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H_2O in Star Forming Regions

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Abstract. This paper will review the importance of the water molecule in the various stages of the star formation process, addressing in particular how the recent observations obtained with the ISO and SWAS satellites have challenged the existing theoretical models.

Water plays a fundamental role during the first stages of the star formation process being one of the main gas coolants in the warm environment of very young stars. Absorption features from water frozen on the icy grain mantles are commonly observed towards massive protostars. Radio maser lines of H_2O are also a typical signature of the first stages of star formation. Recently, thanks to the ISO and SWAS satellites, many H_2O thermal lines have been detected from young sources in different evolutionary stages. Here we review what has been learned from these observations pointing to the changes in the physical and chemical characteristics of water during the star formation process.

In the cold environment of **quiescent molecular clouds** (T ~10-30 K), the production of water in gas phase is triggered by a series of ion-neutral reactions which transform H_3^+ into H_3O^+, followed by dissociative recombination of H_3O^+ into either H_2O, OH or O. From observations recently obtained with the SWAS satellite of the o-H_2O fundamental transition at 557 GHz, abundances of gas-phase water of about $10^{-8} - 10^{-9}$ have been found in a number of molecular clouds (Snell et al. 2000). These values contrast with models for the chemical evolution of dense clouds (e.g. Bergin et al. 1995), which predict abundances of the order of $10^{-6} - 10^{-7}$, for a typical cloud age of more than 10^6 yr. Very low water abundances are on the other hand predicted by models which include grain-surface chemistry (e.g. Hasegawa & Herbst 1993, see also Bergin et al. 2000); in these models, oxygen, which is quickly depleted on the grains, is transformed into icy H_2O and thus it is not available anymore to efficiently produce water in gas phase. In such models however, the final abundance of atomic oxygen is also very low ($< 10^{-7}$), contrasting recent abundance estimates of about 10^{-4} (e.g. Caux et al. 1999).

In **protostellar envelopes** directly heated by the newly formed star, the abundance of water dramatically increases both by thermal evaporation from dust grains at $T_d > 90$ K, and by neutral-neutral reactions with activation energy barriers, which transform oxygen into OH and H_2O, and are efficient at $T > 300$ K (Ceccarelli et al. 1996; Doty & Neufeld 1997). During all the protostellar phase, young stars also develop supersonic bipolar flows of matter which drive strong radiative shocks. In magneto-hydrodynamical C-type shocks, the gas temperature does not reach values larger than $\sim$ 3000 K, and water is expected to be one of the major coolants of the post-shocked gas in a large variety

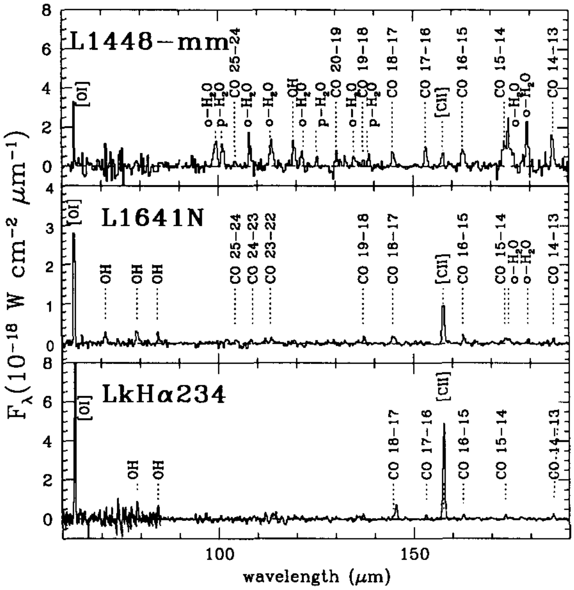

Figure 1. The far infrared ISO-LWS spectra of three YSOs in different evolutionary phases (from the youngest protostar on the top to the oldest pre-main sequence star on the bottom) are shown. Water emission is found to decline as the evolution proceeds, in favour of atomic (OI,CII) and OH emission.

of conditions (e.g. Kaufman & Neufeld, 1996). In such shocks, dust and gas remain decoupled thus making the thermal evaporation very inefficient. However, sputtering and grain-grain collisions can also remove water from grain mantles if the shock velocity is larger than about 15 km s^{-1} (Caselli et al. 1997). A large amount of warm gas-phase water has been indeed detected by the ISO spectrometers. The Orion IRc2 and KL regions have been observed in detail, showing a very complex water spectrum where absorption and emission components coming both from shocked gas and from the hot core surrounding the infrared cluster are simultaneously present (Wright et al. 2000, Harwit et al. 1998 and reference therein). The inferred water abundance exceeds 10^{-4}, thus confirming the predictions from the chemical models.

In other high mass young stellar objects, only the rovibrational transitions from the ν_2 bending mode at 6 μm have been measured (van Dishoeck & Helmich 1996), coming from warm gas ($T \sim 500$ K) and with abundances of few times 10^{-5}. Pure rotational lines of H_2O have been observed in $\sim$ 20 low mass protostars (Giannini et al. 2000; Nisini et al. 2000; Ceccarelli et al., 1999). High abundances ($10^{-5} - 10^{-4}$) are often measured also along the molecular outflows driven by the source, suggesting that H_2O is here mainly produced in shocks. This has been also confirmed by the observations of the SWAS satellite towards few low mass outflow driving sources, where the 557 GHz line appears broad with FWHM of the order of 20 km s^{-1} (Neufeld et al. 2000). When compared with shock models, however, the cooling due to water is never dominant, since more important cooling species appear always to be H_2 and CO (Giannini et al. 2000; Saraceno et al. 1999).

As the protostellar evolution proceeds towards the **pre-main sequence phase**, there is a gradual dispersal of the star circumstellar matter and a declining in the outflow power with time. At the same time, the star acquires more and more of its final mass. Consequently, there is an increasing importance of the gas excitation by the star radiation field which produces large regions of photo-dissociation in their circumstellar envelopes. Here water is dissociated into OH and then OH into oxygen again. Given the different photodissociation rates for H_2O and OH, however, there is a transition zone where the OH/H_2O abundance ratio is enhanced (see Fig. 1 and Giannini et al. 1999). Finally, at the end of the pre-main sequence evolution, water can still be found along the protoplanetary disks, mainly in solid form in the grain mantles.

In conclusion, the observations of water obtained with ISO and SWAS in different environments, have allowed for the first time to extensively prove chemical models in which H_2O play a fundamental role. Several questions, however, still remain unanswered and call for better instrumentation in terms of spectral and spatial resolution that will become available with planned space missions over the next decade (SIRTF, FIRST, NGST).

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