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The Spitzer ice legacy: Ice evolution from cores to protostars

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Ices regulate much of the chemistry during star formation and account for up to 80% of the available oxygen and carbon. In this paper, we use the Spitzer c2d ice survey, complimented with data sets on ices in cloud cores and high-mass protostars, to determine standard ice abundances and to present a coherent picture of the evolution of ices during low- and high-mass star formation. The median ice composition H2O:CO:CO2:CH3OH:NH3:CH4:XCN is 100:29:29:3:5:5:0.3 and 100:13:13:4:5:2:0.6 toward low- and high-mass protostars, respectively, and 100:31:38:4:-:-:- in cloud cores. In the low-mass sample, the ice abundances with respect to H2O of CH4, NH3, and the component of CO2 mixed with H2O typically vary by <25%, indicative of co-formation with H2O. In contrast, some CO and CO2 ice components, XCN and CH3OH vary by factors 2-10 between the lower and upper quartile. The XCN band correlates with CO, consistent with its OCN- identification. The origin(s) of the different levels of ice abundance variations are constrained by comparing ice inventories toward different types of protostars and background stars, through ice mapping, analysis of cloud-to-cloud variations, and ice (anti-)correlations. Based on the analysis, the first ice formation phase is driven by hydrogenation of atoms, which results in a H2O-dominated ice. At later prestellar times, CO freezes out and variations in CO freeze-out levels and the subsequent CO-based chemistry can explain most of the observed ice abundance variations. The last important ice evolution stage is thermal and UV processing around protostars, resulting in CO desorption, ice segregation and formation of complex organic molecules. The distribution of cometary ice abundances are consistent with with the idea that most cometary ices have a protostellar origin.

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