WATER COOLING IN PROTOSTELLAR OBJECTS: RESULTS FROM ISO-LWS AND FUTURE ROLE OF FIRST

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Abstract

We review the results of the far-infrared emission line spectra of the water molecule obtained with the Long Wavelength Spectrometer onboard of ISO on a sample of protostellar and pre-Main Sequence sources.

Water is expected to play an important role in the cooling of shock-excited regions associated with the star formation process. ISO has found that in most of the sources water is not the dominant coolant and has lower abundances than expected according to current C-type shock models. These results have been recently confirmed by the observations of SWAS. We outline here the possible explanations.

FIRST, with its high spatial and spectral resolution with respect to ISO, will be able to identify and disentangle different emitting regions and excitation conditions, allowing an accurate study of shock excited regions, including the measure of molecular abundances in post-shock chemical environment. Moreover, due to the improved sensitivity, statistically significant samples of protostellar and pre-Main Sequence objects will be observed with the FIRST spectrometers. Among other issues, FIRST is therefore expected to resolve the *water problem*.

Key words: Stars: formation ISM: jets and outflows – Missions: ISO, FIRST

1. The water problem

Before the spectroscopic observations performed with the Infrared Space Observatory (ISO) (Kessler et al. 1996) and those of the Submillimeter Wave Astronomy Satellite (SWAS) (Melnick et al. 2000) water was considered to play a fundamental role in the thermal balance of both dense molecular clouds and star forming regions.

In dense molecular cores the water abundance is expected to be enhanced due to ion-neutral reactions involving H_3^+ and H_3O^+. However, the water abundance in dense cores as measured by SWAS (see Table 1) is lower with respect to the expected values according to models (e.g. Bergin et al. 1995).

On the other hand, water was expected to dominate the cooling in shock-excited protostellar regions (with shock velocities higher than ~ 10 km s^{-1}) for the following reasons:

1. the temperature highly increases behind shock fronts allowing the water production from gas phase reactions between H_2 and O (e.g. Kaufman & Neufeld 1996);
2. sputtering can remove H_2O from grain mantles for shock velocities larger than ~ 15 km s^{-1} (e.g. Caselli et al. 1997);
3. the water abundance can be enhanced by thermal evaporation, even if the process results quite inefficient in shocked regions (while its importance grows in protostellar envelopes directly heated by the newly formed star).

However, also for young stellar objects (YSOs) the water abundance as derived from ISO observations is lower than expected. In this work we focus our attention on water emission in YSOs and we show how FIRST will be able to obtain observational data to clarify this problem.

Table 1. Water abundances expected and measured in dense cores ($T \sim 10$K, $n \sim 10^5$cm^{-3}*) and in YSOs (*$T > 300$K, $n > 10^5$cm^{-3}*)*

	X(H_2O)		
	expected	SWAS †	ISO
Dense cores	$10^{-6} - 10^{-7}$	$10^{-8} - 10^{-9}$	—
YSO	$> 10^{-4}$	$< 10^{-6}$	$10^{-4} - 10^{-5}$

Notes: (†): Snell et al.(2000); Neufeld et al.(2000);

1.1. Comparison between ISO and SWAS

In Table 1 the expected water abundances are compared with the values derived from the ISO-LWS and the SWAS observations. The ISO-LWS (80″ beam) has measured in most YSO abundances of $10^{-6} < X(H_2O) < 10^{-4}$ (Saraceno et al. 1998), with the exceptions of L1448, NGC1333 IRAS4, CepE (see Table 2 for details) and Orion KL (Harwit et al. 1998), while SWAS (3′.3 x 4′.5 beam) has detected abundances of $< 10^6$ (Neufeld et al. 2000, Snell et al. 2000). These differences can be smoothed away taking

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Table 2. [OI], CO *and* H_2O *cooling and water abundances in protostellar and pre-Main-Sequence sources observed with the ISO-LWS*

Source	Class†	L_{BOL} $L_\odot$	$L_{[OI]}$ $L_\odot$	L_{CO} $L_\odot$	L_{H_2O} $L_\odot$	$X(H_2O)$	References
B335 FIR	0	3	0.002	0.004	< 0.001	$< 10^{-5}$	(1)
IRAS 16293	0	27	0.005	0.027	0.017	2×10^{-5}	(2)
L 1448 MM	0	10	0.008	0.030	0.045	5×10^{-4}	(3)
L 1448 IRS3	0	9	0.019	0.035	0.008	3×10^{-5}	(4)
HH 25 MM	0	6	0.024	0.043	0.023	$\sim 7 \times 10^{-7}$	(5)
NGC 1333-IRAS4	0	14	0.009	0.088	0.097	1.1×10^{-4}	(6)
Cep E MM	0	75	0.181	0.445	0.324	$3 - 6 \times 10^{-4}$	(6)
IRAS 18273	0	46	0.032	0.100	0.066	4×10^{-5}	(6)
IC 1396 N	I	235	0.10	0.63	0.17	4×10^{-5}	(7)
SSV 13	I	80	0.66	0.03	0.007	6×10^{-6}	(8)
T Tau	II	28	0.014	0.01	0.008	$1 - 3 \times 10^{-5}$	(9)
HH 26 C	HH	—	0.022	0.033	0.020	$\sim 7 \times 10^{-6}$	(5)
HH 54 B	HH	—	0.026	0.010	0.002	$\sim 10^{-5}$	(10)

Notes: (†): 0, I, II and HH indicate Class 0, I, II and Herbig-Haro objects, respectively.
References: (1): Nisini et al. (1999a); (2) Ceccarelli et al. (1999); (3): Nisini et al. (1999b); (4): Nisini et al. (2000); (5): Benedettini et al. (2000); (6): Giannini et al. (2000); (7) Saraceno et al. (2001); (8): Molinari et al. (1999); (9): Spinoglio et al. (2000); (10): Liseau et al. (1996).

into account that the two spectrometers map different excitation conditions and different scales, which are in any case always larger than the shock-excited emitting regions.

1.2. Comparison between models and ISO data

For each protostellar and pre-Main Sequence source with detected water lines in their ISO-LWS spectra we give in Table 2 the Class, the bolometric luminosity, the [OI], CO and H_2O cooling, as well as the derived water abundance. This latter is in most cases below the model expectations. This can be better seen in Fig.1, where the H_2O/CO and [OI]63μm/CO cooling ratios are compared with the values foreseen by the C-type shock models of Kaufman & Neufeld (1996). The threshold temperature for H_2O formation is reached in C-type shocks when the velocity reaches ~ 15 km s^{-1}. In these conditions water increases by one or two orders of magnitude (depending on density): therefore outflow sources - known to be shock excited regions - were expected to lie in the upper left part of the diagram. However, contrary to expectations, none of the observed sources is located in this part of the diagram, where the inferred shock velocities are in excess of ~ 20 km s^{-1}, but they cluster in the middle of the diagram, where the corresponding shock velocities are all within the unlikely narrow range $10 < v_{shock} < 20$ km s^{-1}. This is in contradiction with the fact that the observed sources show a wide range of post-shocked temperatures indicating velocities between 10 and 30 km s^{-1}.

Alternatively, at least in the cases where the derived temperature are of the order of 300K or even less, the low

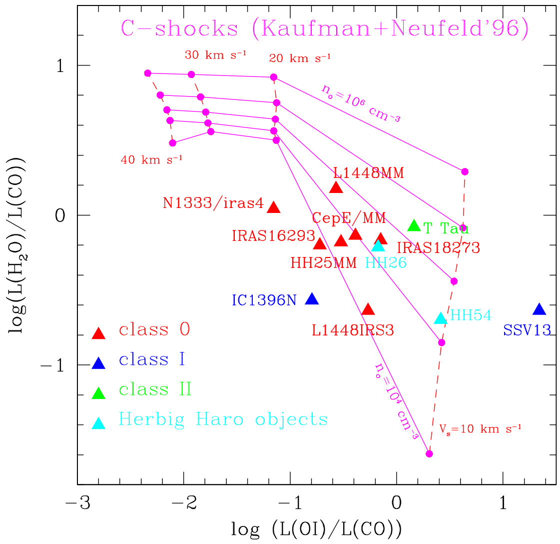

Figure 1. Cooling ratio of water-to-CO versus that one of [OI]63μm*-to-CO for protostellar sources together with the C-type shock models of Kaufman & Neufeld (1996).*

H_2O/CO cooling ratio might mean that H_2O could be mainly produced by sublimation of grain mantles at temperature relatively low (below 300K), and not through the gas phase reactions (Saraceno et al. 1998). If this were indeed the case, the excitation would be thermal and not due to shocks, but only to the presence of a radiation source. This would explain why the presence of water emission has

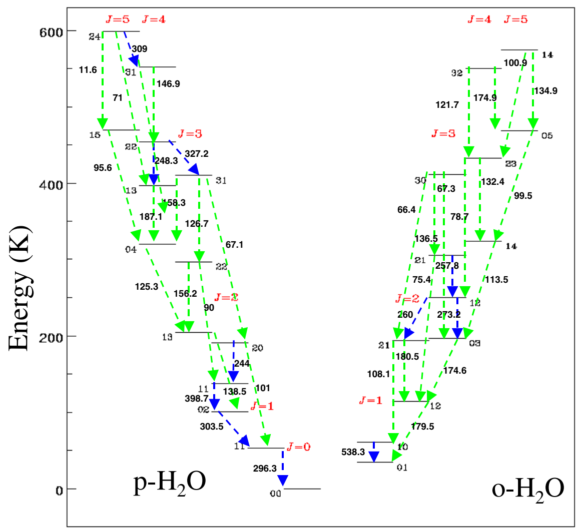

Figure 2. Energy levels diagram of the H_2O *molecule up to 600 K. The green arrows show transitions whose wavelengths lie in the PACS range (60-210* μm*), while the blue arrows are for lines in the SPIRE wavelength range (200-670* μm*). HIFI will observe between 157 and 625* μm.

been found by ISO-LWS especially on-source, and only in few cases off-source. H_2O sublimation from grain mantles has been considered also to explain the CO, H_2O, CO_2, CH_4 abundances in high luminosity sources, where the grains could be (at T $\sim$ 100K) not fully thermalized with the gas (van Dishoeck 1998).

It seems likely that we do not have a full comprehension of what is occurring in these sources and that better observations and more realistic shock models are needed that include the time dependent chemistry and the presence of ionizing radiation fields.

2. H_2O WITH FIRST

We list here the advantages given by FIRST compared to the previous space observatories in revealing water:

- for the first time, it will be possible to observe with the same telescope water lines tracing different physical conditions. Both low (fews tens of K, including the lowest energy rotational transition of ortho-H_2O observed by SWAS) and high (> 1000K) excitation transitions lie in the FIRST spectral range (see Fig. 2);

- much reliable water abundances, with respect to ISO and SWAS, will be measured. This will allow to better understand the role that H_2O plays in the energy budget of star forming regions;

- the improvement that FIRST will give to the H_2O measurements, getting over uncertainties due to large spectral and spatial resolutions, will clarify the discrepancies between the ISO and SWAS data and the theoretical models. In particular, FIRST will measure water abundances on tens arcsec scale, which is comparable to the emission region as derived from the ISO-LWS observations;

- the improved sensitivity (with respect to ISO-LWS) will allow to get statistically significant samples of H_2O sources associated with the star forming process. In particular, since ISO has shown that the Class 0 objects are strong water sources, FIRST maps of large areas of star forming regions will give the chance to investigate the spatial distribution of the earliest objects (see also Nisini et al., this conference);

- Oxygen bearing species (such as H_2O, OH, O and O_2), are particularly suited for the investigation of the chemistry of star forming regions. Information about their relative abundance will be be obtained to determine the evolutionary stages of YSOs (see on outflow evolution Codella et al., this conference).

2.1. WHY PACS AND SPIRE?

The spatial resolution of the FIRST cameras (9.4$''$ for PACS and 20$''$ for SPIRE) will allow to obtain detailed line maps of star forming regions. The temperature and density structures will be investigated. Line mapping will be a powerful tool to disentangle the complex scenario of star forming regions. It will be possible to identify and to study the spatial distribution of the low and high excitation shock components along the outflow axis, the occurrence of ionization fields and PDRs.

Fig.3 shows an example of how *line mapping* with the FIRST imaging spectrometers (PACS and SPIRE) would be able to trace the physical and chemical conditions in molecular outflows. The three ISO-LWS spectra at the right of the figure are originated in the large circles delimitating the ISO-LWS beam at three different positions along the outflow. FIRST can obtain a complete spectrum at a much greater detail (shown by the grid), making possible to study for the first time the shock excited gas along the outflow with a spatial scale of the order of $\sim$ 10$''$.

2.2. WHY HIFI?

The high spectral resolution of HIFI (up to $\sim$ 0.03 km s^{-1}) will allow to resolve the line profiles. The outflow velocity gradient will be obtained and the contribution of the outflowing gas will be discriminated from that of the quiescent emission originated both from the cloud and from the YSO warm envelope. The complex dynamics of the regions where multiple star formation occurs (e.g. T Tauri) can be studied in details.

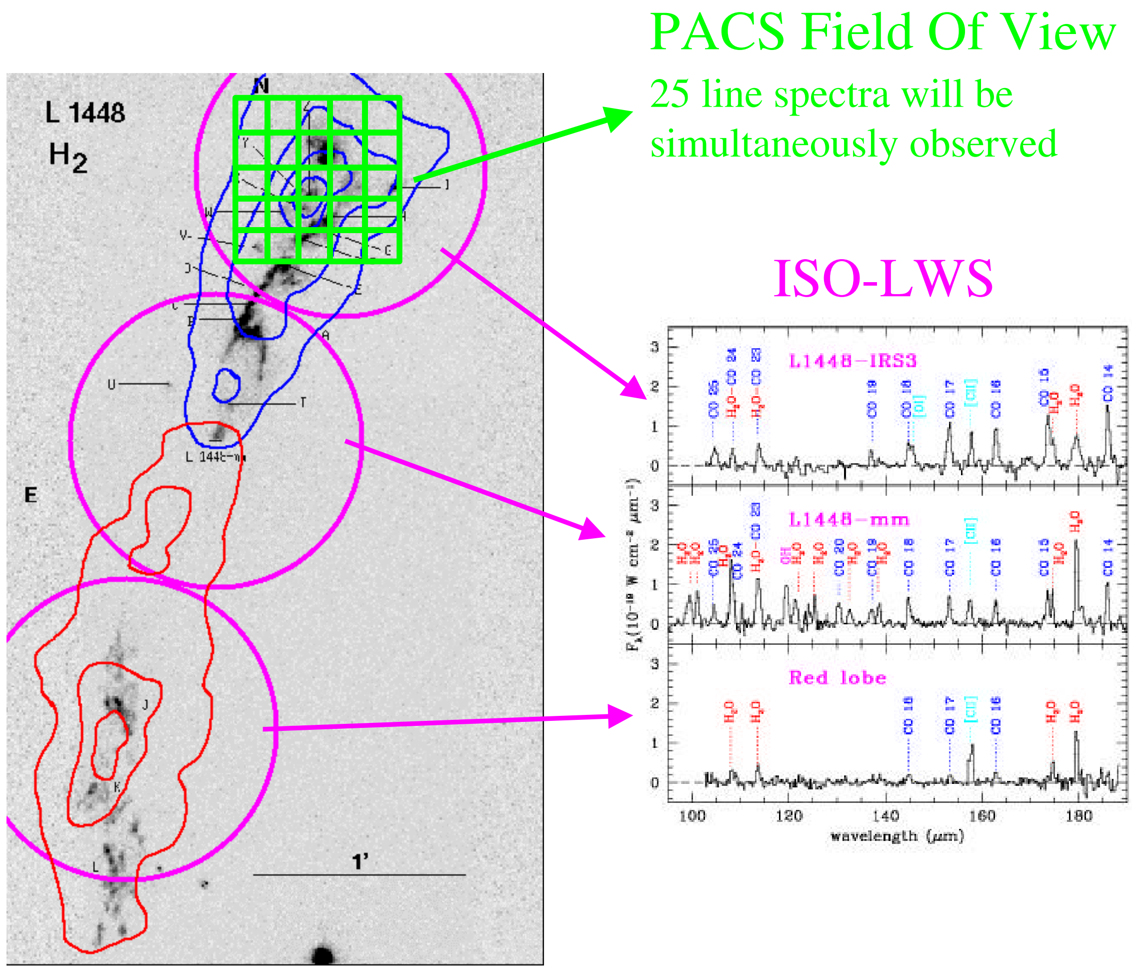

Figure 3. ISO-LWS spectra of the L1448 outflow (Nisini et al. 2000). The upper and middle panels show the spectra of the two Class 0 protostars L1448-mm and L1448-IRS3, while the lower panel presents the spectrum of the outflow red lobe. The violet circles stand for the large ISO beam. The green grid shows the PACS Field Of View (47 × 47 arcsec) and its high spatial resolution (9.4 arcsec).

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