NASA’s Planetary Science Missions Present and Future Plans

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Planetary Science missions have revolutionized our understanding of the origin and evolution of the solar system. Planetary scientists are also enabling human space exploration by studying and characterizing planetary environments beyond Earth and identifying possible resources that will enable safe and effective human missions to destinations beyond low Earth orbit. Robotic explorers are gathering data to help us understand how the planets formed, what triggered different evolutionary paths among planets, what processes are active, and how the Earth formed, evolved, and became habitable. To search for evidence of life beyond Earth, we’ve used this data to map zones of habitability, studied the chemistry of unfamiliar worlds, and revealed the processes that lead to conditions necessary for life. In addition, we have significantly increased our ability to detect, track, catalog, and characterize near-Earth objects that may either pose hazards to Earth or provide destinations and resources for future exploration.

NASA’s Planetary Science Division (PSD) and space agencies around the world are collaborating on an extensive array of missions exploring our solar system. NASA has always encouraged international participation on our missions both strategic and competitive and other Space Agencies have reciprocated and invited NASA investigators to participate in their missions.

NASA PSD has a fleet of assets and partnerships that are focused on the exploration and understanding of the Solar System. Indeed, we are living in a golden age of discovery with a large number of operating missions ranging from orbiting Mercury to heading for beyond Pluto.

In my talk I will present an overview of current and possible future PSD missions. As we have we just launched OSIRIS-Rex, and announced the Discovery Program selections, we continue the implementation of the New Frontiers mission and the InSight mission. As our present fleet of missions continue to provide immense amounts of data from the Moon, Mars, and all the way to Pluto, we continue work to deliver NASA's contributions to fly on international missions such as ESA's JUICE mission consisting of one U.S.-led science instrument and hardware for two European instruments: the radar, ultraviolet spectrometer, and the particle environment package.

Future NASA Mars missions include NASA’s InSight lander designed to study the Mars interior and the Mars 2020 rover that will produce rock cores from a geologically diverse sight for potential future return. In addition to the strong international scientific program at Mars, NASA is developing the capabilities needed to send humans to Mars in the 2030s and beyond.

The exploration of the outer Solar System has recently revealed remarkable information regarding “ocean worlds” such as Europa and Enceladus, which have oceans or seas of liquid water beneath their icy surfaces. The Cassini mission has discovered vast oceans of liquid hydrocarbons on Saturn’s moon Titan and a submerged salt-water sea on Saturn’s moon Enceladus. Titan also has seas and lakes of liquid methane/ethane on its surface. With these new discoveries, small worlds have become a primary focus in the search for possible life elsewhere in the Solar System.

But regardless of the destination, international partnerships are an excellent, proven way of amplifying the scope and sharing the science results of a mission otherwise implemented by an individual space agency. The exploration of the Solar System is uniquely poised to bring planetary scientists, worldwide, together under the common theme of understanding the origin, evolution, and bodies of our solar neighborhood. In the past decade we have witnessed great examples of international partnerships that made various missions the success they are known for today. As Director of Planetary Science at NASA I will continue to seek cooperation with our strong international partners in support of planetary missions.

Keywords: NASA, Planetary, Missions, International

JUICE/GALA-J (1) : The Ganymede Laser Altimeter (GALA) for the JUICE mission - Introduction and current status

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We present an introduction, current status, and role of the Japan team for the Ganymede Laser Altimeter (GALA) for the Jupiter Icy Moon Explorer (JUICE) mission. JUICE is a mission of ESA to be launched in 2022, and GALA is one of the payloads of JUICE.

Major objectives of GALA are to provide topographic data of Ganymede, the largest satellite of Jupiter, and to measure its tidal amplitudes. The latter is crucially important to detect and to characterize an underground ocean on Ganymede. Furthermore, GALA support geological studies, e.g., identification of characterization of tectonic and cryo-volcanic regions, impact basins, and craters. GALA also provides information on surface roughness and the albedo.

For the laser altimetry, GALA emits and receives laser pulses at about 500 km altitude above Ganymede. Wavelength, energy, and repetition frequency of the laser plus are 1064 nm, 17 mJ, and 30 Hz, respectively. Reflected beam from the Ganymede surface is received by the receiver telescope with 25 cm diameter aperture, re-focused by the BEO including a narrow band-pass filter, and then detected by the APD detector.

Development of GALA is carried out in international collaboration from Germany, Japan, Switzerland, and Spain. GALA-Japan will develop the Backend Optics (BEO), the Focal Plane assembly (FPA) including an avalanche photo-diode (APD) detector, and the Analog Electronics module (AEM) in the receiver chain.Development of hardware, the structure and thermal models and following models, was started. In the presentation, we will report the newest project status updated for the conference date.

Keywords: JUICE, GALA, Jupiter, Ganymede, Laser altimeter

Variations of Io's volcanic activity seen in Jupiter's extended sodium nebula

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Io, which is one of the Galilean moons of Jupiter, is the most volcanically active body in the Solar System. Volcanic atmosphere is ionized and picked-up by Jupiter's co-rotating magnetic fields. This plasma distributes in Jupiter's inner magnetosphere and forms a structure called Io plasma torus. Major constituents in the torus are sulfur and oxygen ions, and most of these ions have emissions lines at UV wavelengths. Although this is a minor constituent, NaCl+ should be included in the torus since Cl+ ions was detected from the ground, and neutral sodium atoms show the most distinct emission at sodium D-line wavelengths in the torus. Not only in the torus, sodium emission can be observed also in a vast region whose extent is 1,000 Juipter's radii around Jupiter. This structure is called Jupiter's sodium nebula, or Mendillo-sphere. This means these sodium atoms have enough velocity to escape from Jupiter's and Io's gravitational-spheres.

These sodium atoms seem to be originated from sodium chloride in Io's volcanic gas. This gas becomes Io's ionospheric plasma. Pick-up of these NaCl+ ions from Io's ionosphere and their subsequent destruction in the plasma torus produces fast from of neutral sodium atoms, then Jupiter's sodium nebula is formed. This sodium nebula can be observed from the ground using small telescopes.

We have been making observations of Jupiter's sodium nebula atop Heleakala in Maui island, Hawaii, and found the nebula shows variations that seem to correspond to those in Io's volcanic activity. Since 2013, we have been making the observations in conjunctions with the Hisaki and Juno spacecraft. The most distinct event during this campaign was seen in 2015. Other than this, several minor enhancements were observed.

In this presentation, we will show latest sodium data that is representative of Io's volcanism. Also, comparisons of the sodium data with Hisaki’ s torus data and Io's infrared observations will be shown.

Keywords: Io, Jupiter, volcanism

A Survey of D-type Spectra on the Moon based on Hyperspectral Remote Sensing

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Spectral D-type asteroids are characterized by dark, red-sloped, and featureless spectra in the visible and near-infrared wavelengths, and are though to be composed of rocks rich in organic compounds. The Martian two satellites, Phobos and Deimos, resemble spectrally D-type asteroids, suggesting that their origins are by capture of D-type asteroids outside the Martian system, while we need to explain how they were captured and evolved into near-circular and equatorial orbits around the Mars. Alternative explanation is that the two satellites originated from the accumulation in a disc of debris orbiting around the Mars that were ejected by a giant impact of a protoplanet. If so, dark, red-sloped, and featureless spectra for these satellites may be accounted for by alteration due to shock processes and/or space weathering. In addition, while Phobos possesses the red and blue units that are spectrally different in the visible and near infrared wavelengths, there is no information about the difference in composition between the two units. Furthermore, recent observations with the continuous spectral reflectance (hyperspectral) data for the Moon revealed that rocks composed of anorthosites affected by space weathering show dark, red-sloped, and featureless spectra, which may resemble D-type spectra. Therefore, it remains unknown of what kind of materials the bodies showing D-type spectra are composed.
From this point of view, we focus on the Moon, because the huge data set of the hyperspectral data obtained by the recent lunar missions allow us to examine whether and what kinds of D-type like spectra could exist on the lunar surface. In this presentation, we discuss the occurrence trends and spectral characteristics of dark materials on the lunar surface based on the data mining analysis with the hyperspectral data obtained by Spectral Profiler onboard the lunar mission SELENE/Kaguya.

Keywords: Remote Sensing, Hyperspectra, Moon, Mars, Asteroid, Kaguya/SELENE

A new method to constrain the termination ages of lunar tectonic structures

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Mare ridges, lobate scarps, and straight rilles are representative tectonic structures on the Moon. Mare ridges are interpreted as the surface expressions of thrusts and folds. Lobate scarps and straight rilles are interpreted as tectonic structures formed by thrusts and normal faults, respectively. Their formations are thought to have resulted from the subsidence of massive mare basalt fills, which has been the most popular hypothesis of the origin of lunar tectonics since the 1970's. The subsidence should have occurred syndepositionally. Since major volcanic activities on the Moon are thought to have ceased around 3.0 Ga, tectonic activities should have ceased simultaneously. However, recently found some structures are inconsistent with the hypothesis. In order to clarify the origins of the tectonic structures on the Moon, their formation ages would be a clue, although they have been only obscurely constrained.

In this study, we developed a new technique, which was named “one-dimensional crater chronology”, to constrain the termination ages of tectonic structures quantitatively. The craters superposed on a thrust indicate that they were formed after the thrust activities ceased. Therefore, the linear number densities of the superposed craters indicate the elapsed time after the thrust activities ceased. We simulated lunar surface to derive the crater size frequency distributions of craters on linear fault traces and to derive the linear number densities of craters as a function of time. The one-dimensional crater chronology requires the linear number density of superposed craters to estimate the termination age.

We applied the newly developed technique to a mare ridge in the northwestern Imbrium region. The termination age of the formation was estimated as young as ~0.2 Ga. This young ridge formation is inconsistent with the conventional hypothesis. The global cooling of the Moon or the cooling of the PKT region are possible origins.

Keywords: Moon, Tectonics, Formation Age

3D collision simulation of sintered dust aggregates

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Dust aggregate is an aggregate of particles formed by collision coalescence of particles, become a material for the planetesimal. In order to form a dust aggregate, it is necessary that it does not break even if aggregates collide with each other. Some 3D collision simulation to research the collision velocity for catastrophic disruption has been carried out.

However, in the 3D collision simulation, the sintering effect was not taken into account. Sintering is a phenomenon that the surface molecule of the substance moves by warming the substance at a temperature slightly lower than the melting point. When sintering proceeded, the plasticity is lost and substance becomes brittle while it becomes hard. Considering aggregate sintering, the contact surface between the particles becomes thick, and the behavior when aggregates collide with each other is also change. Currently, Aggregate collision simulation with the effect of sintering in two dimensions is already done. The result of the research shows that aggregates break at lower collision velocity when sintering occurs.

In this study, a 3D collision simulation with the effect of sintering was carried out. That purpose is to compare 2D and 3D with respect to the effect of sintering on collision of dust aggregates.

First, on the basis of the model used in the 2D collision simulation with the effect of sintering, we made the model that can be applied to three dimensions. We introduced a force that is applied when the two contacting particles twist, which is not taken into account in the 2D simulation. In this simulation, we investigated the critical velocity for catastrophic disruption and how the number of contact points changed as a result of collision.

As a result of 3D simulation, depending on the progress of sintering, the different critical velocity for catastrophic disruption was obtained. The critical velocity for catastrophic disruption of sintered aggregates is lower than it of non-sintered aggregates. Also, although the qualitative tendencies of the result are similar between 2D and 3D, there are differences such as rebound.

This study showed that sintering affected collision of dust aggregates in 3D. When sintering occurs, the aggregate that collided is easily broken like the result in 2D simulation .

From now on, we need to further study the distribution of fragment and aggregate compression.

Keywords: Sintering, Dust aggregate, Simulation

Heating inside a highly-porous dust aggregate

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At the beginning of planetary formation, highly porous dust aggregates are formed. Outside the snowline, the main component of an aggregate is H_2O ice. Because H_2O ice is formed as amorphous ice, its thermal conductivity is small. Thermal conductivity of icy dust aggregate is small accordingly. Then it is possible to heat up inside an aggregate due to decay of radionuclides contained in silicate cores of dust grains. It is shown that the temperature increases substantially inside an aggregate, leading to crystallization of amorphous ice. During the crystallization, temperature further increases enough to proceed sintering. The mechanical properties of icy dust aggregates can change greatly, and collisional evolution of dust aggregate is affected by sintering. The latent heat of crystallization depends on chemical composition of ice. The maximum temperature depends on the composition accordingly. If the amount of impurities is large, heating by crystallization is suppressed.

Keywords: dust aggregate, heating, sintering

Collisional Growth and Internal Density Evolution of Icy Dust Aggregate in Disk Formation Stage

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Planetesimals are building blocks of planets so it is important to investigate when and where planetesimals form in protoplanetary disks. However, there are some obstacles to form planetesimals from dust by collisional growth. One of the most serious barrier is the radial drift of macroscopic dust aggregates toward the central star due to the gas drag. On the other hand, it is suggested that highly porous dust aggregates break through the radial drift barrier. In the minimum mass solar nebula model, highly porous icy dust aggregates can grow to planetesimal-sized objects by direct collisional growth inside the disk (Okuzumi et al. 2012, Kataoka et al. 2013). However in these studies, it is not considered when the collisional growth begins in protoplanetary disks. If there is no process that suppresses collisional growth of icy dust aggregates, collisional growth may begin from the protoplanetary disk formation stage.

To investigate how the disk evolution in disk formation stage affects the collisional growth and internal density evolution of porous icy dust aggregates, we have calculated the evolution of radial size distribution of icy dust aggregates using the disk model including mass accretion from molecular cloud core developed by Nakamoto & Nakagawa (1994) and Hueso & Guillot (2005).

As a result, we find that icy aggregates cannot become highly porous as previous studies (Okuzumi et al. 2012, Kataoka et al. 2013), and they suffer the radial drift without growth to planetesimal-sized object. Because the small dust particles from molecular cloud core contribute the growth of aggregates in earlier phase of their growth, the aggregates cannot have many voids until they become large size that collisional compression works effectively. This result suggests that a process that suppresses collisional growth of icy dust aggregates in early stage of protoplanetary disks is present and the age of planetesimals would not be very young.

Dust and gas co-evolution with dust-gas backreaction in protoplanetary disks

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Planetesimal formation has to overcome two major barriers. The first one is the radial drift barrier. Dust particles in protoplanetary disks feel a headwind from the surrounding disk gas. Due to the gas-dust friction, dust particles lose their angular momentum and drift inward. The second one is the fragmentation barrier. The collision velocity of dust particles can be too high for the particles to stick together.
Recently, Gonzalez et al. (2017) have shown in their 3D SPH simulations that the backreaction from dust to gas affects the disk gas structure so that the dust particles can overcome these barriers. In their simulations, dust particles pile up due to the fragmentation or rapid growth. This dust concentration provides a positive torque for the surrounding gas and makes the gas moving outward. The modified gas structure prevents dust particles from drifting inward. However, Gonzalez et al. (2017) have only performed simulations with large viscosity and specific disk conditions, hence how the effect of the backreaction depends on disk parameters is still unclear.
Here we present analytic expressions of gas and dust velocities in protoplanetary disks including the effect of backreaction from dust to gas. These analytic formulas allow us to describe the dust and gas co-evolution including the effect of the frictional force from dust particles. The analytic formulas suggest that the backreaction forces the gas move outward even if the dust-to-gas mass ratio is lower than the standard value of 10^{-2}, as long as the gas viscosity is small. We also present the results of 1D and 2D dust-gas two-fluid simulations to demonstrate the backreaction changes their evolution. We find that when the viscosity is small or the dust-to-gas mass ratio is high, the outward motion of the gas provides a positive surface density gradient in some part of the disk.

Keywords: protoplanetary disks

Rocky Planetesimal Formation by Gravitational Instability of a Porous Dust Disk

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Recently, it is proposed that porous dust aggregates are formed by pairwise accretion of silicate dust aggregates, which can avoid the radial drift and fragmentation barriers during their growth if the dust monomer size is on the order of nm [1]. Indeed, it is suggested that dust monomers in protoplanetary disks are not same as sub μm-sized interstellar dust grains, but they have experienced evaporation and condensation [1]. Moreover, matrix grains in primitive meteorites [2] and interplanetary dust particles [3] contain nm-sized grains.
We investigate the gravitational instability (GI) of the disk consisting of porous dust aggregates of nm-sized silicate monomers. We calculate the equilibrium random velocity of the dust aggregates considering gravitational scattering and collisions among them, gas drag, and turbulent stirring and scattering according to Michikoshi & Kokubo (2016) [4], and then evaluate Toomre's stability parameter Q [5]. The condition for the GI is defined as $Q < 2$ taking into account the non-axisymmetric mode [6].
We find that for the minimum mass solar nebula (MMSN) model at 1 au, the disk becomes gravitationally unstable as the dust aggregates evolve through gravitational compression if turbulent strength is $\alpha < 5\times 10^{-5}$. We also derive the critical disk mass and dust-to-gas ratio for the GI as a function of α.
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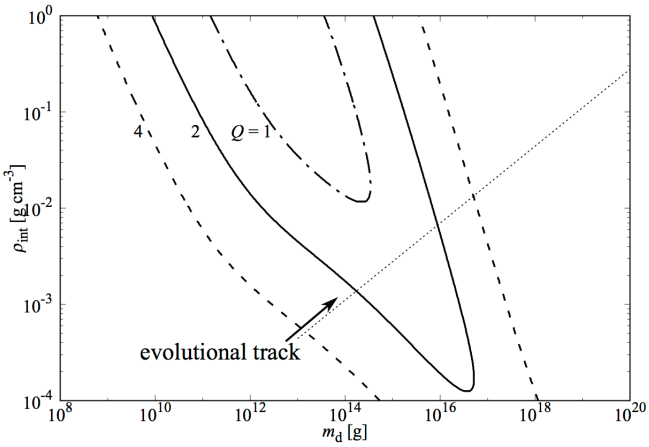
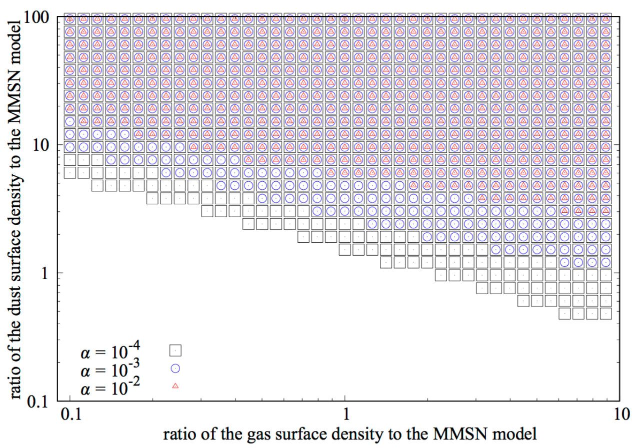
Figure 1. (left) Toomre's Q in the m_d-ρ_{int} plane at 1 au for the MMSN disk with $\alpha = 10^{-5}$, where m_d is the mass and ρ_{int} is the mean internal density of the dust aggregates. The dash-dot, solid, and dash contours correspond to Q = 1, 2, and 4, respectively. The dot line shows the evolutional track of dust aggregates.
Figure 2. (right) Disk parameters for the GI at 1 au. The red triangle, blue circle, and black square shows α = 10^{-2}, 10^{-3}, and 10^{-4}, respectively.

Keywords: planetesimal formation, protoplanetary disk, gravitational instability, porous dust aggregate





Condition of the efficient formation of dense dust clumps due to the streaming instability

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Planetesimal formation is the key process for the planetary system formation. There are, however, many theoretical difficulties to form planetesimals. The fragmentation barrier is one of the most serious problem for planetesimal formation (Blum & Munch, 1993). The maximum size of dust particles is limited to about millimeters to centimeters by this barrier. We need a model to connect these small dust particles or pebbles to planetesimals.

The streaming instability is one of the promising process to form planetesimals (Youdin & Goodman, 2005; Johansen et al., 2012). This instability can form the dense dust clumps consisting of millimeter- or centimeter-sized particles. These dense dust clumps are sometimes gravitationally bound and are considered to form planetesimals by subsequently self-gravitational collapse.

Whether the streaming instability can form dense dust clumps depends on the particle size and the dust-to-gas ratio of protoplanetary disks. Carrera et al. (2015) conducted a parameter survey to find the critical dust-to-gas ratio for strong clumping due to the streaming instability at each particle size.

In this study, we focus on the efficiency of the formation of dense dust clumps. We conducted 2D simulations of dust-gas system like Carrera et al. (2015). We investigated how much dust particles contribute to clumping in the parameter space where indicated as being appropriate for formation of dense dust clumps by Carrera et al. (2015). Then we compared the mass of the entire dust particles that contributed to clumping with the mass of solar system planets, looking for conditions suitable for solar system formation. We found that a sufficient amount of particles contribute to clumping when dust-to-gas ratio is 0.04 even though the dust particles have relatively small radius about 1 mm.

Keywords: Protoplanetary disk, Planetesimal formation, Planetary system formation

Co-Accretion of Chondrules and Fluffy Matrices

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Chondrules are the principal components of the most common meteorites, chondrites. This facts may mean that rocky planetesimals in our solar system are formed via accretion of chondrules. However, it is not yet understood how chondrules grow into planetesimals.
Several pieces of meteoritical evidence suggest that chondrites contained abundant nanograins in their matrices. These nanograins must play a key role for growth of dust aggregates. Therefore we examined a scenario in which rocky pkanetesimals are formed via co-accretion of chondrules and fluffy aggregates of nanograins.
Though our scenario succeeded in forming rocky planetesimals, we also found a new problem for "chondritic" planetesimal formation. If the mass fraction of chondrules is not hight enough, and the density of matrices is too low to stop chondules when dust aggregates collide, then the retainment of chondrules in fluffy matrices is nontrivial. Future work on this point is needed.

Keywords: Rocky planetesimal, Chondrule

Effects of magnetically-driven disk winds on type I migration

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Magnetically-driven disk winds would alter the surface density slope of gas in the inner region of a protoplanetary disk ($r < 1$au), which in turn affects migration of low-mass planets (type I migration). Recently, the effect of disk wind torque has been considered, showing that it would carve out the surface density of the disk from the inside out.

The direction and rate of type I migration depend on the surface density slope of gas and saturation of the corotation torque. We investigate migration of low-mass planets in disks evolving via disk winds. In MRI-active disks, the surface density slope can be flat in the inner region, and migration of super-Earth mass planets is suppressed. In MRI-inactive disks, in which a positive surface density slope can be achieved, planets in the sub-Earth mass range may undergo outward migration.

It has also been pointed out that the wind torque induces global gas flows (wind-driven accretion), which may modify the desaturation effect of the corotation torque. Then, we investigate effects of wind-driven accretion (global gas flows) on type I migration. In MRI-inactive disks, in which the wind-driven accretion dominates the disk evolution, the gas flow at the midplane plays an important role. If this flow is large, the corotation torque is efficiently desaturated. Then, the fact that the surface density slope can be positive in inner region due to the wind torque can generate an outward migration region extended to super-Earth mass planets. In this case, we observe that no planets fall onto the central star in N-body simulations with migration forces imposed to reproduce such migration pattern.

Keywords: Magnetically-driven disk winds, Type I migration, Protoplanetary disk, N-body simulation

Satellite formation via pebble accretion in circumplanetary disks

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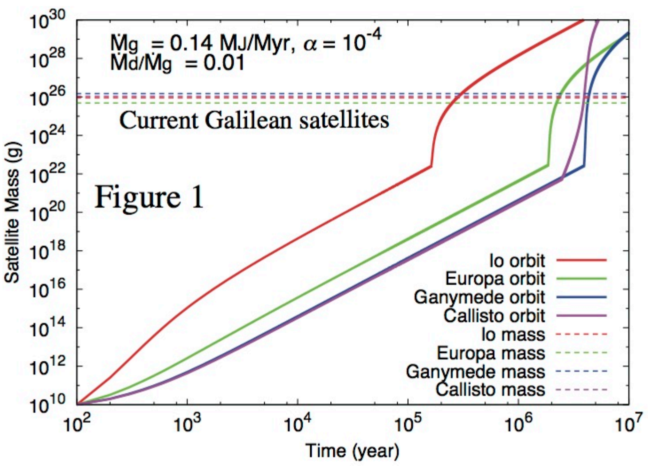
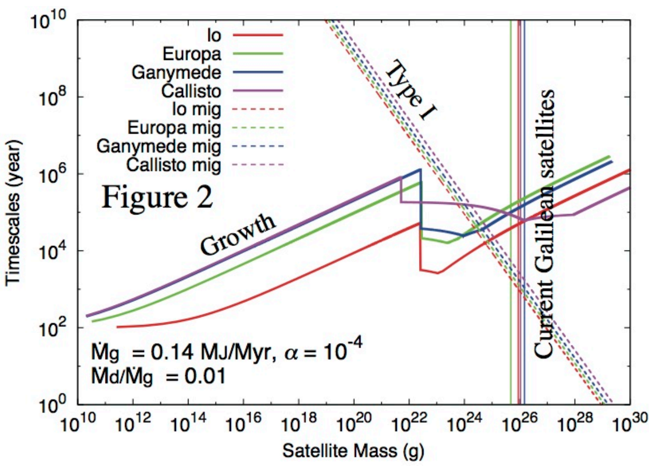
The four icy satellites around Jupiter called "Galilean satellites" are considered to have formed in a circumplanetary disk. In Shibaike et al. in prep., we calculated the growth and drift of dust particles in a steady circumplanetary disk and investigated the success condition of satellitesimal formation. We found that the dust-to-gas inflow mass flux ratio has to be higher than unity for the satellitesimal formation in the circumplanetary disk by the collisional growth of the dust particles and that the all dust particles drift to Jupiter in other conditions. However, it is difficult to achieve this success condition.
Recently, a new planetary formation model called "pebble accretion" has been attracted attention. In this model, several protoplanets accrete a lot of cm-sized dust particles (called "pebbles") drifted from the outer region of the protoplanetary disk and grow rapidly to planets.
In this work, we applied this "pebble accretion" model to satellite formation. We calculated the growths of the protosatellites accreting the dust particles growing and drifting in the circumplanetary disk. Figure 1 represents the growths of the protosatellites on the fore fixed current Galilean satellites' orbits when the gas inflow mass flux is 0.14*MJ*/Myr and the strength of turbulence in the viscous accretion disk is $\alpha=10^{-4}$. We found that there is a possibility that the protosatellites can grow to the planets with the mass of the Galilean satellites, 10^{23} kg, within 10^5-10^7 years even in the case with that the dust-to-gas mass inflow flux ratio is 0.01. Figure 2 represents the timescales of the growths of the protosatellites and the inward drifts by Type I migration. Our estimate suggested that the protosatellites drift to Jupiter by the Type I migration because the growth timescales become longer than the drift timescales when their mass reach 10^{21} kg. We used a simple model assuming steady states in these estimates. We will discuss the satellite formation in unsteady states, in other words, the evolutions of the circumplanetary disk and the orbits of the protoplanets in our talk.

Keywords: Satellite, Pebble accretion, Protosatellite, Circumplanetary disk, Galilean satellites, Type I migration





Terrestrial magma ocean origin of the Moon: A numerical study of a giant impact incorporating the difference of the equations of state for liquids and solids

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The origin of the Moon is one of the most important topics in the planetary science and geophysics.
Since the giant impact (GI) scenario was suggested, it has been believed that the Moon was formed by the impact of relatively large object (Mars-size) to a growing Earth.
Recently, however, the GI has been challenged; the isotope ratios of particular elements show nearly identical values for the bulk component of the Earth and that of the Moon.
This means that the Moon should have been formed from the proto-Earth originated materials.
However, previous numerical simulations of the GI concluded that the Moon was formed from the impactor.
In order to resolve this problem, several modified models to the GI have been suggested.
However, most of them have difficulties to explain much higher angular momentum and the dissimilarity of the FeO content.
Recently, a new model, to form the Moon from the Earth’ s magma ocean, is suggested.
According to this scenario, the majority of heating occurs in the terrestrial magma ocean, which results in the ejection of the target-originated materials.
Since the formation of the FeO-rich magma ocean is a natural consequence of the formation of the proto-Earth, this scenario can also explain the dissimilarity of the FeO content.
We carried out the numerical simulations of GI in which the magma ocean is modeled with an equation of state for liquid.
We show the comparisons of the GI between liquid equation state and solid one.

Collisional fragmentation of planetesimals in the giant impact stage

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Mars-sized protoplanets formed in a protoplanetary disk further grow to be terrestrial planets via mutual collisions between protoplanets or "giant impacts" after gas depletion, which are believed to from the terrestrial planets in the solar system. The resultant planets mainly have eccentricities much larger than those of Earth and Venus, so that the dynamical friction of a planetesimal disk is needed for eccentricity damping. However, planetesimals stirred by planets are dynamically so hot that collisional fragmentation of planetesimals inhibits the dynamical friction. Therefore, the N-body simulation including collisional fragmentation as well as dynamical friction is required for the investigation of giant impact stage. We newly develop the N-body code with protoplanets and super particles representing planetesimals and smaller fragments. Through the simulations with the code, we give constrains on the total mass and radii of planetesimals remaining in the giant impact stage.

Keywords: Planet formation, collisional fragmentation

Terrestrial Planet Formation: Constraining the Formation of Mercury

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The formation of Mercury remains poorly understood. Importantly, previous works have not considered the formation of Mercury in the context of formation of the other terrestrial planets.

We investigated terrestrial planet formation by performing N-body simulation runs using hundreds of embryos and thousands of disk planetesimals representing a primordial protoplanetary disk. To investigate the formation of Mercury, these simulations considered an inner region of the disk (the Mercury region) and disks with and without mass enhancements beyond the ice line location in the disk.

Although Venus and Earth analogs (considering both orbits and masses) successfully formed in the majority of the runs, Mercury analogs were obtained in lesser runs. Our Mercury analogs concentrated at orbits with semimajor axes slightly smaller than that of Mercury ($a = 0.39$ au), relatively small eccentricities/inclinations, and median mass $m \sim 0.2$ Earth masses with variations within a factor of a few. In addition, we found that our Mercury analogs acquired most of their final masses from embryos/planetesimals initially located between the disk inner edge and ~1–1.5 au within 10 Myr, while the remaining mass came from a wider region up to ~3 au at later times. These results suggest that to reproduce the orbit and mass of Mercury, the protoplanetary disk should have an inner edge at a 0.3 au with mass peak located beyond 0.6 au. Also, the Mercury region should be mass depleted.

Keywords: planet formation, inner solar system, terrestrial planets, Mercury, solar system

Re-analysis of images of GANYMEDE

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Ganymede is one of Jupiter’ s moons. Numerous images of its surface have been obtained by the Voyager and Galileo spacecraft, which allow us to investigate the global distributions of dark/bright terrains or impact craters exceeding 20km in diameter. However, most of Ganymede is imaged at a resolution of 1km/pixel or higher, and therefore, we can hardly examine the global distribution of smaller features of Ganymede. I re-analyses the Voyager and Galileo images, using multi-flame image restoration.

Keywords: GANYMEDE

Atmospheric Evolution of the Terrestrial Planets during the Heavy Bombardment: the Effects of the Element Partitioning

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The atmospheres on terrestrial planets are believed to be formed as a consequence of the impact degassing and erosion of volatiles during the Heavy Bombardment Period. Despite their common origin, there are distinct gaps in the noble gas abundances in the atmospheres on Venus, Earth, and Mars; compared to Earth, Venus is enriched and Mars is depleted in noble gases roughly by two orders of magnitude, respectively. The origin of these gaps has been poorly understood.

A possible mechanism to create these gaps is the partitioning of elements in the different surfacial environments: the runaway greenhouse on Venus, the carbon cycle on Earth, and the CO_2-ice formation on Mars. Although noble gases are mainly partitioned into the atmosphere, the distinct environments on the three planets create the differences in the noble gas concentrations in their atmospheres, leading the differences in the escape rates of noble gases due to the impact erosion.

We calculated the evolution of early atmospheres during the Heavy Bombardment Period by solving deterministic differential equations. Atmospheric components are, H_2O, CO_2, N_2, and noble gases. Because the abundances of noble gases are small, we treated both N_2 and noble gases as a component N_2 in our numerical model. The new idea of this work is to consider the partitioning of elements between atmosphere and other reservoirs. Whereas all volatiles are partitioned into atmosphere on Venus, H_2O and CO_2 are partitioned into oceans and carbonates on Earth and into ice on Mars. We set the upper limits of the partial pressures of H_2O and CO_2 considering the phase equilibrium and the steady state of the carbon cycle. Impact erosion of atmospheres and impactors are taken into account by using models of Svetsov (2000) and Shuvalov (2009). We assumed carbonaceous chondrites from the main asteroid belt as impactors. Total masses of impactors correspond to 1% of the planetary masses.

We found that the resulting abundances of N_2 and noble gases differ only by ~10% among the three planets. This is caused by the dominance of the replenishment of atmophiles over the erosion. The small differences in the abundances were due to the differences in the surface temperature and in the size of planets. The partitioning of elements was found to be less important for the abundances of N_2 and noble gases in the assumed conditions, where the delivery of atmophiles dominates. We also investigated the dependences on the impact erosion models, impactor size distributions, and types of impactors. Based on the results, we discuss the implications for the origins of volatiles and early planetary environments at ~4 Ga.

Keywords: Heavy Bombardment Period, impact erosion, noble gases

Effects of hydrogen on thermal evolution of magma ocean and early surface environment

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The standard model of planet formation suggests that terrestrial planets would experience global melting due to giant impacts, i.e. the formation of a magma ocean. Early atmosphere would form through degassing from the interior, and its greenhouse and blanketing effects would be essential to radiative heat balance at the planetary surface, limiting heat flux from the magma ocean.
Recently, several groups have been working on a coupled evolution of early atmosphere and magma ocean, and have investigated the thermal history and volatile budgets on early terrestrial planets(e.g. Elkins-Tanton 2008, Hamano et al. 2013,2015, Lebrun et al. 2013). They have focused on oxidizing atmospheres consisting of water and carbon dioxide, while early atmosphere might have reducing gaseous species. Hydrogen molecule is one of the candidates, since planets could capture nebula gas during formation or it could be produced by chemical reaction between water and metallic iron that could be scattered on giant impact events. In this talk, we would like to discuss contributions of hydrogen on early evolution of terrestrial planets.

Keywords: Magma ocean, Reducing atmospheres, Formation of oceans, early climate and surface environment

LOW-CO_2 ATMOSPHERE ON EARLY MARS INFERRED FROM MANGANESE OXIDATION EXPERIMENTS.

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Introduction

Both CO_2 and O_2 are important atmospheric components for climate and chemical evolution on early Mars. Several lines of geological and geomorphological evidence show that early Mars has been once warm sufficient to hold liquid water on the surface at least episodically in the late Noachian and early Hesperian [1]. Although early Mars would not be warmed sufficiently by CO_2 alone, climate models presume the presence of a thick CO_2 atmosphere to decrease outgoing longwave radiation and to cause effective collision-induced absorption. However, pCO_2 on early Mars is poorly constrained by geochemical evidence thus far. On the other hand, the Curiosity rover has discovered Mn oxides in fracture-filling materials in sandstones of the Kimberley region of the Gale crater [2]. Given pO_2 capable for deposition of Mn oxides (pO_2 > ~0.01 bar) [3], the findings of Mn oxides indicate that early Mars had a substantial O_2 in the atmosphere.

The present study aims to further constrain the composition of early Mars' atmosphere, especially the CO_2/O_2 mixing ratio, at the time when the Mn oxides were formed. We performed laboratory experiments to generate Mn precipitates from Mn^{2+} in solutions by introducing CO_2/O_2 gas mixtures. We investigated the compositions of Mn precipitates under various compositions of CO_2/O_2.

Materials & Methods

The Mn^{2+} starting solution with 20 mM and pH 8–9 was prepared in an Ar-purged glovebox, where pO_2 remained < 10^{-12} bar. The starting solution was deaerated by pure Ar gas for more than 6 hours prior to the use. Then, we introduced gas mixtures of pure CO_2 and artificial air (N_2/O_2 = 4; pCO_2 < 1ppm) into the starting solution at four different mixing ratios (CO_2/O_2 = 2, 0.2, 0.02, and artificial air) in the glovebox. Note that MnO_2 is thermochemically stable under all of these conditions. Solution samples were collected in several times during the experiments. The samples were filtered through a membrane with pore size of 220 nm. After the reactions, Mn precipitates were collected by filtering the rest of the solutions using a membrane with 220 nm. Mn^{2+} concentrations of the filtered solution samples were measured using inductively-coupled plasma atomic emission spectroscopy (ICP-AES). The collected Mn precipitates were analyzed with X-ray absorption fine structure (XAFS) and X-ray diffraction (XRD).

Results

Our results of the ICP-AES analysis show that Mn^{2+} concentrations in the filtered solutions decrease over reaction time, which indicate that a part of dissolved Mn^{2+} was converted into solid precipitates. Despite both the wide range in CO_2/O_2 ratios and thermochemical stability of MnO_2 under the experimental conditions, the results of XAFS analyses show that all of the Mn solid precipitates formed under these conditions are mainly composed of Mn carbonate, namely $MnCO_3$. These results are consistent with our XRD results. Our results show that $MnCO_3$ precipitated before the formation of MnO_2 even very low CO_2/O_2 of 0.02. This suggests that kinetics of formation of $MnCO_3$ and Mn oxides are the critical factor. On the other hand, the major peaks of the XANES spectra for the collected solid precipitates at CO_2/O_2 = 0 (namely, pure artificial air) would be a mixture of Mn oxides and $Mn(OH)_2$.

Discussion

Our results show that, in order to form MnO_2 in Mn^{2+} solutions by reactions with CO_2/O_2 gas mixtures, the CO_2/O_2 ratio should be lower than 0.02. Assuming pO_2 of ~0.01–0.2 bar, which is capable to form and preserve MnO_2 in sediments [3], the observations of both a lack of $MnCO_3$ and presence of MnO_2 in Gale infer that pCO_2 on early Mars would have been less than 0.004 bar, or 4 mbar. This implies that early Mars may have possessed a low-CO_2 and high-O_2 atmosphere.

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Keywords: Mars, planetary evolution, atmospheric composition

Superflares on G-, K-, M- type stars

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Flares on G, K, M-type stars are sudden releases of the magnetic energy stored around the starspots, like solar flares. Recent high-precision photometry from space shows that "superflares", which are 10-10^4 times more energetic than the largest solar flares, occur on many G, K, M-type stars including Sun-like stars (slowly-rotating G-type main-sequence stars like the Sun) (e.g., Maehara et al. 2012 Nature). Such superflares emit harmful UV/X-ray radiation and high-energy particles such as protons, and may suggest that exoplanet host stars have severe effects on the physical and chemical evolution of exoplanetary atmospheres (cf. Segura et al. 2010 Astrobiology, Takahashi et al. 2016 ApJL). It is then important to know the detailed properties of such superflare events for considering the habitability of planets.

In this presentation, we present statistical properties of superflares on G, K, M-type stars on the basis of our analyses of Kepler photometric data (cf. Maehara et al. 2012 Nature, Shibayama et al. 2013 ApJS, Notsu et al. 2013 ApJ, Maehara et al. 2015 EPS). We found more than 5000 superflares on 800 G, K, M-type main-sequence stars, and the occurrence frequency (dN/dE) of superflares as a function of flare energy (E) shows the power-law distribution with the power-law index of -1.8~-1.9. This power-law distribution is consistent with that of solar flares.
Flare frequency increases as stellar temperature decreases. As for M-type stars, energy of the largest flares is smaller (~10^{35} erg) compared with G,K-type stars, but more frequent "hazardous" flares for the habitable planets since the habitable zone around M-type stars is much smaller compared with G, K-types stars.

Flare frequency has a correlation with rotation period, and this suggests young rapidly-rotating stars (like "young Sun") have more severe impacts of flares on the planetary atmosphere (cf. Airapetian et al. 2016 Nature Geoscience). Maximum energy of flares and flare frequency also depends on the area of starspots, and this suggest existence of large starspots is important factor of superflares.
The statistical properties of superflares discussed here can be one of the basic information for considering the impacts of flares on planet-host stars.

Keywords: flare, Kepler, habitability

The effect of spectral type of central star on climate and climatic evolution of the Earth-like planets in habitable zone

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The climate of the Earth depends on both insolation and the amount of greenhouse gases, especially CO_2, in the atmosphere. Owing to a negative feedback mechanism in carbonate-silicate geochemical cycle system (so called the “Walker feedback”), the amount of CO_2 in the atmosphere (pCO_2) is regulated so that the climate of the Earth may be warm (i.e., the climate is warm enough for liquid water to exist on the surface of the Earth). However, if the CO_2 degassing rate via volcanic activities is below some critical value, the Walker feedback mechanism cannot maintain a sufficient amount of CO_2, and the Earth becomes globally ice-covered. Here, the critical value of the CO_2 degassing rate is a critical condition under which the Earth becomes globally ice-covered owing to a large ice-cap instability. Since albedo of ice depends on the spectrum of the insolation, the critical condition for the Earth to be globally ice-covered is expected to be different from previous estimates when the central star is different from the Sun. The difference in the spectral type of the central star due to different mass also results in different evolutionary timescale of its luminosity which affects the habitable zone (HZ) around it. In this study, we examine the climate and the climatic evolution of the Earth-like planets around different-mass stars.
We use a one-dimensional energy balance model coupled with a carbon cycle model to estimate the climate, and the planetary albedo model is improved in order to examine the effect of the difference in the spectrum of the insolation from the central star. The evolution of the climate is examined based on the evolutions of CO_2 degassing rate and insolation, which are estimated by a parameterized convection model coupled with a mantle degassing model and a luminosity evolution model, respectively. Four types of stars (i.e., M-, K-, G-, and F-type stars) are considered.
Comparing stars with different mass (e.g., M- and G-type stars), pCO_2 of an Earth-like planet around a light star (i.e., the M-type star) tends to be lower than that of an Earth-like planet around a heavy star (i.e., G-type star) for the same luminosity and CO_2 degassing rate. This is because the peak wavelength of the insolation of the light star is longer than that of the heavy star, and because the ice absorbs longer-wavelength radiation more than shorter-wavelength radiation. As a result, the critical CO_2 degassing rate is less in the inner region of the HZ around the light star than in the region around the heavy star. However, when the Earth-planet is in the outer region of the HZ, and pCO_2 is high owing to the Walker feedback, the critical CO_2 degassing rate of the Earth around the light star is almost the same as that of the Earth around the heavy star especially in the outer region of the HZ because the surface albedo does not affect the planetary albedo owing to the dense atmosphere. Thus, regardless of the spectral type of the central star, the timescale for the warm climate of Earth-like planet is about 4 billion years which depends, not on the insolation, but strongly on the evolution of the CO_2 degassing rate of the planet. These results indicate that we should search for the inner region of the HZ around young stars to find Earth-like habitable planets.

Keywords: Exoplanet, Carbonate-silicate geochemical cycle, Habitable planet

Modeling Dust Cloud Structure in Super-Earth GJ1214b: Implications for the Atmospheric Metallicity

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Recent transit observations have revealed that many exoplanets have featureless spectra. Such spectra indicate extremely metal-enhanced atmospheres or the presence of opaque clouds at high altitude. Although thick high-altitude clouds prevent us from directly probing the atmosphere beneath them, their existence might provide us some information about the dynamics and/or composition of the lower atmosphere. However, it is still unclear how atmospheric dynamics and composition would affect cloud structure in exoplanets because most previous studies neglected or at least parameterized the growth microphysics of condensate particles.

In this study, we aim to understand the relationship between the atmospheric metallicity and the vertical extent of dust clouds. Recently, we have developed a new cloud model that takes into account the vertical transport of condensate particles and particle growth via both condensation and coalescence (Ohno & Okuzumi 2017). With our cloud model, we examine the vertical distributions of dust clouds in GJ1214b as a function of atmospheric metallicity.

We find that the cloud top reaches beyond 10^{-3} bar for atmospheric metallicities of 10× solar abundance, but does not reach the height of 10^{-5} bar for all choices of the model parameters. From timescale arguments, we find that the dust cloud structure can be classified into three regimes: *Condensation–Diffusion* regime, *Coagulation– Diffusion* regime, and *Coalescence–Sedimentation* regime. The maximum height of the cloud top occurs at the transition of the *Coagulation–Diffusion* and *Coalescence–Diffusion* regimes. Comparison between the maximum height of the cloud top predicted from our model and the height indicated from the observations of GJ1214b rules out atmospheric metallicities of 1–100× solar abundance for this particular exoplanets. Consequently, our results suggest that the atmosphere of GJ1214b is depleted in hydrogen as suggested by previous independent modeling, or the cloud in GJ1214b is composed of haze particles produced by photochemical reactions at high altitude.

Keywords: super-Earth, Dust Clouds, Atmospheric Metallicity

The structure of mantle convection in super-Earths of various sizes

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The structure of convection in the mantle of super-Earths is one of the most important issues in studies of their thermal history and surface environment which is linked to the habitability of planets. In our past studies (Miyagoshi et al., 2014 ApJL, 2015 JGR), we showed that the effects of strong adiabatic compression substantially reduces the activity of hot ascending plumes and the efficiency of convective heat transport in massive super-Earths(about ten times the Earth’s mass).
In this paper, we show that how convective structure changes as the mass of the planet increases. In the Earth-like size planet, hot plume activity is high, but the activity is reduced as the planet mass increases. When Mp (the planet mass divided by the Earth’s mass) exceeds 4, hot plumes become faint compared with cold ones and their activity becomes negligible. The dimensional thickness of the lithosphere increases as Mp increases in spite of the increasing Rayleigh number. The rms velocity of thermal convection does not significantly depend on Mp. These results suggest that plate tectonics becomes harder to operate as Mp increases.
We also explored the initial transient stage of thermal convection in massive super-Earths. When the shallow mantle is initially hotter than expected from the adiabatic extrapolation from the deep mantle, as expected when the planet is formed from giant impact, transient layered convection continues for as long as several to ten billion years before it yields to a whole layer convection that occurs as the structure in the statistically steady state. Our results suggest that the interior of many of massive super-Earths may be still in the transient stage rather than the steady state now.

Keywords: super-Earths, mantle convection

An improvement of a 1D thermal evolution calculation scheme based on mixing length theory

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Solid-state thermal convection plays a major role in the thermal evolution of solid planetary bodies. Solving the equation system for thermal evolution considering convection requires a 2-D or 3-D modeling, resulting in large calculation costs. A 1-D calculation scheme based on mixing length theory (MLT) requires a much lower calculation cost and is suitable for parameter studies. A major concern for the MLT scheme is its accuracy because of a lack of detailed comparisons with higher dimensional schemes. In this study, I quantify its accuracy by comparing steady-state thermal profiles obtained by 1-D MLT and 3-D numerical schemes for different curvatures, different Rayleigh numbers, and different viscosity contrasts. For isoviscous cases, I find that relative errors for the mean temperature and Nusselt number can be up to >100% and ~50%. In order to improve the accuracy, I propose a new definition of the mixing length, which is a parameter controlling the efficiency of heat transportation due to convection. I find that the use of a smaller peak depth and a larger peak value of the mixing lengths decreases errors. I provide empirical quadratic functions for the peak depth and the peak value leading accurate results. Similar analyses were done for temperature-dependent viscosity cases. I find that the use of the new definition of the mixing length also improves results for time-dependent calculations, indicating that this approach is useful for thermal evolution studies.

Keywords: thermal evolution, numerical calculation

Viscous heating in shock-comminuted rocks: A reappraisal of the shock melting threshold by using a shock physics code

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Impact melts are among the most curious geologic samples because they provide clear evidence of hypervelocity collisions between two planetary bodies at several km/s. Thus, the required shock pressure for incipient melting after pressure release has been studied extensively. It is widely assumed that pressure release is an isentropic process. This assumption is expected to be valid when the shocked matter behaves as a perfect fluid. Since the archived shock pressure under typical collisions between two planetary bodies is thought to be much larger than the Hugoniot Elastic limit, the yield strengths of both intact and comminuted rocks have been neglected in a lot of cases. In this study, we focused on collisions at relatively low velocities, which are that the effects of the material strength cannot be neglected. The effects of internal friction in comminuted rocks, i.e., the yield strength of shock-comminuted rocks, on thermodynamic behavior on an entropy-pressure plane were investigated using the iSALE shock physics code to revisit the threshold of incipient melting against the peak shock pressure. We will present a preliminary result obtained through the numerical experiments at the meeting.
A vertical impact of a sphere onto a flat target are numerical modeled in a two-dimensional cylindrical coordinate. The analytical equation of state (ANEOS) for dunite were used for both projectile and target. Impact velocity was fixed at 6 km/s, which is slightly lower than the bulk sound velocity of dunite. The projectile radius was divided into 50 cells, which is thought to be large enough to investigate the shock pressure distribution with a high accuracy. We assumed that the projectile and the target have any temperature gradients at initial. The initial temperature was set to 220 K, which is close to a radiative-equilibrium temperature at the main belt region. The constitutive model for dunite parameterized in Johnson et al. (2015) was also used with the same input parameters except for the coefficient of internal friction. Lagrangian tracer particles were inserted into each computational cell. We stored the time variation of pressure and entropy into the tracers.
We found that the entropy gradually increases during pressure release in the case of a highly-frictional target contrary to the assumption of isentropic release. A larger value of the internal friction leads to a larger increase of entropy. We also found that the shock melting occurs after ~40 GPa shock compression under our experimental conditions if we used a typical value for the coefficient of the internal friction. This value is lower than a widely-used threshold for shock-induced melting. Our results suggest that (1) the shock melting occurs at a lower impact velocity than previously thought and that (2) the input parameters of the constitutive model in numerical models largely affect the thermodynamic response of geologic materials.

Acknowledgement: We appreciate the developers of iSALE, including G. Collins, K. Wünnemann, B. Ivanov, J. Melosh, and D. Elbeshausen.

Keywords: Hypervelocity collisions, Impact melts, Numerical modeling of impact phenomena

Efficiency of material separation caused by magnetic field in outer space recognized for solid particles in general

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Magnetic field gradient and dust particles coexist in various regions of galactic space. Although the field intensity in these regions are considerably low compared to the experimental conditions available on earth, the immersive microgravity duration in these area may cause specific motion of solid particles, and the translation may cause material fractionation that are observed in these regions. Magnetic separation is generally caused by a magnetic potential induced in the solid particle, and was conventionally used to collect ferromagnetic, ferrimagnetic or strongly paramagnetic materials. Whereas, it was believed that most of the existing material (i.e. diamagnetic & paramagnetic material) required ultra-strong field intensity above 10 Tesla. Field-induced translation was recently observed for single diamagnetic particles released in an area of a monotonically decreasing field, and values diamagnetic susceptibility per unit mass was detected from a small sample;[1][2] in these experiments, the grain was allowed to translate freely in a diffuse area using microgravity conditions. Based on the same principle, we found that ensembles of heterogeneous particles are separated into fractions using a neodymium hand magnet (*go to* YouTube" Magnetic separation of general solid particles realized by a permanent magnet" *for the movie*) [3] .The ensemble consisted of diamagnetic bismuth, diamond and graphite particles, as well as two paramagnetic olivine.
The setup to observe the separation was installed in a wooden box that was attached to the top position of a drop shaft (length ~1.5 m). The duration of the microgravity condition was approximately 0.5 s. With the beginning of microgravity, the a carbon sample stage inside the stage-holder was levitated, which was effective in releasing the grains in a diffuse area; here the stage was spontaneously levitated by a small field gradient applied in the vertical direction. In previous studies, it was technically difficult to release a substance in a diffuse area in μg conditions. The separation of weak magnetic material was realized because the terminal velocity of the particles that translated in an area of B=0 was uniquely determined by the intrinsic susceptibility of the material and also by the field intensity at the initial sample position; the velocity was independent to mass of particle. This relationship was directly deduced from an energy conservation rule. The result achieved here is against the generally accepted notion that ordinary solid materials (i.e. diamagnetic and paramagnetic materials) are magnetically inert. In the diffuse conditions of outer space , the effectiveness of the field-induced separation would be more efficient because the effects of viscous drag, friction and gravity are negligible. Recently the mass independent property of magnetic translation was also confirmed for ferromagnetic and ferri-magnetic grains, namely in iron, nickel and ferrite. This means that proposed principle of material separation is confirmed for all categories of magnetic materials.

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Keywords: material separation, field gradient, diamagnetic anisotropy, paramagnetic anisotropy

Cratering experiments with spherical targets: The curvature effects on the cratering efficiency

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Recent planetary explorations revealed that the surfaces of small bodies are covered by a large number of craters. Impact cratering processes on small bodies are expected to be largely different from those on terrestrial planets mainly because of the following two reasons. The first one is their relatively-low surface gravity. The local material strength rather than gravity is subject to control the crater size on small bodies. All the craters on the asteroids smaller than a few km in diameter are possible to be in the strength-controlled regime (Jutzi et al., 2015). Another reason is the target curvature. Thus, the understanding of the cratering processes on curved surfaces in the strength-controlled regime is essential to investigate the collision environment of small bodies through their histories.
The curvature effects on the cratering processes, such as the cratering efficiency, have not been investigated systematically, although Fujiwara et al. (1993, 2014) have produced distinctive-shaped impact craters mainly on cylindrical targets with a wide range of its radius in a laboratory, and reported the crater diameter/depth/mass increase with and the target curvature. In this study, we performed a series of impact experiments using spherical targets with different diameters. The three-dimensional topography of the produced craters on the spherical surfaces were measured in 0.2 mm/pixel, allowing us to investigate the crater dimensions as a function of the target curvature. Then, we constructed a simple model to describe the effects of target geometry on the increase of the crater radius.
Impact experiments were performed by using a two-stage light-gas gun at the facility of ISAS/JAXA. The gypsum targets were cubes with 9 cm and 15 cm on a side, and spheres with 7.8 cm, 10.9 cm, 17.0 cm, and 24.8 cm in diameter. The bulk density and tensile strength of the target were 1.08 g/cm^3 and 2.4 MPa, respectively. A nylon sphere with 3.2 mm in diameter impacted into the target at ~3.4 km/s. The ratio of the radius of projectile and target (the normalized curvature) are 0.013-0.041. The targets were placed in a styrofoam box, and the target and their fragments were collected from the box in each shot. The spherical surface including a resultant crater was scanned by a high resolution 3-D geometry measurements system (COMS MAP-3D). The volume and depth of the crater was measured with the deviation from the pre-impact surface determined by the topographic data around the crater. The radius of a circle having an area equal to the area occupied by craters on the pre-impact surface was defined as the crater radius.
The resultant craters consist of a circular pit and a spall region around the pit. A larger target curvature led to a broader the spall region. The volume and diameter of the crater increase with the target curvature, although the depth of the crater is almost constant. The volume of spall region and the crater profiles also show that the spall region gets broader and deeper with the target curvature. The volume increase in the spall region mainly contributes to the volume increase of the crater.
We developed a model focusing on the normal component of the force to the target surface without taking into account of the interference zone. The experimental results fell in the area constrained by model curves with reasonable parameters (the radius of the isobaric core and the attenuation rate of the impact induced pressure) on the diagram of the ratio of the crater radius to those on plane surface and

the target curvature. Namely, the distance from the equivalent center to the target free surface is shorter for higher curvature, which mainly contributes to the increase of the crater diameter and volume with the target curvature. The curvatures for some largest craters on the asteroids are within the range of the curvature in this study. The increase of the crater radius originated from the curvature might have to be considered for spall craters in their size range.

Keywords: impact craters, impact experiments, small bodies, morphology, two-stage light-gas gun