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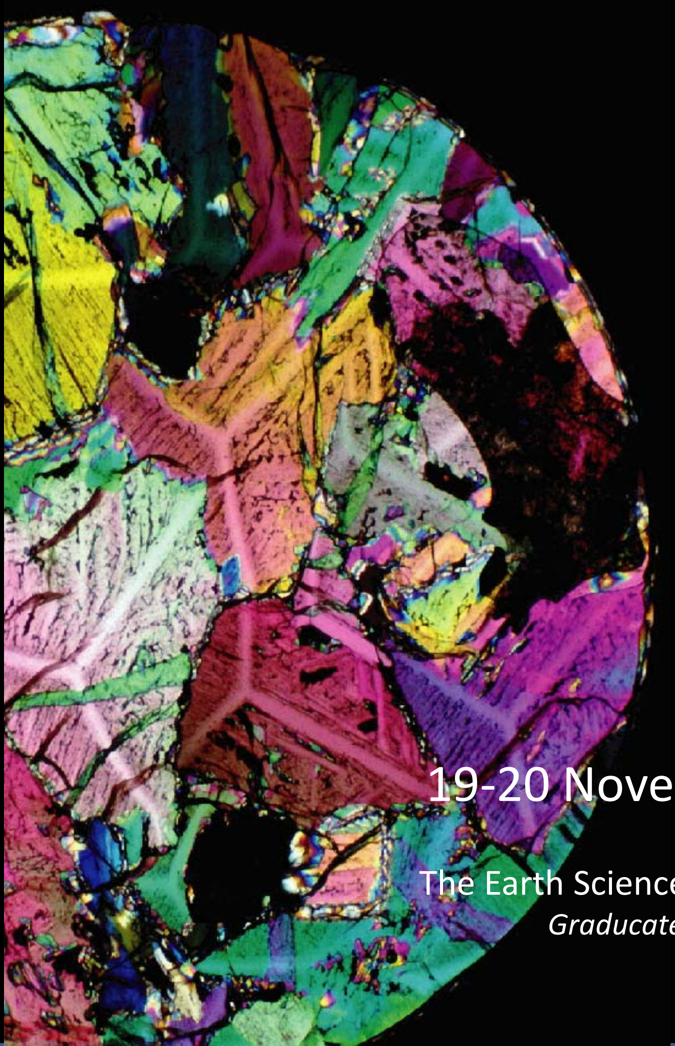
The 1st International Workshop

"Crystallization in The Early Solar Nebula 4.6 Billion Years Ago"



ABSTRACT

This Workshop is supported by Tohoku University Global COE program "Global Education and Research Center for Earth and Planetary Dynamics."

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19-20 November 2008

The Earth Science Building #503
Graduate School of Science
Tohoku University
Sendai, Japan

Organizer:
K. Tsukamoto,
H. Miura
(Tohoku University)

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Organizer: K. Tsukamoto and H. Miura (GCOE Tohoku University)

November 19, 2008

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Crystallization 4.6 Billion Years Ago

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Formation of Organic Material in the Solar Nebula & Delivery of Organics and Water to the Earth

15:20 – 15:40 Break

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Formation process of forsterite via condensation from gas phase around evolved stars and in primitive solar nebula

16:05 – 16:30 Junya Yamada (Tohoku Univ., Japan)
Condensation Experiment of Enstatite Whiskers from Highly Supersaturated Silicate Vapor

16:30 – 16:50 Jun Nozawa (Tohoku Univ., Japan)
Formation mechanism of matrix fine particles revealed by surface nano-topography

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17:10 – 17:35 Kyoko K. Tanaka (Hokkaido Univ., Japan)
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Gas-phase condensation of fine silicate crystals behind planetesimal bow shocks

November 20, 2008

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Formation of rim structure on a chondrule melt droplet during rapid cooling

09:25 – 09:50 Seiji Yasuda (Univ. of Tsukuba/Tokyo Institute of Tech., Japan)
Collision Condition for Compound Chondrule formation

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10:15 – 10:35 Break

10:35 – 11:00 Norihiro Nakamura (Tohoku Univ., Japan)
Shock melt vein as an alternative plaeomagnetic recorder against chondrules: the case study for chondrite and achondrite)

11:00 – 11:25 Makoto Kimura (Ibaraki Univ., Japan)
Genetic relationships of refractory inclusions and chondrules between enstatite, ordinary and carbonaceous chondrites

11:25 – 11:45 Masaaki Miyahara (Tohoku Univ., Japan)
Evidences of the fractional crystallization of wadsleyite and ringwoodite from olivine melts

11:45 – 12:05 Yoshihiro Furukawa (Tohoku Univ., Japan)`
Formation of organic molecules by impact chemical reactions among minerals, water, and gases

12:05 – 12:10 Closing remarks
Katsuo Tsukamoto (Tohoku University, Japan)

Katsuo Tsukamoto[1]

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Crystallization 4.6 Billion Years Ago

Early solar nebula was a gas nebula when formed 4.6 billion years ago. In a few millions years, various forms of crystallization took place from the gas nebula and the present planetary system was formed quite rapidly. The initial crystallization was the formation of fine silicate crystalline particles whose diameter was about 100-400 nm from gas. These fine particles were then melted by shock waves to form melt droplets, a few mm in diameter. These melt droplets and the subsequent silicate spheres (chondrules) were the origin of the present planet systems.

Although these processes were exact crystallization from various phases, no attempt has been done to understand these processes in the language of crystal growth as yet. Therefore various parameters, such as the rate of crystallization, temperature, etc. have not been known, though these are the key parameters for the understanding of the solar system.

The process of crystallization has been regarded as a very slow process in astronomy and in planetary sciences. We have recently succeeded in simulating the crystallization process experimentally using levitation environments, like in microgravity or in gas jet levitation experiments, to conclude that the crystallization process was much more rapid, say, 10^{4-8} times faster. In another word, the crystallization process finished in less than ten seconds for chondrule formation (silicate sphere, a few mm in diameter). However, there are still numerous discrepancies between astronomic observations, crystal growth experiments and the theory of solar system formation.

Furthermore, the interaction of organic materials with inorganic materials in solar system is of interest to retrieve information about the origin of materials and life in the solar system, in which bio-mineralization and colloidal crystallization also play an important role. These processes will be investigated by high resolution in-situ optical observation systems for varieties of crystal growth, which have been developed in the laboratory of the present author. We want to understand the materials formation in early solar nebula about 4.6 billion years ago, and explain the phenomenon in the language of crystal growth in the scale of nanometers.

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Formation of Organic Material in the Solar Nebula & Delivery of Organics and Water to the Earth

Recent studies of Fischer-Tropsch-type catalytic processes have revealed a very unusual phenomenon – the formation of a macromolecular organic coating on every substrate tested to date that is a better FTT catalyst than the original substrate. This catalyst is capable of producing thick layers of organic material on any refractory grain surface in a protostellar nebula, making such nebulae natural organic chemical factories. Delivery of sufficient quantities of volatile organics and water to the terrestrial planets to account for those presently observed has been difficult to explain if the terrestrial planets formed from chondritic starting materials. However, consideration of the radial drift undergone by accreting planetesimals appears to predict the presence of very large quantities of water in the primitive Earth. The real question may be "How did the Earth lose so much water as it accreted?"

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Formation process of forsterite via condensation from gas phase around evolved stars and in primitive solar nebula

Astronomical observation has suggested the presence of crystalline silicates in many kinds of objects. In this study, I will show a demonstration experiment concerning the formation of forsterite, which is most abundant crystalline silicate in space, in laboratory. Mg-bearing silicate grains were synthesized directly from the vapor phase by co-evaporation of magnesium and silicon oxide in a mixed atmosphere of Ar and O_2 in laboratory. It was found that the crystallinity, which was deduced from the shape of the 10 μm feature of the grains depends on the ratio of magnesium to silicon oxide in the vapor phase. When the Mg/SiO_x ratio was high, crystalline forsterite grains were produced owing to annealing of the silicate accompanied by large exothermic energy due to the oxidation of magnesium. The experimental result suggests that the crystallinity of circumstellar silicates could be determined by the balance between heat generation by magnesium oxidation and heat dissipation due to radiation. In addition, it has also been suggested that solar crystalline silicates can be produced after evaporation of precursor silicate in primitive solar nebula. In this situation, later annealing of the silicate fraction or the use of a warm substrate for condensation of crystalline silicate is unnecessary.

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Condensation Experiment of Enstatite Whiskers from Highly Supersaturated Silicate Vapor

We have synthesized enstatite whiskers and platelets from highly supersaturated silicate vapor.

Enstatite ($MgSiO_3$) whiskers and platelets have been observed in CP-IDPs (Bradley et al., 1983) and AMMs (Noguchi et al., JGU meeting 2008). CP-IDPs and AMMs are considered to be one of the most primitive materials in the solar system. However, these has been no report about the vapor growth experiment of such a unique morphology of pyroxene. So we have tried to reproduce these pyroxenes from highly supersaturated silicate vapor (far from equilibrium condition).

A polycrystalline enstatite sphere as evaporation source was prepared in a graphite cell in a vacuum chamber (Ar, 100 Pa). The sphere was heated by a 100W of CO_2 laser irradiation to be evaporated for 100 sec. After the experiments, the condensed enstatite dust was characterized by TEM, FE-SEM, and EDS.

As the temperature T decreases and thus the supersaturation σ of the vapor increases, the enstatite morphology changed from a platelet type to a ribbon type, then to a rod type with spherules. From TEM observation, a ribbon type and a rod type enstatite were elongated along <100> axis and a platelet type were thinner than 100 nm and flattened on (010). These morphologies of ribbon, rod, and platelet types are comparable to those of natural enstatite observed in CP-IDPs and AMMs.

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Formation mechanism of matrix fine particles revealed by surface nanotopography

By means of nanoscale surface observation, we have proposed new approach for investigating fine particles of cosmic materials to reveal their origin and growth conditions. Several different morphologies of polyhedral fine olivine particles with faceted faces have been found in Allende carbonaceous chondrite (4.56 billion years in geochronological age). Molecular level topography of the faceted matrix olivine by Atomic Force Microscopy (AFM) has successfully been performed. The original monomolecular growth steps of these fine particles are precisely recognized on the surfaces of matrix olivine. These growth steps are without doubt the oldest ones that human being has ever observed. The surface pattern suggests that the faceted matrix olivine could have been condensed from the gas phase, and possibly that these olivine crystals had continued to grow under a rapid cooling condition (~0.3 K s^{-1}). The estimated cooling rate agrees well with predictions based on a hypothetical rapid heating and cooling events such as shock wave heating.

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Crystallization processes of silicate particles

Crystallization of liquid (or amorphous solid) proceeds through nucleation followed by growth of crystalline nuclei. Features of crystallization are determined by the two properties of the material: one is the interfacial energy between liquid and crystal and the other is the activation energy of diffusion of molecules. We propose methods evaluating these material properties by comparing theoretical model with the crystallization experiments from liquid or amorphous silicate particles. These evaluations enable us to predict the features of crystallization under conditions different from the experiments. I would like to discuss the crystallization features of chondrules and amorphous silicate particles in the protoplanetary disk.

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Gas-phase condensation of fine silicate crystals behind planetesimal bow shocks

It is considered that fine silicate crystals in primitive meteorites and interplanetary dust particles (IDPs) have great information on the early history of our solar system. The recent laboratory experiments of gas-phase condensation showed that these fine silicate crystals can form by condensation from highly supersaturated silicate vapor. The experiments also suggested that the silicate vapor must be cooled very rapidly (~ 10^4 K/sec) to generate theses crystals. What mechanism could have generated such highly supersaturated silicate vapor in early solar nebula? We consider that a bow shock upstream of planetesimal moving supersonically relative to nebula gas is a strong candidate as the site of gas-phase condensation. The fine silicate particles evaporate as a result of shock-wave heating, then cool rapidly by the expansion of the shocked gas toward the ambient environment. We estimate the cooling timescale of the silicate vapor and consider the conditions of the gas-phase condensation based on the classical nucleation theory. Finally, we conclude that the planetesimal bow shock could generate the fine silicate crystals observed in the primitive materials in our early solar nebula.

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Formation of rim structure on a chondrule melt droplet during rapid cooling

There are two typical patterns in cross section of chondrule textures, radial pyroxene and barred olivine. The barred olivin chondrulres consist of a double structure, i.e., the barred structure inside and the outer rim with the same chemical composition. Synthesis of chondrules has been tried for the past twenty years to reproduce the typical barred texture. The rim formation in cooling has been believed to be easy relatively. However, the formation of rims has not been succeeded and the textures in experiment are still different from the double structure of a natural chondrule. Only one exception, Tsukamoto et al., reproduced the outer rim structures using a levitation technique for the first time; nevertheless the formation mechanism of rims has not been clarified. In this talk, we present a model of the rim growth starting from a seed crystal at the location of surface of pure melt droplet by using a phase field model in three dimensions, which is based on a diffuse interface model. We also discuss the condition of formation of rim structure.

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Collision Condition for Compound Chondrule formation

Some compound chondrules seem to be formed by collisions of two independent particles during heating events in the solar nebula. Although some researchers noticed collision probability of particles so far, they seldom noticed the collision conditions. If two drops experience the high-speed or grazing collision, they cannot coalesce. Or if the viscosities of both drops are too low, they cannot keep their shape and will fuse together by surface tension. In this study, we examined the collision conditions for compound chondrule formation with three-dimensional hydrodynamics simulation.

Firstly, we examined 'condition for coalescence' for various parameters; the collision velocity, angle, the diameters and viscosities of drops. We can categorize the results of drops' collisions into three groups; 'Stretching separation', 'Disruption', and 'Coalescence' and we found that these boundaries can be expressed by comparing the kinetic energy, surface energy, viscous dissipation, and rotational energy.

Secondly, we examined 'condition for keeping shape'. In order to keep their shape, the deformation timescale has to be longer than the cooling timescale. When the relative velocity is relatively low, the deformation is controlled by ram pressure of collision and the deformation time can be understood by the timescale of transit time of two drops. On the other hand, when the relative velocity is relatively high, it is controlled by the surface tension and the deformation time can be understood by damped oscillation.

Now, we obtain the collision condition for compound chondrule formation quantitatively and then we can verify formation models.

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Snow Line in Optically Thick Protoplanetary Disks

Snowline is a boundary in protoplanetary disks over which water ice particles are present due to the low temperature. The location of the snowline may affect the origin of Earth's water and the formation of Jupiter.

The temperature in the disk is determined by the balance between the heating and the cooling. The heating processes in the disk involve the radiation from the central star and the viscous dissipation in the disk. And the cooling is mainly determined by the radiation from the disk. We investigated the location of the snowline in the disk using detailed radiative transfer calculations based on the accretion disk model. One important advantage of our model is to take into account effects of absorption and scattering by icy dust particles in the disk as well as by the silicate particles. We have found that the location of the snowline is further than the location obtained by calculations without including effects of icy particles. This is because the icy particles present in the upper layer of the disk inhibit the radiation flow from the midplane of the disk to the surface from efficient flowing; this is called the blanket effect.

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Shock melt vein as an alternative plaeomagnetic recorder against chondrules: the case study for chondrite and achondrite

Dynamic shock remagnetization alters remanence vectors in meteorites, so that it makes extraterrestrial paleomagnetism complicated. Heavily shocked meteorites of shock stages S5 and S6 often contain a shock-induced melt veins (SMVs), which might have reset the remanence of an asteroidal thermal metamorphism at the time of hypervelocity collisions against a chondrite parent-body. We present micropaleomagnetic and petrologic studies of SMVs in L6S5 Tenham chondrite with c.a. 1mm thick black veins enclosing high-pressure minerals such as ringwoodite and majorite, by SQUID magnetometer. Paleomagnetic data show that the high temperature stable components of SMVs formed a cluster even from different portions of SMV, whereas the stable remanence in surrounding matrix showed a scattered orientation under stereonet projection. Magnetic force microscopy and backscattered electron images confirmed the stable remanence-carrying mineral in SMVs as framboidal or sinusoidal low-Nickel FeNis (kamacite) in a coarse-grained taenite. Blocking diagram for low-Nickel kamacite and thermal demagnetization results suggested that the high component (unblocking temperature = 270-600ºC) is a characteristic shock-induced thermal remanence that has newly been acquired during hypervelocity collision. Therefore, the SMV's newly acquired remanence could have preserved an ancient magnetic field at the time of hypervelocity collisions, and must not have experienced the heating up to 270ºC after the formation. Moreover, I might present a latest result for SMVs in DHO007 eucrite.

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Genetic relationships of refractory inclusions and chondrules between enstatite, ordinary and carbonaceous chondrites

Refractory inclusion is the typical component in carbonaceous chondrites (hereafter CCs). We systematically studied rare inclusions in ordinary (OCs) and enstatite chondrites (ECs), in comparison with chondrules.

The inclusions are usually very poor in abundance in OCs and ECs. Most of the inclusions consist predominantly of spinel. The inclusions in OCs and EC also contain high-Ca pyroxene, nepheline, sodalite and hibonite. Hedenbergite and ilmenite occur in OCs, whereas albite and Ti-rich sulfides are encountered only in EC. The oxygen isotopic compositions of inclusions in OCs and EC are plotted along the CCAM line, in contrast with chondrules in them.

Secondary phases suggest high degrees of the secondary alteration of the inclusions in OCs and ECs. However, ilmenite and hedenbergite are not encountered in ECs, whereas Ti-rich sulfides and albite are observed only in ECs. Therefore, the alteration reaction in ECs took place under reducing conditions.

The inclusions both in OCs and ECs have primary features close to those in CCs. These features strongly suggest that all the inclusions had formed in a common reservoir, and were distributed into the different regions where inclusions mixed with chondrules. Later, the inclusions experienced the alteration reaction under various redox conditions in the different regions.

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Evidences of the fractional crystallization of wadsleyite and ringwoodite from olivine melts

We identified pervasive wadsleyite-ringwoodite assemblages in shock-melt veins of Allan Hills 78003 and Yamato 74445 L6 chondrites. The assemblages were classified into two types based on their mode of occurrences; Type-1) wadsleyite-ringwoodite assemblage in a deformed porphyritic chondrule entrained in the shock-melt veins and Type-2) isolated wadsleyite-ringwoodite assemblage decorating thin wadsleyite-rim in the shock-melt veins. Type-1 assemblage appears to be that identified in the Peace River L6 chondrite. Type-2 was discovered for the first time in this study. Large gap on their compositions between wadsleyite and ringwoodite exists (up to 26 mol% fayalite). The assemblages were formed through fractional crystallization from olivine melts. We could find further unambiguous evidence supporting the fractional crystallization. Type-1 assemblage emerged from olivine pure melt, and Type-2 assemblage from olivine and orthopyroxene melt mixture. The formation of wadsleyite and ringwoodite from olivine melts is by no means restricted to the Peace River L6 chondrite, and appears to be an abundant essential mechanism probably overlooked or misinterpreted in earlier reports.

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Formation of organic molecules by impact chemical reactions among minerals, water, and gases

Frequent impacts of extraterrestrial objects melted the embryonic Earth, forming an inorganic body with a CO_2 and N_2-rich atmosphere. How and when abundant organic molecules appeared in such an inorganic world are fundamental inquiries into the origin of life. In present study, we report a facile impact synthesis of some biomolecules and their precursors from solid carbon (^{13}C), iron, nickel, water, and nitrogen all of which would have been available during impact events on Earth's early oceans. Geological and geochemical studies on the terrestrial, lunar and meteoritic materials suggest that such impacts were frequent on the Hadean Earth and indicate that ordinary chondrite, the most abundant meteorite, contains a substantial amount of iron-nickel and small quantities of solid carbon. Biomolecules and their precursors identified in the present shock recovery experiments are carboxylic acids, amines, and an amino acid. Therefore impacts of extraterrestrial objects on Hadean oceans might have prepared organic molecules in necessary abundance, variety, and complexity for life's origin, because there might be additional, as yet undetermined, products in the recovered samples and because natural impacts necessarily have greater duration and pressure than those of the experiment.

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