Astrochemistry: Recent Successes and Current Challenges
Proceedings IAU Symposium No. 231, 2005
D.C. Lis, G.A. Blake & E. Herbst, eds.

doi:10.1017/S1743921306007319

The Spatial Distribution of Ices in Star-Forming Regions

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Abstract. We present results from an ongoing program to map the spatial distribution of ices in dark cloud cores with the Spitzer Space Telescope and VLT-ISAAC. The ice maps are used to directly trace the freeze-out of CO and the formation of H_2O, CH_3OH and CO_2.

Keywords. infrared: ISM — ISM: abundances — dust, extinction — molecular processes

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1. Introduction

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.

2. Observations and Results

Several observing programs using both the Very Large Telescope and Spitzer to map the spatial variation of the abundances of different ice species in a variety of dark clouds have recently been completed. The maps are obtained by selecting cloud regions with a high density of bright background stars or low-luminosity, highly extincted T Tauri 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 μm ice map of the protostellar envelope of the class 0 protostar Serpens SMM 4 (see also Pontoppidan *et al.* 2004). Additionally, we

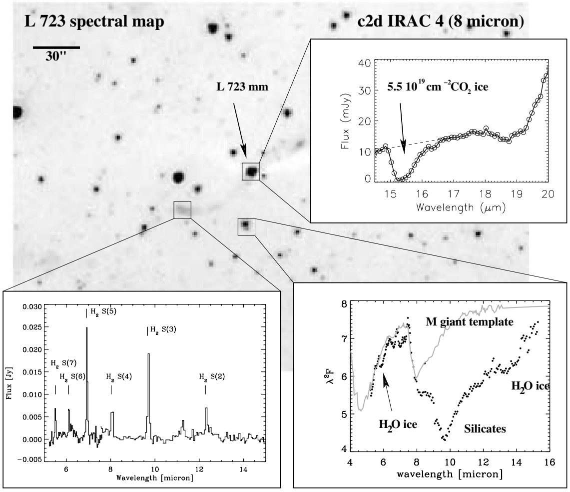

Figure 1. Examples of the Spitzer low-resolution spectra obtained for an ice map of the isolated core L723. Most of the data are spectra of background M and K giants to probe the solid state species in the cloud. We have detected a very high column density of CO_2 ice toward the central class 0 object (Dartois *et al.* 2005, *A&A*, in press).

have obtained a Spitzer map of water and CO_2 ice of the isolated core L723 as well as a combined CO/CO_2 ice map of the Oph 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 $5{-}9\times10^{-5}$ 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). In the Oph F core, the CO ice abundance can be traced down to a freeze-out fraction of 5% using ground-based spectroscopy of the 4.67 μm 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 very dilute in the CO ice that dominates the ice mantle during heavy depletion. Direct comparison between the CO stretching and CO_2 bending mode profiles shows that the ratio of CO to CO_2 molecules during heavy depletion is ∼40. We suggest that this is a direct measure of the formation rate of CO_2 relative to the freeze-out rate of CO at densities higher than a few 10^5 cm^{-3}.

Acknowledgements

Astrochemistry in Leiden is supported by a Spinoza grant from the Netherlands Organization of Scientific Research (NWO). This work is based in part on observations made with the Spitzer Space Telescope (GO-3336 and the Legacy Science program, under contract 1224608), which is operated by the Jet Propulsion Laboratory, California Institute of Technology under NASA contract 1407.

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