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Infrared absorption of H_2O toward massive young stars*

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Abstract. We present ISO–SWS observations of absorption lines of gas–phase water within its bending vibrational mode at 6 μm toward four massive young stars, which cover a range in physical parameters. Hot water with an excitation temperature >200 K is detected toward GL 2136 and GL 4176, in addition to GL 2591 discussed by Helmich et al. (this volume). The abundance of water with respect to H_2 is high in these regions, $\sim (2-3)\,10^{-5}$, and comparable to the solid H_2O abundance. In contrast, no gas–phase water absorption lines are seen toward NGC 7538 IRS9. The amount of gas–phase water is correlated with the column density of warm gas along the line of sight. Infrared observations of a larger variety of sources may provide insight into the relative importance of evaporation of grain mantles vs. high temperature gas–phase chemistry in producing the observed high abundance of H_2O.

Key words: ISM: molecules – ISM: clouds – ISM: individual: AFGL 2591, AFGL 2136, AFGL 4176, NGC 7538 IRS9

1. Introduction

The detection of more than 30 infrared absorption lines of water toward AFGL 2591 at 6 μm by Helmich et al. (1996a) using the *Short Wavelength Spectrometer* (SWS) on board the *Infrared Space Observatory* (ISO) (Kessler et al. 1996), has opened up a new avenue for studying the abundance and excitation of water in star–forming regions. The main advantage of this technique compared with emission line observations is that only a pencil beam line of sight toward the infrared source is probed, and that many lines originating from different levels are obtained in the same spectrum. Other gas–phase molecules, such as CO, C_2H_2, HCN and CO_2, can be observed by the same technique, leading to accurate relative abundances (e.g., Mitchell et al. 1990, Evans et al. 1991, Carr et al. 1995, van Dishoeck et al. 1996). Moreover, abundances of these molecules in the solid state can be obtained for the same line of sight, so that the relative amounts in the gas and solid state can be determined (Tielens et al. 1991, van Dishoeck et al. 1996). The ν_2 H_2O band at 6 μm is more suited for this purpose than the ν_3 band at 2.7 μm studied by Knacke & Larson (1991), because the infrared continuum of deeply embedded objects is much stronger at long wavelengths.

Submillimeter observations of $H_2^{16}O$ (e.g., Cernicharo et al. 1994, Tauber et al. 1996), $H_2^{18}O$ (e.g., Jacq et al. 1988, Zmuidzinas et al. 1996, Gensheimer et al. 1996), HDO (e.g., Jacq et al. 1990, Helmich et al. 1996b) and H_3O^+ (e.g., Phillips et al. 1992) have lead to the picture that the water abundance is high, $\sim 10^{-5}$, in hot star–forming cores, but much lower, $< 10^{-6}$, in cold quiescent molecular clouds. The favorite explanation is that in hot cores, the dust temperature is high enough that the icy grain mantles evaporate and return the water and other molecules to the gas phase (e.g., Walmsley & Schilke 1993). Solid water is known to be present in large quantities in dense molecular clouds from ground–based infrared observations at typical abundances of a few times 10^{-5} (Whittet 1993). Alternatively, large abundances of H_2O can be produced by high–temperature gas–phase reactions in shocks or warm dense gas (e.g., Draine et al. 1983, Kaufman & Neufeld 1996, Ceccarelli et al. 1996).

We present here ISO–SWS observations (de Graauw et al. 1996a) of H_2O 6 μm absorption along three additional lines of sight, and compare them with the results obtained for GL 2591 by Helmich et al. (1996a). Three of the sources have been studied from the ground in both solid H_2O and gas–phase CO (Mitchell et al. 1990). The latter data are particularly important, since careful analysis of ^{12}CO and ^{13}CO absorption lines at high spectral resolution has revealed the presence of both cold ($T_{\rm kin}$ = $15-60$ K) and warm ($T_{\rm kin}$ = $200-1000$ K) gas along the lines of sight. The sources are chosen to have a range of temperatures: NGC 7538 IRS9 is the coldest source in which only 2% of the gas is at $\sim$ 180 K, whereas GL 2591 is the hottest in which more than 60% of the gas is at $\sim$ $200-1000$ K. Observations of gas–phase H_2O in these sources provide insight into the origin of the water and the relation with physical parameters.

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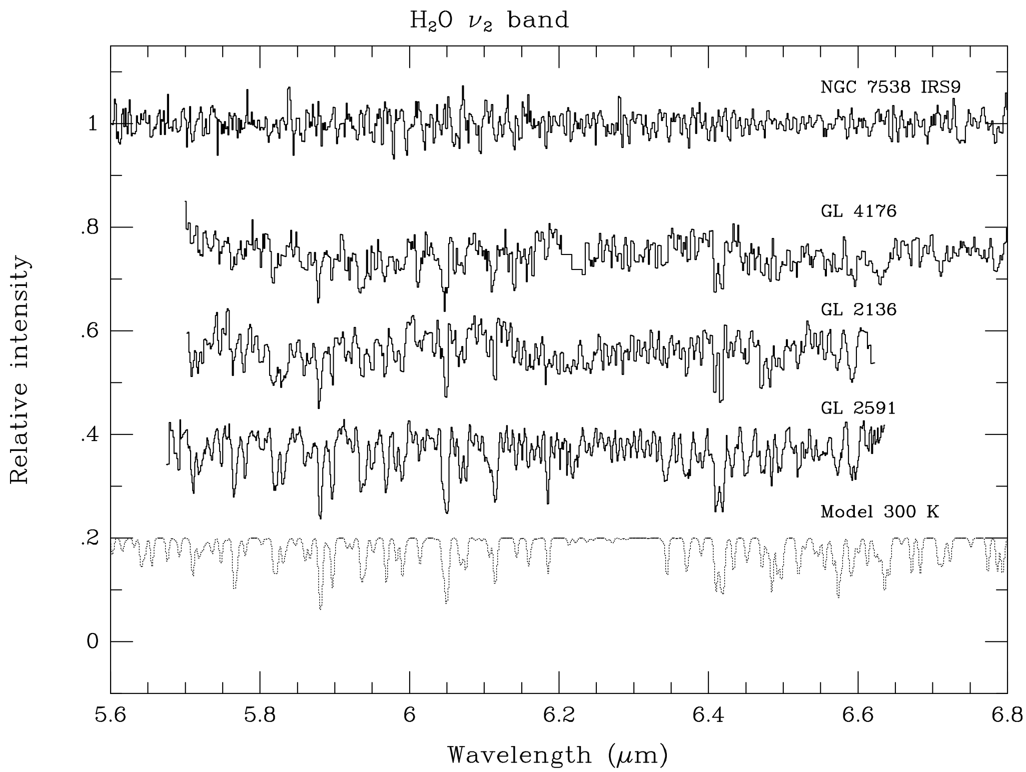

Fig. 1. Normalized spectra of NGC 7538 IRS9, GL 4176, GL 2136 and GL 2591, shifted by 0.0, -0.2, -0.4 and -0.6 respectively. A model H_2O spectrum for a column density of 2. 10^{18} cm^{-2}, T_{ex} = 300 K and b=5 km s^{-1} is shown for comparison.

2. Observations

Observations of the 5.7–6.6 μm region of GL 2136, GL 4176, GL 2591 and NGC 7538 IRS9 were obtained with the ISO–SWS AOT06. Typical integration times were 10 minutes per spectrum. The resolving power of the spectrometer is 1350 at 6 μm. The data were reduced in the standard way. The resulting, normalized spectra are presented in Figure 1. The S/N ratio on the continuum is $\sim 30-50$ in the current spectra, but is expected to improve in the future once the behavior and response of the individual detectors in space is better understood.

3. Analysis

Figure 1 shows that absorption lines of water are detected toward GL 2136, GL 4176 and GL 2591, but that no such features are seen toward NGC 7538 IRS9. The lines out of the lowest levels 0_{00} (0 K above ground), 1_{01} (34 K), 1_{10} (61 K) and 1_{11} (53 K) are most prominent. Higher excitation lines are most clearly seen toward GL 2591, but some features out of e.g. the 2_{11} (137 K), 3_{12} (249 K) and/or 3_{21} (305 K) states are present as well toward GL 2136 and GL 4176. Thus, the water is warm toward all three sources where it has been detected.

Model H_2O spectra have been constructed following Helmich et al. (1996a). In the simplest case of a single homogeneous component with LTE excitation, the spectra depend only on the total H_2O column density, the excitation temperature and the adopted line width. Figure 1 shows a model spectrum with $N(H_2O)$=2. 10^{18} cm^{-2}, T_{ex} = 300 K, and a Doppler parameter b=5 km s^{-1}, which reproduces the observations fairly well. These column densities are summarized in Table 1 as $N_{hot}(H_2O)$, and are estimated to be accurate to better than a factor of two.

The data toward NGC 7538 IRS9 are of high quality, and allow sensitive limits to be placed on the amount of gas phase water. Two possible cases are considered. The first applies to the hot component seen toward this source with T_{ex} = 180 K, for which b=5 km s^{-1} is adopted. The resulting 2σ limit is 3. 10^{17} cm^{-2}, nearly an order of magnitude lower than that toward the other three sources. The second case concerns the cold component with T_{ex} = 16 K. The b value for this component is uncertain, but is unlikely to be much smaller than the observed width $\Delta V \approx 4-5$ km s^{-1} of optically thin submillimeter emission lines (Hasegawa & Mitchell 1995). The inferred upper limit is higher in this case, 1. 10^{18} cm^{-2}, and is listed as $N_{cold}(H_2O)$ in Table 1. The limit on N_{cold} toward GL 2591 is discussed by Helmich et al. (1996a). No reliable values can be obtained for the other two sources.

The observed H_2O column densities $N_{hot}(H_2O)$ correspond to abundances x_{tot} with respect to the total H_2 column density of $(2-3)$ 10^{-5}. Table 1 also includes the fraction of hot gas observed toward three of the sources by Mitchell et al. (1989, 1990) and the abundances x_{hot}=$N_{hot}(H_2O)/N_{hot}(H_2)$, which are up to a factor of two higher for the sources where H_2O has

Table 1. H_2O column densities and abundances

Source	N_{hot}[a] (cm^{-2})	x_{hot} H_2O	x_{tot} H_2O	N_{cold}[b] (cm^{-2})	x_{cold} H_2O	$N_{tot}(H_2)$[c] (cm^{-2})	x_{hot}[c] H_2	T_{hot}[c] (K)	gas/solid[d]
N7538 I9	$< 3.\ 10^{17}$	$< 2.\ 10^{-4}$	$< 6.\ 10^{-6}$	$< 1.\ 10^{18}$	$< 2.\ 10^{-5}$	$5.\ 10^{22}$	0.022	180	<0.04
GL 2136	$2.\ 10^{18}$	$3.\ 10^{-5}$	$2.\ 10^{-5}$	...	...	$1.\ 10^{23}$	0.68	580	0.4
GL 4176	$2.\ 10^{18}$	$\geq 3.\ 10^{-5}$	$3.\ 10^{-5}$	...	...	$8.\ 10^{22}$	...	...	2.2
GL 2591	$2.\ 10^{18}$	$3.\ 10^{-5}$	$2.\ 10^{-5}$	$< 5.\ 10^{17}$	$< 1.\ 10^{-5}$	$1.\ 10^{23}$	0.63	200–1000	1.1

[a] Using b=5 km s^{-1} and T_{ex}=300 K
[b] Using b=2.5 km s^{-1} and T_{ex}=20 K for NGC 7538 IRS9, and b=5.3 km s^{-1} and T_{ex}=38 K for GL 2591
[c] From ^{13}CO observations of Mitchell et al. (1989, 1990), using [^{12}CO/^{13}CO]=60 and [^{12}CO]/[H_2]=2. 10^{-4} based on Lacy et al. (1994). For GL 4176, the H_2 column density is derived from a C^{17}O 2-1 SEST spectrum and the silicate optical depth
[d] Solid H_2O column densities summarized by de Graauw et al. (1996b)

been detected. The limit on x_{hot} toward NGC 7538 IRS9 is not very stringent because only a very small fraction of the gas is at higher temperatures; however, the limit on x_{tot} is significantly lower than that for the other three sources.

No quantitative information on $x_{hot}(H_2)$ is available for GL 4176, although unpublished CO observations by Helmich et al. using IRSHELL (Lacy et al. 1989) on the ESO 3.6m telescope indicate a large fraction of warm gas along that line of sight.

4. Discussion

Table 1 strongly suggests that the abundance of detected gas–phase H_2O with respect to total hydrogen scales with the amount of warm gas. Unfortunately, the data set is not yet large enough to determine whether there is any correlation with the temperature of the warm gas as well. About half of the warm gas toward GL 2591 is at $T \approx 1000$ K (Mitchell et al. 1989), which is high enough for the O + H_2 and OH + H_2 reactions to become significant and drive virtually all of the gas–phase oxygen into water. Such high temperatures could result from shocks associated with the outflows or from radiative heating close to the young stellar object. However, because of activation barriers these reaction do not contribute significantly at $T \approx$200 K. At these temperatures or lower, pure gas–phase chemistry models predict typical H_2O abundances of a few times 10^{-7}, much lower than observed. Thus, observations of gas–phase water toward sources with a range in temperatures can assess the importance of the pure gas–phase formation route.

The alternative explanation for the high gas–phase H_2O abundances in these hot cores is evaporation of icy grain mantles. Table 1 includes the gaseous/solid H_2O ratios, and it is clear that they are comparable whenever warm H_2O is detected. For NGC 7538 IRS9, most of the water is still in solid form, consistent with the fact that the majority of the material is at very low temperatures. This indicates that return of grain mantle material is a viable mechanism, but further observations of H_2O and other molecules are needed to fully test this scheme (see also van Dishoeck et al. 1996).

5. Conclusions

The ISO–SWS observations presented here strengthen the notion that the H_2O abundance is high, a few times 10^{-5}, in hot–core regions. Such large water abundances can result both from evaporation of grain mantles and high–temperature gas–phase reactions. Further infrared observations toward a larger variety of sources will provide constraints on the relative importance of the two formation schemes in massive star–forming regions.

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