Herschel/HIFI spectroscopy of the intermediate mass protostar NGC 7129 FIRS 2 \(^*\), \(^{**}\)

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**ABSTRACT**

Herschel/HIFI observations of water from the intermediate mass protostar NGC 7129 FIRS 2 provide a powerful diagnostic of the physical conditions in this star formation environment. Six spectral settings, covering four \(^{16}\)O and two \(^{18}\)O lines, were observed and all but one \(^{18}\)O line were detected. The four \(^{16}\)O lines discussed here share a similar morphology: a narrower, \(\approx 6 \text{ km s}^{-1}\), component centered slightly redward of the systemic velocity of NGC 7129 FIRS 2 and a much broader, \(\approx 25 \text{ km s}^{-1}\), component centered blueward and likely associated with powerful outflows. The narrower components are consistent with emission from water arising in the envelope around the intermediate mass protostar, and the abundance of \(^{18}\)O is constrained to \(\approx 10^{-7}\) for the outer envelope. Additionally, the presence of a narrow self-absorption component for the lowest energy lines is likely due to self-absorption from colder water in the outer envelope. The broader component, where the \(^{18}\)O/CO relative abundance is found to be \(\approx 0.2\), appears to be tracing the same energetic region that produces strong CO emission at high \(J\).

**Key words.** astrochemistry – stars: formation

1. Introduction

Observations of star formation in nearby molecular clouds have provided a reasonably clear picture of this process for low-mass stars. Nevertheless fundamental questions remain. One of these is the variation in the formation process between low through high-mass stars. The intermediate mass (IM) sub-program within the Water In Star-forming regions with Herschel (WISH) key program (van Dishoeck et al., in prep.) aims to use observations of water, and complementary molecules, to probe the regions around several intermediate mass protostars – focusing on the structure of the envelope and the energetics of the outflow. These sources are usually defined as young stellar objects (YSOs) with bolometric luminosities between \(75 \text{ L}_\odot\) and \(2 \times 10^3 \text{ L}_\odot\). A key goal for the longer term of this investigation is to place IM star formation in context with its low- and high-mass brethren.

An excellent example of an extremely young IM protostar is NGC 7129 FIRS 2 (Eiroa et al. 1998; Fuente et al. 2001, 2005), located at a distance of \(1260 \pm 50\) pc from the Sun (Shevchenko \& Yakubov 1989). With a luminosity of \(500 \text{ L}_\odot\) and estimated stellar mass of \(5 \text{ M}_\odot\), FIRS 2 lies near the middle of the IM luminosity range. The protostar has produced a hot core (Fuente et al. 2005) but has no evidence for a large, well-developed disk – implying it is a young source. A powerful quadrupolar outflow, likely due to the superposition of two bipolar jets, is found very close to this source (Fuente et al. 2001).

NGC 7129 FIRS 2 has been the subject of significant investigation over the last year. A robust model for the enshrouding, and pre-natal, envelope has been proposed by Crimier et al. (2010) utilizing all available far infrared (Spitzer) and submillimeter (JCMT, IRAM) brightness measurements. Additionally, Fich et al. (2010) used Herschel PACS observations of highly energetic CO (up to \(\text{CO} J = 33–32\) which arises from a level at an energy equivalent \(3093 \text{ K}\)) to analyse the energetics associated with NGC 7129 FIRS 2. They found that these CO lines are much brighter than expected from the envelope alone, revealing the need for additional heating beyond simple reprocessing of the protostellar radiation. A warm slab model with temperatures greater than \(1000 \text{ K}\), considered a proxy for shock heating in or along the surfaces of the outflow lobes, provided a much better fit to the CO observations. A lack of spectral resolution in the PACS data hindered further investigation into the connection between the CO lines and the outflow.
Table 1. Observed \(^{16}\)O, \(^{18}\)O, and CO transitions.

| Transition | \( \nu \) (GHz) | \( T_{A}^{lim} \) (K) | \( T_{A}^{peak} \) (K) | \( \nu \) (GHz) | \( T_{A}^{lim} \) (K) | \( T_{A}^{peak} \) (K) |
|------------|----------------|----------------|----------------|------------|----------------|----------------|
| \( ^{16}\)O 1–0 | 1153 | 5.3 | 547.68 | 60.5 |
| \( ^{18}\)O 1–0 | 987 | 100.8 | 994.68 | 100.7 |
| \( ^{18}\)O 1–0 | 752.03 | 136.9 | 548.83 | 79.02 |
| \( ^{18}\)O 1–0 | 1079.37 | 249.4 | 1101.35 | 290.79 |

Notes. (a) Only a preliminary reduction of this observation has been performed, it is discussed only in Sect. 3.2.

In this paper we present a first look at the water spectra obtained toward NGC 7129 FIRS 2 with the HIFI instrument (de Graauw et al. 2010) on the Herschel Space Observatory (Pilbratt et al. 2010). The wealth of spectrally resolved water lines observed provide powerful diagnostic measures for the envelope and the outflow.

2. Observations

Herschel HIFI was used to obtain data for this project during the Herschel science demonstration phase and the HIFI priority science program, from 3–20 March, 2010. The observations were taken using the fast dual-beam switch mode with a standard nod of 3′ using receiver bands 1, 2, and 4. In total, six spectral settings were selected, covering four \(^{16}\)O transitions and two \(^{18}\)O transitions, with integration times between 15 min and 1 h. Two isotopologue lines of CO were also located within these settings. CO 10–9 was also observed on June 15, 2010, with a 10 min integration in band 5 using the fast dual-beam switch mode. The complete set of observed lines are shown in Table 1. All the observations were taken toward NGC 7129 FIRS2, at 21 h 43 m 1 s (J2000). Diffraction-limited beamsizes range from 20′′–40′′ (equivalent to 25 000–50 000 AU at the distance of NGC 7129).

The data were pipelined using HIPE 3.0 (Ott 2010) and the data analysis was completed using both HIPE 3.0 and CLASS. The results of the two analyses were found to be the same to better than twenty percent, where the largest uncertainties were found during the fitting of multiple components. Before the reduction, the chop positions were differentiated to check for extended emission and none was detected. During the reduction, the H and V polarizations were compared to assess quality and then averaged. In most cases the two polarizations showed no significant variations. The \(^{16}\)O 1–0 line, however, showed both a lower peak intensity and line width for the V polarization, resulting in an 8% difference in integrated intensity. For both polarizations, the overall morphology of the spectrum is similar, with the variation likely due to the extended nature of the source and slight offsets in the H and V beam positions. Finally, the WBS and HRS spectra were compared for consistency. Regions containing spurs were excluded from the analysis and the first order polynomial baseline was removed from each spectrum. The WBS data were ultimately smoothed to the goal resolution of 1.1 MHz and the antenna temperature \( T_{A}^{*} \) was converted to \( T_{mb} \) by applying a main beam efficiency of 0.74.

The four \(^{16}\)O transitions were observed and are shown in Fig. 1. The spectra show evidence for at least two components: a narrower line peaked slightly redward of the systemic velocity of the source (~9.8 km s\(^{-1}\)) and a broad line blue-shifted from the systemic velocity. The ground-state transition shows significant self-absorption, with a minimum at ~10.4 km s\(^{-1}\), hints of which can be seen in the other observed transitions, and is likely due to colder water lying along the line of sight toward NGC 7129 FIRS 2, with the most likely source of absorption being the protostellar envelope. Two CO isotopologues were also detected (see Fig. 3). The lowest energy transition lines also show evidence for what blue-shifted self-absorption.

3. Discussion

The \(^{16}\)O lines detected toward NGC 7129 FIRS 2 provide an opportunity to examine the physical and chemical environment of this young IM protostar. Attempts to fit the spectra with two
Gaussian components proved reasonably successful for the excited lines (Table 2 and Fig. 3). For these three lines, the narrower component was well described by a \( \approx 6 \) km s\(^{-1} \) Gaussian centered redward of the systemic velocity of the source near \(-7 \) km s\(^{-1} \) coupled with a broader, 25 km s\(^{-1} \) Gaussian centered near \(-13.5 \) km s\(^{-1} \) (Figs. 1 and 3). The likely additional absorption component in each of these spectra could account for the small variations in the line centroids and widths of the fits. Similar profiles are seen for low- (Kristensen et al. 2010) and high-mass (Chavarría et al. 2010) protostars, where they are named medium and broad components. Even narrower lines, \( \approx 1-2 \) km s\(^{-1} \) \( FWHM \), are seen in self-absorption of the lowest-energy water lines as well as in ground-based emission lines such as CS 3–2. The latter profile also reveals a 6 km s\(^{-1} \) component (Fuente et al. 2005).

Beyond the morphological nature of these lines, it is possible to compare the water emission against model predictions. Fich et al. (2010) note that NGC 7129 FIRS 2 has two main components which may account for the observed emission. The prenatal envelope, which is warmed by the IM protostar embedded within it, may produce water emission. Also, the source powers an energetic outflow which could produce water emission either in the outflow itself or along the shock heated walls, where the outflow interacts with the denser envelope. In the following subsections, we consider the water emission from each of these components and compare the expectations against the HIFI observations.

3.1. Water from a spherical protostellar envelope

The spherical envelope model for NGC 7129 FIRS 2 computed by Crimier et al. (2010) fits the spectral energy distribution from the far infrared through the submillimeter very well and thus provides a reasonable set of physical conditions for examining the observed water emission. This model has an envelope mass of 50 \( M_\odot \), an optical depth at 100 \( \mu \)m of 2.3, an inner radius of 100 AU and an outer radius of 18 600 AU. The temperature at the inner envelope radius is 289 K, falling to 100 K at a radius of 373 AU where the \( H_2 \) density is \( 4.4 \times 10^4 \) cm\(^{-3} \). The density varies as a power-law with index \(-1.4 \).

Model water lines were calculated using the RATRAN code (Hogerheijde & van der Tak 2000) using collisional cross sections for \( H_2O-He \) from Green (1993), scaled by 1.348 to make a first order approximation for collisions with \( H_2 \). An ortho-para ratio of 3 was assumed for \( H_2 \). The density and temperature profile of the Crimier et al. (2010) model were followed and the radial velocity profile was assumed to be the free-fall velocity appropriate to a central object of mass 1.1 \( M_\odot \) (ie. velocity of \(-4.2 \) km s\(^{-1} \) at the inner radius and \(-0.31 \) km s\(^{-1} \) at the outer edge). Models were calculated for two abundance zones in the envelope: a warm, \( >100 \) K inner envelope with a higher abundance and a cooler outer envelope with a lower abundance, perhaps characteristic of a “freeze-out” zone.

As a starting point, we modelled the ortho-\( H_2^{18}O \) \( 1_{02-1_{01}} \) line observation. This line has a similar profile to the narrower components of the \( H_2O \) lines and if it can be reproduced by the spherical envelope model we may conclude that the narrower component of the \( H_2O \) lines also are likely to arise in the envelope. A large number of models were run over a range of inner \((10^{-9}-10^{-4})\) and outer \((10^{-7}-3 \times 10^{-11})\) envelope abundances. The non-thermal velocity width parameter \( b \) was also varied and values \( \geq 3 \) km s\(^{-1} \) were strongly ruled out, while \( b \approx 1 \) km s\(^{-1} \) produced too narrow a line. The best fit was found for \( b \approx 2 \) km s\(^{-1} \).

The abundance of ortho-\( H_2^{18}O \) in the outer envelope is well-constrained to be \( 3 \pm 1 \times 10^{-10} \), while inner envelope abundances between \( 3 \times 10^{-7} \) and \( 1 \times 10^{-5} \) produce results consistent with the integrated flux of the ortho-\( H_2^{18}O \) \( 1_{10-1_{01}} \) line (Table A.1). These are surprisingly high values; indeed, the top end of this range is impossible when the cosmic \( ^{18}O \) abundance is considered. The para-\( H_2^{18}O \) \( 2_{02-1_{11}} \) was modeled in a similar way. The non-detection of this line constrains the outer envelope abundance of para-\( H_2^{18}O \) to \( \leq 3 \times 10^{-11} \). The model fits are insensitive to the inner envelope abundance used (Table A.2) and this may be a consequence of beam dilution.

Assuming that the ratio of 16\(^{16}O/^{18}O = 550 \) is also representative of the ratios of both of the ortho and para \( H_2O/H_2^{18}O \), we examined models for the narrower components of the \( H_2O \) lines with outer envelope abundances near \( 1 \times 10^{-7} \) and inner abundances up to \( 3 \times 10^{-4} \) (limited by the cosmic \( O \) abundance). The best fitting models indicate that the outer envelope abundance of total \( H_2O \) is of order a few \( 10^{-7} \), and are summarised in Table 3.

The ortho to para ratio implied by the best fit outer envelope
Table 3. Overview of best fitting spherical envelope models.

| Isotopologue | Outer abundance(1) | Comment |
|--------------|-------------------|---------|
| o-H2:18O     | $3 \times 10^{-10}$ | implies o-H2:O 1.7 ± 0.5 × $10^{-13}$ |
| p-H2:18O     | $3 \times 10^{-11}$ | implies p-H2:O 1.7 ± 10^{-10} |
| p-H2:O       | $3 \times 10^{-11}$ | Well constrained by both excited para lines |
| p-H2:O       | $3 \times 10^{-6}$  | $\geq 10^{-8}$ required for self-absorption |

Notes. (1) The relative abundance of species listed, and not total H2O (2) Assuming $^{18}$O/$^{16}$O = 500.

abundances is 10^{-1.1}, this is highly unlikely and within the calibration (≤32%) and model uncertainties the ratio is consistent with 3. The abundance of the inner envelope could not be constrained and the observed line profiles were poorly reproduced, particularly in the case of the para lines. Whilst the parameter space of the models are still not fully explored, this suggests limitations in the model used with the assumptions concerning the velocity field and spherical structure most suspect.

3.2. Water from a slab model

Fich et al. (2010) concluded that the energetic PACS CO lines observed toward NGC 7129 FIRS 2 could not be fit by a re-processing spherical envelope model as there was an insufficient volume of warm gas to produce the strong emission observed. It was postulated that the CO emission might arise along shock heated walls in the outflow cavity, where the gas temperature can reach extreme values. NGC 7129 FIRS 2 is known to contain a powerful outflow (Fuente et al. 2001) and observations of low-mass stars have shown that such outflows can produce heated walls via UV photons (van Kempen et al. 2009) and shocks (Giannini et al. 1999; van den Ancker et al. 2000; Nisini et al. 2002; Arce et al. 2007; van Kempen et al. 2010). Fich et al. (2010) used the RADEX code to show that the observed CO emission could be explained within a model of a slab geometry with a temperature of 1100 K, an H2 density of 1.0 × 10^{6} cm^{-3}, and a CO column density of 10^{12} cm^{-2}. This model constrained the lowest temperature at which the CO observations could be adequately fit. A more comprehensive set of CO models was produced for this paper, and a best fit is found for a temperature of 1200 K, an H2 density of 1.0 × 10^{7} cm^{-3} and a column density of CO of 1.7 × 10^{14} cm^{-2}. Assuming a CO abundance of 10^{-4}, these results suggest a slab with thickness dz ≈ 10^{10} cm.

Using these same conditions (1200 K and 10^{7} cm^{-3}), but substituting water for CO, may provide an additional constraint on the possible shock heating conditions, and the conditions under which the broad component of the water lines arise. The water lines observed with HIFI set the limit on the ortho-H2O column at 2.3 ± 0.2 × 10^{13} cm^{-2} while the para-H2O lines observed set a maximum limit in the column at 7.5 ± 0.5 × 10^{12} cm^{-2}, giving an ortho-to-para ratio of 3.

These models imply a water abundance that is approximately five times lower than CO and can be compared with that found from analysis of the H2O and CO line ratios in the line wing, where the emission is optically thin. The CO 10–9 line exhibits a similar profile to that seen in the H2O lines (Fig. A.1) and be compared directly with the H2O 2_0−1_1 line, as they are observed in almost the same beam (22" vs. 19"). The abundance ratio was calculated with RADEX using a density of 10^{6} cm^{-3}. Above $T = 150$ K the results are insensitive to changes in temperature. The abundance ratio is found to be ≈0.2 near the line centre and approaches 0.3 at the highest velocities in the red wing (Table A.3). This is consistent with the findings from the slab model and also with the behaviour seen in the low-mass sources of Kristensen et al. (2010), who report this indicates that ≈10% of the available O is in H2O.

That the same model can be used to fit both the PACS CO observations and the broad component of the HIFI H2O lines supports the hypothesis that these lines arise along shock heated walls in the outflow cavity. Shock models will allow to better constrain the conditions under which these broad lines arise.

4. Conclusions

Herschel HIFI spectroscopy of water in the vicinity of the intermediate mass protostar NGC 7129 FIRS 2 has revealed that the water emission arises from at least two sources. The observed emission lines can be decomposed into both a narrower, ≈6 km s^{-1}, component and a much broader, ≈25 km s^{-1} component. The integrated intensity of the narrower component can be fit by a simple free-falling envelope model with an outer envelope total H2O abundance of ≈10^{-7}, although the shape of the line profiles are not reproduced. The broader component appears to be related to the heated gas already observed in high-J CO lines with PACS and associated with the known energetic outflow. These initial modeling results suggest that a dedicated parameter study for this source should prove extremely fruitful in constraining the physical and chemical conditions in NGC 7129 FIRS 2.

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References

Arce, H. G., Shepherd, D., Gaeth, F., et al., 2007, in Protostars and Planets V, ed. B. Reipurth, D. Jewitt, & K. Keil, 245 Chavarria, L., Herpin, F., Jacq, T., et al., 2010, A&A, 521, L37 Crimier, N., Cceccarelli, C., Alonso-Albi, T., et al., 2010, A&A, 516, A102 de Graauw, Th., Helmich, F. P., Phillips, T. G., et al., 2010, A&A, 518, L6 Fich, M., Johnstone, D., van Kempen, T. A., et al., 2010, A&A, 518, L16 Fuente, A., Neri, R., Martin-Pintado, J., et al., 2001, A&A, 366, 873 Fuente, A., Rizzo, J. R., Caselli, P., Bachiller, R., & Henkel, C., 2005, A&A, 433, 535 Giannini, T., Lorenzetti, D., Tommasi, E., et al., 1999, A&A, 346, 617 Green, S., Maurelens, S., McLean, A. D., 1993, ApJS, 85, 181 Hogerheidt, M., & van der Tak, F. F. S. 2000, A&A, 362, 697 Kristensen, L. E., Visser, R., van Dishoeck, E. F., et al., 2010, A&A, 521, L30 Nisini, B., Giannini, T., & Lorenzetti, D. 2002, ApJ, 574, 246 Ott, S., 2010, in Astronomical Data Analysis Software and Systems XIX, ed. Y. Mizumoto, K.-I. Morita, & M. Ohishi, ASP Conf. Ser. Pilbratt, G. L., Riedinger, J. R., Passvogel, T., et al., 2010, A&A, 518, L1 Shevchenko, V. S., Yakubov, S. D., 1989, SvA, 66, 718 van den Ancker, M. E., Wesselius, P. R., & Tielens, A. G. G. M. 2000, A&A, 355, 194 van Kempen, T. A., van Dishoeck, E. F., Guesken, R., et al., 2009, A&A, 501, 633 van Kempen, T. A., Kristensen, L., Herzeg, G., et al., 2010, A&A, 518, L121
Appendix A:

Table A.1. Summary of o-H$_2^{18}$O 1$_{01}$ model results.

| Envelope abundance | $T_{\text{peak}}$ (K) | $\int T_{\text{MB}} \, dv$ (K km s$^{-1}$) |
|--------------------|----------------------|---------------------------------|
| Inner              | Outer                |                                 |
| 1 x 10$^{-5}$      | 3 x 10$^{-10}$       | 0.017                           |
| 3 x 10$^{-6}$      | 3 x 10$^{-10}$       | 0.018                           |
| 1 x 10$^{-6}$      | 3 x 10$^{-10}$       | 0.017                           |
| 3 x 10$^{-7}$      | 3 x 10$^{-10}$       | 0.016                           |
| 1 x 10$^{-7}$      | 3 x 10$^{-10}$       | 0.015                           |
| 3 x 10$^{-10}$     | 5 x 10$^{-11}$       | 0.008                           |
| 1 x 10$^{-8}$      | 3 x 10$^{-10}$       | 0.010                           |
| 1 x 10$^{-9}$      | 1 x 10$^{-10}$       | 0.009                           |
| 3 x 10$^{-10}$     | 3 x 10$^{-11}$       | 0.008                           |
| 1 x 10$^{-10}$     | 1 x 10$^{-11}$       | 0.008                           |

Notes. The observed line has a $T_{\text{peak}}^{\text{MB}} = 0.015$ K and an $\int T_{\text{MB}} \, dv = 0.071$ K km s$^{-1}$, the best fitting model is selected by comparison with the latter.

Table A.2. Summary of p-H$_2^{18}$O 2$_{01}$–1$_{11}$ model results, which are compared with $\int T_{\text{MB}} \, dv \leq 0.010$ K km s$^{-1}$.

| Envelope abundance | $T_{\text{peak}}$ (K) | $\int T_{\text{MB}} \, dv$ (K km s$^{-1}$) |
|--------------------|----------------------|---------------------------------|
| Inner              | Outer                |                                 |
| 3 x 10$^{-6}$      | 1 x 10$^{-10}$       | 0.0888                          |
| 1 x 10$^{-6}$      | 1 x 10$^{-10}$       | 0.0888                          |
| 3 x 10$^{-7}$      | 1 x 10$^{-10}$       | 0.085                          |
| 3 x 10$^{-6}$      | 3 x 10$^{-11}$       | 0.026                          |
| 1 x 10$^{-6}$      | 3 x 10$^{-11}$       | 0.027                          |
| 3 x 10$^{-7}$      | 3 x 10$^{-11}$       | 0.023                           |
| 3 x 10$^{-6}$      | 1 x 10$^{-11}$       | 0.008                           |
| 1 x 10$^{-6}$      | 1 x 10$^{-11}$       | 0.008                           |
| 3 x 10$^{-7}$      | 1 x 10$^{-11}$       | 0.008                           |

Table A.3. H$_2$O 2$_{02}$–1$_{11}$/CO 10–9 abundance ratios in 5 km s$^{-1}$ intervals, calculated from CO 10–9/H$_2$O 2$_{02}$–1$_{11}$ line ratios, using $n = 10^6$ cm$^{-3}$ and $T > 150$ K.

| dv (km s$^{-1}$) | CO 10–9/$H_2$O 2$_{02}$–1$_{11}$ | H$_2$O 2$_{02}$–1$_{11}$/CO 10–9 |
|-----------------|----------------------------------|--------------------------------|
| -10 to -5       | 3.25                             | 0.27                           |
| -5 to 0         | 3.86                             | 0.22                           |
| 0 to 5          | 4.14                             | 0.21                           |
| 5 to 10         | 1.86                             | 0.47                           |

Fig. A.1. The H$_2$O 2$_{02}$–1$_{11}$ and CO 10–9 transitions; the main isotopologue of CO exhibits a profile similar to the main isotopologues of H$_2$O.