HIFI SURVEY OF WATER LINES FROM PROTOSTARS

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Abstract

Since water is very abundant and easily excited in the circumstellar environments, water lines are an extremely useful tool to probe the innermost regions of the envelopes surrounding low mass protostars as well as the immediate environment of compact and ultra-compact HII regions. In this contribution we discuss the importance to carry out a systematic survey of selected water lines in low and high mass protostars with the high resolution spectrometer HIFI on board FIRST. Given the large amount of observing time necessary to survey a meaningful number of lines in a meaningful statistical sample, this survey can only be achieved by means of a KEY PROGRAM.

Key words: Stars: formation – Missions: FIRST

1. Introduction

Oxygen is the third most abundant element in the Universe, after Hydrogen and Helium. In cold molecular clouds it is mainly in the form of gaseous CO, O and H_2O, (e.g. van Dishoeck & Blake 1998; Caux et al. 1999) and in the form of iced water coated around the grains (e.g. Tielens 1987). However, in star forming regions most of the oxygen can be found in water, because of the evaporation of the grain ice mantles and/or of the formation of water in the gas phase via endothermic reactions (e.g. Kaufman & Neufeld 1996; Ceccarelli, Hollenbach & Tielens 1996). Because of its high abundance and easy excitation in warm interstellar and circumstellar environments water is a powerful tool to probe astrophysical conditions in a broad variety of sources, from protostars to molecular shocks. In this contribution we focus on the case for systematic observations of water lines in low and high mass protostars. We specifically address the *unique* capabilities of HIFI in obtaining high spectral and spatial resolutions observations of the submm rotational transitions of water to study the immediate environment of solar type protostars and compact or ultra-compact HII regions.

2. Low mass protostars

Water lines have been predicted to be the most abundant oxygen bearing molecule and major gas coolants of the warm inner regions of the envelopes surrounding low luminosity protostars (Ceccarelli, Hollenbach & Tielens 1996; Doty & Neufeld 1997). These early predictions were confirmed by the observations of strong water emission in several low mass protostars carried out with the two spectrometers on board the Infrared Space Observatory (ISO) (e.g. Ceccarelli et al. 1999). The detailed analysis of the water line spectrum of the solar type protostar IRAS16293-2422 allowed to reconstruct the physical structure of its envelope and to estimate the two key parameters of the protostar: the mass of the central forming star and its mass accretion rate (Ceccarelli et al. 2000). In addition, the observed water lines enabled us to estimate the water abundance in the cold outer envelope and in the warm innermost regions enriched in water vapour, both because of the evaporation of the water ice previously stored in the cold grain mantles and because of efficient chemical reactions which lock most of the gaseous oxygen into water molecules. What is important to note here is that the model, corroborated by the H_2O line observations, predicts the existence of a misty and warm region at about 150 AU where about 0.035 $M_\odot$ of water vapour collapses towards the center. Once entered into the protoplanetary disk, the water vapour may condense onto the cold grains, which then aggregate to form icy planetesimals imprinted with this first collapse phase memory (Chick & Cassen 1997).

Given the relatively low sensitivity, low spatial resolution and low spectral resolution, the ISO observations had some obvious limitations, which will be certainly overcome by FIRST. With its higher sensitivity, and spatial and spectral resolutions, FIRST will be able:

a) to increase the sample of solar type protostars where the study of water line emission is possible;
b) to disentangle the water emission associated with the infalling gas against the emission due to shocked material of the outflowing gas;
c) to resolve the line emission thus making possible kinematical studies: note that since high energy lying water lines originate in the innermost regions, where the infall velocity is the highest, they can be resolved by the HIFI spectrometer and used to probe the infall;
d) and finally, to measure water abundances in the cold envelopes with a sensitivity at least an order of magnitude better than SWAS.

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FIRST will be the only instrument able to observe efficiently and routinely water lines from solar type protostars for many years to come.

In conclusion, the water lines observable with FIRST are of paramount importance to derive key parameters for the process of a solar type protostar:

- the mass of the central forming stars and their accretion rates;
- the water abundance in the cold gas of the outer envelope and
- the enrichment of water of the innermost regions, which may ultimately form planetary systems.

The knowledge of these parameters in a statistically meaningful and well selected sample of solar type protostars would be invaluable to understand the processes that lead to the formation of stars and planetary systems.

Line list

It is proposed to survey around a dozen water lines. The lines are selected on the basis of theoretical predictions (Ceccarelli, Hollenbach & Tielens 1996), supported by the ISO observations in the few objects so far observed. In order to make realistic predictions we ran a grid of models for different protostar luminosities, masses, mass accretion rates, water abundances etc. The selected lines (Tab. 1) represent the result of this modeling effort. In addition to $H_2^{16}O$ lines we propose to survey also two key $H_2^{18}O$ lines, which will allow to derive in detail the column densities of the observed lines and therefore to better reconstruct the envelope structure. Finally three HDO lines will also be surveyed, appropriately selected to derive the water deuteration through the envelope. Although it is in principle possible to observe HDO from ground, the very few observations available in literature show that these observations are very difficult. On the other hand it is now clear that in solar type protostars molecules like H_2CO and NH_3 present extremely large degrees of deuteration, more than 10% being in the deuterated forms of these molecules (Ceccarelli et al. 1998; Loinard et al. 2000; Roueff et al 2000). It will therefeore be extremely important to study the deuterated form of H_2O in the same objects to understand the route of deuteration of these molecules.

Target list

It is proposed to survey some of the nearby low mass star forming regions: Taurus, ρ Ophiuchus, Perseus, Serpens, Orion and Chameleon are obvious examples. Overall these complexes contain about 80 embedded low luminosity protostars, two thirds of them with luminosities between 1 and 3 $L_\odot$, and the remaining with higher luminosities. Comparison of objects within the same region have been already shown to be extremely useful to draw evolutionary pictures (e.g. Saraceno et al. 1996; Bontemps et al. 1996). Comparison between different regions highlights if and which macroscopic parameters enter in the process of the low mass star formations, such as for istance the sound speed in the parent cloud (e.g. Shu et al. 1987).

Table 1. Water line fluxes for a 30 $L_\odot$ protostar of 0.8 $M_\odot$, accreting at 3×10^{-5} $M_\odot yr^{-1}$, and located at a distance of 160 pc (more details in Ceccarelli et al. 2000).

Frequency (GHz)	Transition	o/p	Flux erg s^{-1} cm^{-2}
556.9	$1_{1,0}-1_{0,1}$	o	4.2E-13
752.0	$2_{1,1}-2_{0,2}$	p	1.5E-13
916.1	$4_{2,2}-3_{3,1}$	p	2.2E-14
970.3	$5_{2,4}-4_{3,1}$	p	1.7E-14
1097.4	$3_{1,2}-3_{0,3}$	o	1.3E-13
1153.1	$3_{1,2}-2_{2,1}$	o	2.1E-13
1158.3	$6_{3,4}-5_{4,1}$	o	1.2E-14
1162.9	$3_{2,1}-3_{1,2}$	o	1.1E-13
1228.8	$2_{2,0}-2_{1,1}$	p	1.0E-13
1296.4	$8_{2,7}-7_{3,4}$	o	3.6E-15
1440.9	$7_{2,6}-6_{3,3}$	p	5.5E-15
1602.2	$4_{1,3}-4_{0,4}$	p	8.0E-14

Time estimate

To calculate the observing times we request a 2σ detection level over three channels (each of 1/3 of the predicted line width). Using the HIFI available spectrometers we propose to observe the lines In Table 1. The system temperatures used to give the estimate of the observing time are roughly those given as the “baseline” on page 48 of the Scientific and Technical case for HIFI (Part I). Based on the mentioned model predictions and such observing time estimates to observe a meaningful set of water lines in sources whose luminosity is about 1 $L_\odot$ will take around four hours per source (no overheads are taken into account yet). To survey the proposed star forming regions will need therefore about 300 hours of observations (with no overheads), which makes this study only possible via a KEY PROGRAM.

3. High mass protostars

In the second part of this contribution we address the question of the complex environment of embedded massive O- or B-type stars which have not yet fully dispersed their natal cloud material. We specifically wish to use the high spectral and spatial resolutions achieved with HIFI in the submm rotational transitions of water to study the immediate environment of compact or ultra-compact HII regions. These regions are detected throughout the Galaxy in both the radio and far infrared domains. Several of them have been mapped with radio interferometers and are known as luminous IRAS sources. Their total luminosity is of the order of 10^3 $L_\odot$ or more and may reach 10^5 $L_\odot$ in the extreme case of W3(OH). They are often associated with massive molecular clouds and masers and they sometimes exhibit pronounced molecular outflows. The spatial resolution of FIRST, of the order of 15″ to 20″ -or less for the highest frequencies of water-, does not permit mapping the most compact HII regions although it helps to discriminate the embedded object from the more extended molecular environment. However, depending on the target and the selected transition we expect to observe both absorption and emission in several transitions of water, including maser emission, from the gas layers in the neighbourhood of the HII region (see (i) and (ii) below). In HII regions most of the oxygen is found in water because icy grain mantles have been evaporated or because endothermic gas phase reactions dominate (see the Introduction). Combined with easier excitation in warm regions water is thus an efficient coolant of the neutral material surrounding the ionized gas associated with the HII region.

(i) **Absorption** lines are most interesting because they probe the compressed neutral regions lying along the line of sight to the HII regions with excitation less than the background emission. These lines thus nicely compensate for the lack of spatial resolution.

(ii) **Emission** from warm water such as that detected toward the Orion hot core (e.g. Cernicharo et al. 1999) could be present in gas layers with temperatures of order 100 K or above. Detectability of this gas depends on the filling factor of the FIRST telescope beam and does not specifically probe the gas immediately against the HII region. On the other hand, the anomalously excited lines leading to strong maser emission because of shocks and collisional and infrared pumping of water could also be detected despite beam dilution. These masing transitions trace the warmest and densest pockets of the gas or just trace the shocked regions; they allow us to investigate the small-scale clumpiness of the outer neutral gas layers against the HII region.

In conclusion, by surveying a number of submm transitions of water in a large sample of sources throughout the Galaxy we expect to derive a statistical view of the complex physical conditions prevailing in the gas surrounding embedded massive stars. We thus hope to bring new light on the early evolutionary stages of embedded massive objects.

Line list

Absorption Lines

A first analysis of the gas lying in front of a limited number of compact HII regions has been made on the basis of ground-based observations of several transitions of the OH radical (eg. Wamsley et al. 1986; Baudry et al. 1993). The data show that the kinetic temperature of the neutral gas is of order 100 to 200 K. The ammonia observations made in the hot cores associated with compact HII regions confirm this result and suggest that velocity and temperature gradients can be present in the cores (eg. Cesaroni et al. 1998). Besides, ISO-SWS observations already showed the potentiality of this technique (e.g. van Dishoeck & Helmich 1996; Helmich et al. 1996; van Dishoeck et al. 1998; Wright et al. 2000). To identify the strongest H_2O absorption lines (Table 2) in the neutral gas in front of the compact HII regions we used the model results by Doty & Neufeld (1997) who explicitely computed the water line spectra of massive protostars.

Table 2. Predicted water absorption lines for a cloud of mass 100 $M_\odot$, illuminated by a central source of luminosity varying beteewn 10^3 and 10^5 $L_\odot$, as computed by Doty & Neufeld (1997).

Freq. (GHz)	Transition	$^{16}O/^{18}O$ o/p	Line Luminosities ($L_\odot$) $10^3 L_\odot$	$10^4 L_\odot$	$10^5 L_\odot$
1101.7	$1_{1,1} - 0_{0,0}$	^{18}O-p	4.1(−3)	9.3(−3)	2.5(−2)
1113.3	$1_{1,1} - 0_{0,0}$	^{16}O-p	1.5(−2)	5.3(−2)	2.5(−2)
1655.9	$2_{1,2} - 1_{0,1}$	^{18}O-o	1.5(−2)	5.5(−2)	1.4(−1)
1661.0	$2_{2,1} - 2_{1,2}$	^{16}O-o	1.5(−2)	5.1(−2)	8.7(−2)
1669.9	$2_{1,2} - 1_{0,1}$	^{16}O-o	3.8(−2)	1.9(−1)	7.4(−1)
1716.8	$3_{0,3} - 2_{1,2}$	^{16}O-o	2.1(−2)	9.6(−2)	2.1(−1)

Maser Lines

Many ortho and para rotational levels of water lie close to each other and thus tend to be easily inverted. Accordingly, if these levels correspond to allowed radiative transitions they can give rise to maser amplification. The strongest water maser emission is that of the $6_{1,6} - 5_{2,3}$ transition which is easily detected from the ground at 22 GHz in a broad variety of sources. The 22 GHz line always show maser emission and is nearly always associated with regions of on-going star formation. In such regions maser action is likely to be observed in several submm lines. The strong 22 GHz maser emission can be explained by the collisional pumping of dense neutral gas which has been heated by shocks, either fast and dissociative (J-type shocks; Elitzur et al. 1989) or slower and non-dissociative (C-type shocks; Melnick et al. 1993) which can heat the gas up to about 1000 K.

Following the results of Neufeld & Melnick (1991) we expect rather strong maser emission from about a dozen of lines in the frequency range 500 to 1500 GHz which is accessible to HIFI. The opacities of these lines depend on the cloud geometry, the collision rates and the volumic density. In order to be independent both of the geometry and the gas density we scale the submm transition opacities to that of the 22 GHz transition. Using Neufeld & Melnick's model we select 7 submm transitions that are at least 0.1 to 0.2 times the 22 GHz line intensity and fall in the HIFI receiver tuning range (Table 3). The opacities in the table are relative to that at 22 GHz arbitrarily assumed to be -10 for a gas at 1000 K; other mm/submm transitions observed from the ground are given in Table 3 for comparison. Theoretical predictions of Neufeld & Melnick (1991) show that maser emission is expected from several transitions under a wide range of astrophysical conditions. Therefore, FIRST observations of several submm transitions of water combined with ground-state observations (Table 3) can be used to constrain the physical conditions in the H_2O emitting layers. We wish to observe the seven lines in Table 3 not accessible from the ground. They trace the densest gas layers and we expect that the ratio of some of these lines together with ground-based observations will give an estimate of the gas temperature.

Table 3. Predicted strong maser transitions in shocked regions.

Frequency (GHz)	Transition	o/p	Relative Opacity[a]	
22.2	$6_{1,6} - 5_{2,3}$	o	-10	(ground)
183.3	$3_{1,3} - 2_{2,0}$	p	-4.6	(ground)
325.2	$5_{1,5} - 4_{2,2}$	p	-4.9	(ground)
439.2	$6_{4,3} - 5_{5,0}$	o	-3.6	(ground)
470.9	$6_{4,2} - 5_{5,1}$	p	-1.1	(ground)
530.4	$14_{3,12} - 13_{4,9}$	o	-1.7	
620.7	$5_{3,2} - 4_{4,1}$	o	-4.1	
906.2	$9_{2,8} - 8_{3,5}$	p	-1.2	
970.3	$5_{2,4} - 4_{3,1}$	p	-6.5	
1158.3	$6_{3,4} - 5_{4,1}$	o	-5.5	
1440.8	$7_{2,6} - 6_{3,3}$	p	-2.9	
1542.0	$6_{3,3} - 5_{4,2}$	p	-1.7	

[a] The 22 GHz opacity is arbitrary.

Target list

We propose to survey all major HII regions also known as bright IRAS sources. We concentrate our selection on sources which have been detected in the 22 GHz line with the Medicina 32-m survey (Palagi et al. 1993; Brand et al. 199; Codella et al. 1994). The IRAS Point Source Catalogue is used to select (somewhat arbitrarily) objects brighter than 1000 Jy at 60 and 100 μm. The 22 GHz H_2O maser sources are selected according to their total integrated flux; we take here sources brighter than about 100 Jy km s^{-1}. The initial survey list includes about 150 objects. (It includes some major complexes such as W49, W51 or W75; these regions contain several individual HII regions which can sometimes be well separated by the FIRST-HIFI beam.) Our source list will be further refined using the most recent surveys of methanol masers in HII regions (see also the contribution by Molinari et al. in this volume).

Time estimate

At the moment it is difficult to make an exact estimate of the time required to observe with the HIFI available spectrometers a total of $\sim$ 150 target sources in all transitions of water mentioned above. Using the goal system temperatures expected in the various HIFI receiver bands we believe that $\sim$ 2 hours are required per source. For a statistical analysis of a meaningful sample of sources taken from our survey list we grossly estimate that more than 200-300 hours are required to cover all water lines of interest. This can be achieved only if the FIRST Observatory decides to support KEY PROGRAM observations.

4. CONCLUSIONS

We discussed that water lines are the main gas coolants in a variety of conditions typical of the gas surrounding protostars, both massive and solar type protostars. For this reason water lines are unique tools to probe this gas, its thermal, physical and chemical structure. In this contribution we presented the case for a sistematic study from the envelopes of low and high mass protostars. We wish to emphasize once again that **FIRST will be the only instrument able to observe efficiently and routinely water lines from protostars for many years to come.** Given the large observing time necessary to gather a meaningful number of lines in a meaningful number of sources, the proposed program can only be achieved if the FIRST Observatory decides to endorse **KEY PROGRAMS**.

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