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WISHES COMING TRUE: WATER IN LOW-MASS STAR-FORMING REGIONS WITH HERSCHEL

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Abstract. Water is a key molecule for tracing physical and chemical processes in star-forming regions. The key program "Water in star-forming regions with *Herschel*" is observing several water transitions towards low-mass protostars with HIFI. Results regarding the 557 GHz transition of water are reported here showing that the line is surprisingly broad, and consists of several different velocity components. The bulk of the emission comes from shocks, where the abundance is increased by several orders of magnitude to $\sim10^{-4}$. The abundance of water in the outer envelope is determined to $\sim10^{-8}$, whereas only an upper limit of 10^{-5} is derived for the inner, warm envelope.

1 Introduction

Observing velocity-resolved molecular emission and absorption lines is crucial for tracing the physical and chemical processes of star formation. The kinematical information contained in such a line will often reveal physical components that are not spatially resolved by standard single-dish observations including the infalling molecular envelope and shocks on both large (>1000 AU) and small (<1000 AU) spatial scales (e.g., Arce et al. 2007). The velocity-resolved data will also allow a determination of the abundance of the relevant molecule in each physical component. One of the goals of the key program "Water in star-forming regions with *Herschel*" is to measure the abundance of water and related molecules in all components of star-forming objects (van Dishoeck *et al.* 2011).

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The abundance of water is very low, 10^{-9}–10^{-8}, in the cold quiescent parts of the molecular envelope, where the bulk of water is in the form of ice on dust grains. As the temperature increases closer to the protostar, all water evaporates and the abundance increases by several orders of magnitude, up to $\sim 10^{-5}$–10^{-4}. Water is also frozen out onto dust grains in shocks, but sputtering of the grain mantles effectively releases all water into the gas phase. At the same time, any atomic oxygen will be pushed into water through neutral-neutral reactions in the warm post-shock gas. Both processes lead to a jump in the abundance by up to four orders of magnitude, to $\sim 10^{-4}$. These processes have already been inferred by a combination of SWAS and ISO data (e.g., Boonman *et al.* 2003). SWAS resolved the H_2O 1_{10}–1_{01} transition at 557 GHz, but in a much larger beam and at a lower sensitivity than what is currently possible with the Heterodyne Instrument for the Far-Infrared on *Herschel* (Bergin et al. 2003, Franklin et al. 2008). These factors make it possible to detect water in a larger number of protostars, including the more evolved Class I sources, as well as detecting higher-excited lines and the rare isotopologue $H_2^{18}O$.

2 Observations and results

Observations were carried out with HIFI on *Herschel* (de Graauw *et al.* 2010) centered on the source position of 29 low-mass Class 0 and I protostars (see van Dishoeck *et al.* 2011 for a complete source list and details of each source). A number of different transitions are targeted using *Herschel*-HIFI, but only observations of the $H_2^{16}O$ and $H_2^{18}O$ 1_{10}–1_{01} transitions at 557 and 548 GHz, respectively, are reported here ($E_{\rm up}/k_{\rm B}$=60 K). The beam size is $39''$ corresponding to 5500–18,000 AU depending on the distance of the source (140–450 pc). The spectral resolution is $<$0.1 km s^{-1}. Normalized spectra are presented in Fig. 1 for 12 Class 0 and 2 Class I sources in the 557 GHz transition, as well as one Class 0 source in the $H_2^{18}O$ ground-state line (Kristensen *et al.* in prep.).

$H_2^{16}O$ emission is detected towards all sources, both Class 0 and I. These results constitute the first detection of cold H_2O in a Class I object as well as the detection of cold $H_2^{18}O$ in a low-mass protostar. The lines have several characteristics in common, although they originate in different sources. First, the lines are all surprisingly broad, the broadest line having a total $FWHM$ of $>$100 km s^{-1}. Even the $H_2^{18}O$ line is very broad, the example shown here for NGC1333 IRAS4B has a $FWHM$ of $\sim$30 km s^{-1}. Second, the lines can be decomposed into three components each of which is represented by a Gaussian: a broad component ($FWHM$>20 km s^{-1}); a medium-broad component (5<$FWHM$<20 km s^{-1}); and a narrow component ($FWHM$<5 km s^{-1}). The broad and medium-broad components are often centered on the source velocity, but this is not always the case (NGC1333 IRAS2A has the medium component centered on the source velocity, while the broad component is offset by 10 km s^{-1}; in NGC1333 IRAS4B the opposite is the case; Kristensen *et al.* 2010). The narrow component is most often seen in absorption, sometimes it appears as both absorption and emission in an inverse P-Cygni-type profile. This component is located at the source velocity

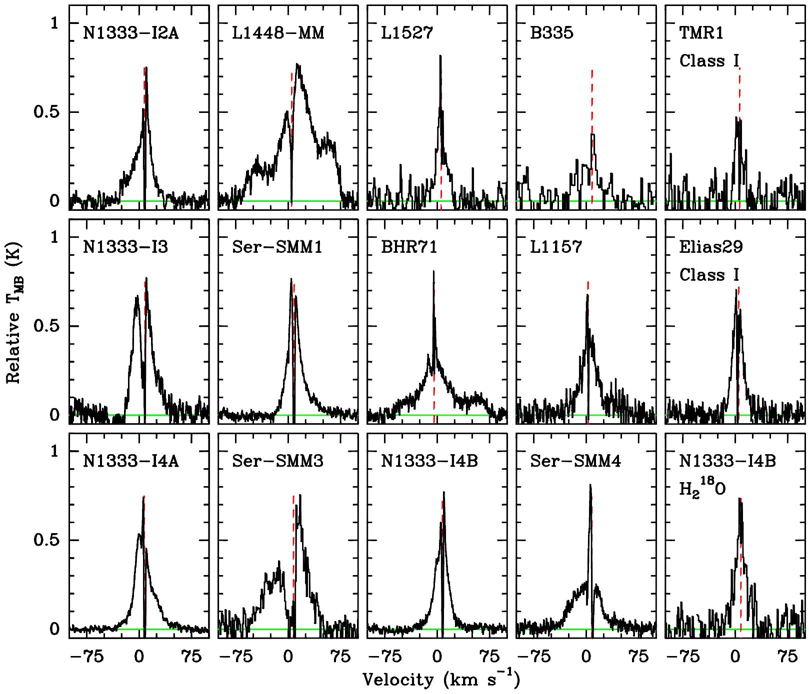

Fig. 1. H_2O 1_{10}–1_{01} 557 GHz emission from the Class 0/I low-mass protostars in WISH. Emission has been scaled to the same intensity to enhance differences in the profile shape.

in both cases. The absorption is often saturated in the Class 0 sources, i.e., all of the continuum photons are also absorbed by H_2O. The $H_2^{18}O$ transition is also self-absorbed, indicating that the envelope is optically thick even in $H_2^{18}O$.

3 Interpretation

Because of the width of the broad and medium components, these can be attributed directly to shocks. Kristensen *et al.* (2010) argued that the broad component arises in the interaction between the envelope and the outflow (on scales of >1000 AU), i.e., along the outflow cavity walls, whereas the medium-broad component arises in shocks in the inner, dense envelope (on scales of <1000 AU). The width of the H_2O lines compared to, e.g., CO lines is a direct testament to the H_2O abundance being enhanced by many orders of magnitude in the shock. The enhancement is due to the combination of sputtering of the icy grain mantles and to a series of neutral-neutral reactions that essentially lock up any atomic oxygen in H_2O through reactions with H_2. These reactions are only possible at T>250 K and the enhancement has been measured with H_2O/CO increasing with velocity to ∼1 (Franklin *et al.* 2008, Kristensen *et al.* 2010). The narrow component is due to the large-scale envelope that is either in-falling or simply aborbing emission.

One of the sources, NGC1333 IRAS2A, has been modeled in detail to constrain the abundance of H_2O in the envelope. The only clear sign of this quiescent gas is the deep self-aborption. Combination of the 557 GHz absorption with that seen in the ground-state para-H_2O line (1_{11}–0_{00} at 1113 GHz) (but not in higher-exceited lines) constrains the outer-envelope abundance to $\sim10^{-8}$. The lack of any clear narrow emission signature in even the $H_2^{18}O$ lines severely limits constraints on the abundance in the inner parts of the envelope, where H_2O has evaporated from the grain surface. The inferred upper limit is $<10^{-5}$ (Kristensen *et al.* 2010, Visser *et al.* in prep.).

The next step will consist of 2D modeling for each protostar. Such a model has already been developed and tested for the low-mass protostar HH46 (van Kempen *et al.* 2010, Visser *et al.* in prep.). The model consists of three separate physical components: the molecular envelope heated by the accretion luminosity of the protostar, UV-heating of the outflow cavity walls and shocks along the cavity walls. The first two processes are modeled simultaneously using the radiative transfer code LIME (Brinch & Hogerheijde 2010) and the shocks are added using the model results from Kaufman & Neufeld (1996). With this model it is possible to reproduce the CO ladder from J=2–1 up to J=40–39, and work is currently underway to do the same for H_2O.

4 Conclusions

$H_2^{16}O$ 1_{10}–1_{01} emission is detected towards all Class 0 and I protostars. Furthermore, $H_2^{18}O$ 1_{10}–1_{01} is detected towards several of the sources. The lines are all observed to be very broad, including the $H_2^{18}O$ line, indicating an origin in shocks. These shocks are attributed to different physical processes in the protostellar environment. The abundance of H_2O has been determined to be 10^{-4} in the shocks, whereas it is $\sim10^{-8}$ and $<10^{-5}$ in the outer, cold and inner, warm envelope, respectively. Further modeling will be done to constrain the abundance in a total sample of 29 low-mass protostars being observed as part of the WISH program.

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