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Water line emission in low-mass protostars*

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1. Introduction

In the quiescent ISM, most water molecules are believed to be frozen into the icy mantles of the dust grains (e.g. van Dishoeck & Blake 1998). However, if a phenomenon energetic enough to evaporate or destroy those mantles occurs, water can be released into the gas phase. In addition, at temperature larger than about 250 K, endothermic reactions in the gas phase can efficiently transform the oxygen not locked into CO molecules into H_2O molecules (Graff & Dalgarno 1987). Both effects can lead to high enhancements of the water gas phase abundance, and lead to intense emission in its far infrared rotational lines. Energetic phenomena and heating are known to occur near low-mass protostars: powerful outflows create strong shocks (e.g. Hollenbach & McKee 1989; Kaufman & Neufeld 1996), while in the infalling envelopes, heating due to the central source and/or to compression of the gas, may be sufficient to produce large over-abundances of water (Ceccarelli, Hollenbach & Tielens 1996).

2. Observations and Results

To study the water emission in low mass protostars, we observed a sample of seven young (Class 0 or I) sources, all of which located in the ρ-Ophiuchus and NGC 1333 cloud complexes (Table 1: note that 16293-SE is a recently discovered young source (Loinard et al., in prep.)). While the distance to ρ-Oph is fairly well known (120 pc – Knude & Hog 1998), the distance to NGC 1333 remains a matter of debate. The distance commonly used is 350 pc, but Cernis (1993) recently proposed a somewhat lower value of 200 pc. The latter value will be used here, but we emphasise that most of our conclusions would stand essentially unaffected if 350 pc was used instead.

The H_2O spectra were obtained using the *Long Wavelength Spectrometer* (hereafter LWS) on board the ISO satellite in the LWS01 mode. They cover the spectral range from 45 to 200 μm at a resolution of about 250; the beamwidth is $\sim 80''$ (Swinyard et al. 1996). A more detailed description of the observations, data analysis and observed fluxes is given in Ceccarelli et al. (1999a).

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Table 1: Basic parameters of the observed sources

Source	D (pc)	L ($L_\odot$)	Class	Cloud
IRAS16293	120	27	0	ρ Oph
16293-SE	120	2	0	ρ Oph
EL29	120	36	I	ρ Oph
IRAS2	200	13	I	NGC1333
IRAS4	200	9	0	NGC1333
IRAS6	200	9	I	NGC1333
SVS13	200	27	I	NGC1333

3. Discussion

Ceccarelli et al. (1999a) showed that the measured H_2O flux is not correlated with the SiO flux detected towards each source, while it seems to be correlated with the 1.3mm continuum flux. This situation suggests either that *water forms in low (≤ 50 km s^{-1}) velocity shocks (which however do not occur where the high velocity shocks probed by SiO emission are found)* or that *water does not originate in shocks.* Furthermore, either *water emission is associated to the thermal emission from the envelopes themselves*, or *it originates in shocks where the shocked material belongs to the envelopes.*

3.1. Physical conditions of the emitting gas

The ratio between the H_2O line fluxes in IRAS16293 and IRAS4 are fairly similar in all the detected lines (Ceccarelli et al. 1999a), implying that the physical conditions in both sources (i.e. gas temperature and density) are similar as well. For the other sources, the small number of transitions detected does not significantly constraint the parameter space.

To constraint the physical conditions of the emitting gas, we modelled the H_2O lines using an LVG code. The model was applied to IRAS16293 and IRAS4, and used the ratios between the 179, 174, 132 and 75 μm lines (which cover the widest range of upper level energies). Comparison between the model predictions and the observed line ratios (Fig. 1) shows that the emitting gas is dense ($n \geq 10^7$ cm^{-3}) and warm ($T \sim 100$ K) and that the lines are optically thick. In particular, the lines at 132 μm and 75 μm set stringent constraints on the density and column density, which has to be larger than about 10^{16} cm^{-2} (Ceccarelli et al. 1999b). One of the best fit to the IRAS4 data is obtained for $n = 2 \cdot 10^8$ cm^{-3}, T = 200 K, and $N(H_2O) = 10^{16}$ cm^{-2} (where we used a linewidth equivalent to Δv=10 km s^{-1}). The ratio between the predictions of this model and the observed values (top of Fig. 2) implies a beam filling factor of about $1/800 \times \frac{\Delta v}{10\text{km s}^{-1}}$. The corresponding angular size of the emitting region is therefore $\sim$ 2-3$''$, corresponding to a physical size of a few hundred AU. Slight discrepancies between the model and the observations occur systematically for the shorter wavelength lines, and may be a consequence of the lack of continuum background in our computations.

Finally, we note that the ratio between the 179 and the 174 μm lines is five times greater in HH54B than in all our sources. This indicates that the emitting regions are either much denser or much warmer (or both) in our sources than in HH54B, where the emission was ascribed to a mild shock (Liseau et al. 1996). In conclusion, the analysis of this paragraph and of the previous one lead to a rather clear situation and two possibilities to explain the observed H_2O emission: a) it is emitted in a very dense, warm and compact region, excited by a dense and relatively slow shock close to the central object, maybe caused by the interaction of the outflow with the inner regions of the circumstellar envelope, or b) to the thermal emission of these regions. We will consider in more detail these two possibilities in the next two paragraphs.

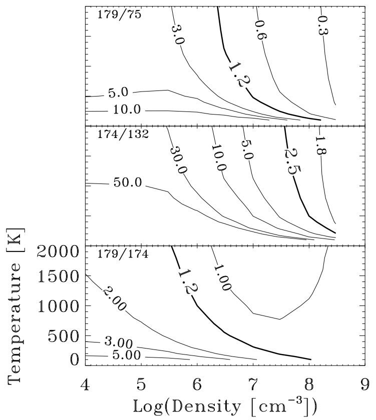

Fig. 1: Ratios between the 179 and 174 μm lines (bottom), 174 and 132 μm lines (middle) and 179 and 75 μm lines (top), assuming N(H_2O)=10^{16} cm^{-2} and Δv=10 km s^{-1}. The observed values are shown by the thick lines.

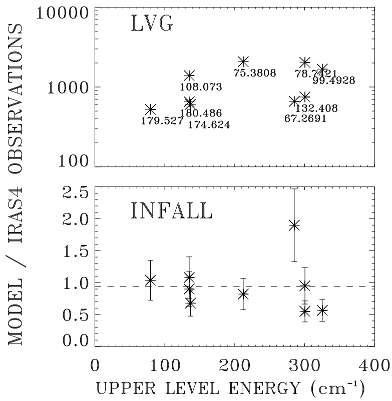

Fig. 2: Ratio between LVG model (top) or "infalling envelope" model (bottom) and observations of IRAS4.

3.2. The dense shock hypothesis

As noted above, if the H_2O emission has to be attributed to a shock this is a shock totally different to those responsible for the SiO emission: it must have a rather low velocity ($\leq$ 50 km s^{-1}). The presence of such a shock very close to the central object and due to the interaction of the outflow with the dense environment is suggested by the strong 22 GHz H_2O maser emission ($\sim 10^{-9}$ L_{bol}) with velocities ($\geq$ 7 km s^{-1}) in excess of the relevant Keplerian velocities (e.g. Claussen et al 1996). The best-fit LVG model mentioned in the previous paragraph predicts a 22 GHz luminosity $\sim 4 \cdot 10^{-11}$ $L_\odot$, much lower than the mentioned observations. Moreover the masers in the IRAS4 and IRAS16293 differ by orders of magnitudes, whereas the H_2O FIR emission is very similar. This may suggest that the FIR emission is *not* related to the 22 GHz emission arising from the outflow.

3.3. The infalling envelope model

The second possibility is that the observed H_2O lines originate from the warm inner region of the envelope. In order to test this hypothesis we used the model of an infalling envelope developed by Ceccarelli, Hollenbach & Tielens (1996), which self consistently computes the chemical composition, thermal balance and emerging far infrared line spectrum within the framework of the "inside-out" collapse (Shu 1977). Fig. 3 shows the 179 μm line flux as function of two key parameters of the model, the mass accretion rate and central mass.

The H_2O line fluxes observed towards IRAS4 can be well reproduced by this model for a central source mass of $\sim$ 0.3 $M_\odot$ and a mass accretion rate of $\sim 3 \cdot 10^{-5}$ $M_\odot$ yr^{-1} (bottom of Fig. 2). In this model, the H_2O emission originates $\leq$ 150 AU from the central source, where the density is $\geq 5 \cdot 10^7$ cm^{-3}, and the temperature high enough to evaporate the icy dust grain mantles. This infall model also predicts that the 22 GHz H_2O line should maser at a distance $\sim$ 80 AU from the central source, have a luminosity $\sim 3 \cdot 10^{-10}$ $L_\odot$, and a velocity close to

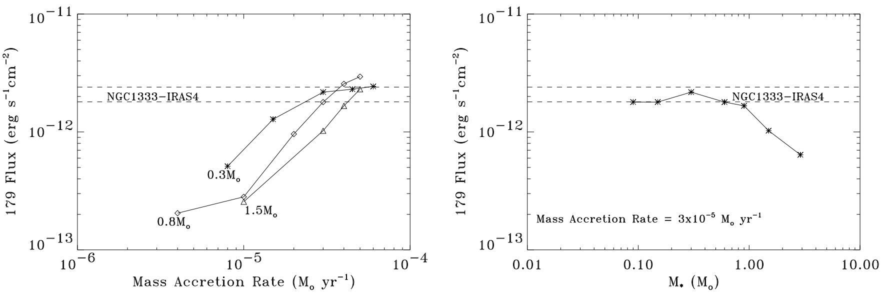

Fig. 3: The computed 179 μm line flux as a function of the mass accretion rate and central mass.

the systemic velocity. Most of the components towards IRAS4 reported by Claussen et al. (1996) have velocities which differ from that of the source, and are likely to be associated to the outflow. However, one component at about the velocity of the source was detected (bottom of their Fig. 3) with an intensity in good agreement with the predictions of this model.

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