LETTER TO THE EDITOR

Water emission from the high-mass star-forming region IRAS 17233-3606*,**

High water abundances at high velocities

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ABSTRACT

We investigate the physical and chemical processes at work during the formation of a massive protostar based on the observation of water in an outflow from a very young object previously detected in H2 and SiO in the IRAS 17233–3606 region. We estimated the abundance of water to understand its chemistry, and to constrain the mass of the emitting outflow. We present new observations of shocked water obtained with the HIFI receiver onboard Herschel. We detected water at high velocities in a range similar to SiO. We self-consistently fitted these observations along with previous SiO data through a state-of-the-art, one-dimensional, stationary C-shock model. We found that a single model can explain the SiO and H2O emission in the red and blue wings of the spectra. Remarkably, we found one common area, similar to that found for H2 emission, fits both the SiO and H2O emission regions. This shock model subsequently allowed us to assess the shocked water column density, \( N_{\text{H}_2\text{O}} = 1.2 \times 10^{18} \text{cm}^{-2} \), mass, \( M_{\text{H}_2\text{O}} = 12.5 M_\odot \), and its maximum fractional abundance of 1.4 \( \times 10^{-4} \). The corresponding water abundance in fractional column density units ranges between \( 2.5 \times 10^{-5} \) and \( 1.2 \times 10^{-5} \), in agreement with recent results obtained in outflows from low- and high-mass young stellar objects.

Key words. stars: formation – stars: protostars – ISM: jets and outflows – ISM: individual objects: IRAS 17233–3606 – astrochemistry – shock waves

1. Introduction

The formation mechanism of high-mass stars (\( M > 8 M_\odot \)) has been an open question despite active research for several decades, with the main reason being that the strong radiation pressure exerted by the young massive star overcomes its gravitational attraction (Kahn 1974). Controversy remains about how high-mass young stellar objects (YSOs) acquire their mass (e.g., Krumholz & Bonnell 2009), either locally in a prestellar phase or during the star formation process itself, being funnelled to the centre of a stellar cluster by the cluster’s gravitational potential. Bipolar outflows are a natural by-product of star formation and understanding them can give us important insights into the way massive stars form. In particular, studies of their properties in terms of morphology and energetics as function of the luminosity, mass, and evolutionary phase of the powering object may help us to understand whether the mechanism of formation of low- and high-mass YSOs is the same or not (see, e.g., Beuther et al. 2002).

Water is a valuable tool for outflows as it is predicted to be copiously produced under the type of shock conditions expected in outflows (Flower & Pineau Des Forêts 2010). Observations of molecular outflow powered by YSOs of different masses reveal abundances of \( H_2O \) associated with outflowing gas of the order of some \( 10^{-5} \) (e.g., Emprechtinger et al. 2010; Kristensen et al. 2012; Nisini et al. 2013). Recently, the Water In Star-forming regions with Herschel (van Dishoeck et al. 2011) key program targeted several outflows from Class 0 and I low-mass YSOs in water lines. \( H_2O \) emission in young Class 0 sources is dominated by outflow components; in Class I YSOs \( H_2O \) emission is weaker because of less energetic outflows (Kristensen et al. 2012). Comparisons of low-excitation water data with SiO, CO, and \( H_2 \) reveal contrasting results because these molecules seem to trace different environments in some sources (Nisini et al. 2013; Tafalla et al. 2013) while they have similar profiles and morphologies in others (Lefloch et al. 2012; Santangelo et al. 2012). Observations of massive YSOs (e.g., van der Tak et al. 2013) confirm broad profiles due to outflowing gas in low-energy \( H_2O \) lines. However, the coarse spatial resolution of
Six water lines and one H\textsuperscript{18}O transition were observed towards the positions \(\alpha_{2000} = 17^h26^m42^s50, \delta_{2000} = -36°09′18″00\) (OBSIDs 1342242862, 1342242863, and 1342242875), and \(\alpha_{2000} = 17^h26^m42^s54, \delta_{2000} = -36°09′20″00\) (OBSIDs 1342266457 and 1342266536). Conversion to \(T_{\text{mb}}\) was done using the beam efficiencies given in Table B.1 and a forward efficiency of 0.96. Data were taken simultaneously in H and V polarisations using the acousto-optical Wide-Band Spectrometer. OBSIDs 1342242862, 1342242863, and 1342242875 were acquired in spectral scan mode with a redundancy of 4 to allow for sideband separation. The data were calibrated using the standard calibration pipeline within HIPE 11.0 (Ott 2010). Sideband separation was performed using the GILDAS\textsuperscript{1} CLASS package. OBSIDs 1342266457 and 1342266536 were taken in single-pointing mode and level 2 data were exported into CLASS90 where they were analysed in detail. After inspection, data from the two polarisations were averaged together.

### 3. Observational results

Figure 2 shows the H\textsubscript{2}O spectra towards IRAS 17233. In all transitions, we detected water at high-velocities with respect to the ambient velocity (\(v_{\text{LSR}} = -3.4\text{~km~s}^{-1}\), Bronfman et al. 1996); indeed, IRAS 17233 presents one of the broadest profiles in the \(1_{11} - 0_{00}\) transition in high-mass YSOs (van der Tak et al. 2013) known to date. The ground-state line shows narrow absorptions at \(-18\) and \(+6\text{~km~s}^{-1}\). They might be due to different clouds along the line of sight. However, the SiO(8–7) line, observed with a similar angular resolution (Paper II), has a well-defined emission peak at \(-18\text{~km~s}^{-1}\) (see Fig. 2) although broader than the H\textsubscript{2}O absorption. Zapata et al. (2008) detected H\textsubscript{2}O maser spots coming from the region shown in Fig. 1. These absorptions might be due to cold water associated with the outflows. The H\textsubscript{2}O and H\textsubscript{18}O ground-state lines have deep blue-shifted absorptions against the continuum and the outflow at velocities up to \(-50\text{~km~s}^{-1}\), while the main isotopologue line shows red-shifted emission up to \(50\text{~km~s}^{-1}\).

\(1\) http://www.iram.fr/IRAMFR/GILDAS
and its H$_2^8$O equivalent up to +17 km s$^{-1}$. High-velocity red-shifted emission is detected up to +50/60 km s$^{-1}$ in all other lines, except in the highest energy line (p-H$_2$O 4$_{22}$–3$_{13}$) where emission is detected only up to +18 km s$^{-1}$. The red-shifted wing of the 1163 GHz line and the blue-shifted wing of the 752 GHz transition are contaminated by hot-core-like features. Emission up to −70 km s$^{-1}$ is detected in the other transitions.

Comparison of the H$_2$O and H$_2^8$O 1$_{11}$–0$_{00}$ profiles in the red-wings shows that the main isotopologue line is deeply affected by absorption also at high velocities since red-shifted emission is detected from 1.3 km s$^{-1}$ in H$_2^8$O and only from 9 km s$^{-1}$ in H$_2$O (Fig. 2). The line ratio between the two 1$_{11}$–0$_{00}$ isotopologue lines ranges between 0.95 and 0.3 in the blue wing ([−30, −20] km s$^{-1}$), establishing very high opacities for the main isotopologue transition even at high velocities and suggesting that it may be contaminated by a component in emission. Indeed, assuming negligible excitation with respect to the continuum, the opacity of the H$_2^8$O line is between 0.02 and 0.3 in the velocity interval [−50, −4] km s$^{-1}$ (see Eq. (1) of Herpin et al. 2012). This corresponds to a column density of H$_2$O of 8.4 × 10$^{11}$ cm$^{-2}$ at the peak of the absorption, down to 5.5 × 10$^{10}$ cm$^{-2}$ in the high-velocity wing (−50 km s$^{-1}$). The total p-H$_2$O column density over the velocity range [−50, −4] km s$^{-1}$ is 1.2 × 10$^{13}$ cm$^{-2}$. Assuming that the 1113 GHz thermal continuum has the same distribution as at 1.4 mm (deconvolved beam at FWHM of 5′.3 × 2′′.7, Paper I and Fig. 1), we corrected the continuum emission for beam dilution in the Herschel beam (Table B.1) and estimate a p-H$_2$O column density of 2.4 × 10$^{14}$ cm$^{-2}$, which corresponds to a total column density of H$_2$O of 5.3 × 10$^{17}$ cm$^{-2}$ for a standard isotopic ratio $^{16}$O/$^{18}$O = 560 (Wilson & Rood 1994) and an ortho-to-para ratio of 3. This is most likely a lower limit to the H$_2$O column density since the 1113 GHz thermal continuum is probably more compact than that at 1.4 mm.

Given the complexity of the 1113 GHz line at low-velocities, we focussed our analysis on the outflow component detected at high-velocities. The similarity of the SiO and H$_2$O profiles suggests a common origin of the high-velocity emission in the two molecules. Therefore, we limited our analysis to the velocity ranges [+10, +39] km s$^{-1}$ and [−30, −20] km s$^{-1}$ used in Paper II. For the 1163 GHz line, we used the velocity range [+10, +18] km s$^{-1}$. We did not include the 752 GHz blue wing in the analysis because of severe contamination from other features.

4. Shock-model of the water emission

In Paper II, we demonstrated that the SiO emission in OF1 can be reproduced by a C-type shock model. We interpreted the SiO (8–7) and (5–4) emission at high velocities as due mostly (~60%) to the OF1 outflow and modelled their maximum brightness temperature and wing-integrated line ratio. Our best fit was found for a pre-shock density $n_0 = 10^6$ cm$^{-3}$, shock velocity $v_s = 32$ km s$^{-1}$, magnetic field strength $B = 100\mu$G, and an age between 500 and 1000 yr, in agreement with observations (Paper I). The emitting area of the SiO (5–4) transition is similar to that of H$_2$, 6 arcsec$^2$, with an upper limit of 22 arcsec$^2$. Our goal is to determine if the SiO-fitting shock can also reproduce the observed H$_2$O emission. Since the SiO modelling was performed towards a position −9″ off from the Herschel pointing, our first step was to verify that the model of Paper II is also valid on this position. We then post-processed the shock model with an LVG module to calculate the radiative transfer of water lines (Gusdorf et al. 2011). We thus compared modelled maximum brightness temperatures and integrated intensities to their observed values for two lines of o-H$_2$O and four lines of p-H$_2$O, under the exact same assumptions as adopted for SiO: emitting area of 6 arcsec$^2$, with 60% of the emission due to OF1. Error bars are ±20% of the observed values. Three models are shown: the model of Paper II with level populations in statistical equilibrium (‘s-e’ in red) with $v_s = 32$ km s$^{-1}$, one with a slower shock velocity ($v_s = 30$ km s$^{-1}$, blue), and a model in stationary-state (‘s-s’ in green).

![Fig. 3. Observed and modelled maximum brightness temperatures (circles), and integrated intensities (squares) for the red lobe of OF1. Data (in black) are corrected for an area of 6 arcsec$^2$, and for 60% of the emission due to OF1. Error bars are ±20% of the observed values. Three models are shown: the model of Paper II with level populations in statistical equilibrium (‘s-e’ in red) with $v_s = 32$ km s$^{-1}$, one with a slower shock velocity ($v_s = 30$ km s$^{-1}$, blue), and a model in stationary-state (‘s-s’ in green).](Image 351x632 to 513x766)
Since both shock velocities used in our analysis are well above the gas phase above a shock velocity threshold of 20–25 km s$^{-1}$ which standard models predict a total release of material towards our models is work in progress in a larger framework of studying higher-energy transitions. The inclusion of photo-dissociation in L11, page 4 of 7.

The SiO(8–7) and H$_2$O profiles (in particular that of the maximum H$_2$O fractional abundance with respect to shock model, and we have constraints on the area of the emission. Although photo-dissociation probably a

The SiO and H$_2$O profiles is found in other sources at high energy H$_2$O lines, simple C-shocks models can be used to model the results of sputtering of the ices in the grain mantles, and of high-density chemistry. Given the sputtering is simultaneous to the temperature rise, 45 yr is the time scale for the high-temperature chemistry under these shock conditions. Given which standard models predict a total release of material towards the gas phase above a shock velocity threshold of 20–25 km s$^{-1}$ (e.g., Draine et al. 1983; Flower & Pineau des Forêts 1994).

Since both shock velocities used in our analysis are well above the threshold shock speed for water, the derived H$_2$O abundance does not change significantly at $v_{ls} = 30$ km s$^{-1}$.

5. Discussion and conclusions

The SiO(8–7) and H$_2$O profiles (in particular that of the 1113 GHz line) suggest a common origin of the H$_2$O and SiO emission in IRAS 17233. This result is based on emission at high

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5. Discussion and conclusions

The SiO(8–7) and H$_2$O profiles (in particular that of the 1113 GHz line) suggest a common origin of the H$_2$O and SiO emission in IRAS 17233. This result is based on emission at high velocities and is different from the findings that SiO and H$_2$O do not trace the same gas in molecular outflows from low-mass YSOs at low-velocities and/or in low-energy lines (Santangelo et al. 2012; Nisini et al. 2013). However, an excellent match between SiO and H$_2$O profiles is found in other sources at high velocities (Lefloch et al. 2012).

With the limitations previously discussed, we find that the shock parameters of OF1 are comparable with those found for low-mass protostars with a higher pre-shock density. The derived water abundance is compatible with values of other molecular outflows (e.g., Emprechtinger et al. 2010; Herczeg et al. 2012). While often measurements of H$_2$O abundances have large uncertainties because the H$_2$ column density is inferred from observations of CO or from models (for a compilation of sources, abundances and methods, see van Dishoeck et al. 2013), the value inferred in our analysis is consistently derived, as the H$_2$O and H$_2$ column densities are outcomes of the same model. Moreover, the estimated H$_2$O column density matches the data. Although photo-dissociation probably affects the low-energy H$_2$O lines, simple C-shocks models can be used to model higher-energy transitions. The inclusion of photo-dissociation in our models is work in progress in a larger framework of studying the effect of an intense UV field on shocks.

Estimates of H$_2$O mass are not easily found in the literature. Busquet et al. (2014) modelled water emission in L1157-B1 through J- and C-type shocks. Their H$_2$O column densities derived over the whole profile translate in to masses in the range 0.009–0.125 $M_{\odot}$ for a hot component of 2″$^2$–5″ size and $<(0.7 – 1.5) \times 10^{-3}$ $M_{\odot}$ for a warm component with a size of $\leq 10''$. Our estimate of 12.5 $M_{\odot}$ for the H$_2$O mass of OF1 therefore seems to be compatible with previous results.

In summary, we presented the first estimate of the abundance of water in an outflow driven by a massive YSOs based on a self-consistent shock model of water and SiO transitions. We inferred a water abundance in fractional column density units between $1.2 \times 10^{-3}$ and $2.5 \times 10^{-2}$, which is an average value of the water abundance over the shock layer. Additionally, our model indicates that the maximum fractional abundance of water locally reached in the layer is $10^{-2}$. Finally, we inferred the water mass of the OF1 outflow to be 12.5 $M_{\odot}$.

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Appendix A: Water abundance problem: the point of view of observers and modellers

The goal of this appendix is to clarify the possible confusion of the meaning of “water abundance” between the observing and modelling communities. The rigorous comparison of observations to models requires the knowledge of constraints such as the length/age of the shock, as this section discusses now. We base this discussion on the model used to fit both the SiO and H$_2$O emission in the OF1 shock region of IRAS 17233–3606 with the following input parameters: pre-shock density $n_i = 10^6$ cm$^{-3}$, shock velocity $v_s = 32$ km s$^{-1}$, and magnetic field strength (perpendicular to the shock direction) $B = 1$ mG. Whether the radiative transfer of water is calculated along the shock equations in the model (so-called “s-s” in Fig. 3, “DRF” in Tables B.2–B.5) or a posteriori from the outputs of the shock model (“s-e” in Fig. 3, “AGU” in Tables B.2–B.5) does not change the thermal profile of the shock layer, nor the associated water abundances (e.g. Gusdorf et al. 2011). Everything stated in this appendix is therefore applicable to both “s-s” and “s-e” models.

In one-dimensional, stationary shock models (e.g., this work, Gusdorf et al. 2011; Draine et al. 1983; Kaufman & Neufeld 1996; Flower & Pineau Des Forêts 2010) the physical and chemical conditions are self-consistently calculated at each point of a shocked layer. The end product is a collection of physical (temperature, velocity, density) and chemical (abundances) quantities obtained at each point of the shocked layer. The position of each point is marked by a distance parameter with respect to a origin typically located in the pre-shock region. The position of the last point in the post-shock region then corresponds to the shock width. Typically, these shock models are used in a face-on configuration, so that the width one refers to is along the line-of-sight direction. Alternatively, the position of a point in the shock layer can be expressed through a time parameter: the time parameter for the last point in the post-shock region then corresponds to the flight time that a particle needs to flow through the total width of the shock. The correspondence between the time and distance parameters related to a neutral particle ($v$ and $c$) is hence given by $t_n = \int (1/v_n) \, dz$, where $v_n$ is the particle velocity. While the shock width cannot be constrained by observations, an upper limit to the flight time is given by the dynamical age, which is inferred from mapped observations of spectrally resolved lines.

Figure A.1 shows for this model the variation of the temperature of the neutral particles ($K$), as well as those of the water and total local densities ($n(H_2O)$ and $n_{tot}$ in cm$^{-3}$) and their ratio $x(H_2O) = n(H_2O)/n_{tot}$ in the shock layer versus the distance parameter. To illustrate the relation between time and distance parameters through the shock layer, we have marked three points on each curve: $3.1 \times 10^{15}, 5.15 \times 10^{15}, 10^{16}$ cm, which correspond to 500, 1000, and 2150 yr, in our model. In our case, the highest value for the time parameter is constrained by the dynamical shock age of OF1, 500–1000 yr. Water abundance is often defined by modellers as the maximum fractional local abundance of water through the shock layer, that is, between the pre-shock region before the temperature rise and the maximum shock age ($x(H_2O)_{max} = 1.4 \times 10^{-4}$ for our model, top panel of Fig. A.1). On the other hand, local quantities cannot be accessed through observations. Integrated quantities (against the width of the shock layer along the line of sight) such as column densities are measured by observers. Generally, “observational water abundances” are hence given in fractional column density units, that is, the ratio of the water column density divided by the total column density. This ratio is different the maximum fractional abundance of water that is generally provided and used by modellers. The difference between the two values is illustrated by comparing the upper panel of Fig. A.1 with its lower panel, which shows the evolution of the water and total column densities, $N_{H_2O}$ and $N_{tot}$, and of their ratio $y(H_2O) = N(H_2O)/N_{tot}$.

In the modellers’ view, referring to the distance parameter as “z”, these column densities are defined by

$$N(H_2O) [\text{cm}^{-2}] = \int_0^{z_{max}} n(H_2O) [\text{cm}^{-3}] \, dz,$$  \hspace{1cm} (A.1)

$$N_{tot}[\text{cm}^{-2}] = \int_0^{z_{max}} n_{tot}[\text{cm}^{-3}] \, dz,$$  \hspace{1cm} (A.2)

where $z_{max}$ is the total shock width, that is, the distance corresponding to the maximum value of the time parameter. In our case, the value of the fractional column density of water can be
read in the bottom panel of Fig. A.1: \( y(\text{H}_2\text{O}) = 2.5 \times 10^{-5} \) (if the adopted dynamical age is 500 yr), \( = 1.2 \times 10^{-5} \) (if the adopted dynamical age is 1000 yr). We note that this value is about an order of magnitude lower than the maximum fractional abundance of water reached in the same shock layer.

We note that the decrease in the \( y(\text{H}_2\text{O}) \) curve is artificial and only due to the 1D nature of the model. Indeed, in the post-shock region, the total density of the gas is conserved (because it cannot escape sideways, for instance like in the case of a bow-shock), while the gas-phase water density decreases until all water molecules re-condensate on the interstellar grains because of the temperature decrease. The total column density hence increases (lower panel of Fig. A.1), while the water column density is constant, resulting in a decrease of the water column density ratio with the distance or time parameter. It is therefore essential to have a measurement of the dynamical time scale to stop the calculation at a realistic time to obtain a fractional column density of water as realistic as possible.

**Appendix B: Additional tables and figures**

**Table B.1.** Summary of the observations.

<table>
<thead>
<tr>
<th>Line</th>
<th>( E_\text{up} ) (GHz)</th>
<th>( T_{\text{sys}} ) (K)</th>
<th>( \delta_v ) (( \text{km s}^{-1} ))</th>
<th>RMS (K)</th>
<th>OBSIDs mode( ^{\text{e}} )</th>
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<tr>
<td>( p-\text{H}<em>2\text{O} 4</em>{23} \rightarrow 3_{13} )</td>
<td>1207.639</td>
<td>454.5</td>
<td>17.6</td>
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<td>( o-\text{H}<em>2\text{O} 3</em>{31} \rightarrow 2_{21} )</td>
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<td>0.64</td>
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<td>18.3</td>
<td>0.64</td>
<td>836.130</td>
</tr>
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<td>( p-\text{H}<em>2\text{O} 1</em>{11} \rightarrow 0_{00} )</td>
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<td>0.74</td>
<td>389.100</td>
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<td>1101.698</td>
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<td>0.74</td>
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<td>137.0</td>
<td>28.2</td>
<td>0.74</td>
<td>187.200</td>
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**Notes.** (1) Pickett et al. (1998). (2) Half-power beam width and main beam efficiency from Roelfsema et al. (2012). (3) DBS stands for dual beam switch mode.

**Table B.2.** Observed and modelled maximum line temperatures \( (T^{\text{max}}, \text{K}) \) for the red lobe.

<table>
<thead>
<tr>
<th>( \nu ) (GHz)</th>
<th>( E_\text{up} ) (K)</th>
<th>Beam( ^{\text{c}} ) (( \text{K} ))</th>
<th>FF( ^{\text{b}} ) (no unit)</th>
<th>( T^{\text{max}} ) obs (K)</th>
<th>( T^{\text{max}} ) AGU32 (K)</th>
<th>( T^{\text{max}} ) AGU30 (K)</th>
<th>( T^{\text{max}} ) DRF32 (K)</th>
<th>( T^{\text{max}} ) DRF30 (K)</th>
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<td>1113</td>
<td>53.4</td>
<td>19.1</td>
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<td>20.9</td>
<td>21.7</td>
</tr>
</tbody>
</table>

**Notes.** (1) Inverse of the beam filling factor at each frequency considering an emitting area of 6 arcsec\(^2\). (2) Observed maximum temperature corrected for filling factor and 60% contribution of OF1. (3) Modelled maximum temperature following Gusdorf et al. (2011) with \( v_s = 32 \text{ km s}^{-1} \). (4) Modelled maximum temperature following Gusdorf et al. (2011) with \( v_s = 30 \text{ km s}^{-1} \). (5) Modelled maximum temperature following Flower & Pineau Des Forêts (2010) with \( v_s = 32 \text{ km s}^{-1} \).
Table B.3. Observed and modelled integrated intensities ($\int T \mathrm{d}v$, K km s$^{-1}$) for the red lobe.

| $\nu$ (GHz) | $E_{\nu}$ (K) | Beam (″) | $FF^{-1(1)}$ (no unit) | $\int T \mathrm{d}v|_{\text{obs}}$ K km s$^{-1}$ | $\int T \mathrm{d}v|_{\text{corr}}^{(2)}$ K km s$^{-1}$ | $\int T \mathrm{d}v|_{\text{AGU32}}^{(3)}$ K km s$^{-1}$ | $\int T \mathrm{d}v|_{\text{AGU30}}^{(4)}$ K km s$^{-1}$ | $\int T \mathrm{d}v|_{\text{DRF32}}^{(5)}$ K km s$^{-1}$ |
|------------|---------------|-----------|---------------------|-----------------------------------------------|------------------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|
| 1113       | 53.4          | 19.1      | 48.5                | 32.0                                          | 931.42                                        | 1743.0                                        | 1547.0                                        | 2006.7                                        |
| 988        | 100.8         | 21.5      | 61.4                | 42.4                                          | 1562.1                                        | 2914.0                                        | 2606.0                                        | 2810.5                                        |
| 752        | 136.9         | 28.2      | 105.1               | 36.6                                          | 2307.5                                        | 2112.0                                        | 1894.0                                        | 1976.3                                        |
| 1153       | 249.3         | 18.4      | 45.3                | 38.4                                          | 1043.7                                        | 5188.0                                        | 4512.0                                        | 3366.6                                        |
| 1163       | 305.3         | 18.2      | 44.5                | 21.1                                          | 563.4                                         | 462.5                                         | 752.1                                         |
| 1208       | 454.3         | 17.6      | 41.4                | 13.0                                          | 322.9                                         | 194.2                                         | 158.0                                         | 223.8                                         |

Notes. (1) Inverse of the beam filling factor at each frequency considering an emitting area of 6 arcsec$^2$. (2) Observed integrated intensity corrected for filling factor and 60% contribution of OF1. (3) Modelled integrated intensity following Gusdorf et al. (2011) with $v_s = 32$ km s$^{-1}$. (4) Modelled integrated intensity following Gusdorf et al. (2011) with $v_s = 30$ km s$^{-1}$. (5) Modelled integrated intensity following Flower & Pineau Des Forêts (2010) with $v_s = 32$ km s$^{-1}$.

Table B.4. Observed and modelled maximum line temperatures ($T_{\text{max}}$, K) for the blue lobe.

<table>
<thead>
<tr>
<th>$\nu$ (GHz)</th>
<th>$E_{\nu}$ (K)</th>
<th>Beam (″)</th>
<th>$FF^{-1(1)}$ (no unit)</th>
<th>$T_{\text{max}}^{\text{obs}}$ (K)</th>
<th>$T_{\text{max}}^{\text{corr}}^{(2)}$ (K)</th>
<th>$T_{\text{max}}^{\text{AGU32}}^{(3)}$ (K)</th>
<th>$T_{\text{max}}^{\text{AGU30}}^{(4)}$ (K)</th>
<th>$T_{\text{max}}^{\text{DRF32}}^{(5)}$ (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>988</td>
<td>100.8</td>
<td>21.5</td>
<td>121.8</td>
<td>121.8</td>
<td>1.1</td>
<td>83.3</td>
<td>229.3</td>
<td>215.9</td>
</tr>
<tr>
<td>1153</td>
<td>249.3</td>
<td>18.4</td>
<td>89.5</td>
<td>89.5</td>
<td>1.2</td>
<td>66.3</td>
<td>735.9</td>
<td>676.1</td>
</tr>
<tr>
<td>1163</td>
<td>305.3</td>
<td>18.2</td>
<td>88.0</td>
<td>88.0</td>
<td>1.0</td>
<td>53.9</td>
<td>79.4</td>
<td>61.0</td>
</tr>
<tr>
<td>1208</td>
<td>454.3</td>
<td>17.6</td>
<td>81.8</td>
<td>81.8</td>
<td>0.5</td>
<td>23.6</td>
<td>35.4</td>
<td>20.9</td>
</tr>
</tbody>
</table>

Notes. (1) Inverse of the beam filling factor at each frequency considering an emitting area of 3 arcsec$^2$. (2) Observed maximum temperature corrected for filling factor and 60% contribution of OF1. (3) Modelled maximum temperature following Gusdorf et al. (2011) with $v_s = 32$ km s$^{-1}$. (4) Modelled maximum temperature following Gusdorf et al. (2011) with $v_s = 30$ km s$^{-1}$. (5) Modelled maximum temperature following Flower & Pineau Des Forêts (2010) with $v_s = 32$ km s$^{-1}$.

Table B.5. Observed and modelled integrated intensities ($\int T \mathrm{d}v$, K km s$^{-1}$) for the blue lobe.

| $\nu$ (GHz) | $E_{\nu}$ (K) | Beam (″) | $FF^{-1(1)}$ (no unit) | $\int T \mathrm{d}v|_{\text{obs}}$ K km s$^{-1}$ | $\int T \mathrm{d}v|_{\text{corr}}^{(2)}$ K km s$^{-1}$ | $\int T \mathrm{d}v|_{\text{AGU32}}^{(3)}$ K km s$^{-1}$ | $\int T \mathrm{d}v|_{\text{AGU30}}^{(4)}$ K km s$^{-1}$ | $\int T \mathrm{d}v|_{\text{DRF32}}^{(5)}$ K km s$^{-1}$ |
|------------|---------------|-----------|---------------------|-----------------------------------------------|------------------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|
| 988        | 100.8         | 21.5      | 121.8               | 9.8                                          | 114.9                                        | 2914.0                                        | 2606.0                                        | 2810.5                                        |
| 1153       | 249.3         | 18.4      | 89.5                | 12.2                                          | 653.3                                        | 5188.0                                        | 4512.0                                        | 3366.6                                        |
| 1163       | 305.3         | 18.2      | 88.0                | 7.9                                           | 415.1                                        | 534.6                                         | 462.5                                         | 752.1                                         |
| 1208       | 454.3         | 17.6      | 81.8                | 3.7                                           | 183.1                                        | 194.2                                         | 158.0                                         | 223.8                                         |

Notes. (1) Inverse of the beam filling factor at each frequency considering an emitting area of 3 arcsec$^2$. (2) Observed integrated intensity corrected for filling factor and 60% contribution of OF1. (3) Modelled integrated intensity following Gusdorf et al. (2011) with $v_s = 32$ km s$^{-1}$. (4) Modelled integrated intensity following with $v_s = 30$ km s$^{-1}$. (5) Modelled integrated intensity following Flower & Pineau Des Forêts (2010) with $v_s = 32$ km s$^{-1}$.