the USB. The dashed line indicates $v_{lsr} = 10.5$ km s$^{-1}$.

previous millimeter observations (Berné et al. 2009). All these components are schematically shown in Fig. 1.

2. Observations

The observations were made with the HIFI instrument onboard Herschel (Pilbratt et al. 2010; de Graauw et al. 2010) during the priority science phase 2 in the frequency switch (FSW) observing mode with a reference position at the offset (+10$^\circ$.0). Two receiver settings were observed, one in Band 1a with the WBS centered at 536.066 GHz (LSB) and the other in Band 4a with the WBS centered at 971.800 GHz (LSB). These settings were observed toward both positions, IF [RA = 06$^\circ$40$^\prime$46.2", Dec = +06$^\circ$23’08.3” (J2000)] and MP [RA=06$^\circ$40$^\prime$46.87", Dec = +06$^\circ$23’18.3” (J2000)]. In this letter we present the observations toward the MP because the study of the spatial distribution of the molecular tracers is postponed for a forthcoming paper. The data were reduced using HIPE 3.0 pipeline. The adopted intensity scale was antenna temperature. In addition to Herschel data, we used the HCO$^+$ (1 → 0), HCO$^+$ (3 → 2), CS (2 → 1), $^{13}$CO (1→0), $^{13}$CO (2→1), C$^{18}$O (1 → 0) and C$^{15}$O (2 → 1) observed with the IRAM 30m telescope.

3. Results

We detected the CH 1 → 0, HCO$^+$ 6 → 5, CS 11 → 10, o–H$_2$^{18}O 10 → 10, $^{13}$CO 5 → 4, C$^{15}$O 5 → 4, and NH 1 → 0 lines in the
For optically thick lines, we obtained a lower limit to the true column density and rotation temperature (this is very likely the case for $^{13}$CO). For CH and NH we assumed a reasonable value of the rotation temperature. Previous molecular observations at millimeter wavelengths showed the existence of gas with densities up to $n = 4 \times 10^6$ cm$^{-3}$ and $T_k = 50$ K in the molecular ridge (Choi et al. 2000; Rizzo et al. 2003, 2005). Berné et al. (2009) derived a density, $n = 4 \times 10^7$ cm$^{-3}$ and a gas kinetic temperature of ~570 K for a thin gas layer around the H II region on basis of the H$_2$ rotational lines. These two n-T pairs of values can produce the rotation temperatures derived from our observations. However, the gas layer at 570 K cannot account for the observed line intensities. For instance, assuming a standard C$^{18}$O abundance of $2 \times 10^{-5}$, this hot layer will produce a C$^{18}$O S(3-2) line intensity of $T_B \sim 0.09$ K, i.e. 2% of the observed value. Therefore, the emission of the observed lines is mainly coming from the dense ($n = 4 \times 10^{10}$ cm$^{-3}$) molecular ridge.

We detected the $^{12}$H$_2^{16}$O $1_{01} \rightarrow 1_{00}$ line in the MP. Using the non-local radiative transfer code of Cernicharo et al. (2006) and assuming the densities and temperatures prevailing in the dense molecular ridge ($T_k = 50$ K, n(H$_2$) = $4 \times 10^{10}$ cm$^{-3}$), we obtained an excitation temperature for the ground state transition of $\sim 8.5$ K. With this low excitation temperature, we need N($^{12}$H$_2^{16}$O) = $2.7 \times 10^{12}$ cm$^{-2}$ to fix our observations. Assuming a $^{18}$O/$^{16}$O ratio of ~500, this implies an ortho-water abundance of $\sim 2 \times 10^{-8}$. The excitation temperature is not very sensitive to the gas kinetic temperature. To assume a gas kinetic temperature as high as 500 K would increase the excitation temperature by a factor of 2, and decrease the estimated $^{12}$H$_2^{16}$O column density by a factor of 10. To assume a lower hydrogen density would be more critical, because the excitation temperature would drop to very low values (a few K), and the line would become very weak and optically thick which would prevent any good estimate of the $^{12}$H$_2^{16}$O column density. The water abundance estimated in Mon R2 is similar to that obtained toward the Orion Bar by Olofsson et al. (2003) using ODIN observations. In that case, the spatial resolution of the ODIN observations did not allow the authors to resolve the dense PDR. Moreover, their estimate was based on observations of the ground state transition of the main water isotopologue, which is optically thick. The agreement between the two measurements could therefore be fortuitous. Recent SPIRE observations of the Orion Bar have provided an upper limit to the water abundance of a few $10^{-7}$ (Habart et al. 2010).

To interpret the observed NH $1_1$-$0_2$ line absorption, a knowledge of the continuum level is needed. Unfortunately, the line was observed in FSW mode, which removes the continuum. Hence, the continuum level had to be estimated from previous measurements. In particular, Dotson et al. (2010) measured an intensity of 280 Jy/beam using the CSO telescope (beam = 20$''$) at 350 $\mu$m (=857 GHz). Assuming a spectral index $\beta$ of $\sim 3$, we estimate a continuum flux of 411 Jy at 974 GHz. This value corresponds to a brightness temperature of 0.8 K in the HIFI beam. Taking into account the uncertainty in $\beta$ and the different beams of Herschel and CSO, we estimate that the accuracy of the continuum intensity at 974 GHz is about a factor of 2. Assuming $T_ex = 10$ K, and an intrinsic linewidth of 4 km s$^{-1}$, the line opacity inferred from the observed absorption feature implies a NH column density of $(1-5) \times 10^{13}$ cm$^{-2}$ (a factor $\sim 1.5$ higher if $T_ex = 20$ K). Taking $\sim 5 \times 10^{22}$ cm$^{-2}$ as an upper limit for N(H$_2$) (the NH absorption likely arises in a external layer of more diffuse gas), the NH abundance would be greater than $(1.0-0.2) \times 10^{-9}$. These abundances are comparable to the NH abundance first inferred by ISO toward Sgr B2 (Cernicharo et al. 2000; Goicoechea et al. 2004).

4. Discussion

4.1. Chemical model

We explored the possibility of explaining the molecular abundances observed in Mon R2 in terms of PDR chemistry. To do this, we used the updated version of the Meudon PDR code (Le Petit et al. 2006; Goicoechea & Le Bourlot 2007). As input parameters we used a plane-parallel slab with a thickness of 10 mag and a minimum value $< 10^{-10}$ (see Fig. 4). The observation of high excitation lines of water will allow us to derive the water abundance profile and further constrain the chemical modeling. The model falls short by more than one order of magnitude however to predict the NH column density. The NH abundance is $< 10^{-8}$ all across the PDR (see Fig. 4). As argued below, this is very likely due to the main contribution to the

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**Table 2. Molecular column densities**.

<table>
<thead>
<tr>
<th>Mol</th>
<th>$T_{rot}$ (K)</th>
<th>Observed (cm$^{-2}$)</th>
<th>PDR Model (cm$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{13}$CO</td>
<td>27</td>
<td>$4.7 \times 10^{16}$</td>
<td>$3.5 \times 10^{16b}$</td>
</tr>
<tr>
<td>C$^{18}$O</td>
<td>34</td>
<td>$6.9 \times 10^{15}$</td>
<td>$3.5 \times 10^{15b}$</td>
</tr>
<tr>
<td>H$^{13}$CO$^+$</td>
<td>20$^a$</td>
<td>$1.7 \times 10^{12}$</td>
<td>$9.3 \times 10^{11b}$</td>
</tr>
<tr>
<td>CS</td>
<td>25</td>
<td>$6.3 \times 10^{13}$</td>
<td>$6.7 \times 10^{13}$</td>
</tr>
<tr>
<td>o–H$^{13}$CO</td>
<td>8.5$^a$</td>
<td>$2.7 \times 10^{12}$</td>
<td>$2.9 \times 10^{12d}$</td>
</tr>
<tr>
<td>CH</td>
<td>19$^a$</td>
<td>$5.6 \times 10^{13}$</td>
<td>$3.3 \times 10^{14}$</td>
</tr>
<tr>
<td>NH</td>
<td>10–20$^a$</td>
<td>1–5 $\times 10^{13}$</td>
<td>$5.1 \times 10^{14}$</td>
</tr>
</tbody>
</table>

**Notes.**
- $^{a}$ The rotational diagrams used the 30 m and HIFI lines.
- $^{b}$ assumed rotational temperature;
- $^{d}$ assuming $^{12}$C$^{13}$C = 50 and $^{16}$O/$^{18}$O = 500; $^{c}$ from Rizzo et al. (2005); $^{d}$ assuming an ortho-to-para ratio of 3.
spherical envelope with inner radius model, we adopted the physical structure derived in Sect. 4.1 (a
the HIFI data are still to come), we made a preliminary model
structure of the molecular core. Although the complete model-
ning of the HCO+ rotational lines is consistent with the
molecular gas being expanding with an expansion velocity law,
v_e = 0.5 \times (R/R_{out})^{-1} \text{ km s}^{-1}.\) Based on our o–H$_2$O 1$_0 \rightarrow 1_0$ ob-
observations, we estimate an ortho-water abundance of \(\sim 2 \times 10^{-8}\). Because shocks are unimportant in this region and our estimate is based on the rarer isotopologue observations that avoids opacity problems, this water abundance estimate is probably the most accurate in PDWs thus far.

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References
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Fig. 1. Overview of the PDR associated with Mon R2. Gray scales represent the CS 7–6 line emission map from Choi et al. (2000). The blue contours represent the intensity of the \[\text{[Ne II]}\] line (0.02–0.1 \(\text{erg s}^{-1} \text{cm}^{-2} \text{sr}^{-1}\)) in linear steps), and the green contours the intensity of the \(\text{H}_2\) S(3) rotational line at 9.7 \(\mu\text{m}\) (1.5–4.5 \(\times\) \(10^4\) \(\text{erg s}^{-1} \text{cm}^{-2} \text{sr}^{-1}\)) in linear steps). The circles indicate the Herschel beam in band 1a (40"") and band 4a (21"") centered on the molecular peak (MP).

Fig. 4. Results of the chemical modeling of the dense PDR surrounding the UCHII region Mon R2.

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