In situ cryogenic transmission electron microscopy observation on the formation of hydrogen-ordered hexagonal ices and its astrophysical implications

T. Yamazaki,[1] A. Kouchi,[1] K. Murata,[1] H. Katsuno,[1] H. Nada,[2] T. Hama,[3] and Y. Kimura[1]

[1]*Institute of Low Temperature Science, Hokkaido University, Japan*
[2]*Faculty of Engineering, Tottori University, Japan*
[2]*Komaba Institute for Science, The University of Tokyo, Japan*

Water ice is ubiquitous in molecular clouds, protoplanetary disks, and icy bodies of the outer solar system. In addition to the formation of various molecules on water ice in molecular clouds, water ice also has an important role for the formation of planetesimals in protoplanetary disks. It is therefore essential to clarify how the ice exist (e.g., phase) under such low-temperature and low-pressure environments. To investigate the ice under such environment, here we developed ultra-high vacuum cryogenic transmission electron microscopy [1] and observed water ice and its structural changes [2].

Two types of ice, cubic ice I (ice Ic) and hexagonal ice I (ice Ih), were observed while annealing under the microscope. First, ice was deposited on the 5 nm amorphous SiN_x membrane by controlling the partial pressure of H_2O at 140 K for ice Ic, and 150 K for ice Ih. Then, the ice was annealed at 83-130 K for ice Ic and 120-150 K for ice Ih. During annealing, electron diffraction patterns were acquired to investigate its structural changes.

Many diffraction spots in the electron diffraction patterns appeared with time, some of them do not belong to either ice Ic or ice Ih. To determine the origin of these diffraction spots, we calculated the *d*-spacings and diffraction intensities of several ice polymorphs that form under the experimental conditions. Then we found that the possible origin of these diffraction spots was hydrogen-ordered phases, that the ice Ic or Ih having specific hydrogen positions. We plan to discuss the formation of these ice phases and their impacts on chemical and physical evolution in a planetary system.

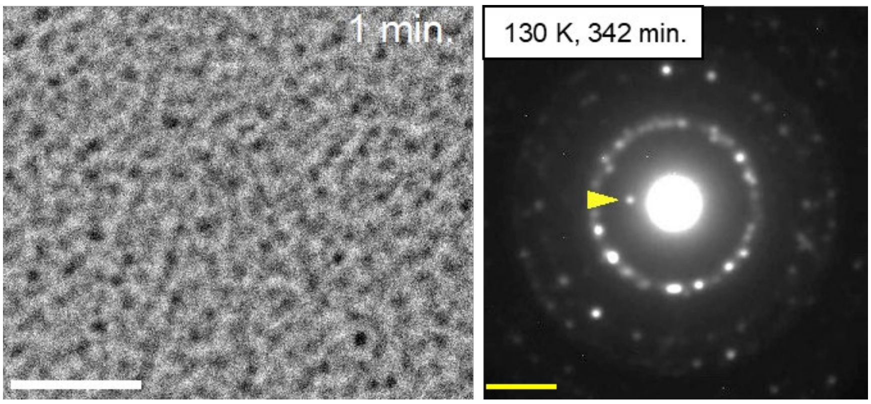

Figure 1: Examples of a TEM image of initial water ice sample of ice Ic crystals (left) and an electron diffraction pattern with a diffraction spot not observed in ordinary ice Ic and Ih (right). The TEM image was taken immediately after the start of annealing (1 min later), and the electron diffraction pattern was acquired by annealing at 130 K for 342 min. The arrowhead on the right indicates the diffraction spot corresponding to *d*-spacing of 6.4 Å, which is not observed in ordinary ice.

References

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