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大型氷天体内部における氷 VII 相の塑性流動
Plastic deformation of ice VII in sub-Neptune-size icy planets

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It is indispensable to construct flow laws of high-pressure ices to understand the convecting interiors of large icy moons and planets. Ice VII is stable over large pressure ranges and possibly major constituent of the icy mantle of the recently found Sub-Neptune-size icy planet (Beaulieu et al., Nature2006). Rheology of high-pressure ices has been studied by using a gas-medium deformation apparatus up to several hundreds MPa. To expand the pressure range in the interior of the large icy objects, we newly conducted a synchrotron radiation study on high-pressure ice rheology.

Plastic deformation experiments of ice VII were carried out by using a deformation-DIA (D-DIA) apparatus installed at NE7A of Photon Factory, Japan (Shiraishi et al., HPR2011). We used monochromatic X-ray (50 keV, collimated to 100-500 microns) and obtained two-dimensional X-ray diffraction (2D-XRD) patterns every 3-5 minutes using imaging plate (IP). The number of diffraction spots on IP that fulfill the Bragg condition is proportional to the grain density. We expect to observe changes of the grain size from the evolution of numbers of diffraction spots as a function of time (Kubo et al., JPCS2010). Differential stress of the sample in uniaxial compression can be measured from distortions of Debye ring on IP. X-ray radiography image is used to determine the sample strain during plastic deformation.

We first compressed water enclosed in teflon capsule using D-DIA at 300K, and synthesized relatively coarse-grained ice VII showing spotty diffraction patterns. Then, the polycrystalline ice VII was uniaxially deformed at 3-10 GPa, 300-650K, and constant strain rates of around 10-5-10-6/s. The total strain reached up to 30%. We observed that the flow stress increases from 40 MPa to about 300 MPa with the pressure from 4 GPa to 10 GPa, at the strain rate of 5x10-5/s and 300K. The flow stress of ice VII is almost comparable to that of ice VI previously reported in the gas apparatus (Durham et al., JGR1996) at around 4GPa, but the pressure dependence is smaller in ice VII. The number of diffraction spots increased with plastic strain, which may indicate dynamic recrystallization of ice VII in the dislocation creep regime. Based on the relationship between the number of spots and the grain sizes in standard samples, we estimated the grain size decreased from 30-40 micron to 10-20 micron during the plastic deformation. Although some further improvements are needed to conduct the quantitative grain-size measurement, we expect that these experimental methods based on synchrotron radiation are useful to explore both GSI and GSS creep of high-pressure ices.

The stress and the temperature dependence of the strain rate will be analysed to construct the flow law of ice VII. It has been known that the diffusion mechanism in water ice changes at high pressures from molecular to ionic migration (e.g., Katoh et al., Science2002). It has also been suggested that a plastic ice phase may appear when heating ice VII above several GPa (e.g., Takii et al., JCP2008). These changes may affect the ice VII rheology in sub-Neptune-size icy planets. Our present deformation experiments cover these conditions and quantitative analysis of the obtained creep data is indispensable to know the effects on the plastic deformation of ice VII.