Numerical Calculations of Terrestrial Planet Formation

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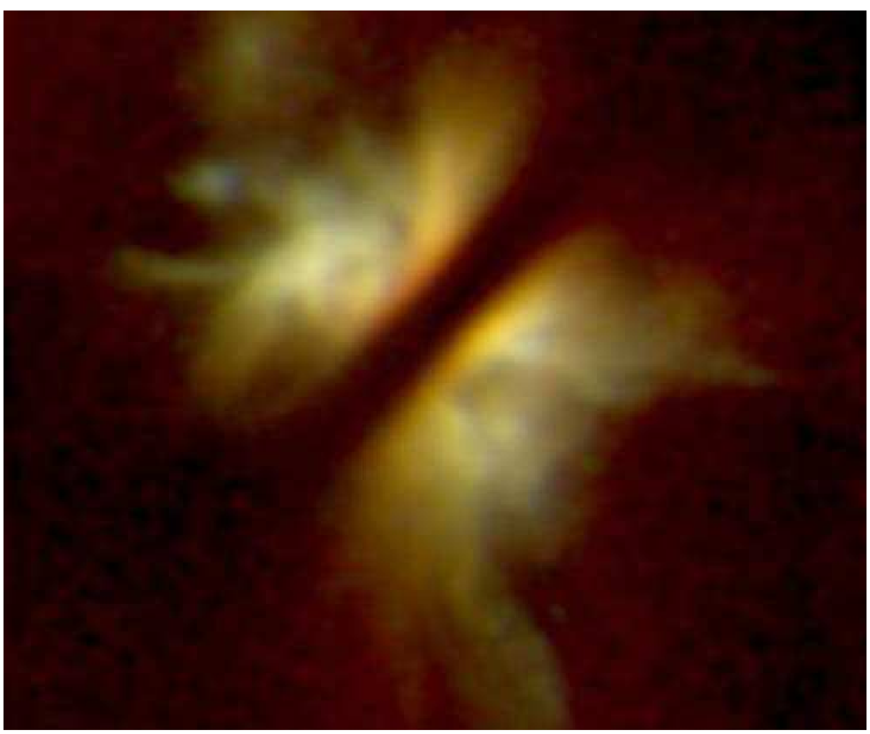
abstract

We describe numerical calculations of terrestrial planet formation using a hybrid multiannulus coagulation+n-body code. The code allows us to follow the collisional evolution of cm to m sized bodies into terrestrial mass planets and an associated debris disk. Our numerical simulations form terrestrial mass planets in 1-10 Myr at 0.5-2 AU. As rocky planets grow, they stir up leftover planetesimals along their orbits. The resulting cascade of collisions produces a debris disk. With current facilities, the infrared excess of the debris is visible for 10-30 Myr. Planned facilities such as TPF/Darwin may be sensitive enough to detect structure in the debris, including wakes from terrestrial planets.



http://jwstsite.stsci.edu/science/planetary.shtml

I. Introduction

Observations:

- Ubiquitous disks of gas & dust surround young stars (e.g., Wyatt et al. 2003).
- The majority of the gas disappears by ∼1 Myr.
- Debris disks form within 10–100 Myr. (e.g., Greaves & Wyatt 2003)

Planetesimal Theory:

- Planetesimals form in the dusty midplane of a protoplanetary disk by coagulation and/or gravitational instability (Goldreich & Ward 1973; Youdin & Shu 2003).
- Terrestrial planets grow by mergers of 1–10 km planetesimals (e.g., Wetherill & Stuart 1993; Chambers 2001).
- Planets stir up leftover planetesimals to disruption velocity (Williams & Wetherill 1994); cascade of collisions grinds left-overs to **observable dust**.

II. Calculations

Simulations of rocky planet formation:

- Coagulation calculations (early evolution only; Safronov 1977; Wetherill & Stewart 1983; Kenyon & Luu 1998, 1999)
- N-body calculations (late evolution only; e.g., Duncan, Levison & Lee 1998; Chambers 2001)
- Hybrid code to model all stages of planet formation (e.g., Jewell & Alexander 1996; Weidenschilling et al. 1997)

Coagulation code features:

- 32 annuli of width 0.01 AU centered at 1 AU
- Initial surface density of 1–5 MMSN in 1–10 km planetesimals on nearly circular orbits ($e = 10^{-4}$)
- Gravitational stirring, gas drag, Robertson-Poynting drag

N-body code features:

- Eighth-order accurate, adaptive, ODE solver for particle orbits
- Accelerated reference frames (Encke [1857] method) for orbit determination
- Direct orbital element modification (e.g., de/dt) as specified by coagulation code
- Fast merger identification based on particle indices saved during force evaluations

III. Tests of the code

- Coagulation code tests: Kenyon & Bromley (2001, 2002)
- N-body integrator dynamic range (Fig. 1), and stability (Fig. 2)
- Coagulation versus direct N-body
- Merger tests: 10 cm "grapefruits" on opposing 1 AU orbits; Greenzweig & Lissauer (1990) planetary accretion rates.

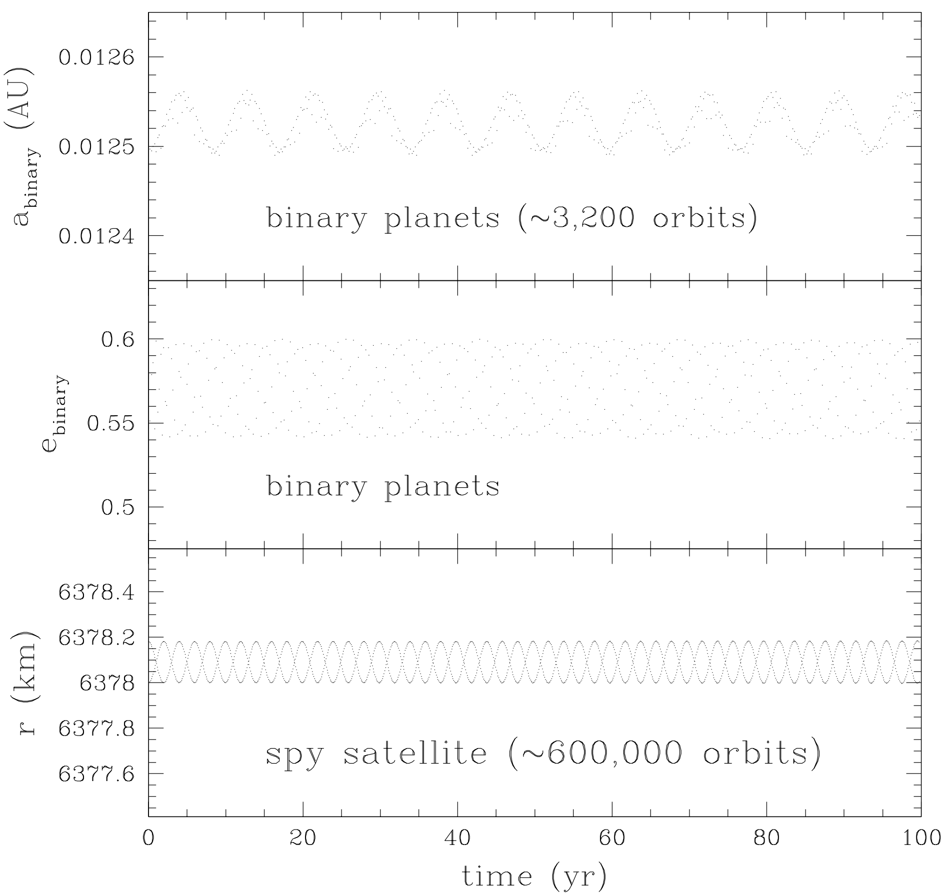


Figure 1. Orbit parameters from simulations of a hard-binary "jupiters" at 1 AU (Duncan, Levison & Lee 1998; upper two panels) and a "spy satellite" on a surface-skimming orbit about the Earth (lower panel). These runs test dynamic range and interpolation in the N-body code.

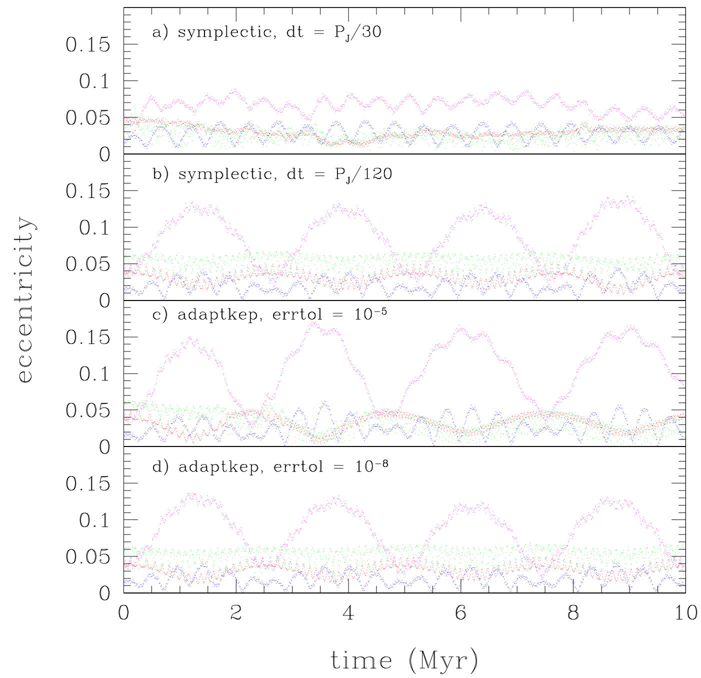


Figure 2. Evolution of eccentricity of the major planets as calculated with our adaptive integrator and a fixed-timestep symplectic integrator.

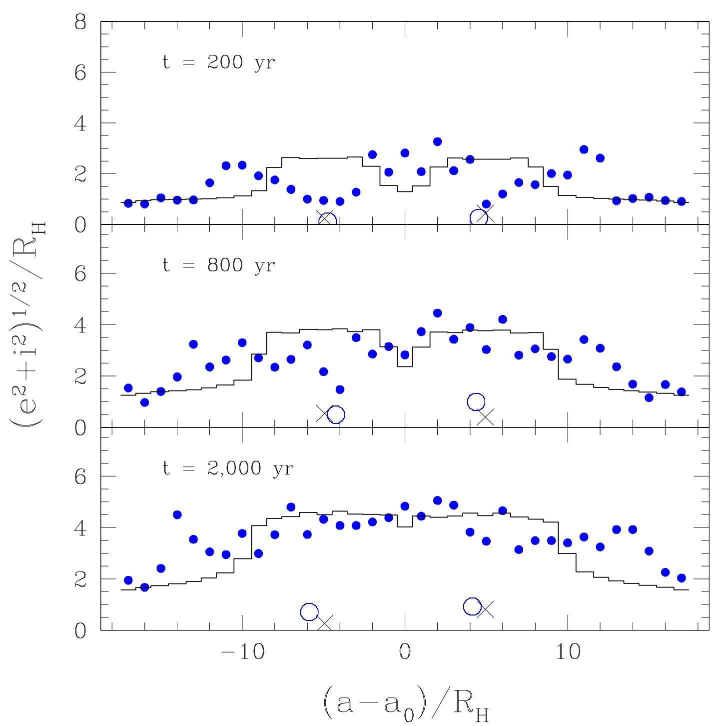
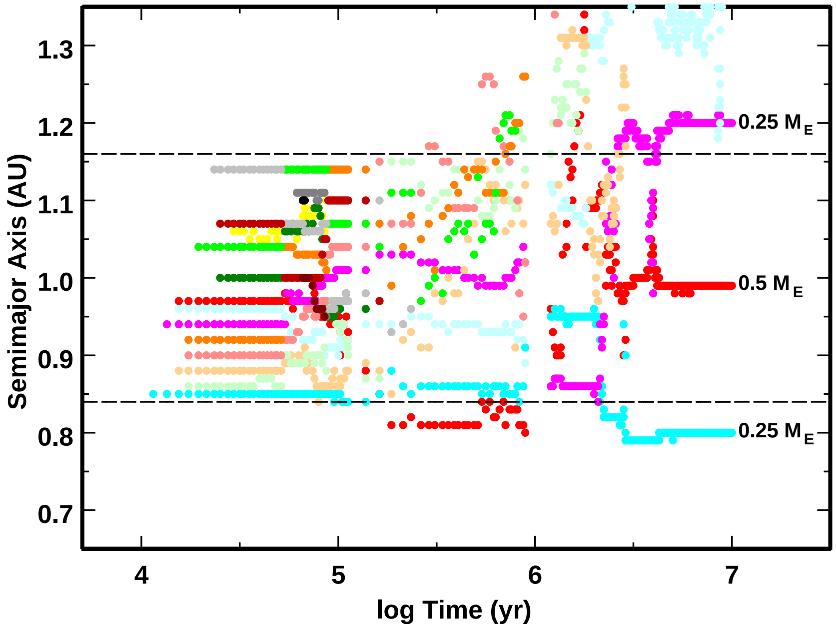


Figure 3. Gravitational stirring by two planets in a swarm of 800 low mass bodies. (Blue: N-body code; black: coagulation code).

IV. Results

- Our numerical calculations demonstrate the detailed process of terrestrial planet formation from a sea of small planetesimals.
- Simulations with our hybrid code produces Earth-massed objects at 1 AU within $O(10)$ Myr (Fig. 4).
- Fragmentation processes during the early stages of terrestrial planet formation (as tracked by the coagulation code) produce observable amounts of dust (Fig. 5; Kenyon & Bromley 2004).
- The Spitzer Space Telescope can detect excess infrared emission associated with terrestrial planet formation. A statistical analysis of data from young stars will provide a test of the models presented here.
- Upcoming adaptive-optics instruments will be able to resolve the rings of dust produced near 1 AU during terrestrial planet formation.
- Had distant observers viewed the Earth 4.5 billion years ago, using technology available to us today, they could have inferred the formation of the Earth.



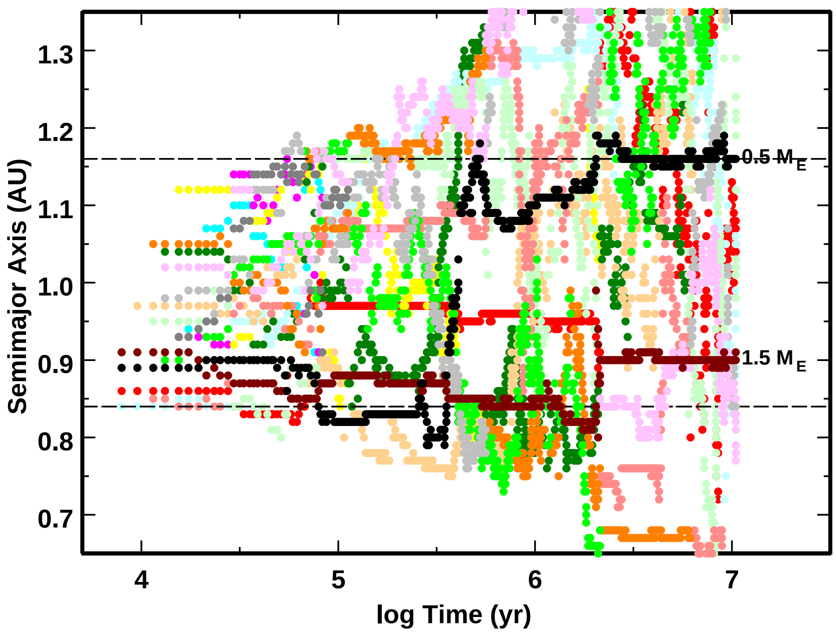


Figure 4. The evolution of heliocentric distance for rocky planets in two simulations which differ in initial surface density ($\Sigma_0 = 20$ g/cm^2 upper panel; twice this value for the lower panel). The dashed lines indicate boundaries of the planetesimal grid. Initial N-body masses are $\sim 2\times10^{25}$ g. N-bodies accrete mass from the planetesimals and from mergers with other N-bodies. After 10^7 yr, three planets in the lower density simulation (the largest of which is 50% of the mass of the Earth) have cleared all but one smaller n-body from the grid. Evolutionary processes are generally accelerated in the higher mass disk and produce a planet which is 1.5 times the mass of the Earth.

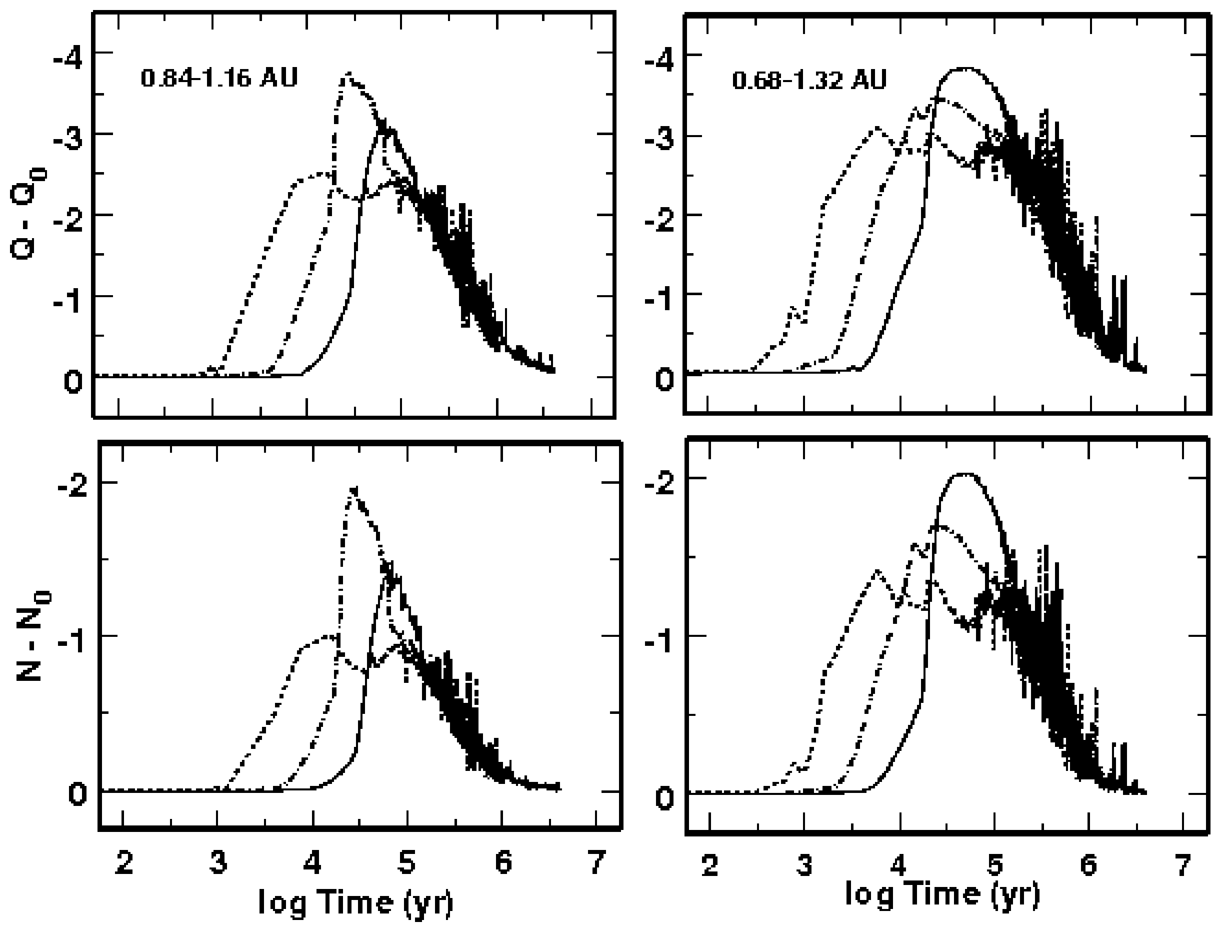


Figure 5. Evolution of broadband 10 μm (N-N$_0$) and 20 μm (Q-Q$_0$) excess radiation from dust during terrestrial planet formation. The left panels are for a model in a narrow ring of material near 1 AU, while the right panels are for a broader region. Fragmentation of planetesimals in these rings, triggered by terrestrial planet formation, produces copious amounts dust. At the peak of dust production, roughly 10^5 yr, starlight reprocessed by the dust can be a sizable fraction of the stellar luminosity in these wavebands. The three curves in each plot are for models with initial surface densities Σ_0 of 8, 16 and 32 g/cm^2; the excess radiation is greater for larger Σ_0.

acknowledgements

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