Using Methanol Beacons to Find Water in the Dark

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Cold interstellar water

Water is one of the most important molecules in the astrochemistry of the interstellar medium and the dominant ice component in dark molecular clouds. However, there has only been one reported detection of cold gas-phase water in a prestellar core - L1544 (Caselli et al. 2012). Measuring water gas-phase abundances in a sample of dark clouds can shed light on the nature of gas-grain interaction at low temperatures (~10 K) – an issue that remains unresolved after more than 30 years of investigation.

Methanol beacons of ice desorption

How do we find the cold gas-phase water? Methanol (CH_3OH) is a molecule that can only form by grain-surface reactions. Molecular maps of dark clouds show that CH_3OH is enriched in some regions/ clumps but not in others (Buckle et al. 2006), suggesting that ice mantles must have been removed by a transient process. As water and methanol have similar physisorption binding energies (Sandford & Allamandola, 1993) any such process should therefore also release water molecules. When CH_3OH molecules have been injected into the gas, protonation followed by electron dissociative recombination will almost exclusively break them up (Geppert et al. 2006). At the same time, gas phase dissociative recombination of protonated water re-forms water and OH molecules (which can go on to form water again) and so the post-desorption lifetime of H_2O molecules is much longer than that of CH_3OH (see Figure 4). Thus, methanol peaks in dark clouds can be our beacons to find water.

The beacon sample

From the sources mapped by Buckle et al (2006) two methanol peaks, offset from their local dense core position as well as $C^{18}O$ peaks, is included in our sample – in L1512 and TMC-1C. An even stronger methanol peak in TMC-1 (Takakuwa et al. 2003) is targeted as well.

The Barnard 5 cloud in Perseus (B5) has been mapped extensively in methanol as well as a suite of other species (Charnley et al. 2013), showing a highly chemically differentiated structure similar to that found in the sample by Buckle et al. (2006). As seen in Figure 1, the strongest methanol emission arise far from the protostellar source IRS1, at the 'methanol 'hotspot', while the second most intense emission peak is closer. Both those positions were selected for our study.

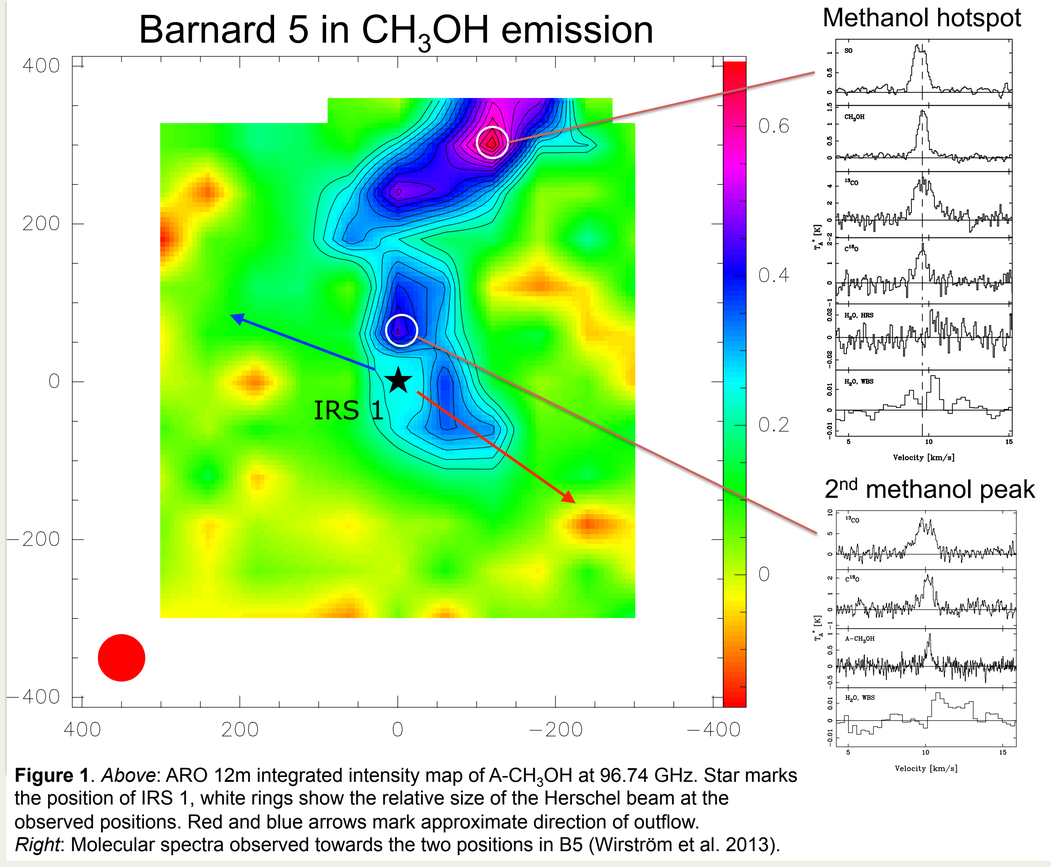


Figure 1. *Above*: ARO 12m integrated intensity map of A-CH_3OH at 96.74 GHz. Star marks the position of IRS 1, white rings show the relative size of the Herschel beam at the observed positions. Red and blue arrows mark approximate direction of outflow. *Right*: Molecular spectra observed towards the two positions in B5 (Wirström et al. 2013).

Water observations

The ground-state transition of o-H_2O ($J=1_{10}$-1_{01}) at 556.9360 GHz has been observed with Herschel HIFI in identical settings towards the sample of 5 sources. This resulted in a 6σ detection of water emission towards the methanol hotspot in B5, a tentative (3σ) detection towards the second methanol peak of B5, and non-detections towards the three remaining sources. Figure 1 shows the WBS water spectra towards the two B5 methanol peaks compared to other molecular spectra at these positions, with v_{LSR} velocities marked by dashed vertical lines. From this it is apparent that both water line profiles can be interpreted as self-absorbed emission lines at the systemic velocities. The asymmetry in peak intensities, with a suppressed blue component, is then indicative of low velocity expansion or outflow motion in the water gas.

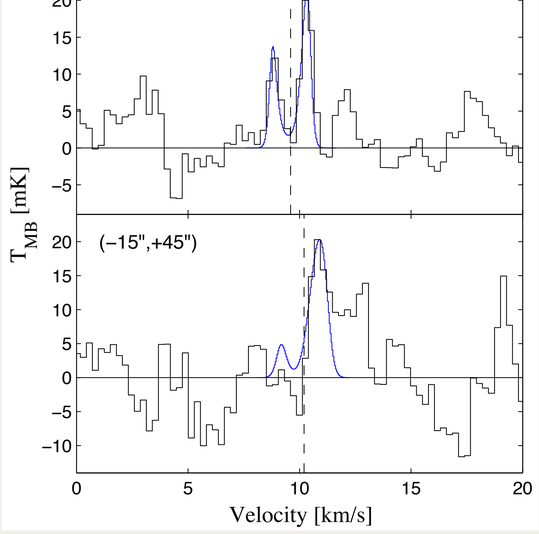
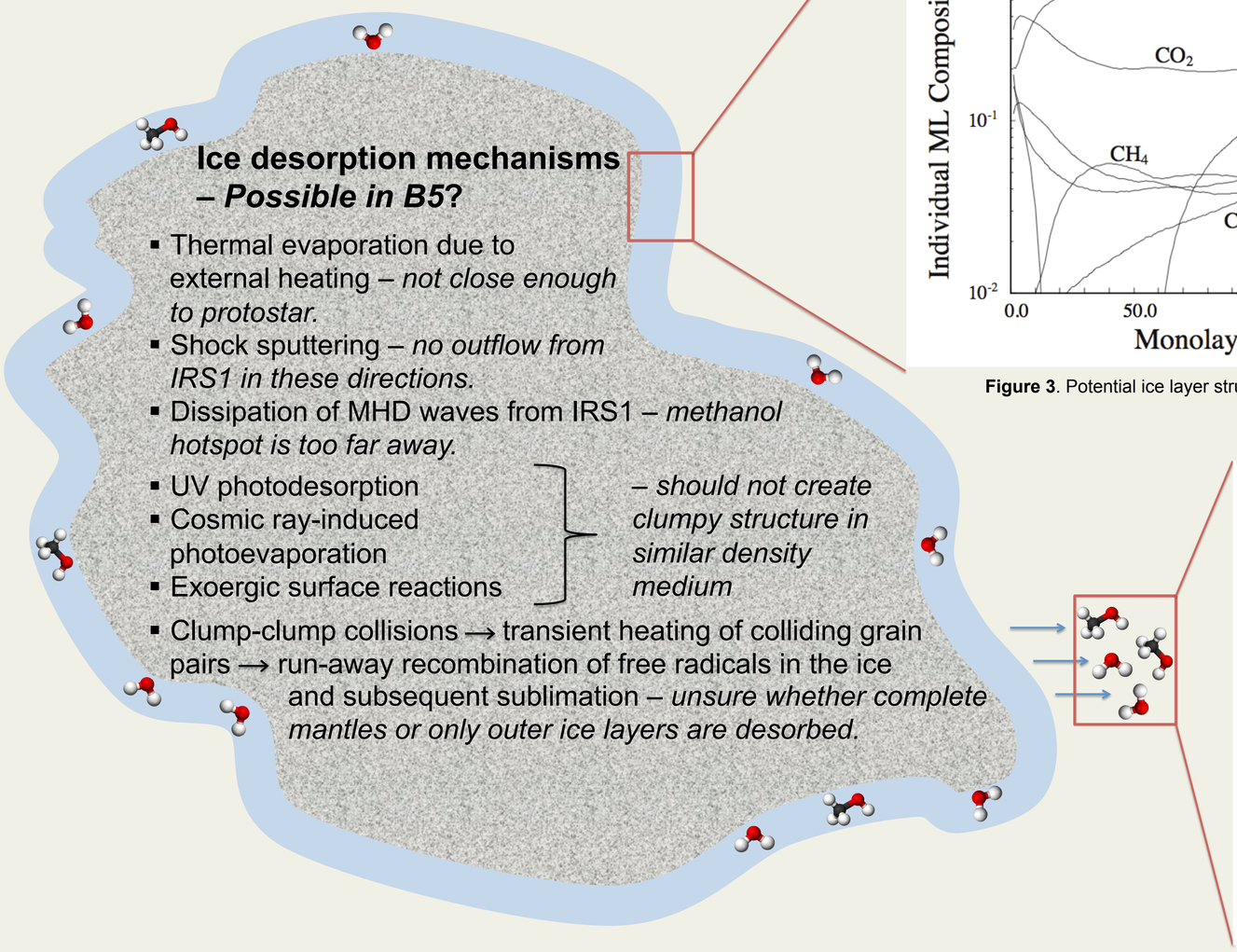


Figure 2. Water spectra generated from ALI models of expanding clouds in blue, compared to observed WBS spectra in black. Cloud v_{LSR}'s are marked by vertical dashed lines.



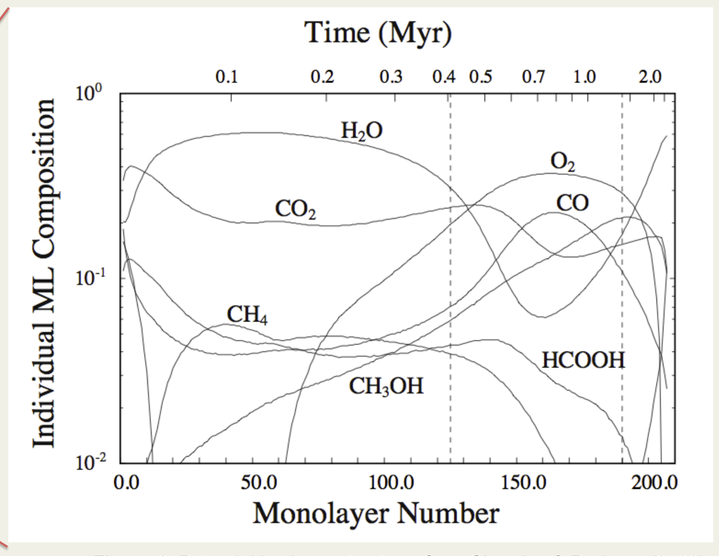


Figure 3. Potential ice layer structure, from Charnley & Rodgers (2009)

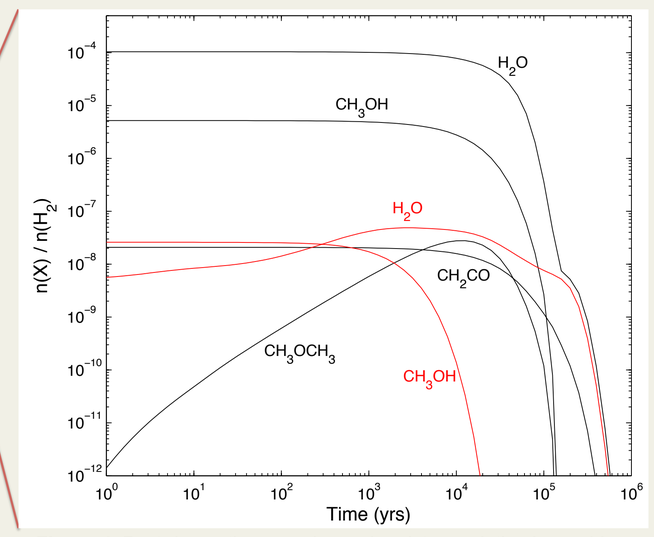


Figure 4. Post-desorption gas-phase chemistry evolution in a cold, dark cloud environment (T_{kin}=10 K, $n(H_2)$=4x10^4 cm^{-3}, A_V=10). Black curves represent complete ice mantle removal, red ones a case where only 0.5% of mantles are affected, and there only 1% of water ice.

Analysis

In order to interpret the water line profiles suggested by our observations we use an ALI code written by P. Bergman to solve the radiative transfer in a spherically symmetric model cloud. Figure 2 shows how slowly expanding gas can reproduce the observed water features towards both positions in B5, with expansion velocities increasing from zero at the center to 0.12 and 0.50 km/s in the outer parts for the hotspot and second methanol peak, respectively. In order to reproduce the deep central absorptions, outer envelopes of lower densities have to be added to the constant temperature/ density central clump. Water abundances are, however, constant throughout the model cloud. Table 1 compares the resulting o-H_2O and CH_3OH/H_2O abundances (assuming H_2O OPR=3) to the upper limits derived for the three remaining sources using the non-LTE radiative transfer code RADEX .

Implications for desorption

The fact that we detect gas-phase water at two methanol peak positions in the B5 molecular cloud supports the view that the water has recently been desorbed from dust grain mantles. While the derived H_2O/H_2 abundance at the methanol `hotspot' is more than an order of magnitude greater than that found in L1544 by Caselli et al. (2012), it is several orders of magnitude smaller than what would be expected if complete mantle disruption had occurred. Typically, methanol ice abundances are a few percent relative to water ice, but we find H_2O/CH_3OH gas-phase ratios in both B5 positions close to unity, indicating partial mantle removal of methanol-rich ice. Theoretical models of grain mantle formation predict that methanol predominantly resides in the outer ice layers, as exemplified in Figure 3. Thus, our observations are consistent with a desorption mechanism only affecting the outer ice mantle layers – possibly clump-clump collisions, see above.

The high gas-phase CH_3OH/H_2O limits in TMC 1 implies very methanol enriched outer mantles. However, severe water self-absorption similar to what is observed in B5 causes underestimates of the water upper limits.

Source	o-H_2O / H_2	CH_3OH / H_2O
B5 hotspot	2×10^{-8}	1.5 / <0.1
B5 2nd peak	6×10^{-9}	0.8 / <0.1
L1512	$<2\times10^{-8}$	>1.6
TMC-1C peak	$<4\times10^{-9}$	>9.2
TMC-1 peak	$<4\times10^{-9}$	>4.8

Table 1. Water abundances relative to H_2 and methanol in sample sources.

References

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Thanks

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