High-resolution Global N-body Simulation of Planetary Formation with Fragmentation

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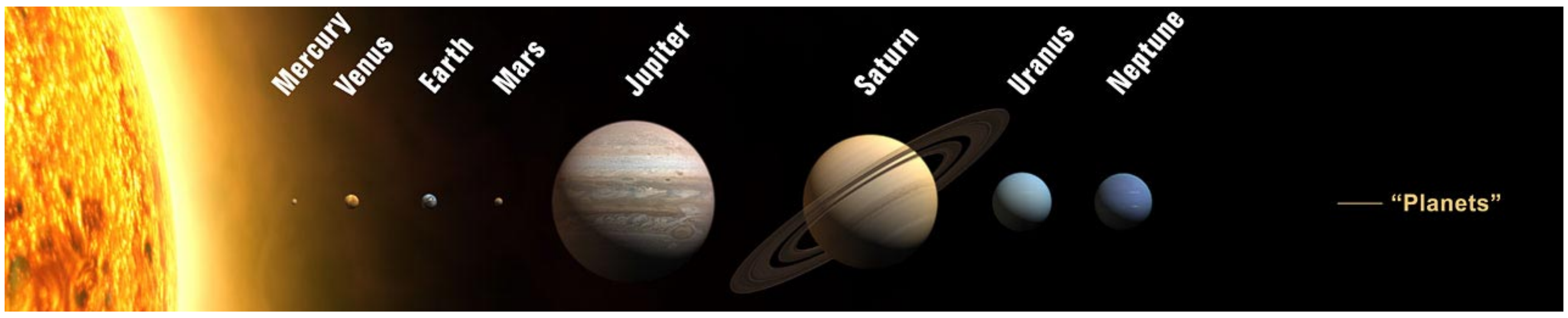


What we did

- N-body simulations starting from planetesimal disk (0.7 AU to 4.0 AU), including the ice line(N~82000).
- Assumed that the largest runaway bodies outside the ice line to grow to 0.1 Earth mass and restarted the simulation.
- Included the effect of the disk gas (gas drag and type-I migration).
- Carried out simulations that the number of bodies increases due to fragmentation.

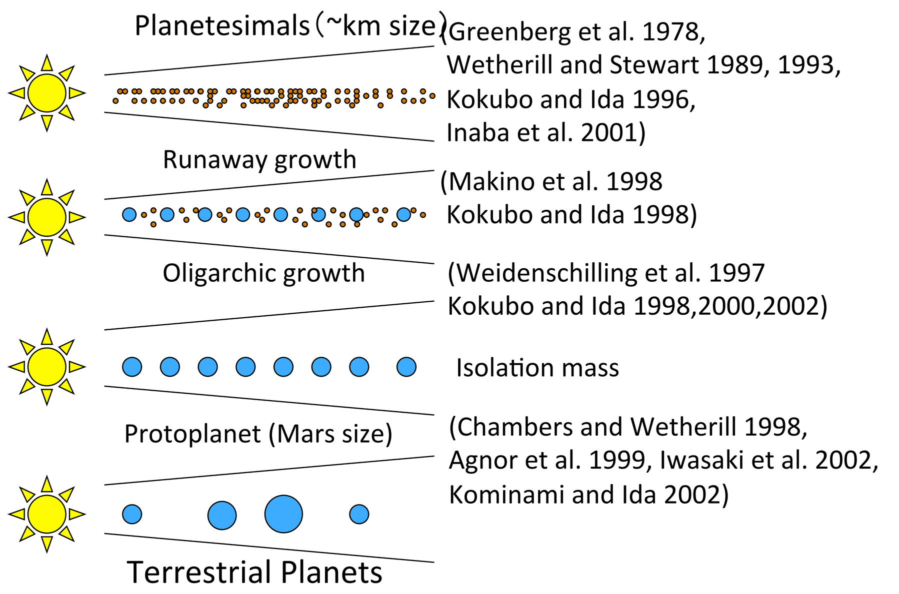
Result

- The outer protoplanet moves outward and the inner protoplanet moves inward.
- Gas drag suppresses the random velocity increase and the migration continues.
- Type-I migration can be overcome when fragments are included in the simulations.

Discussion

- Dependence of the distance of outward migration depends on the size of the fragments. Small fragments tend to enhance the outward migration.

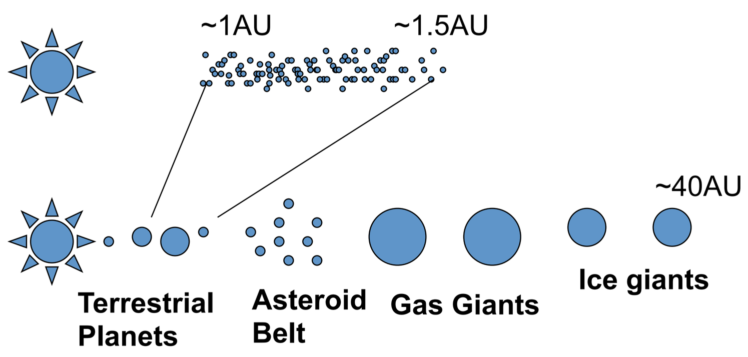
<1>Past N-body Simulations



Planet formation has been investigated thoroughly by N-body simulations.

<2>Problem of Past Simulations

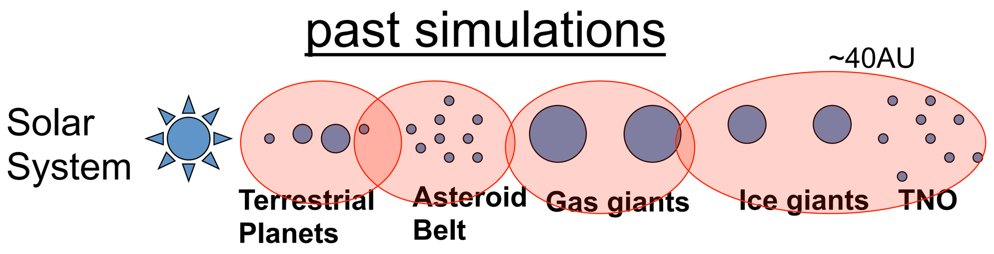
N-body simulations were limited to narrow regions



Number of particles were limited because of the simulation cost

No global simulation has been carried out yet.

<3>Questions that could not be answered by past simulations



- Will classical runaway and oligarchic growth be still valid?
- The effect of including the snow line : Discontinuity of solid surface density in the disk
- What will happen dynamically when the gas giant cores start to accrete gas and the masses start to increase?
- Explanation of water abundance on the Earth

In this study, we focus on the Snow line inclusion

<4>Results acquired by Including the Snow Line (Kominami et al. 2016)

(1) Bimodal Planetary Growth
Runaway growth should proceed in the inner edge and beyond the ice line as well.

(2) Gas Giants' Core Formation
Runaway bodies outside the ice line can be gas giants' cores accreting planetesimals and gas

(3) Outward Migration to Form Initial Condition For Nice Model
Planetesimal driven migration happens for the mass difference between the core and the planetesimals

(4) Increase of the random velocity stops the migration

<5>In-situ Formation Timescale

Time scale for the protoplanets to grow to the gas accreting mass around 30AU

$t_{\rm formation} \sim 10^{10}$years

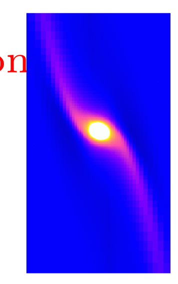
$t_{\rm solar.system} \sim 10^9$year $< t_{\rm formation}$

$t_{\rm gas.disk} \sim 10^6$year $< t_{\rm formation}$

In-situ formation can not explain the Solar system structure

<6>Effect from the Gas Disk

(1) gas drag
(Adachi et al. 1976, Tanaka & Ida 1999) Both damps the semimajor axis and random velocity
(2) Tidal interaction with the gas disk
(e.g. Ward 1986, Tanaka et al. 2002, Tanaka and Ward 2004)



Planet triggers a wave structure

Results in angular momentum decrease

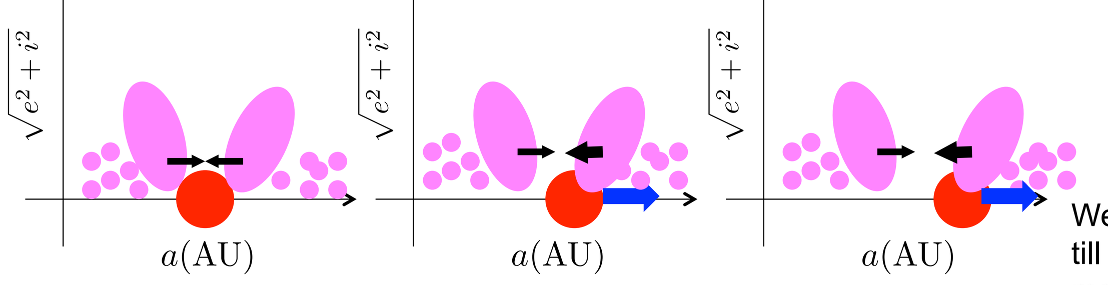
The structure exerts a torque on the planet

(Morohoshi and Tanaka 2003)

When $m > m_{\rm moon}$ type-I migration effect drags the planet toward the Sun leaving little solid material in the disk.

<7>Planetesimal Driven Migration

(Ida et al. 2000, Minton and Levison 2014)



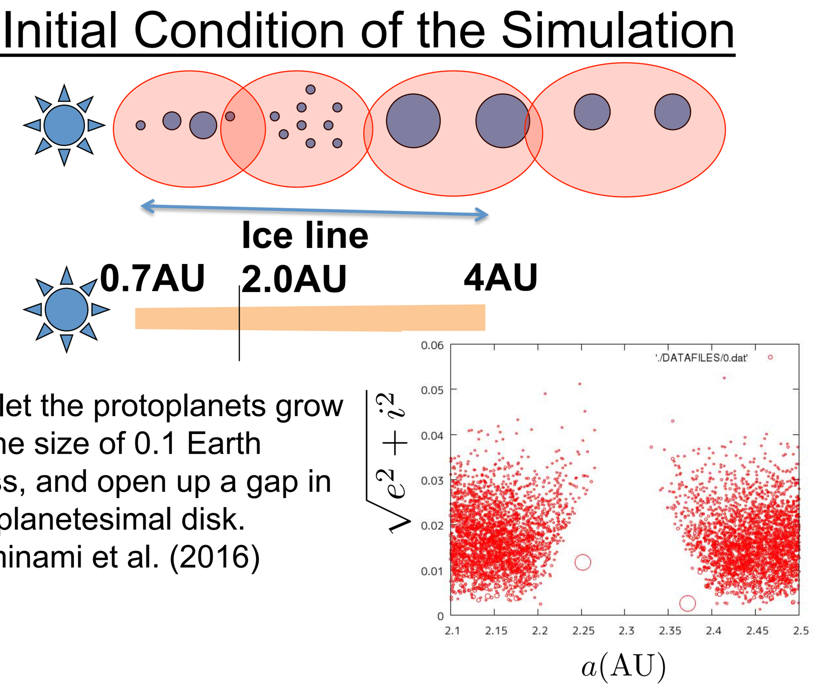
Protoplanet scatters the planetesimals. Planetesimals have symmetric distribution.

If a "Kick" is added to the protoplanet, the distribution becomes asymmetric

Number of planetesimals at the right is larger and this asymmetric distribution continues

In order to reproduce this migration, we need to simulate $\sim 10^5$ planetesimals' orbital evolution for at least $\sim 10^5$ orbits

<8>Initial Condition of the Simulation



We let the protoplanets grow till the size of 0.1 Earth mass, and open up a gap in the planetesimal disk. Kominami et al. (2016)

<9>K computer at RIKEN (Kobe)

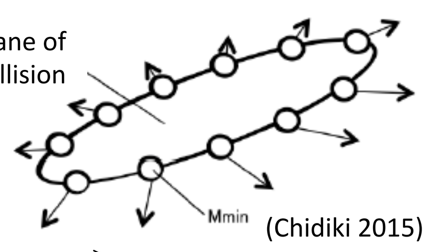
http://www.aics.riken.jp/en/k-computer/system

We developed the fastest parallel N-body code (Kninja) for the orbital integration of planet accretion. The performance efficiency is ~30% of the theoretical peak.

<10>Method and Fragmentation Model

Direct N-body simulations that calculates the gravity of each particle (N-body simulations).

- Integration scheme is 4th order Hermite scheme
- Include the fragmentation model

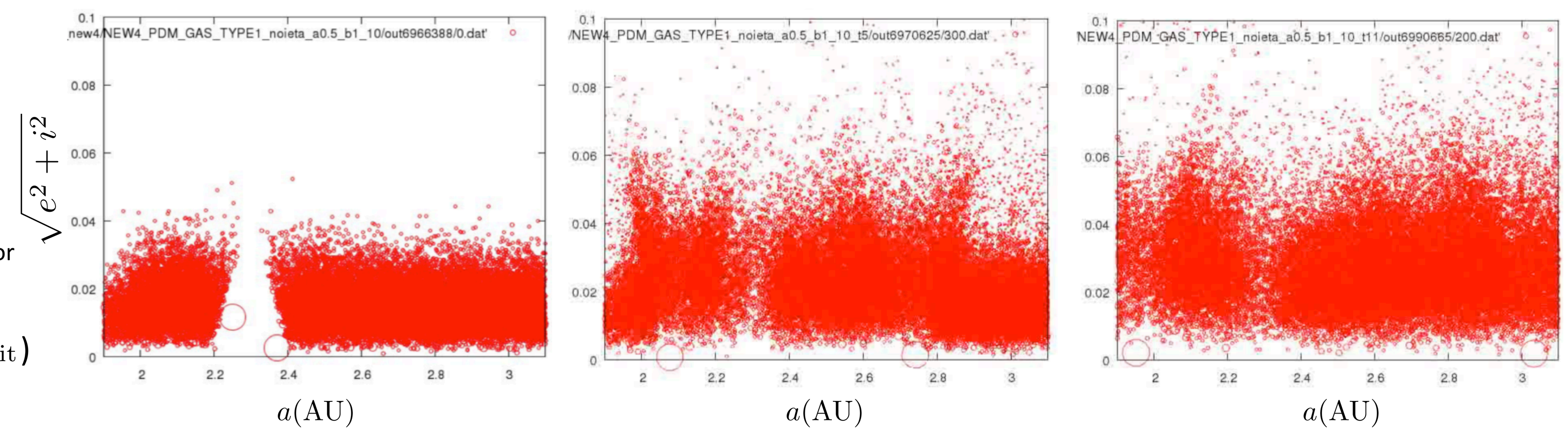


Velocity of the fragments are set to be 1.05 times the escape velocity of $m_{\rm imp} + m_{\rm tar}$
The fragments are distributed on a plane spanned by relative position vector and relative velocity vector.

$m_{\rm tar} > m_{\rm imp}$
1, set the minimum mass of the fragments ($m_{\rm min} = b \cdot m_{\rm init}$)
2, large mass forms at the center of mass. $m_{\rm k} = (1-a)m_{\rm imp} + m_{\rm tar}$
3, fragments form from $am_{\rm imp}$
4, number of fragments is $n_{\rm f} = \frac{am_{\rm imp}}{m_{\rm min}}$
5, if $n_{\rm f} = 0, 1$, perfect accretion is assumed

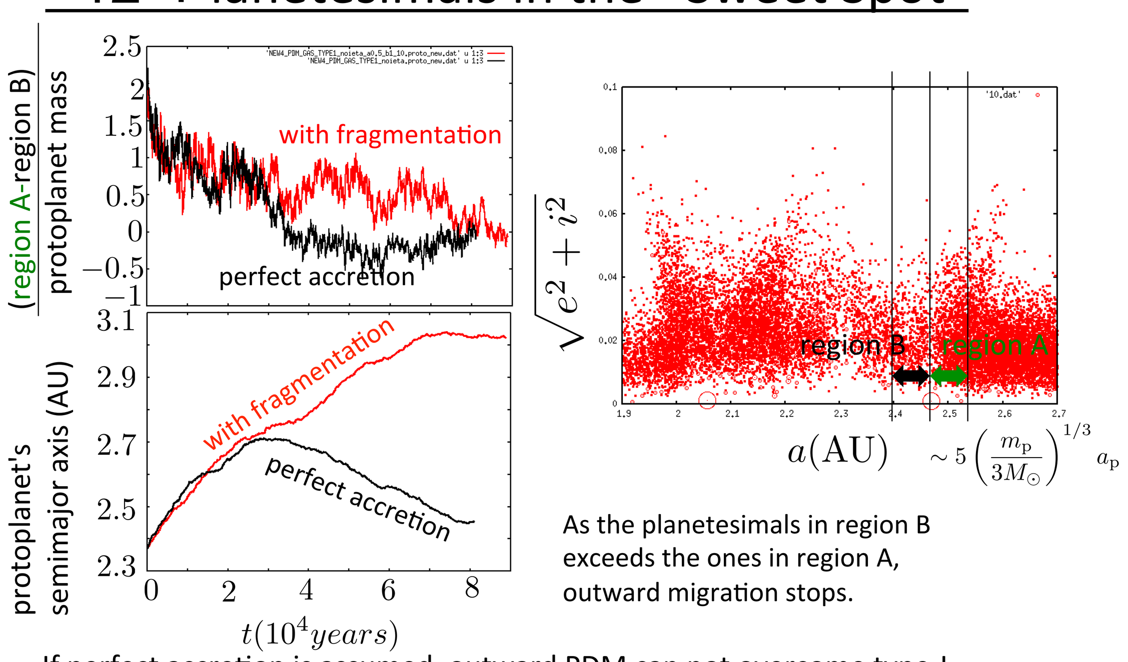
<11>Simulation Result

$a = 0.5, b = 1/10$



In the case with the fragmentation, the outward migration continues. This phenomenon did not appear using large planetesimals.

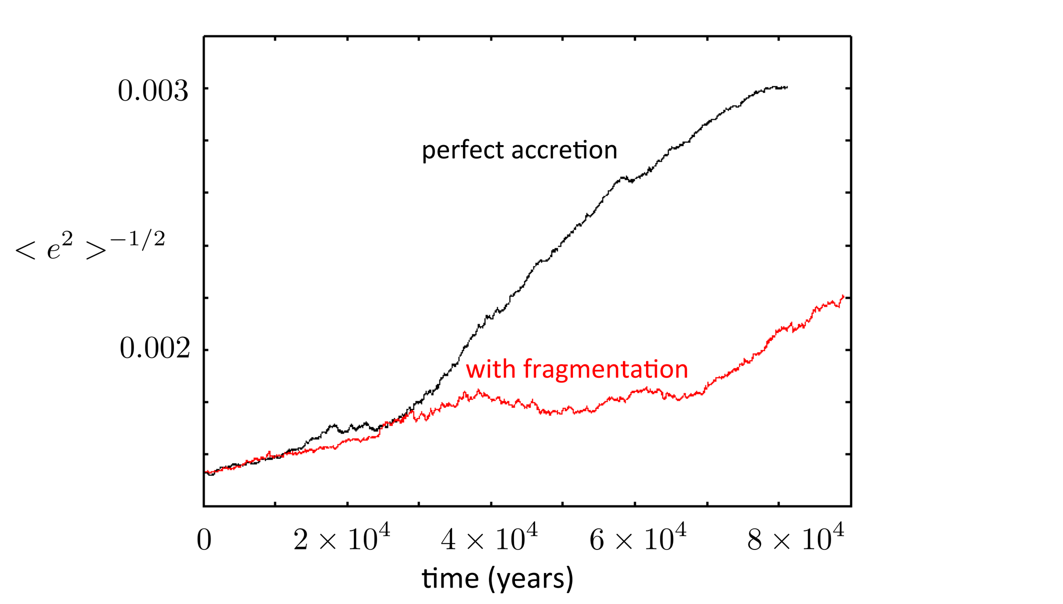
<12>Planetesimals in the "Sweet Spot"



As the planetesimals in region B exceeds the ones in region A, outward migration stops.

If perfect accretion is assumed, outward PDM can not overcome type-I.
Outward migration needs at least 0.5 protoplanet "sweet spot" mass.

<13>Eccentricity Evolution of the mass $10^{-9}M_\odot$



In the case with the fragmentation, the eccentricity does not increase so much compared to the case of perfect accretion.
Dynamical friction from the fragments seems to damp the ecc.

<14>Summary and Discussion

Classical planet formation theory has been investigated using N-body simulations.

One phenomenon that can not be neglected is the migration of the protoplanets and the collisional fragmentation.
Small planetesimals and the fragments damps the eccentricity of the moderately small planetesimals, which enhances the outward PDM.

If smaller particles and larger number of particles are incorporated, simulation outcome drastically changes.

We are developing a code (P3T + FDPS) which can treat a large number of particles and see if runaway and oligarchic growth mode, and other physical phenomena change.