4-1 Study Suggests the Existence of Ferroelectric Ice in Outer Space
－A Neutron Diffraction Study of Ice XI－

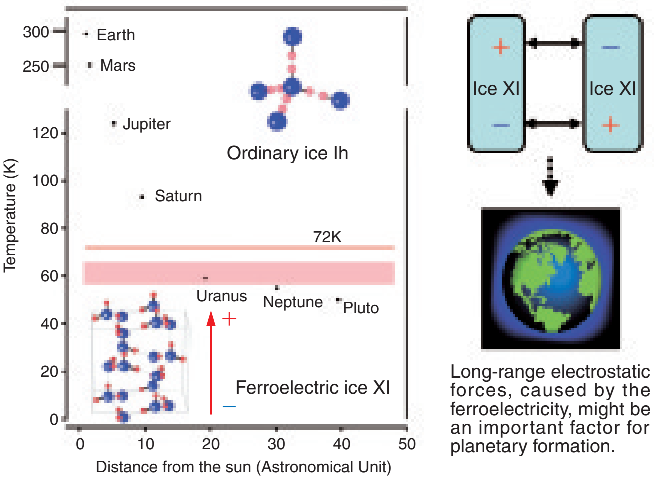

Fig.4-2 The area (below the red line of 72 K) where ice XI exists as a stable form in the solar system. The red area represents temperatures (57 - 66 K) at which ice Ih is able to transform to ice XI. Uranus and its satellites are in the red area. The surface temperature of Neptune, Pluto and their satellites is cooler, but just below the surface of these objects the temperature is in the red area. Blue and red circles are oxygen and hydrogen. Since water molecules are aligned along the c-axis (vertical direction), ice XI has ferroelectricity.

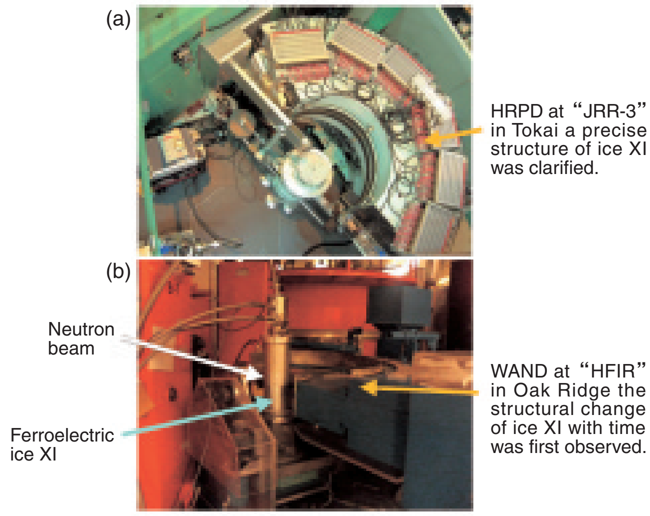

Fig.4-3 (a) High Resolution Powder Diffractometer (HRPD) located at our research reactor (JRR-3) in Tokai. We revealed the structure of ferroelectric ice in detail using HRPD. The formation processes of ferroelectric ice were investigated by the Wide-Angle Neutron Diffractometer (WAND, (b)). WAND at the High Flux Isotope Reactor (HFIR) of the Oak Ridge National Laboratory is operated under the "US-Japan Cooperative Program on Neutron Scattering".

Neutrons are sensitive to hydrogen (H), and a neutron diffraction study gives us accurate information about H atoms. Recently, we made an imitation of the ice of cold space and measured neutron diffraction of the ice. We found that the position of hydrogen became ordered at the temperatures (below -200℃) of Uranus, Neptune and Pluto. H of the water molecule (H_2O) has a positive charge. When H is ordered, ice polarizes to have a positive and negative end and becomes ferroelectric. Based on the neutron measurements, we propose that ferroelectric ice, named ice XI, exists in the universe (Fig.4-2).

In ordinary ice, named ice Ih, H is equally distributed around adjacent oxygen atoms. Ice Ih has no polarization. On the other hand, ice XI polarizes as indicated by the red arrow in Fig.4-2. Thus, the particles of ice XI have long-range electric attraction to each other. The small ice XI of several micrometers in solar nebula may grow quickly and attract electrons and ions. This special character of ice XI becomes a key that solves the mystery of planet formation and material evolution.

The structure of ice was examined in detail by our neutron diffractometer (Fig.4-3(a)) in Tokai. The structural changes with time were investigated by a high intensity diffractometer (Fig.4-3(b)) at a high flux reactor of the Oak Ridge National Laboratory. From the time-resolved measurements, we found the temperature conditions for the transformation of the largest fraction of ice into ice XI using the lowest level of impurity dopant. The red area in Fig.4-2 represents temperatures (57-66 K) at which ice Ih is able to transform to ice XI. Once ice XI is formed at this temperature condition, it remains in this form at any temperature below 72 K. The ice Ih with dopant transforms to ice XI in one week. The movement phenomenon observed in this hydrogen over the course of one week is estimated to take about 10,000 years in ice without the catalyst. Therefore, ice in outer space which anneals at temperatures of 57-66 K and is kept below 72 K for 10,000 years becomes ferroelectric ice XI.

This research suggests that future telescopes will find huge ferroelectric ice in space. We expect that there is ferroelectric ice XI on Uranus, Neptune, and Pluto, their satellites, and icy objects in the outer solar system. A neutron study concerning ice forms inside these objects is underway.

Reference

Fukazawa, H. et al., Existence of Ferroelectric Ice in the Universe, Astrophysical Journal Letters, vol.652, no.1, 2006, p.L57-L60.