From K computer to the post-K computer

*Junichiro Makino[1]

1.Department of Planetology, Graduate School of Science / Faculty of Science, Kobe University

I'll describe the overview of the post-K computer project and how the scientific research using it will be organized, in particular in the field of planetary science.
K computer was completed in 2011 and its public use was started in 2012. It has the peak speed exceeding 10PF, being still the fastest supercomputer in Japan and the fourth fastest in the world. For the scientific research using K computer, five "strategic fields" were selected, and each field got the budget of around 500M JYE/year to develop application software for K computer and to do scientific research using K computer. For planetary and heliosphere sciences, in Field 5 "The origin of the matter and the univerce", large scale simulations of the convective zone of Sun and planetary formation have been performed. For these simulations, application programs which could achieve high efficiency on up to a few tens of thousands of computing nodes have been developed, and helped to obtain important results.
In 2014, the project to develop the successor of K computer ("post-K computer") was started. Its goal is the achieve the application performance 100 times that on K computer. It will be completed in 2019-2020 timeframe. The design and production will be done by Fujitsu, which developed K computer as well. The post-K will have the general-purpose many-core architecture and torus network, similar to those of K computer. For the post-K computer, nine "priority issues" and four embryotic issues have been selected. Planetary science is included to one of the four embryotic issues. For the priority issues, the organizations to perform the research and development have already been selected, but for embryotic issues they are yet to be selected (as of January 2016). At the time of the meeting, hopefully, the organization will be fixed, and I'll describe the status of the "embryotic issue" for planetary science.

Keywords: large-scale simulation, computational science

Complex organic molecules in star- and planet-forming regions

*Yuri Aikawa[1]

1.Center for Computational Sciences, University of Tsukuba

Complex organic molecules (COMs) are intensively searched for around solar-mass protostars in recent years. For example, glycolaldehyde ($HCOCH_2OH$), the simplest sugar, was detected around IRAS16293 in the ALMA Science Verification program (Jorgensen et al. 2012). COMs are expected to be more abundant in ice mantles than in the gas phase, because their sublimation temperature is relatively high, and because grain-surface reactions would play significant roles in their formation. COMs in star-forming regions, especially in ice mantle, could be an important reservoir of organic compounds in the planetary-system formation and/or mother molecules of prebiotic molecules. It is, however, very difficult to directly observe COMs in ice mantle. Combination of line observations (of gaseous COMs) and theoretical modeling of gas-grain chemistry is thus needed to understand the formation and destruction of COMs in the gas phase and ice mantle. Computational modeling efforts include (i) radiation hydrodynamics of star formation, (ii) gas-grain chemical network calculations and (iii) physical/chemical calculations to determine the rates and efficiencies of various chemical reactions and micro processes. In this contribution, I will review recent progresses, especially in (ii) and (iii).

Keywords: astrochemistry, formation of star and planetary systems

Computational planetary science using FDPS (Framework for Developing Particle simulator)

*Masaki Iwasawa[1], Ataru Tanikawa[2,1], Natsuki Hosono[1], Takayuki Muranushi[1], Junichiro Makino[4,1,3]

1.RIKEN, 2.The University of Tokyo, 3.Tokyo Institute of Technology, 4.Kobe University

Particle-based simulations are widely used in the field of computational astronomy. Examples include the cosmological simulations or the planet-formation simulations with gravitational *N* body code, the simulations of star and galaxy formation with the Smoothed Particle Hydrodynamics (SPH) code or other particle-based codes, and the simulations of planetesimals formation with the Discrete Element Method (DEM) code. To develop an efficient program for particle-based simulation for large-scale parallel machines computer is not easy, and to some extent the efforts of many researchers have been spent on the programming and tuning. However, the algorithms of particle-based simulations are largely similar. Thus we have developed a framework which helps the researchers to develop efficient programs for particle-based simulation on large parallel machines, which we call Framework for Developing of Particle Simulators, or FDPS.
In this presentation, we introduce concept and implemantaion of FDPS. We also show some applications for planetary science using FDPS.

Keywords: Simulations, Planet formation

High-resolution N-body Simulations for Planet Formation: To 100 Million Particles, and Beyond

*Yasunori Hori[1,2], Shoichi Oshino[3], Michiko Fujii[4], Masaki Iwasawa[5]

1.Astrobiology Center, National Institutes of Natural Sciences, 2.Exoplanet Detection Project, National Astronomical Observatory of Japan, 3.Center for Computational Astronomy, National Astronomy Observatory of Japan, 4.Department of Astronomy, University of Tokyo, 5.Advanced Institute for Computational Science, RIKEN

In a collisional system, close encounters play an important role in dynamical evolution. Gravitational interactions between particles undergoing a close encounter are big bottlenecks in N-body simulations because of high computational costs. In fact, a direct N-body simulation in the context of planet formation faces a wall of ten thousand particles. Toward high-resolution N-body simulations with 100 million particles and beyond, we have developed three tips to overcome this sort of big wall, implementing them into our N-body code for planet formation: (i) a tree-based hybrid N-body scheme which reduces numerical integrations of gravitational interactions among particles, PPPT method (Oshino et al. 2011), (ii) GPU clusters which allow us to handle a large number of particles, (iii) parallelization and optimization for accelerating numerical integrations, specifically, a multi-purpose platform for a parallelized particle-particle simulation, the so-called “Framework for Developing Particle Simulator” (FDPS: Iwasawa et al. 2015). In this talk, we introduce what our brand-new N-body code is like and its performance and capability. We also show our preliminary results of N-body simulations of terrestrial planet formation, using ~ 0.1-1 million planetesimals.

Keywords: Planet formation, N-body simulation, GPU

Global High-resolution N-body Simulation of Planet Formation: Planetesimal Driven Migration with Type-I Migration

*Junko Kominami[1], Hiroshi Daisaka[2], Junichiro Makino[3], Masaki Fujimoto[4]

1.Tokyo Institute of Technology, 2.Hitotsubashi University, 3.RIKEN AICS, 4.JAXA

By means of fully self-consistent N-body simulations, we investigated whether outward Planetesimal Driven Migration (PDM) takes place or not when the self gravity of planetesimals is included. We performed N-body simulations of planetesimal disks with large width (0.7 - 4AU) which ranges over the ice line. The simulations consisted of two stages. The first stage simulations were carried out to see the runaway growth phase using the planetesimals of initially the same mass. The runaway growth took place both at the inner edge of the disk and at the region just outside the ice line. This result was utilized for the initial setup of the second stage simulations in which the runaway bodies just outside the ice line were replaced by the protoplanets with about the isolation mass. In the second stage simulations, the outward migration of the protoplanet was followed by the stopping of the migration due to the increase of the random velocity of the planetesimals. Due to this increase of random velocities, one of the PDM criteria derived in Minton and Levison (2014) was broken. In the current simulations, the effect of the gas disk is not considered. It is likely that the gas disk plays an important role in planetesimal driven migration. Hence, we also carried out N-body simulations of PDM including the gas drag and type-I migration. Type-I migration and gas drag are known as the effects that drag the planeteismals and protoplanets toward the central star. We showed that the random velocity of the planetesimals are subdued by the gas drag and enhances the outward migration. We found that in Minimum Mass Solar Nebula (MMSN), there were a period that outward PDM overcomes the type-I mirgation.

New developments in planetary formation theory of solar system derived from ABEL model

*Shigenori Maruyama[1], Toshikazu Ebisuzaki[2]

1.Earth-Life Science Institute, Tokyo Institute of Technology, 2.RIKEN

The Earth was formed as dry rocky planet without atmosphere nor ocean at 45.6Ga. Atmospheric and oceanic components were added at 4.4Ga by late heavy bombardment. This 2 step formation model of the Earth is named ABEL model (Advent of Bio-Elements Landing Model). The origin of solid Earth is enstatite chondrite which has been already clearly indicated by analysis of oxygen isotopic composition and other isotopic data. At the same time, the origin of water on the Earth is carbonaceous chondrites which is backed by hydrogen isotopic ratio. These 2 facts have been thought to be contradictory, but ABEL model is able to explain them perfectly. Also this model explains this two-step formation was the precursor of the reaction as metabolism.

Here, we give a comprehensive views for the research of planetary formation theory of solar system based on ABEL model for followings. (1) Moon formation theory (Giant Impact model), (2) Chemical zoning of asteroid belt with observational facts (they does not support the Grand Tack model that suggests random distribution of chemistry), (3) Chronology research based on meteorites, (4) H2 gas escaped during first 3 hundred million years after the formation of protoplanetary disk.

Based on above information, we give new developments in planetary formation theory of solar system.

Keywords: Planetary formation theory, ABEL model

Modeling the evolving interiors of planets

*Masaki Ogawa[1]

1.Division of General Systems Studies, Graduate School of Arts and Sciences, University of Tokyo

There is a clear correlation between the size of a terrestrial planet and the style of tectonic activities that are caused by mantle convection in that planet: There is no clear indication of tectonic activities on the present Moon where the Rayleigh number of the mantle is below the critical Rayleigh number; plume magmatism has occurred almost throughout its 4.5 Gyr history on Mars where the Rayleigh number marginally exceeds the critical value; plume magmatism and tectonic activities are pervasive on the present Earth and Venus where the Rayleigh number is well above the critical value. To develop a comprehensive model of tectonic activities and evolution of these planets, it is necessary to systematically explore the elementary processes that exert control over mantle dynamics. Through my two-dimensional models of magmatism in convecting mantle, I have listed several crucial elementary processes: (1) the magmatism-mantle upwelling feedback that operates in Mars, Venus, and the Earth; (2) mantle bursts that occurs in the Earth and Venus owing to an interaction between magmatism and a high pressure induced solid-solid phase transition of mantle materials; (3) plate tectonics that occurs on the Earth probably because of the ocean that the planet hosts. Here, I argue that a three-dimensional modeling of these processes is necessary for ultimate understanding of mantle evolution in terrestrial planets.

Keywords: mantle evolution, mantle convection, magmatism

Thermal convection in the mantle of massive super-Earths

*Takehiro Miyagoshi[1], Masanori Kameyama[2], Masaki Ogawa[3]

1.Japan Agency for Marine-Earth Science and Technology, 2.Ehime University, 3.University of Tokyo

Understanding thermal convection in the mantle of super-Earths is one of the most important key to clarifying their thermal history, surface environment, and habitability. The reason is that the plate motion, material circulation, the vigor of core convection and planetary dynamos are controlled by the thermal convection.

In contrast to the Earth’s interior, the strong adiabatic compression effect is important in massive super-Earths. We have studied the thermal convection in massive super-Earths (about ten times the Earth’s mass) with this effect by the ACuTEMAN method [Kameyama M., 2005]. We also take account for high Rayleigh number which is relevant for super-Earths, and temperature-dependent viscosity contrast and depth-dependent thermal expansion coefficient.

The summary of results is as follows. (a) The activity of ascending hot plumes is considerably lowered compared with that of descending cold plumes. (b) The efficiency of heat transport by thermal convection is lowered compared with the results of Boussinesq (no adiabatic compression) models. The thickness of plate at the surface is considerably thicker than that of the Earth. (c) From the convective regime diagram, the threshold value of viscosity contrast for transition to the stagnant-lid regime convection increases as Rayleigh number increases in contrast to the result of Boussinesq models (in which the threshold value is constant). The details of a-c are given in Miyagoshi et al. [2014, 2015].

We also found that the convection remains in the initial transient stage for a substantial portion of the thermal history of massive super-Earths. In the transient stage, the convection is layered. Cold plumes descend from the surface very slowly, and the convection remains inactive in the upper layer, until the cold plume heads descend to the layering boundary. The layering boundary is located at the depth where the actual temperature gradient coincide with the adiabatic temperature gradient. After the initial transient stage, cold plumes penetrate through the boundary, and the convective structure changes to the whole layer one.

Keywords: super-Earths, mantle convection

Development of cumulus parameterization based on cloud-resolving model

*Yuya Baba[1]

1.Japan Agency for Marine-Earth Science and Technology

A cumulus parameterization was developed using cloud-resolving model. Cloud-resolving model was used to estimate macrophysical cloud properties which were considered in the cumulus parameterization through modeling of entrainment and detrainment rates. Analysis on composite structure of updraft convective clouds simulated by cloud-resolving model indicated that there was similarity in the both structures of deep and shallow convection. The similar structures were possible to be modeled using updraft velocity of cloud mass flux in conjunction with in-cloud buoyancy and detrainment. Based on the composite analysis on data obtained from the cloud-resolving model, (organized) entrainment could be parameterized using in-cloud buoyancy and a recently proposed (organized) detrainment model. The developed cumulus parameterization diagnoses the updraft velocity when the model determines updraft convective cloud structure, considering lateral mass exchanges performed by entrainment and detrainment. The downdraft cloud structure was analogously parameterized by height-dependent entrainment using negative in-cloud buoyancy which was produced by evaporation (and sublimation) of precipitation. The diagnosed cloud structure was generalized in which shallow and deep convection was treated in a unified manner.

An atmospheric general circulation model (AGCM) was developed employing a composite grid system and recently presented parameterizations (land surface, non-orographic gravity wave and boundary layer schemes), and the developed cumulus parameterization was implemented into the AGCM, in order to examine sensitivity to the selected parameters and physical performance of the scheme. Evaluations of the scheme were performed using the AMIP-type low-resolution experiments against climatological reanalysis data. In the evaluations, difference of detrainment model was especially examined, and it was found that (organized) detrainment model had significant impact on the model’s physical performance. This was because the present entrainment rate was modeled using detrainment rate, and thus these parameters were strictly connected each other. Although all employed detrainment models were based on the fact that detrainment was proportional to buoyancy loss in convective clouds, a detrainment model originally developed for shallow convection showed worse physical performance, and detrainment model which was based on cloud-resolving model and did not separate modeling procedure for different convection depths worked better.

Keywords: cumulus parameterization, cloud-resolving model, atmospheric general circulation model

Toward simulations of weather and climate of planetaries in general

*Yoshi-Yuki Hayashi[1]

1.Department of Planetology/CPS, Graduate School of Science, Kobe University

The aim of this presentation is to visit quickly the present status of numerical simulations for possible weather and/or climate on a planet or a satellite with an atmosphere other than the Earth, and to place some foresight of development of simulation in the near future.

Until almost the end of 20th century, it had not been recognized as a fruitful research but as a hobby work to consider generality and particularity of a surface environment of a planet by demonstrating weather and climate, which may be realized on a given planet, by constructing its virtual atmosphere in a computer. There have been vigorous research activities on the evolution of planetary surface environment from the viewpoint of energy budget analyses by solving the radiation transfer equation for a given set of atmospheric chemical species, but little from the viewpoint of atmospheric circulation with an explicit representation of material transport by the atmospheric motion.

Unfortunately, the present understandings of the weather and climate on the planets in our solar system, for which we can utilize observational data by the use of exploration devices and/or telescopes to a certain extent is not enough for us to predict confidently the environments of exoplanets or the planets of our solar system in the early stages of its evolution. The a-periodic appearance of the Martian global dust storms still remains to be understood. The four day circulation (the rapid zonal wind) which characterize the looks of Venus remains to be understood in a dynamically consistent fashion where atmospheric disturbances and their roles are revealed. The banded structure observed in the atmospheres of the giant planets still remains in a stage with many controversial arguments. This is because the development of observations for the Earth's environment which enables the development of weather and/or climate prediction can not be expected for the planets in our solar system and for
exoplanets. The issue to proceed the research activities in these fields is to establish reliable ways of verification for numerical
methods with the lack of such observational backups. As an effort to respond this issue, our group is now constructing a series of
hierarchical models and a group of software libraries to support them.

Keywords: numerical simulation, planetary environment in general, weather and climate

Toward *N*-Body calculations with a larger number of particles : parallel computation for Particle-Particle Particle-Tree scheme using FDPS

*Akihisa Yamakawa[1], Junichiro Makino[2], Saitoh Takayuki[3], Junko Kominami[3], Kosuke Takeyama[1]

1.Tokyo Tech, 2.RIKEN, 3.ELSI

Formation processes of terrestrial planets through planetesimal accretion have been studied using *N*-body calculations and several important formation processes have been found, such as the runaway growth and the oligarchic growth (Kokubo and Ida 1996, 1998). However, in almost all simulations the perfect accretion was assumed and relatively narrow region (e.g. 0.98AU-1.02AU) was simulated using small numbers of particles ($< 10^5$), because calculation cost is $O(N^2)$. To simulate planetary formation in more realistic conditions, it is necessary to take into account fragmentation, to handle a larger number of particles and to integrate them for longer time.

Therefore, we have developed a parallel implementation of P^3T(Particle-Particle Particle-Tree) scheme, which reduces the calculation cost from $O(N^2)$ to $O(N \log N)$.

In P^3T scheme, the gravitational force between two particles is split into short-range and long-range contributions. Short-range forces are evaluated by direct summation and integrated with the fourth order Hermite scheme with the block time steps. For long-range forces, we use a combination of Tree code and the leapfrog integrator with the constant time steps. Using this scheme, we can calculate *N*-Body problems accurately in low calculation cost of $O(N \log N)$. In order to accelerate P^3T scheme by parallel computation, we use FDPS(Framework for Developing Particle Simulator) which is a library to process the tree part at high speed.

In this talk, we show that it is possible to perform *N*-Body calculations for planet formation with a larger number of particles than those in the previous studies by parallel computation with P^3T scheme using FDPS.

Keywords: n-body simulations, planetary formation, planetesimals

A Mesh-free method for free surfaces and contact discontinuities

*satoko yamamoto[1,2], Junichiro Makino[4,2,3]

1.Graduate School of Science and Engineering,Tokyo Institute of Technology, 2.Advanced Institute for Computational Science, RIKEN, 3.ELSI ,Tokyo Institute of Technology, 4.Graduate School of Science, Kobe University

In Earth and Planetary Sciences, mesh-free methods for compressive fluids are widely used for fluid simulations in which large deformations occur. As a traditional mesh-free method, Smoothed Particle Hydrodynamics (Lucy 1977 and Gingold & Monaghan 1977; hereafter SPH) is generally used. However, SPH cannot accurately handle free surfaces and contact discontinuities, where the density distribution is not differentiable.

There are two causes for this limitation. First, in many of mesh-free methods, the density of a fluid element is derived directly from the distribution of fluid elements instead of using the equation of continuity. However, the approximation formula in which the density can be derived without implicit method, does not satisfy partition of unity, causing an error. Second, the physical quantities and derivatives are estimated by the SPH approximation formula. This formula is zeroth-order accurate in space and second-order accuracy with respect to the number of neighbor fluid particles which interact with a fluid particle. Therefore there are large errors at free surfaces and contact discontinuities.

To solve this problem, we developed a high-order mesh-free method for compressive fluid. As a solution for the first problem, we integrate the equation of continuity in the new method. In addition, for the second problem, we adapt a space high-order approximation formula to mesh-free methods for compressive fluids. The formula is based on Tamai et al. (2013), in which they formulate a high-order approximation for mesh-free methods for incompressible fluids. Then we express free surface with the boundary condition which the pressure is constant. In addition, for contact discontinuities, we introduce the appropriate boundary condition depending on what it is a contact discontinuity.

We also compare the results of numerical tests of our new method to the results of SPH. These results show that our method can handle free surfaces and contact discontinuities better than SPH. However, the new method cannot accurately handle contact discontinuities with indifferentiable pressure. Therefore, we need other prescriptions for these contact discontinuities, which we will address in future work.

Keywords: Fluid calculation method

Comprehensive tests of artificial viscosities, their switches and derivative operators used in Smoothed Particle Hydrodynamics

*Natsuki Hosono[1], Takayuki R Saitoh[2], Junichiro Makino[1,2]

1.RIKEN, Advanced Institute for Computational Science, 2.EARTH-LIFE SCIENCE INSTITUTE

In the field of astrophysical and planetary science, hydrodynamical numerical simulations for rotating disk play important role.
So far, Smoothed Particle Hydrodynamics (SPH) has been widely applied for such simulations.
It, however, has been known that with SPH, a cold and thin Kepler disk breaks up due to the unphysical angular momentum transfer.
There are two possible reasons for the breaking up of the disk; the artificial viscosity (AV) and the numerical error in the evaluation of pressure gradient.
However, which one is dominant has been still unclear.
Thus, we performed a systematic survey of how the lifetime of a cold disk varies depending on known implementations of AV and various switchs.
As a result, we found that the angular momentum transfer due to AV at the inner edge triggers the breaking up of the disk in the case of Monaghan (1997)'s AV.
We also found that with the classical von-Neumann-Richtmyer-Landshoff type AV with a high order derivative estimate the disk survives for more than 100 orbits.

Keywords: numerical hydrodynamics

Tandem Planetary Formation Theory

*Toshikazu Ebisuzaki[1], Yusuke Imaeda[1]

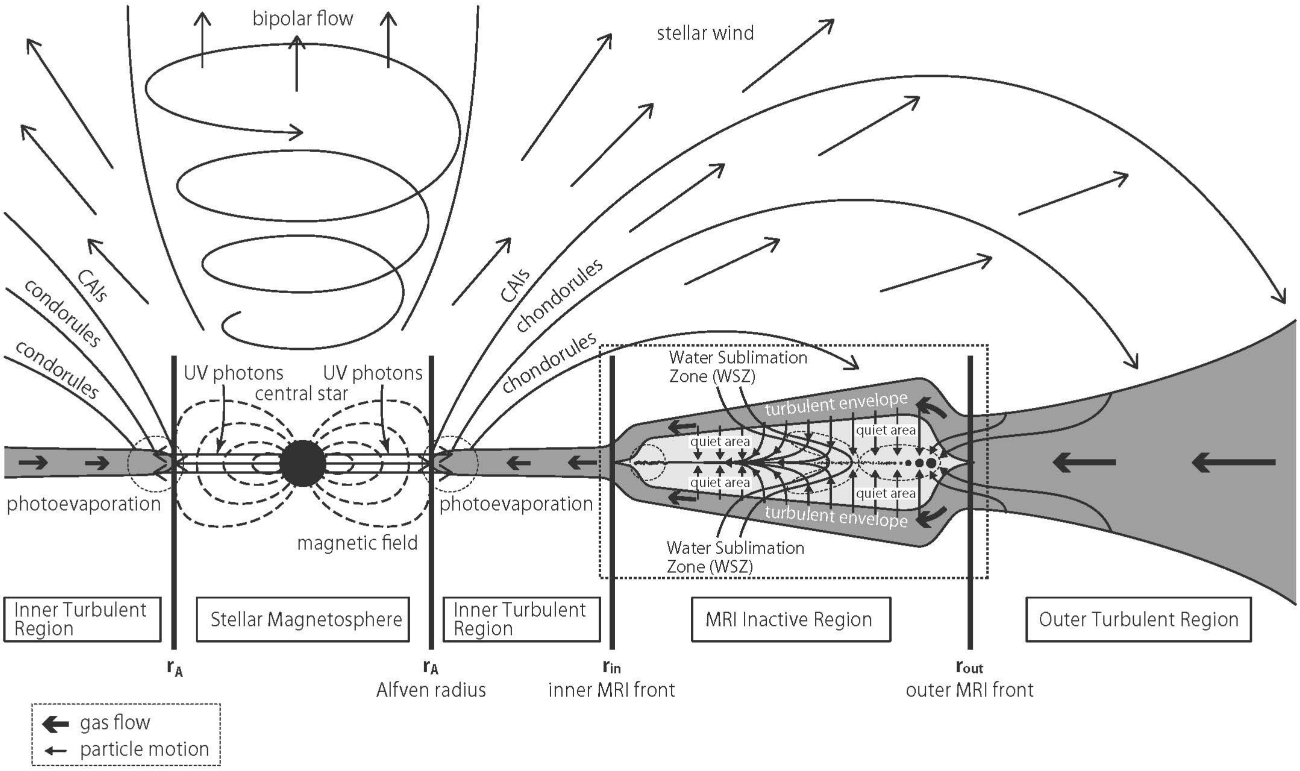
1.RIKEN

We have obtained a steady-state, 1-D model of the accretion disk of a protostar taking into account the magneto-rotational instability (MRI). We find that the disk is divided into an outer turbulent region (OTR), a MRI suppressed region (MSR), and an inner turbulent region (ITR). The outer turbulent region is fully turbulent because of MRI. However, in the range, r_{out} (= 8 - 60 AU) from the central star, MRI is suppressed around the midplane of the gas disk and a quiet area without turbulence appears, because the degree of ionization of gas becomes low enough. The disk becomes fully turbulent again in the range r in (= 0.2 - 1 AU), which is called the inner turbulent region, because the midplane temperature become high enough (\gt 1000 K) due to gravitational energy release.

Planetesimals are formed through gravitational instability at the two distinct sites, outer and inner MRI fronts (the boundaries between the MRI suppressed region (MSR) and the outer and inner turbulent regions), because of the radial concentration of the solid particles. At the outer MRI front, icy particles grow through low-velocity collisions into porous aggregates with low densities. They eventually undergo gravitational instability to form icy planetesimals. On the other hand, rocky particles accumulate at the inner MRI front, since their drift velocities turn outward due to the local maximum in gas pressure. They undergo gravitational instability in a sub-disk of pebbles to form rocky planetesimals at the inner MRI front.

The tandem regime is consistent with the ABEL model, in which the Earth was initially formed as a completely volatile-free planet. The water and other volatile elements came later through the accretion of icy particles by the occasional scatterings in the outer regions.

Keywords: Planetary Formation, Accretion Disk, Magneto-Rotational Instability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MRI Inactive Region
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Alfven radius
r_{in}
inner MRI front
r_{out}
outer MRI front
gas flow
particle motion

Formura: Programming Language for High-performance Structured Lattice Stencil Computation

*Takayuki Muranushi[1], Junichiro Makino[1]

1.RIKEN Advanced Institute for Computational Science

Recently, programming and performance optimization have become a big burden in simulation science. In studies of planetary formation and evolution, many applications can be reduced to explicitly solving some partial differencial equations (PDEs). We have been developing Formura, a programming language for stencil computations, that can generate explicit solver codes for PDEs.

In formura, we can describe discretized PDE-solving algorithms using convenient and familiar mathematical notations such as functions, discretized differentiation operators, rational lattice indices such as half-grid coordinates. We will report the current development status, sample codes, and performance measure of formura.

Keywords: simulation geoscience, structured lattice simulation, High-performance computing

Mantle convection simulations from technical viewpoints

*Masanori Kameyama[1], Takehiro Miyagoshi[2], Takatoshi Yanagisawa[2], Masaki Ogawa[3]

1.Geodynamics Research Center, Ehime University, 2.Japan Agency for Marine-Earth Science and Technology, 3.University of Tokyo, Komaba

In this presentation, we will discuss (a rather personal view of) the possible directions of the advanced numerical studies of mantle dynamics in concert with the progress of high-performance computing in the next era. We will start with a brief overview of the research targets and outcrops of the numerical modelings of mantle convection to date from a viewpoint of geosciences. Then we will discuss the scientific goals which the mantle dynamics researchers are to tackle with in coming years, together with the technical issues in terms of both software and hardware developments.

Keywords: terrestrial planets, mantle convection, numerical simulation

Martian dust devil statistics from high-resolution large-eddy simulations

*Seiya Nishizawa[1], Masatsugu Odaka[2], Yoshiyuki O. Takahashi[3], Ko-ichiro SUGIYAMA[4], Kensuke Nakajima[5], Masaki Ishiwatari[2], Shin-ichi Takehiro[6], Hisashi Yashiro[1], Yousuke Sato[1], Hirofumi Tomita[1], Yoshi-Yuki Hayashi[3]

1.RIKEN AICS, 2.Hokkaido Univ., 3.Kobe Univ., 4.ISAS, 5.Kyushu Univ., 6.Kyoto Univ.

Martian dust devil has an important role in Martian atmospheric circulation, and we examine statistics of Martian dust devil with a high-resolution (up to 5 m) and wide-domain (about 20 x 20 km^2) large-eddy simulation of the Martian planetary boundary layer. In this study, we define strong isolated vortex as dust devil. We clarified the distributions of size and intensity and concluded that the maximum vertical vorticity of an individual dust devil has an exponential distribution, while the radius and circulation have power-law distributions.

We also examine dependency of the statistics on experimental resolution with a grid-refinement experiment. These statistics will lead to more accurate estimation of dust injection from the surface to the atmosphere and a more sophisticated parameterization of the dust injection for use in general circulation models.

Keywords: Mars, dust devil

Numerical explorations of climates of terrestrial exoplanets

*Masaki Ishiwatari[1], Satoshi Noda[2], Kensuke Nakajima[3], Yoshiyuki O. Takahashi[4], Shin-ichi Takehiro[5], Yoshi-Yuki Hayashi[4]

1.Faculty of Science, Hokkaido University, 2.Graduate School of Science, Kyoto University, 3. Department of Earth and Planetary Sciences,Flculty of Sciences,Kyushu University, 4.Graduate School of Science, Kobe University, 5.Research Institute for Mathematical Sciences, Kyoto University

More than thousand exoplanets have been discovered by Kepler space telescope. Some exoplanets are called as Super Earths which is defined as planets with mass several times of Earth mass. Investigations for exoplanets similar to Earth are a base of discussion on the possibility of existence of extrasolar life, and a lesson for understandings of climate stability and the existence condition of mild climate like Earth's. From the circumstances of increasing the number of objects of climate research, we are aiming to explore the varieties of planetary climate numerically.

Our objectives are to grasp the variety of planetary climate, and to understand the existence condition of the ocean. Occurrence conditions of the snowball state and the runaway greenhouse state are important for examining the existence of the ocean. As an investigation on the snowball state, Budyko (1969)'s climate regime diagram is well known, which shows appearances of the snowball state, partially frozen state, no-ice state according to the value of solar constant. The runaway greenhouse state is defined as a state in which incident flux given to the atmosphere exceeds the radiation limit: the upper limit of outgoing longwave radiation (OLR) emitted from the top of the moist atmosphere on a planet with ocean (Nakajima et al., 1992). In the runaway greenhouse state, thermal equilibrium cannot be realized and entire ocean evaporates. We have performed some experiments on the snowball state and the runaway greenhouse state with an atmospheric general circulation model.

The model we have utilized is a atmospheric general circulation model, DCPAM (http://www.gfd-dennou.org/library/dcpam). Subgrid physical processes are parameterized with standard methods used in terrestrial Meteorology. The amount of cloud water is calculated with integrating a time dependent equation including generation, advection, turbulent diffusion, and extinction of cloud water. Extinction rate of cloud water is simply assumed to be proportional to the amount of cloud water, and extinction time is given as an external parameter. Since we focus on parameter sweep experiment, our style of numerical experiment is to perform many numbers of small scale computation. Contrary to the meridionally one-dimensional model of Budyko (1969), three-dimensional GCM needs a large amount of computational resources. Computational resources which we need are small scale ones suitable for parameter sweep, in addition to large scale computational resources used for high resolution experiment.

With DCAPM, we have examined the occurrence condition of the runaway greenhouse state for synchronously rotating planets, aqua planets, and land planets. Our results seem to suggest that, regardless the existence of clouds and solar flux distribution, the runaway greenhouse state appears with the increased value of solar constant for which global mean absorbed solar radiation flux exceeds the maximum values of OLR.

Our experiments so far are based on present Earth configuration: radiation scheme for present Earth (Chou et al., 1996; Chou et al., 2001) is used, and the values of extinction time of cloud water is tuned with observational data of present Earth. Surface process is also simply represented in our model. The entire surface is assumed to be a ``swamp ocean'' with zero heat capacity. At present, in order to expand model applicability, we are developing a radiation scheme of H_2O-CO_2 atmosphere and a dynamical ocean model. We are planning to draw climate regime diagrams including the snowball state and the runaway greenhouse state for various exoplanet configurations concurrently with model development.

Keywords: atmospheric general circulation model, exoplanet, habitability, runaway greenhouse state, snowball state

Effects of dynamical boundary condition on banded structure produced by convection in a rotating spherical shell

*Youhei SASAKI[1], Shin-ichi Takehiro[2], Keiichi Ishioka[3], Kensuke Nakajima[4], Yoshi-Yuki Hayashi[5]

1.Department of Mathematics, Kyoto University, 2.Research Institute for Mathematical Sciences, Kyoto University, 3.Department of Earth and Planetary Sciences, Kyoto University, 4.Department of Earth and Planetary Sciences, Kyushu University, 5.Department of Earth and Planetary Sciences, Kobe University

Surface flows of Jupiter and Saturn are characterized by the broad prograde zonal jets around the equator and the narrow alternating zonal jets in mid- and high-latitudes. ``Shallow'' models can produce narrow alternating jet sin mid- and high-latitudes, while the equatorial jets are not necessarily prograde. On the other hand, ``deep'' models, can produce equatorial prograde flows easily, while it seems to be difficult to generate alternating jets in mid- and high-latitudes. Heimpel and Aurnou (2007) proposed thermal convection in rapidly rotating thin spherical shell models and show that the equatorial prograde zonal jets and alternating zonal jets in mid- and high-latitudes can be produced simultaneously when the Rayleigh number is sufficiently large and convection becomes active even inside the tangent cylinder. However, they assume eight-fold symmetry in the longitudinal direction and calculate fluid motion only in the one-eighth sector of the whole spherical shell. Such artificial limitation of the computational domain may influence on the structure of the global flow field. For example, zonal flows may not develop efficiently due to the sufficient upward cascade of two-dimensional turbulence, or stability of mean zonal flows may change with the domain size in the longitudinal direction.

On these accounts, we performed long time numerical experiment of thermal convection in the whole thin spherical shell domain, where the experimental setup is same as that of Heimpel and Aurnou (2007). The result shows that the banded structure disappears and one broad eastward zonal jet appears in mid- and high- latitudes of each hemisphere, suggesting that the solution of Heimpel and Aurnou (2007) is not a statistically steady state but a transient state.

However, this solution where the inverse cascade efficiently operates presumably depend on the stress free dynamical boundary condition on the inner and outer spheres. Therefore, in this study, we change the stress free condition to the no-slip condition at the inner sphere to examine effects of dynamical boundary condition on the emergence of surface banded structure. The no-slip condition at the lower boundary may be more realistic for the application of the gas giant planets, since MHD drag is thought to operate in the transition between the neutral and electrically conducting layers.

We consider Boussinesq fluid in a spherical shell rotating with constant angular velocity. The non-dimensionalized governing equations consist of equations of continuity, motion, and temperature. The non-dimensional parameters appearing in the governing equations, the Prandtl number, the Ekman number, the modified Rayleigh number, and the radius ratio, are fixed to 0.1, 3×10^{-6}, 0.05, and 0.85, respectively. The thermal boundary condition is fixed temperature.

Free-slip condition is adopted at the top boundary, while no-slip condition is applied at the bottom boundary. The initial condition of the velocity field is state of rest and that of the temperature field is conductive state with random temperature perturbations.

After time integration for about 12000 rotation period, a strong equatorial prograde surface zonal jet and weak alternating banded zonal jets emerge. In contrast to the case of free-slip condition at both boundaries, this banded structure in mid- and high-latitudes is maintained until about 19000 rotation periods. The reason why the banded structure does not disappear is considered to be inhibition of inverse cascade caused by the Ekman friction which dissipates large scale flow efficiently.

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Reference:
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A numerical experiment of aquaplanet climates with a coupled atmosphere-ocean-sea ice model

*Yuta Kawai[1,2], Yoshiyuki O. Takahashi[1], Masaki Ishiwatari[5], Seiya Nishizawa[2], Shin-ichi Takehiro[4], Kensuke Nakajima[3], Hirofumi Tomita[2], Yoshi-Yuki Hayashi[1]

1.Kobe Univ., 2.RIKEN AICS., 3.Kyusyu Univ., 4.Kyoto Univ., 5.Hokkaido Univ.

To explore the diversity of climates on exoplanets, some planetary atmospheric scientists have been conducting numerical experiments of exoplanet climates. Our research group also has been performing numerical study of climates on a planet globally covered ocean (aquaplanet) to understand the role of atmospheric and oceanic circulation on determining planetary climates. For example, Ishiwatari et al. (2007) discussed the diversity of climates and multiple equilibrium states with three-dimensional atmospheric general circulation model. But, at that time, ocean dynamics is not considered entirely, because they used greatly simplified ocean. Actually, if there is ocean on a planet, oceanic heat transport also has an important role on determining and maintaining planetary climates. In fact, the heat transport carried by the ocean is an important component of Earth’s heat budget (Trenberth and Caron 2001). Recently, Rose et al. (2009) discovered the presence of a new stable climate state in one-dimensional meridional energy balance with the oceanic heat transport effect. The recent improvements of computational performance have been able to explore aquaplanet climates with a coupled atmosphere-ocean-sea ice model. Smith et al. (2006) is pioneer work in aquaplanet experiments with coupled models. After their studies, with couple models some researchers have been investigating the dependence of some planetary parameters, such as solar constant, rotation period and rotation angle (e.g., Ferreira et al., 2011).

To explore aquaplanet climates considered both atmospheric and oceanic circulation, our research group is now developing atmospheric general circulation model, oceanic general circulation model, and thermodynamic sea ice mode, and coupling these models. The ocean model calculates the large-scale distributions of current velocity, temperature and salinity explicitly, while the effects of some sub-grid scale processes, such as small-scale eddies and convection, are parameterized. The thermodynamic sea ice model calculates the thickness and temperature of sea ice. These models are coupled with atmospheric model, DCPAM, with a coupler library (Arakawa et al., 2011). For simulations of high resolution and parameter studies to span a wide range of climatic regimes, this couple model is a parallel program, which can run in some parallel computational environments. Furthermore, in order to accelerate temporal integration of ocean model, we adopt the following temporal integration method. First, the coupled model is run over few years. Next using atmospheric forcing from the coupled run, ocean-sea ice model alone is integrated over few hundred years. This cycle is repeated until the coupled system reaches quasi-equilibrium state.

To check behavior of our coupled model, we are now conducting numerical experiments of an aquaplanet climate in which present Earth’s parameters are given. Initially, atmosphere and ocean are isothermal (280 K) at rest. The couple system is driven by annual and diurnal mean incoming solar flux. Using above temporal integration method, we can currently perform about 20-30 cycles of integration (equivalent to about 4000 years integration for the ocean). After this long time integration, we have obtained global patterns of atmospheric and oceanic circulations similar to the result of previous studies (e.g., Marshall et al., 2007). But the thickness of sea ice and thus ocean salinity continue to increase. One of the reasons is probably that meridional transport of sea ice is not considered. We are also checking heat and water budgets. Therefore, an immediate task is to obtain equilibrium state in our coupled model. In the near feature, using the coupled model, we will examine solar constant dependence of aquaplanet climates, and consider the role of the atmospheric and oceanic circulation on the climates.

Keywords: aquaplanet , coupled atmosphere-ocean-sea ice model