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The spatial distribution of ices in star-forming regions

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Abstract. A significant fraction of the molecular component in dense clouds exists in the form of condensed ices. In the densest star-forming cores, more than half of all molecules apart from H_2 can be frozen out onto dust grains. Thus, a full understanding of the chemical state of a molecular cloud requires detailed observations of the structure and abundances of common ices such as water, CO_2, CH_3OH, NH_3 and CO. The only way to directly observe ice in dense interstellar clouds is via absorption bands in the mid-infrared wavelength regime. Thus, infrared continuum sources located behind or inside the cloud of interest are required. The sensitivity of ground-based 8-10 m class telescopes and the Spitzer Space Telescope now allows for spectroscopy of fainter sources concentrated close enough in the plane of the sky to produce multiple lines of sight through the same cloud fragment. Combining multiple lines of sight will produce a spatial map of the abundances of solid state species in a given cloud.

We present results from several ongoing observing programs using both the Very Large Telescope and the Spitzer Space Telescope to map the spatial variation of the abundances of different ice species in a variety of dark clouds. The maps are obtained by selecting cloud regions with a high density of bright background stars. Absorption spectra of the ices present along the line of sight are obtained with both ground- and space-based mid-infrared spectrometers. Combining the spectra from different lines of sight produces a map of ices with spatial resolutions of 10–60", comparable to maps of gas-phase molecules obtained with single-dish millimeter telescopes.

These results include a Spitzer $5 - 40\,\mu$m ice map of the protostellar envelope of the class 0 protostar Serpens SMM 4. This is a followup study to an earlier map of water and methanol ice (Pontoppidan et al. 2004). We will also present results from Spitzer water ice mapping of the isolated core L723 as well as a combined CO/CO_2 ice map of the F core in the Ophiuchus molecular complex (Pontoppidan et al. in prep) obtained using ISAAC on the VLT and Spitzer-IRS.

We generally find that the local abundance of water ice is almost constant at $5 - 9 \times 10^{-5}$ w.r.t. H_2 in most dark cloud environments, and only increases beyond this at very high densities. The abundance of CO ice is found to be highly density dependent in cold cloud environments in accordance with simple freeze-out models and CO gas-phase observations (Jørgensen et al. (2005) and references therein). The CO ice abundance can be traced down to a freeze-out fraction of 5% using ground-based spectroscopy of the $4.67\,\mu$m C-O stretching mode. The abundance of CO_2 ice is moderately density dependent and increases in abundance by a factor of two for the Oph-F core from the outer part at 50 000 AU to the innermost 5000 AU. The profile of the CO_2 bending mode indicates that the CO_2 ice formed at higher densities is either relatively pure or mixed with CO ice. Finally, species such as methanol and NH_4^+, the latter presumably traced by the $6.85\,\mu$m band, are found to have highly variable abundances with no obvious relation to density.

We model the distribution of the various ice species using simple freeze-out models. In princi-

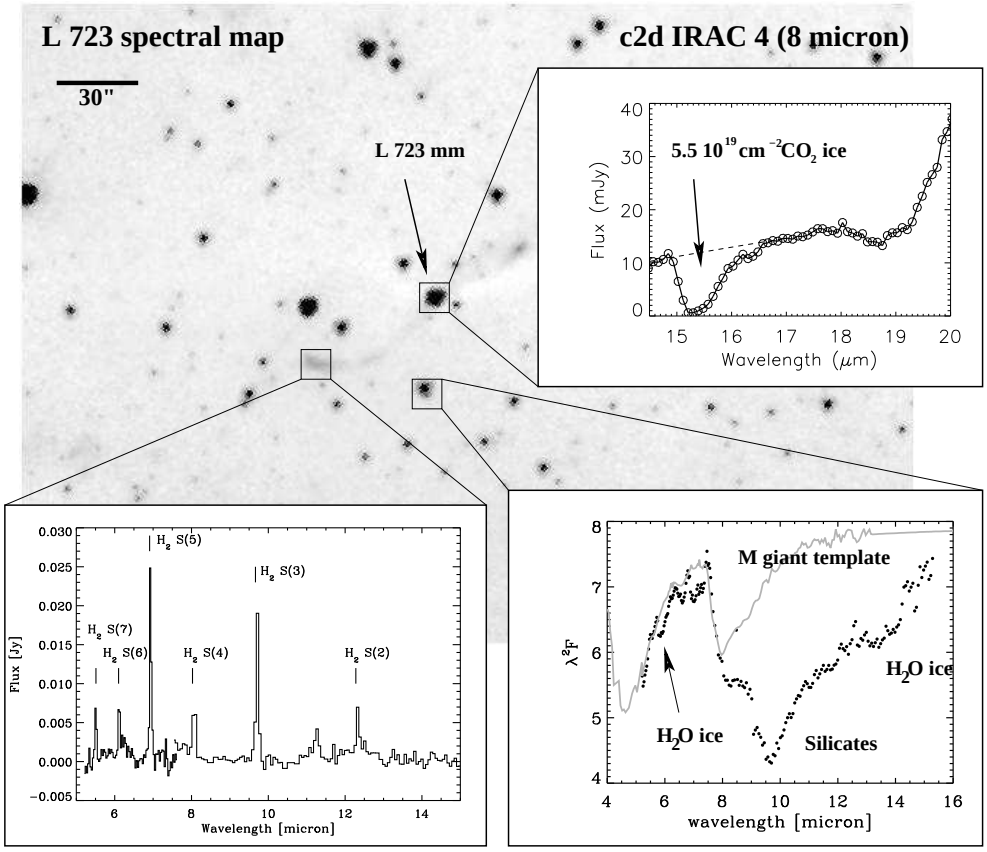

Figure 1. Examples of the Spitzer low-resolution spectra obtained for an ice map of the isolated core L723. Most of the data are spectra of background M and K giants to probe the solid state species in the cloud. However, we also see shocked molecular hydrogen from the outflow ($\sim$ 700 K). Additionally, we have detected a very high column density of CO_2 ice toward the central class 0 object (Dartois et al., in prep.).

ple, combining the observed ice maps with millimeter continuum maps, basic physical properties of the ices, such as formation efficiencies and empirical relations between different species can be derived.

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