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

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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

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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

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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

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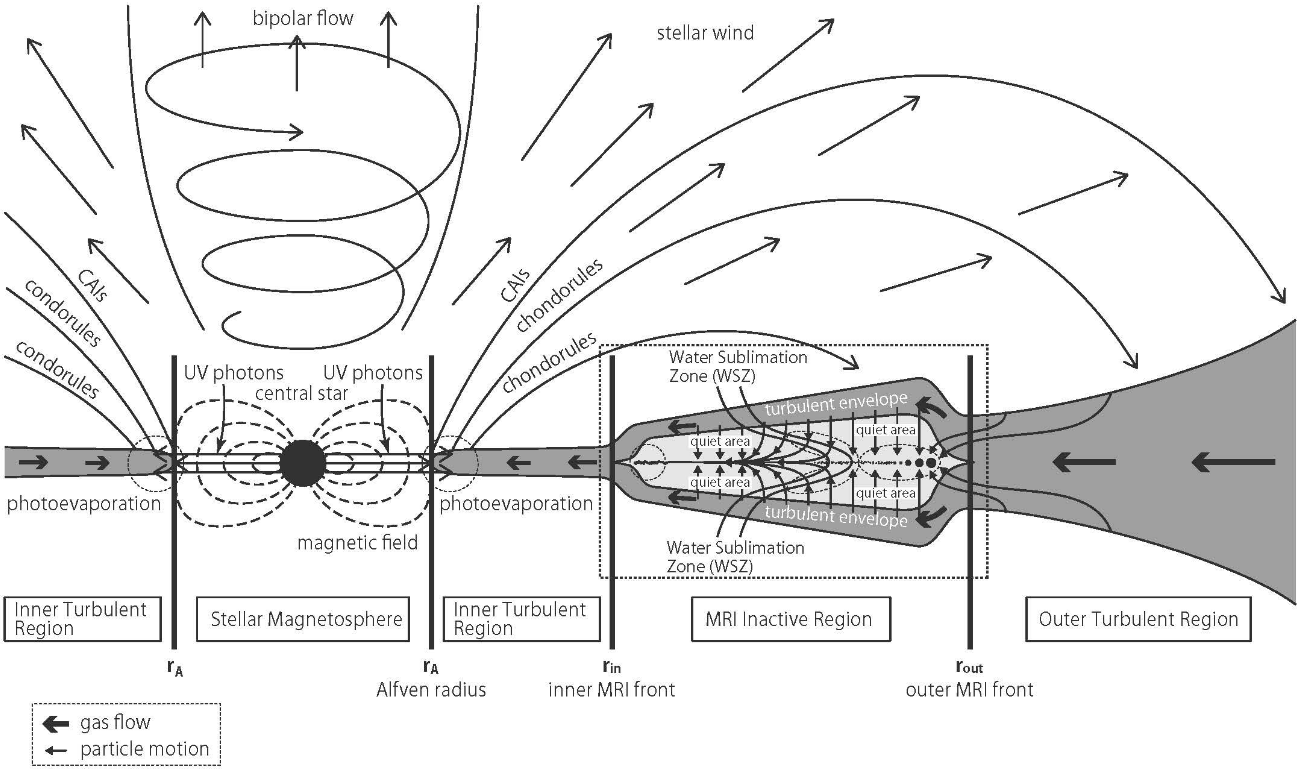
We have obtained a steady-state, 1-D model of the accretion disk of a protostar taking into account the magneto-rotational instability (MRI). We find that the disk is divided into an outer turbulent region (OTR), a MRI suppressed region (MSR), and an inner turbulent region (ITR). The outer turbulent 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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Formura: Programming Language for High-performance Structured Lattice Stencil Computation

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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

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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

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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

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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

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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, $3x10^{-6}$, 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:

- Heimpel, M., & Aurnou, J., Icarus, 187, 540--557, April 2007.

Keywords: atmospheres of the gas giant planets, banded structure, equatorial prograde jet, Rossby waves, Jupiter, Saturn

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

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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