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HERSCHEL/HIFI REVEALS THE FIRST STAGES OF STELLAR FORMATION

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Abstract. The understanding of the star formation is still on progress. Especially, the formation of high-mass stars is much less understood than the low-mass case: even the time order of observational phenomena is uncertain. Water, one of the most important molecules in the Universe, might elucidate key episodes in the process of stellar birth, and especially could be a major role in the formation of high-mass stars. For both types of stars, the source chemical composition is not well known and even less known is the chemical evolution of the interstellar matter throughout the various phases of star formation. This talk presents the first results of the various Herschel Space Observatory star formation key-programs. One of the instruments on-board HSO, HIFI, is the most powerful spectrometer never built, covering a huge frequency range, most of them unaccessible from ground. In particular, one of the KP, WISH, aims at following the process of star formation during the various stages and at using the water as a physical diagnostic throughout the evolution.

Keywords: ISM: molecules, abundances, stars: formation, protostars, early-type, line: profiles

1 Introduction

In the deeply embedded phase of star formation, it is often only possible to trace the dynamics of gas in a young stellar object (YSO) through resolved emission-line profiles. The various dynamical processes include infall from the surrounding envelope towards the central protostar, molecular outflows, and strong turbulence. One of the goals of the Herschel Space Observatory (HSO) and of its spectrometer HIFI is to probe these processes and determine the abundance of the chemical species as a function of evolution (van Dishoeck et al., submitted to PASP).

Three instruments are on board the HSO, launched on May 14th, 2009: the Photodetector Array Camera and Spectrometer PACS, the Spectral and Photometric Imaging Receiver SPIRE, and the Heterodyne Instrument for the Far-IR HIFI. HIFI is composed of the Wide Band Spectrometer WBS and of the High Resolution Spectrometer (built by the CESR and the LAB). HIFI allows to observe between 250 and 625 microns (bands 1-5), and between 157 and 213 microns (bands 6-7). HIFI is a major step forward compared to other space facilities because of higher spatial resolution (3-5 w.r.t. SWAS/ODIN, 8 with ISO-LWS), higher sensitivity (10 w.r.t. SWAS/ODIN), higher spectral resolution (up to 125 kHz), and larger colder aperture, and more observing time than balloon and airborne instruments.

The OB stars are the main contributors to the evolution and energy budget of galaxies. Their formation, however, has not been understood yet and the classical scheme for low-mass star formation (Andre 2000) cannot be applied as such to OB stars. Indeed, young OB stars and protostars strongly interact with the surrounding massive clouds and cores, leading to a complex and still not clearly defined sequence of objects from pre-stellar cores that are often believed to be hosted in the so-called IR dark clouds, to high-mass protostellar objects (HMPOs), to hot molecular cores (HMC) and uItra compact HII regions (e.g. Beuther 2007; Menten 2005).

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2 Spectral surveys of protostars

Spectral surveys are essential to study the chemical content of the star forming regions (SFRs) because different molecules are produced in different regions with different physical conditions and because different molecular transitions are excited in regions with different temperatures and densities. They aim at answering to the following questions: 1) what is the degree of complexity of the molecules in SFRs ? ; 2)When and how do they form and evolve ?
Two Guaranteed Time Key-Programs (GT-KP) are dedicated to the study of star formation through spectral surveys: HEXOS (Herschel observations of EXtra-Ordinary Sources, Bergin et al.) towards Orion KL, and CHESS (Chemical HErschel Surveys of Star- forming regions, Ceccarelli et al.) towards a sample of protostars, from low- to high-mass. First results about deuteration (Vastel 2010) and the detection of the new species H_2O^+ and H_2Cl^+ (Lis 2010).

3 Water in Star forming regions

The WISH GT-KP (Water In Star forming regions with Herschel, PI: E. van Dishoeck) aims at probing the stellar formation through water observations with HIFI and PACS towards a large sample of low-, intermediate- and high-mass protostellar objects and circumstellar disks. The large variations of water abundance (e.g. evaporation from dust grains for T> 100K) depending on the physical conditions allow to test different regions, and, hence, to characterize different evolutionnary stages. Also, water is a very good probe of gas flows (infall, outflow). But maybe more important, water plays a crucial role in the energy balance and, as an efficient cooling agent, could help to understand how massive stars can form. Finally, water molecules are the main oxygen reservoir.

3.1 Low-mass prestellar cores and protostars

First Herschel results show the first observation of water in low-mass protostellar cores. Caselli (2010) have made the first detection of water ($1_{10} - 1_{01}$) in pre-stellar core, L1544 (Taurus) and derive an upper limit for its abundance of 10^{-9} (density of 10^5 cm−3).

The first water maps of outflows/jets have been performed by Nisini (2010) and show large variations of water abundance depending on the importance of the shocks and on the evolutionary stage of the object.

Kristensen (2010) have studied NGC 1333 (L$\sim$ 20$L_\odot$, d$\sim$250 pc) and derived water abundance of $10^{-5} - 10^{-4}$ in the outflow while water is less abundant in the envelope (10^{-9}). IRAS4A clearly exhibits an infall signature. The bulk of the emission comes from shocks in the molecular jets, both at small scale (a few 100 AU) and at large scale; emission from the passively heated envelope is also seen.

From Benz (2010), Bruderer (2010), the origin of the water emission is now clearly established:
- a passively heated envelope with a hot core (compact region of $\sim$200 AU) where H_2O evaporates.
- along outflows where the water emission extends from, and where the water abundance increases within the shocks.

3.2 Intermediate-mass protostars

WISH observations towards intermediate-mass protostars (Johnstone 2010) revealed powerful outflows. The water emission comes from the hot part of the envelope (T> 100K) where its abundance is $\sim 10^{-5}$. Self-absorption from the external envelope is observed.

3.3 High-mass protostellar objects

The study of the high-mass protostar formation represents a large fraction of the WISH KP. This part is led by F. Herpin, F. van der Tak and F. Wyrowski. It consists of HIFI pointed observations of 14 water lines, including rare isotopic lines ($H_2{}^{18}O$, $H_2{}^{17}O$) in 19 sources (more deep H_2O $1_{10} - 1_{01}$ observation of four infrared-dark cloud cores) at different evolutionary stages (mid-IR-quiet and mid-IR-bright massive dense cores, hot molecular cores and UCHII regions). Maps of water emission with HIFI ($1_{10} - 1_{01}$, $2_{02} - 1_{11}$, $1_{11} - 0_{00}$) and PACS maps in 4 lines of 6 proto-clusters are also performed. The goal is to determine the abundance and distribution of water in the envelopes, massive outflows, and to precise the filling, cooling and chemistry of intra-cluster gas.

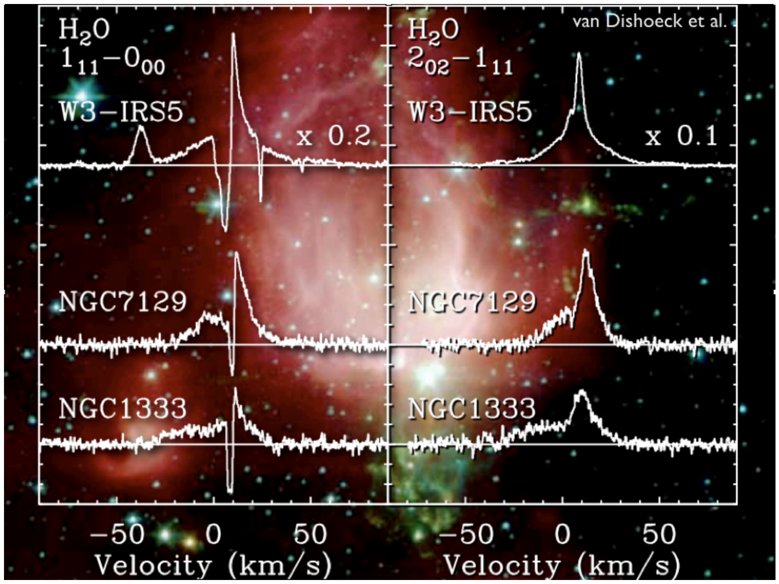

Fig. 1. Comparison of the HIFI water $1_{11} - 0_{00}$ and $2_{02} - 1_{11}$ line profiles between a low-mass (NGC 1333, Kristensen et al. 2010), intermediate-mass (NGC 7129, Johnstone et al. 2010) and high-mass (W3-IRS5, Chavarria et al. 2010) protostellar object.

The observations include chemically related species (O, OH, H_3O^+), radiation diagnostics of UV and X-rays, and a few key high-J CO lines too. The interpretation of the data is made through the line profile analysis and a line modelling using MC3D (Wolf 2003) for the continuum and RATRAN (Hogerheijde 2000) for the lines.

A first look to the water line profiles towards objects with different mass shows that water lines are stronger and more complex in high-mass protostellar objects (see Fig.1). The DR21(Main), in Cygnus X (L=45000 $L_\odot$, d=1.7 kpc) region, a relatively evolved object, was observed by the HSO (VanderTak 2010) in the ^{13}CO 10-9 and H_2O $1_{11} - 0_{00}$ (1113 GHz) lines. The profiles exhibit different components coming from the outflow, the protostellar envelope itself, and a foreground cloud. The high water abundance ($7{\times}10^{-7}$) in the warm outflow is probably due to the evaporation of water-rich icy grain mantles, while the H_2O abundance is kept down by freeze-out in the dense core ($1.6{\times}10^{-10}$) and by photodissociation in the foreground cloud (4×10^{-9}).

Marseille (2010) published the first comparison of water spectra (H_2O and $H_2{}^{18}O$ $1_{11} - 0_{00}$, H_2O $2_{02} - 1_{11}$) obtained in W43-MM1 (mid-IR quiet HMPO), W33A (mid-IR bright HMPO) and G31.41+0.31 and G29.96-0.02 (HMC). The higher abundance ($> 10^{-8}$) derived for G31.41+0.31 and W43-MM1 is not clearly linked to luminosity, mass and temperature or assumed evolutionary stage of the source.

The mid-IR bright massive dense core W3-IRS5 (Perseus region, d=2.0 kpc) was studied by Chavarria (2010). Several water lines have been observed and modelled. Emission in the rare isotopologue lines is only reproduced in the models by including a jump in the water abundance in the inner envelope. The emission in the rare species comes from the inner envelope where the water abundance is greatly enhanced (evaporation from dust grains). Emission from this region could be the expected contribution from the passively radiatively heated inner envelope. The signature of outflow (high-velocity emission of 33-40 km/s) is seen, but no infall is observed. Profiles reveal absorption from the cold molecular cloud ($T \leq 10$ K) in which the proto-stellar envelope is embedded. From the model interpretation, we conclude that the water emission is coming from the 2 sources first observed by Rodon (2008). The water abundance is 10^{-4} in the inner protostellar envelope ($T > 100$K) while it is $10^{-8,9}$ in the outer envelope (see Fig.2).

Finally, a large study of the demistry has been made by Benz (2010) for W3-IRS5 and Bruderer (2010) for AFGL2591 within the WISH KP. Through the observations of various hydrides, a radiation diagnostics in the systems protostar-disk-outflow is possible. Actually, hydrides are produced at high temperatures via reactions with atomic ions within strong UV or X fields. The following species have been detected: OH, CH ($2\ 10^{-8}$ in AFGL2591), NH (10^{-9}), SH, OH^+ ($3\ 10^{-10}$), CH^+ (10^{-8}), NH^+, SH^+, H_2O, H_2O^+($7\ 10^{-10}$), H_3O^+. The first detection of OH^+ and H_2O^+ reveals the gas phase path to produce water, and, hence, complete the water chemical puzzle. They conclude that FUV radiation from central protostar irradiates and heats the walls of the outflow cavity making the abundance of CH^+, OH^+ and NH^+ to increase by several orders of magnitude in the

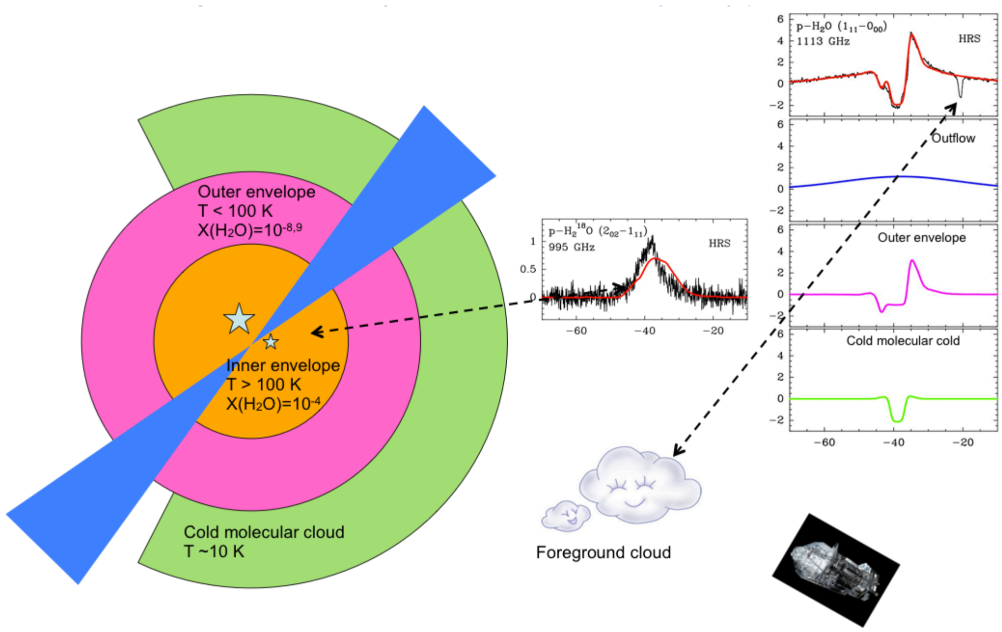

Fig. 2. Schematic view of W3-IRS5 high-mass massive dense core and of the different components of the water line profiles (Chavarria et al. 2010).

walls of the outflow.

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