Water abundance variations around high-mass protostars: HIFI observations of the DR21 region


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ABSTRACT

Context. Water is a key molecule in the star formation process, but its spatial distribution in star-forming regions is not well known.

Aims. We study the distribution of dust continuum and H2O and 13CO line emission in DR21, a luminous star-forming region with a powerful outflow and a compact H II region.

Methods. Herschel-HIFI spectra near 1100 GHz show narrow 13CO 10–9 emission and H2O 111–000 absorption from the dense core and broad emission from the outflow in both lines. The H2O line also shows absorption by a foreground cloud known from ground-based observations of low-J CO lines.

Results. The dust continuum emission is extended over 36″ FWHM, while the 13CO and H2O lines are confined to ≈24″ or less. The foreground absorption appears to peak further North than the other components. Radiative transfer models indicate very low abundances of H2O in the foreground cloud and higher H2O abundances of ∼2×10−9 in the dense core and cloud and its fragmentation (Zinnecker & Yorke 2007).

Interstellar H2O is well known from ground-based observations of the 22 GHz maser line. Previous space-based submm and far-IR observations have measured H2O abundances ranging from 10−8 in cold gas to 10−3 in warm gas (ISO: Van Dishoeck & Helmich 1996; SWAS: Melnick & Bergin 2005; Odin: Bjerkeli et al. 2009) but did not have sufficient angular resolution to determine the spatial distribution of H2O. In contrast, space-based mid-IR and ground-based mm-wave observations have high angular resolution but only probe the small fraction of the gas at high temperatures (Van der Tak et al. 2006; Watson et al. 2007).

This paper presents observations of an H2O ground state line at >3× higher angular resolution than previously possible for such lines. Through radiative transfer models, we compare the abundance distribution of H2O with that of 13CO and dust. The source DR21 (Main) is a high-mass protostellar object (L = 45 000 L⊙) located in the Cygnus X region at d = 1.7 kpc (Schneider et al. 2006), about 3° South of the well-known DR21(OH) object (also known as W75S). Maps of the 1.2 mm dust emission show a dense core with a mass of 600–1000 M⊙ and a size of 0.19 × 0.14 pc FWHM, surrounded by an extended envelope with mass 4750 M⊙ and size 0.3 pc (Motte et al. 2007). Gas densities of 105−106 cm−3 are derived from both the mm-wave continuum and HCN and HCO+ line emission (Kirby 2009). Signs of active high-mass star formation are the bright mid-IR emission (272 Jy at 21 µm), the presence of an H2O 22 GHz maser (see catalog of Braz & Epchtein 1983) and emission from ionized gas extending over 20–30′ (Roelfsema et al. 1989). Together with the powerful molecular outflow (Garden et al. 1991) these signs indicate that the source is relatively evolved within the embedded phase of high-mass star formation, beyond the “ultracompact HII region” phase.

1. Introduction

The water molecule is a key species throughout the formation of stars and planets. In the gas phase, it acts as a coolant of collapsing interstellar clouds; in the solid state, it acts as glue for dust grains in protoplanetary disks to make planetesimals; and as a liquid, it acts as transporter bringing molecules together on planetary surfaces, a key step towards biogenic activity. Water is a key molecule in the star formation process, but its spatial distribution in star-forming regions is not well known.

Key words. ISM: molecules – stars: formation – astrochemistry – ISM: individual objects: DR21

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et al. (1989). A strip map was made in the N-S direction, spanning receiver band 4b, with the Space Observatory (Pilbratt et al. 2010) on June 22, 2009. Spectra were taken in double sideband mode using receiver band 4b, with \( v_{13} = 1107.990 \text{ GHz} \) and \( v_{RF} = 6 \text{ GHz} \). The data were taken during the performance verification (PV) phase using the double beam switch observing mode with a throw of 2.5 to the SW. The position observed is RA 20:39:02.38, Dec +42:19:33.5 (J2000), close to radio peak C from Roelfsema et al. (1989). A strip map was made in the N-S direction, spanning offsets from +90” to −90” at a 10” spacing, half the beam size of 21” FWHM at our observing frequency, which corresponds to 0.17 pc at the distance of DR21. This beam size was measured before launch and is 10% larger than the diffraction limit due to spillover effects.

Data were taken with two backends: the acousto-optical wide-band spectrometer (WBS) which covers 1140 MHz bandwidth at 1.1 MHz (0.30 km s\(^{-1}\)) resolution, and the correlator-based high-resolution spectrometer (HRS), which covers 230 MHz bandwidth at 0.48 MHz (0.13 km s\(^{-1}\)) resolution. Two polarizations are available except for the HRS data of \( ^{13}\text{CO} \). 1

The system temperature of our data is 340–360 K DSB and the integration time is 67 s per position (ON+OFF). Calibration of the raw data onto \( T_A^* \) scale was performed by the in-orbit system (Roelfsema et al., in prep.;) conversion to \( T_{NH} \) was done assuming a beam efficiency of 0.67 as estimated by the Ruze formula and validated by raster maps of Saturn (M. Olberg, priv. comm.). Currently, the flux scale is accurate to \( \pm 10\% \) which will improve when the telescope efficiency and sideband ratio are measured on Mars. The calibration of the data was performed in the Herschel interactive processing environment (HIPE; Ott 2010) version 2.1; further analysis was done within the CLASS\(^2\). After inspection, data from the two polarizations were averaged together to obtain rms noise levels of 97 mK on 0.5 MHz channels for the WBS data, 195 mK on 0.24 MHz channels for the \( ^{13}\text{CO} \) HRS data and 244 mK on 0.24 MHz channels for the \( \text{H}_2\text{O} \) HRS data.

2 Spectroscopic data are taken from the CDMS catalog (Müller et al. 2005) at http://cdms.de

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**Fig. 1.** Spectra of \( ^{13}\text{CO} \) 10–9 (left) and \( \text{H}_2\text{O} \) 1\(^{11}\)–0\(^{09}\) (right) lines toward DR21, taken with the WBS backend.

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**2. Observations**

The DR21 region was observed with the Heterodyne Instrument for the Far-Infrared (HIFI; de Graauw et al. 2010) onboard ESA’s Herschel Space Observatory (Pilbratt et al. 2010) on June 22, 2009. Spectra were taken in double sideband mode using receiver band 4b, with \( v_{13} = 1107.990 \text{ GHz} \) and \( v_{RF} = 6 \text{ GHz} \). The data were taken during the performance verification (PV) phase using the double beam switch observing mode with a throw of 2.5 to the SW. The position observed is RA 20:39:02.38, Dec +42:19:33.5 (J2000), close to radio peak C from Roelfsema et al. (1989). A strip map was made in the N-S direction, spanning offsets from +90” to −90” at a 10” spacing, half the beam size of 21” FWHM at our observing frequency, which corresponds to 0.17 pc at the distance of DR21. This beam size was measured before launch and is 10% larger than the diffraction limit due to spillover effects.

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Figure 2. Spectra of $^{13}$CO $10-9$ (top) and H$_2$O $1_{11}-2_{02}$ (bottom) lines toward the central position, taken with the HRS backend, with Gaussian decompositions overplotted.

Figure 3. Plots of observed intensity versus spatial offset with Gaussian models superposed.

4. Discussion and conclusions

To estimate the H$_2$O and $^{13}$CO abundances from our data, we have run spherical radiative transfer models following Marseille et al. (2008). First, the dust continuum emission was modeled with the MC3D program (Wolf & Henning 2000) with the source size and luminosity kept fixed at the values in Sect. 1. The continuum data are consistent with a power-law density profile $n = n_0 (r/r_0)^{-\alpha}$ with the index $\alpha = 1.5$ as expected for evolved protostellar envelopes (Van der Tak et al. 2000). Derived temperatures range from 117 K at the adopted inner radius of 0.01 pc to 23 K at the outer radius of 0.3 pc; densities drop from $3 \times 10^7$ cm$^{-3}$ to $2 \times 10^5$ cm$^{-3}$. This temperature and density profile was adopted for the line radiative transfer with the RATRAN program (Hogerheijde & van der Tak 2000). The abundance of H$_2$O was varied between $10^{-10}$ and $10^{-7}$ and the $^{13}$CO abundance between $10^{-7}$ and $10^{-6}$, both independent of radius.

The red lines in Fig. 4 show the results of our best-fit model. The fit to the line profiles at the central few positions is good if.
introduce a factor of ~2 uncertainty each. To estimate $N^{(13)}(\text{CO})$ for the foreground cloud, we use the $J = 1 \rightarrow 0$ observations by Jakob et al. (2007).

Table 1 summarizes our derived column densities and abundances of $^{13}$CO and H$_2$O in the various physical components of the DR21 region. Our H$_2$O abundance in the dense core is ~100x lower than previous determinations (Sect. 1) but should be regarded as a lower limit. At the low temperatures and high densities in the core, most H$_2$O is likely frozen on grains, and the observed line may arise in a small region with a high H$_2$O abundance. The derived $^{13}$CO abundance for the core is ~4x lower than expected for the above values of the CO isotopic ratios and abundance, which suggests that even some CO is frozen out in the outer parts of the core. The density of the foreground cloud is too low for significant freeze-out, but with $Av \approx 1.2$ mag, photodissociation is rapid for H$_2$O but not for $^{13}$CO.

The high H$_2$O abundance for the outflow is likely related to its temperature of ~200 K, which is high enough to have H$_2$O released from the dust grains by thermal evaporation, or possibly by shocks (Melnick et al. 2008). Further enhancement may be expected in even warmer gas (≥250 K) when neutral-neutral reactions drive most gas-phase oxygen into H$_2$O, but such gas is not probed by our data. Future HIFI observations of high-excitation H$_2$O lines towards protostars of all masses will however very likely reveal this effect.

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References
Ott, J. 2010, ADASS XIX, in press