Origins: From the Protosun to the First Steps of Life
Proceedings IAU Symposium No. 345, 2018
B. G. Elmegreen, L. Viktor Tóth & M. Güdel, eds.

doi:10.1017/S1743921319002072

ALMA observations of sulfur-bearing molecules in protoplanetary disks

H. Nomura[1], **A. Higuchi**[2], **N. Sakai**[2], **S. Yamamoto**[3], **M. Nagasawa**[4], **K.K. Tanaka**[5], **H. Miura**[6], **T. Nakamoto**[1], **H. Tanaka**[5], **T. Yamamoto**[7], **C. Walsh**[8] **and T.J. Millar**[9,10]

[1]Department of Earth and Planetary Sciences, Tokyo Institute of Technology, Japan
[2]RIKEN Cluster for Pioneering Research, Japan
[3]Department of Physics, The University of Tokyo, Japan
[4]School of Medicine, Kurume University, Japan
[5]Department of Astronomy, Tohoku University, Japan
[6]Graduate School of Natural Sciences, Nagoya City University, Japan
[7]Institute of Low Temperature Science, Hokkaido University, Japan
[8]School of Physics and Astronomy, University of Leeds, UK
[9]ARC, School of Mathematics and Physics, Queen's University Belfast, UK
[10]Leiden Observatory, Leiden University, The Netherlands

Abstract. It is thought that protoplanets formed in protoplanetary disks excite the orbital motion of the surrounding planetesimals, and the bow shocks caused by the highly excited planetesimals heat their icy component evaporating into gas. We have performed model calculations to study the evolution of molecular abundances of the evaporated icy component, which suggests sulfur-bearing molecules can be good tracers of icy planetesimal evaporation. Here we report the result of our ALMA observations of sulfur-bearing molecules towards protoplanetary disks. The lines were undetected but the obtained upper limits of the line fluxes and our model calculations give upper limits of the fractional abundances of $x(H_2S) < 10^{-11}$ and $x(SO) < 10^{-10}$ in the outer disk. These results are consistent with the molecular abundances in comets in our Solar system.

Keywords. astrochemistry, planetary systems: protoplanetary disks, ISM: molecules

---

Protoplanetary disks are the natal birth place of planets and ALMA observations are now revealing the physical and chemical structure of planet forming regions in disks. ALMA long baseline observations have detected gaps and rings which suggest possible formation of giant planets in disks. Meanwhile, molecular lines are useful tracers of physical and chemical properties of the disks.

Theoretically, it is thought that once (proto)planets are formed in disks, eccentricities of planetesimals are increased due to gravitational interactions. As a result, bow shocks are formed around the icy planetesimals that evaporate via shock heating. The evaporation rates and orbital evolution of such icy planetesimals under various conditions of disks and (proto)planets have been investigated (Tanaka *et al.* 2013; Nagasawa *et al.* 2014, 2018). For example, if a Jovian planet exists at an orbital radius of around 20 au, planetesimals can be excited to a velocity of 3 — 6 km s^{-1} inside a disk radius of 20 au. The excited velocity is high enough for bow shocks to evaporate icy planetesimals and low enough that the evaporated molecules are not dissociated in the hot gas caused by the bow shock.

We have performed model calculations of time evolution of the abundances of evaporated icy molecules, using a gas-phase chemical reaction network with desorption and

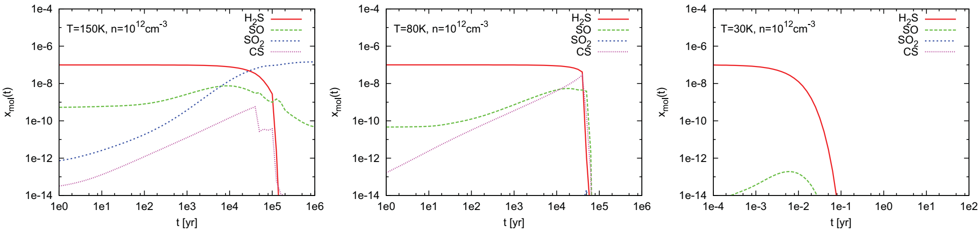

Figure 1. Time evolution of the fractional abundances of molecules evaporated from icy planetesimals. The behaviors are different depending on the dust temperature in the disk.

adsorption of molecules from/onto grains. Figure 1 shows the resulting time evolution of the abundances of sulfur(S)-bearing species at different temperatures. S-bearing molecules are known as shock tracers and can be abundant in the gas-phase only after they are evaporated from the ice. For example, emission from SO molecule has recently been observed around protostellar disks surrounded by an infalling envelope, suggesting the existence of a shock at the centrifugal radius (e.g., Sakai *et al.* 2017, Miura *et al.* 2017). In our model, the S-bearing parent molecules in ice are assumed to be H_2S and OCS. The figure shows that after the evaporation from ice, H_2S is destroyed by gas-phase reactions to form SO and then SO_2 with a timescale of 10^{4-5} yrs. Since the freeze-out temperature of SO_2 ($T_d \sim 130$ K) is higher than those of H_2S and SO ($T_d \sim 60$ K), SO_2 formed via the gas-phase reactions is quickly frozen out on grains except for in the very inner disk where the dust temperature is high ($T_d > 130$ K). In the cold outer disk ($T_d <$ 60 K) even H_2S and SO are frozen out on grains quickly. Thus, we expect H_2S and SO to become abundant in the region with 60 K $< T_d <$ 130 K, which corresponds to the giant planet forming region in disks, after the evaporation of icy planetesimals.

Based on our model calculations, we have executed ALMA observations of the 217 GHz H_2S $2_{2,0} - 2_{1,1}$ and 220 GHz SO $6_5 - 5_4$ lines in Band 6 towards 10 T Tauri disks in the Taurus molecular clouds on 1, 17 and 27 of August 2016 in Cycle 3 (2015.1.01207.S), aiming to observe molecules evaporated from icy planetesimals as a tracer of (proto)planet formation in these disks. The lines were undetected but we obtained the upper limits of the line flux densities of 12 − 19 mJy and 18 − 25 mJy for the H_2S and SO lines, respectively.

We have performed radiative transfer calculations of the molecular lines by using the density and temperature profiles of a disk model and assuming the gas-phase abundances of H_2S and SO in the outer disk, considering non-thermal desorption of molecules from icy grains. This is an analogue of the recent ALMA observations of methanol towards a protoplanetary disk, which suggests non-thermal desorption of methanol from ice in the outer disk (Walsh *et al.* 2016). By comparing the model calculations and the upper limits of the line flux densities in our ALMA observations, we have derived the upper limits of the fractional abundances with respect to hydrogen nuclei of $x(H_2S) < 10^{-11}$ and $x(SO) < 10^{-10}$. The obtained upper limits of the fractional abundances are consistent with those observed towards comets in our Solar system.

References

Miura, H., Yamamoto, T., Nomura, H. *et al.* 2017, *ApJ*, 839, 47
Nagasawa, M., Tanaka, K. K., Tanaka, H., *et al.* 2014, *ApJL*, 794, L7
Nagasawa, M., Tanaka, K. K., Tanaka, H., *et al.* 2018, *ApJ*, in press (arXiv:1812.05250)
Sakai, N., Oya, Y., Higuchi, A. *et al.* 2017, *MNRAS*, 467, L76
Tanaka, K. K., Yamamoto, T., Tanaka, H. *et al.* 2013, *ApJ*, 764, 120
Walsh, C., Loomis, R., Oberg, K.I. *et al.* 2016, *ApJL*, 823, L10