Observations of volatiles in protostellar cores and protoplanetary disks

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I will review current understanding of composition and evolution of volatiles in star- and planetary system- formation revealed by ALMA and other telescopes, together with theoretical insights and interpretations.
Sun-like stars are formed by gravitational collapse of a dense cloud core. In such cold dense gas, various molecules are formed not only by gas-phase reactions but also by grain-surface reactions. In fact, absorption bands of solid (ice) water, CO_2 and methanol have long been observed in infrared in molecular clouds and protostellar cores. Infrared observation is, however, effective only for ices with relatively high abundance and a clear absorption band. Once the protostar is formed, molecules in ice mantle sublimate and can be observed in radio wavelength. Even in pre-ALMA era, various complex organic species and carbon chains have been detected in the central warm region of protostellar cores (Ceccarelli et al. 2007; Sakai et al. 2008). In ALMA Science Verification Program, Glycolaldehyde, the simplest sugar, is detected towards a protostellar core (IRAS16293) for the first time (Jorgensen et al. 2012). The complex organic species show in general a very compact (< a few 100 AU) emission (Taquet et al. 2015). Quantitative estimates of their abundances, thus requires high-spatial resolution observation by ALMA. Deuterium fractionation of sublimated water is revealed by observations using Herschel and Plateau de Bure interferometer (Coutens et al. 2014). The D_2O/HDO ratio is ~1.2×10^{-2}, which is seven times higher than HDO/H_2O ratio ~ 1.7×10^{-3}. Such fractionation can be naturally explained, if the water ice is formed in two stages; early phase of molecular clouds and dense prestellar/protostellar cores (Furuya et al. 2016). ALMA observations of CO, carbon chains (e.g. C_3H_2)and SO have started to reveal disk formation (Sakai et al. 2014a; 2014b; Ohashi et al. 2014). The position-velocity diagram shows a ring-like distribution of SO emission, which could be tracing the accretion shock.
In Class II objects, i.e. the protoplanetary disks, ALMA clearly revealed spatial distributions of molecular emission lines. Theoretical models of disk chemistry predicted a layered structure of PDR layer, warm molecular layer and freeze-out midplane layer in the vertical direction (Aikawa et al. 1999; Aikawa et al. 2002; Bergin et al. 2007). This layered structure is clearly revealed by the channel map of CO (Rosenfeld et al. 2013). Observations also clearly revealed radial distributions of molecular lines. For example, N_2H^+ and DCO^+ emission shows ring structures, which is considered to correlate with CO snow lines (Qi et al. 2013; Matthews et al. 2013; Oberg et al. 2015; Aikawa et al. 2015). Theoretical models also show that N_2H^+ can be a good probe of ionization rate in the disk midplane (Cleeves et al. 2015; Aikawa et al. 2015). Another highlight is the first detection of complex organic species, CH_3CN, in the disk around MWC480 (Oberg et al. 2015). Although CH_3CN can be formed both in the gas-phase and grain surfaces, the observed abundance ratio of HCN:HC_3N:CH_3CN is better explained by the help of grain-surface reactions. Finally, detailed observations (e.g. CO and HD) and modeling of well-studied disk TW Hya indicates that CO is significantly depleted even in the region warmer than its sublimation temperature; i.e. most CO might be converted to other molecules (Favre et al. 2013). In theoretical models, CO is converted to less volatile species such as CO_2, CH_3OH and hydrocarbon ices (Aikawa et al. 1999; Bergin et al. 2014; Furuya et al. 2014). Since CO is normally the dominant carrier of carbon, depletion of CO, if verified in further observations and analysis, means the conversion of bulk carbon to less volatile molecules.

Keywords: astrochemistry, protoplanetary disks, star- and planetary system-formation

