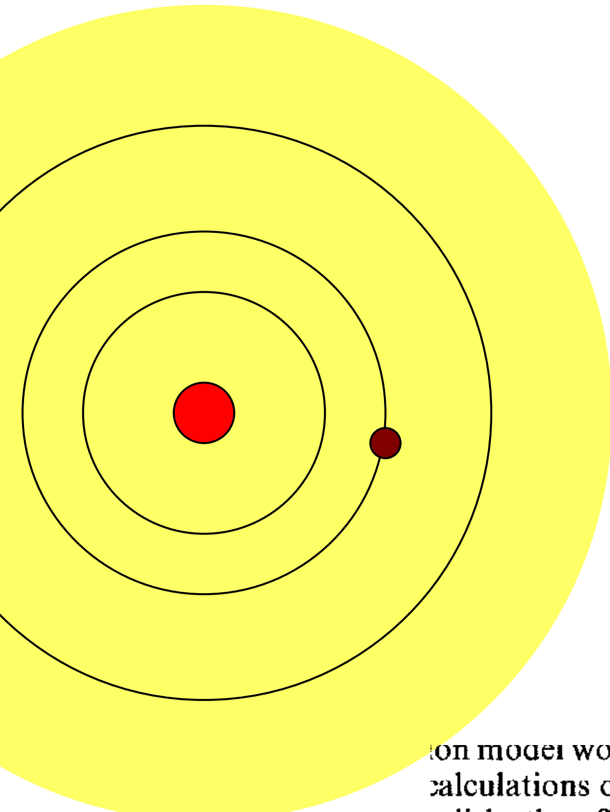
星・惑星系の形成過程 入門

中本泰史 (東工大)

1. 形成過程の概観
2. 分子雲の重力収縮
3. 原始惑星系円盤
4. 固体微粒子の進化
5. 微惑星から惑星へ
6. 惑星系の形成

惑星移動 (Type I migration)

Lindbrad 共鳴



$$\kappa = m(\Omega - \Omega_p)$$

↑　　　　　　　　　　　ケプラー回転の時

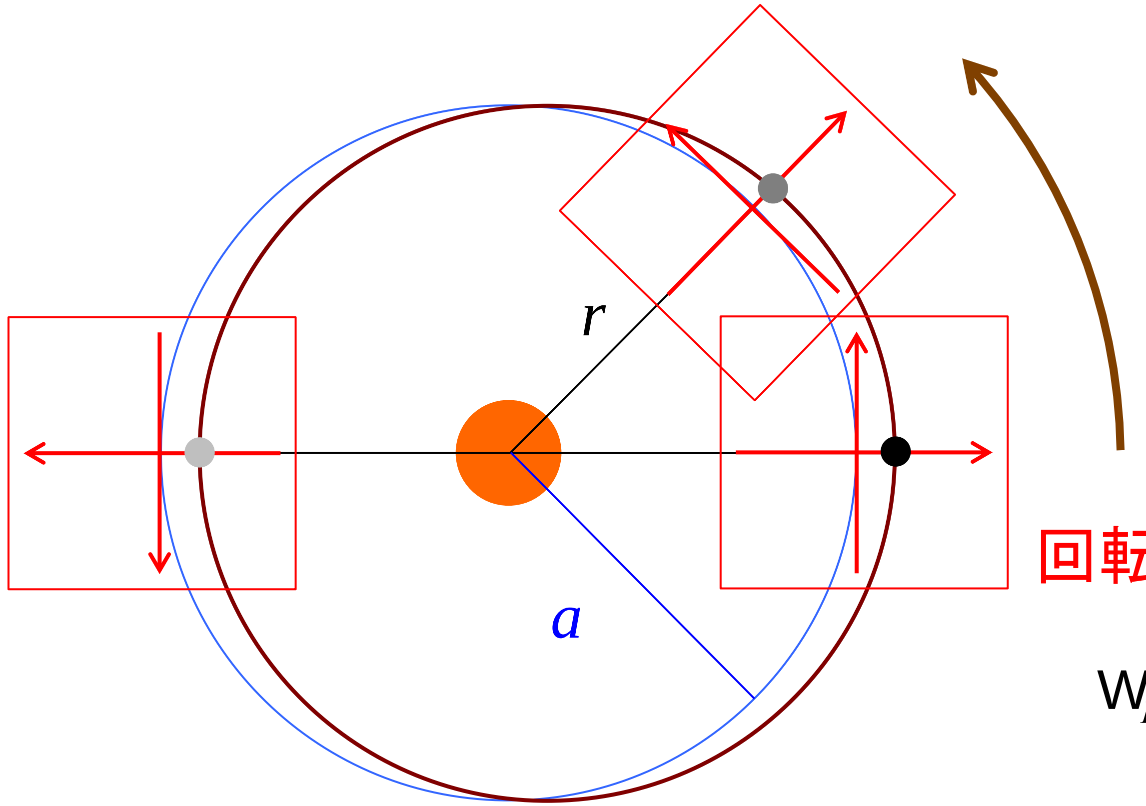
エピサイクリック振動数 = Ω

固有振動数 = 会合周波数の整数倍

$$r_L = \left(1 \pm \frac{1}{m}\right)^{2/3} r_p$$

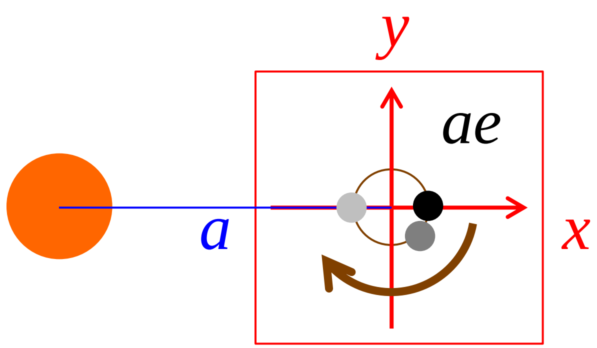
…ion model would require an extremely small intrinsic viscosity to account for the gap size.
…calculations on gap formation, it was often assumed that the waves excited near LRs are loca…
… disk, the effective viscosity may not be adequate to inhibit wave propagation. If the per…
…small and amplitude of the wave is linear, the excited density waves can propagate to large d…
…d transfer angular momentum effectively over a large region of the disk (see Fig. 1*b*). The pro…
…cture of the disk at the location where the waves are dissipated. Thus, the width of the gap ma…
…t derived on the basis of local dissipation. This idea has been suggested as a mechanism for inc…
…division in Saturn's rings by Goldreich & Tremaine (1978). Nonlocal dissipation of density…
…ed in Saturn's rings (Cuzzi, Lissauer, & Shu 1981).
…, we investigate the effect of wave propagation on the process of gap formation. We assume t…
…d by an embedded protoplanet is small. In this limit, wave propagation and viscous dissipatio…

Takeuchi et al. 1996



回転座標系

$$\Omega_K = \sqrt{\frac{GM}{a^3}}$$



エピサイクル運動
(周転円運動)
周期：T_K

$$v = ae\Omega_K = V_K e$$

Tanaka et al. 2002

・等温ガス円盤，3D構造
・トルク

$$t_I = \frac{1}{2.7+1.1q}\left(\frac{M}{M_*}\right)^{-1}\left(\frac{\Sigma_g r^2}{M_*}\right)^{-1}\left(\frac{c_s}{V_K}\right)^2 \Omega_K^{-1} \qquad \Sigma_g \propto r^{-q}$$

$$\approx 5\times 10^4 \left(\frac{M}{M_{\mathrm{Earth}}}\right)^{-1}\left(\frac{r}{1\ \mathrm{AU}}\right)^{3/2}\ \mathrm{yr}$$

「惑星落下問題」

Paardekooper & Mellema 2006

- 非等温ガス円盤
- 3D流体計算
  with 輻射エネルギー輸送
- トルク

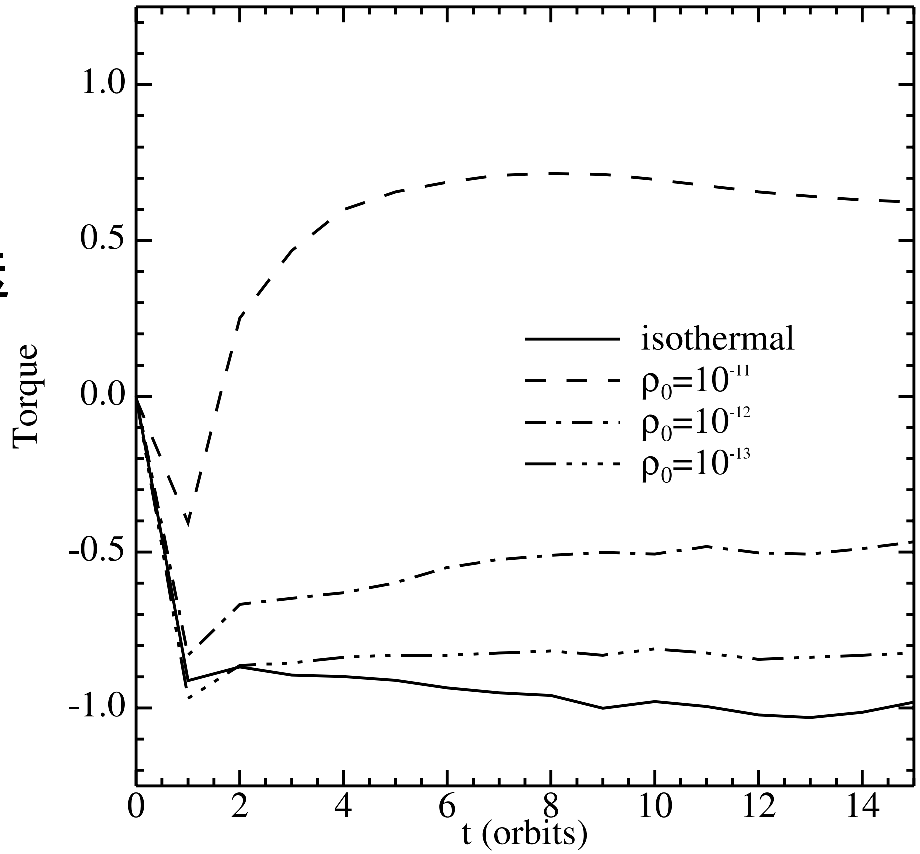


Fig. 1. Total torque on a 5 $M_\oplus$ planet as a function of time for three different midplane densities, together with the isothermal result. The torques are normalized to the analytical value found by Tanaka et al. (2002), which is reproduced by the isothermal simulation. For high densities (and thereby for high opacities) the torque becomes positive, indicating outward migration.

重力相互作用する2体の運動

Nishida 1983

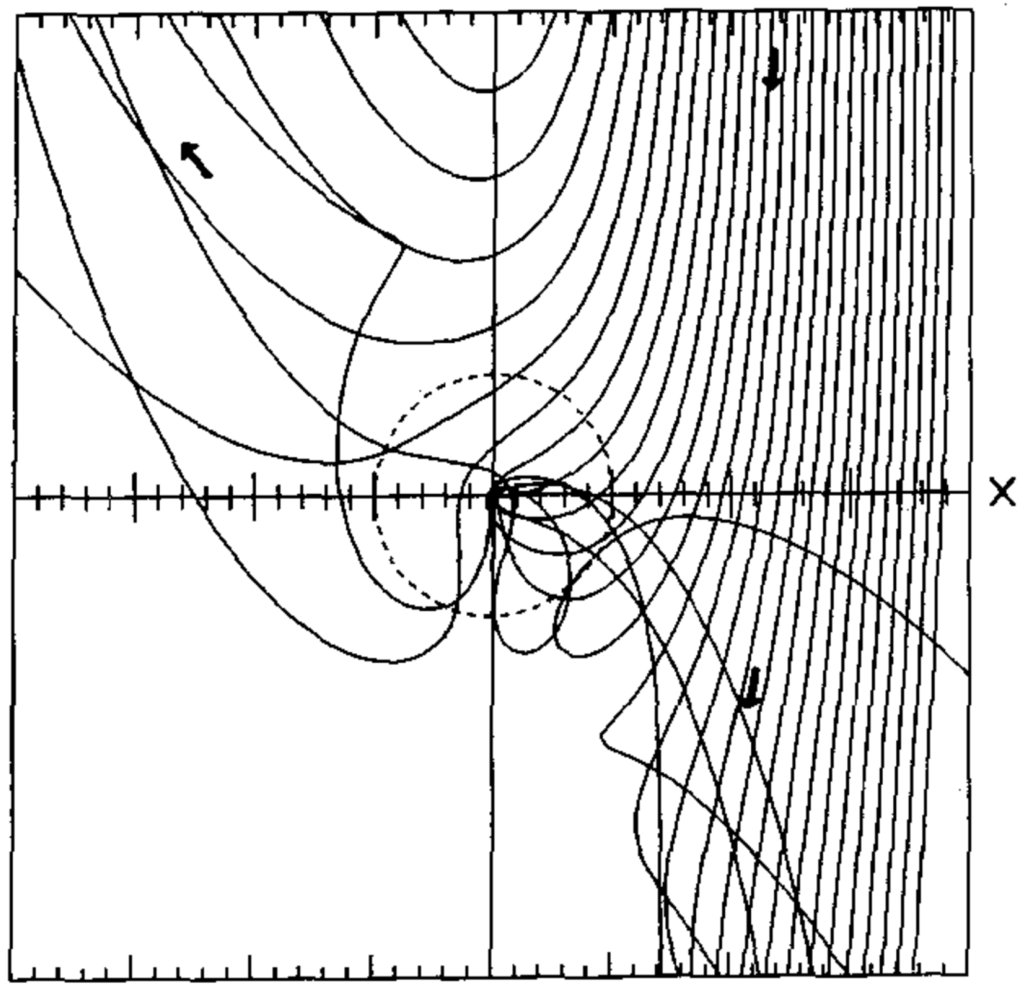


Fig. 2. Examples of particle orbits with various values of $\tilde{b}_i$ and with $\tilde{e}_i \fallingdotseq 0$. The dotted circle represents the Hill sphere. All the particles with $1.75 < \tilde{b}_i < 2.50$ enter the sphere.

Type I migration in optically thick accretion discs

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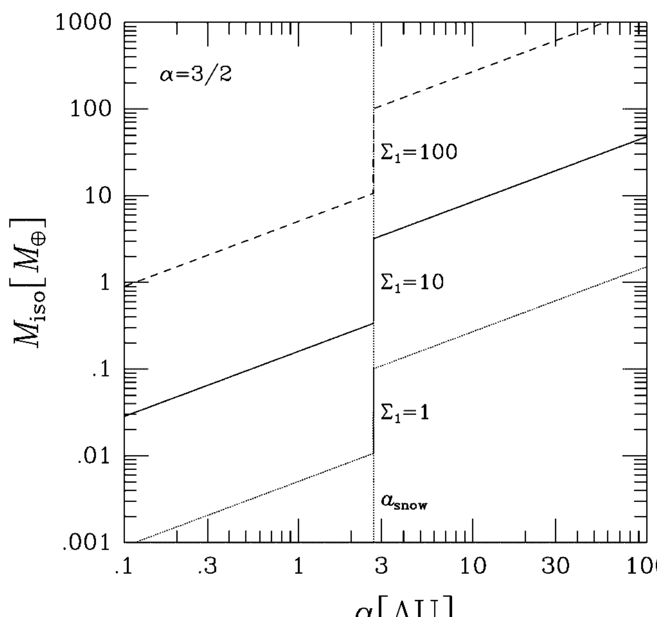
孤立質量

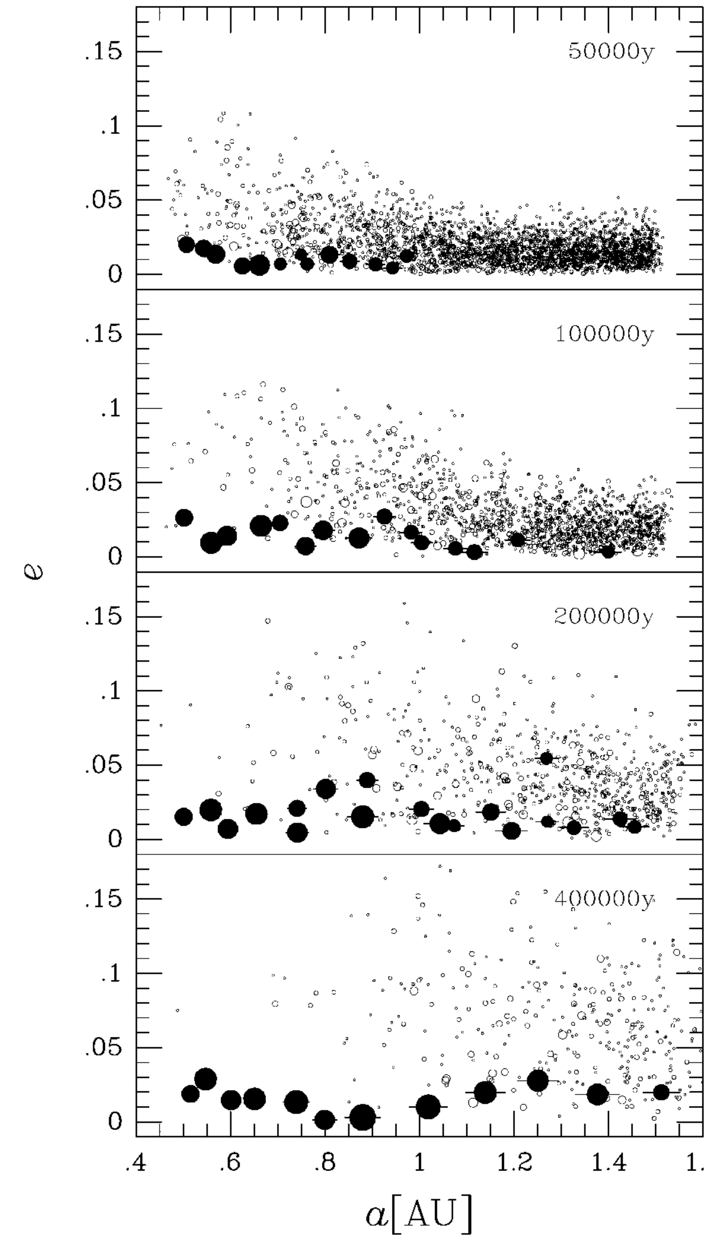
$$\Delta r \sim 10 r_H$$

＋円盤モデル
(初期微惑星空間分布)

→ 原始惑星の質量

$$M_{iso} = 2\pi r \times 10 r_H \times \Sigma_{\rm solid}$$

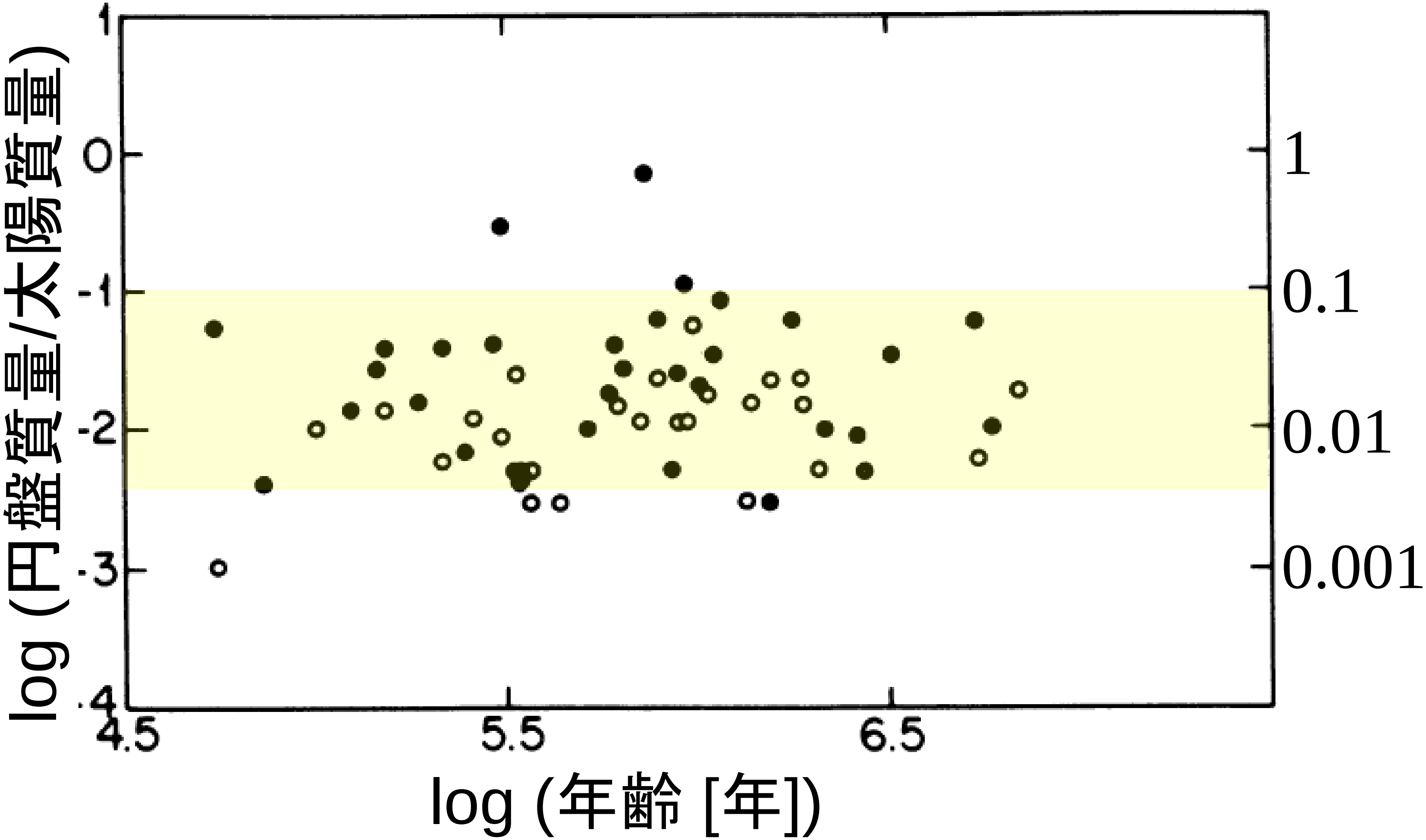




Kokubo & Ida 2002

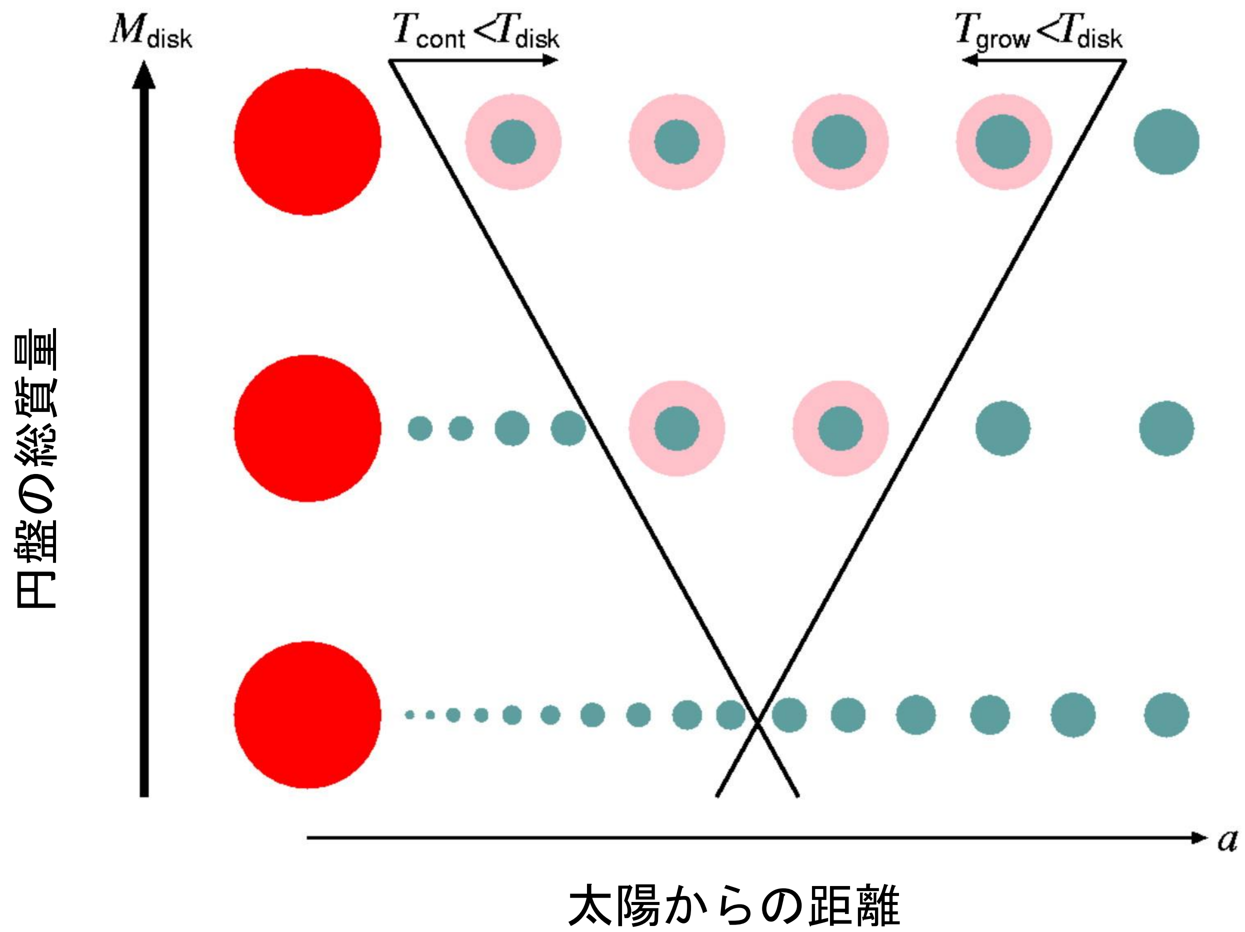
FIG. 1*a*

原始惑星系円盤の質量



Beckwith *et al*. 1990, *AJ* **99**, 924

ガス・塵微粒子円盤 → 微惑星 → 原始惑星



(Kokubo & Ida 2002)

惑星系の多様性

Ida & Lin 2004

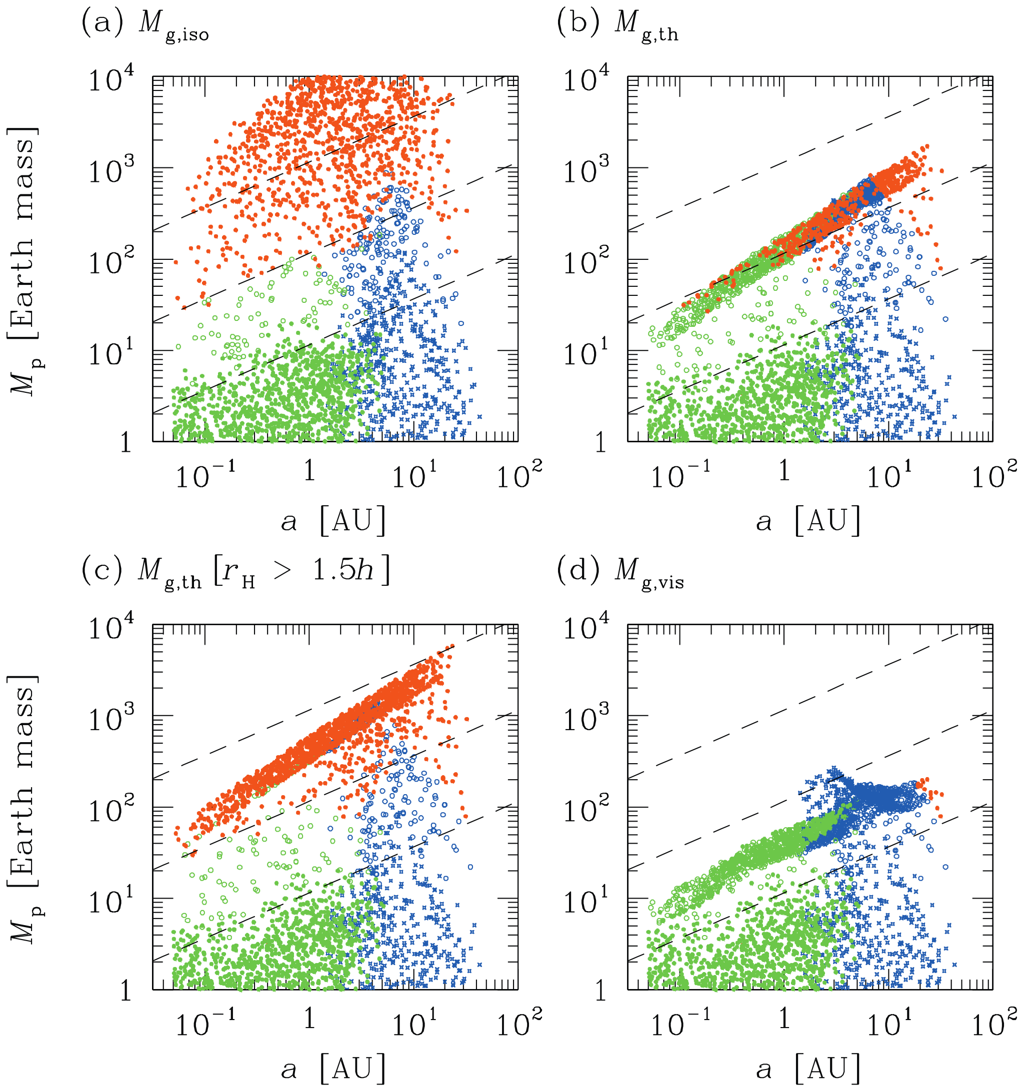
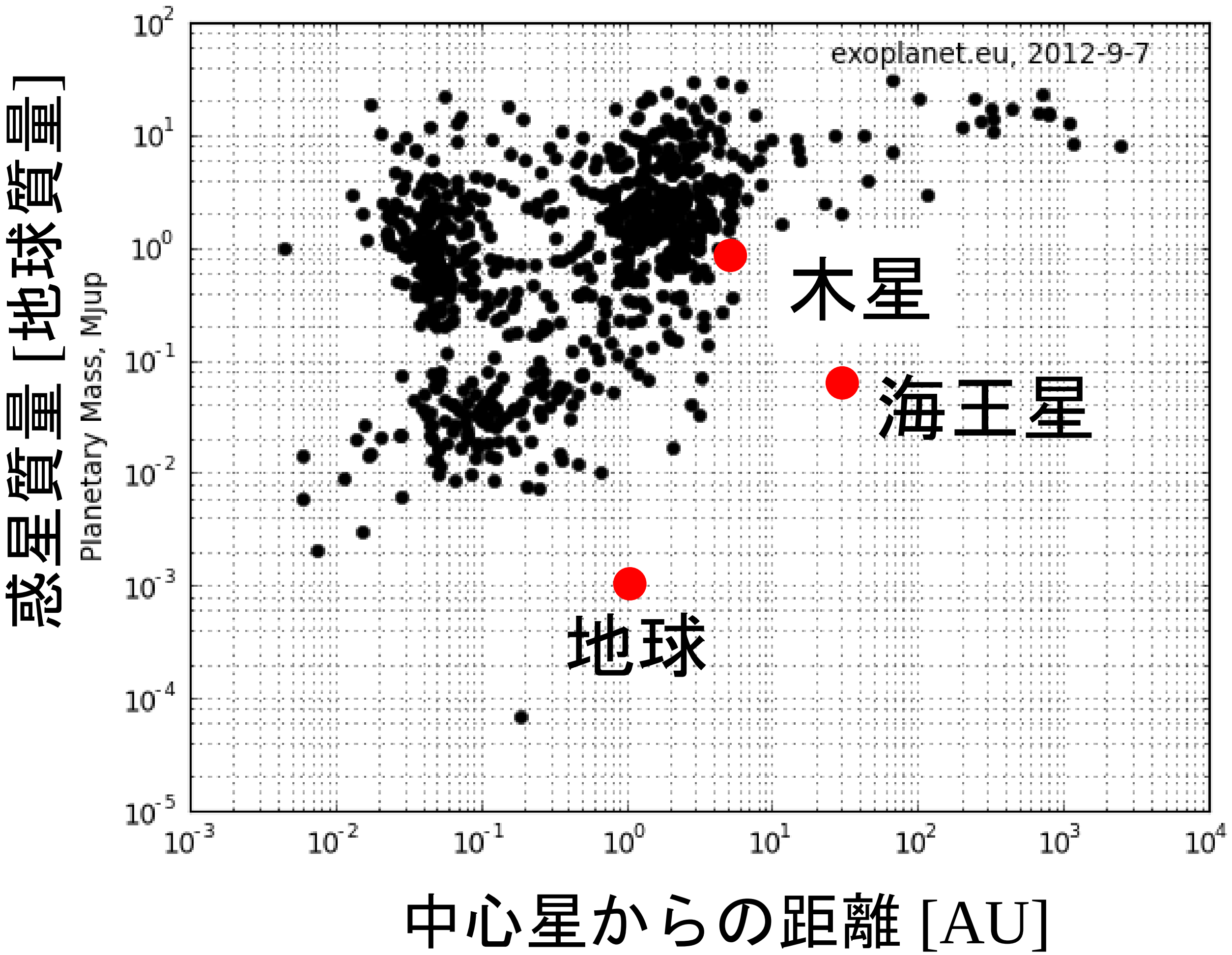
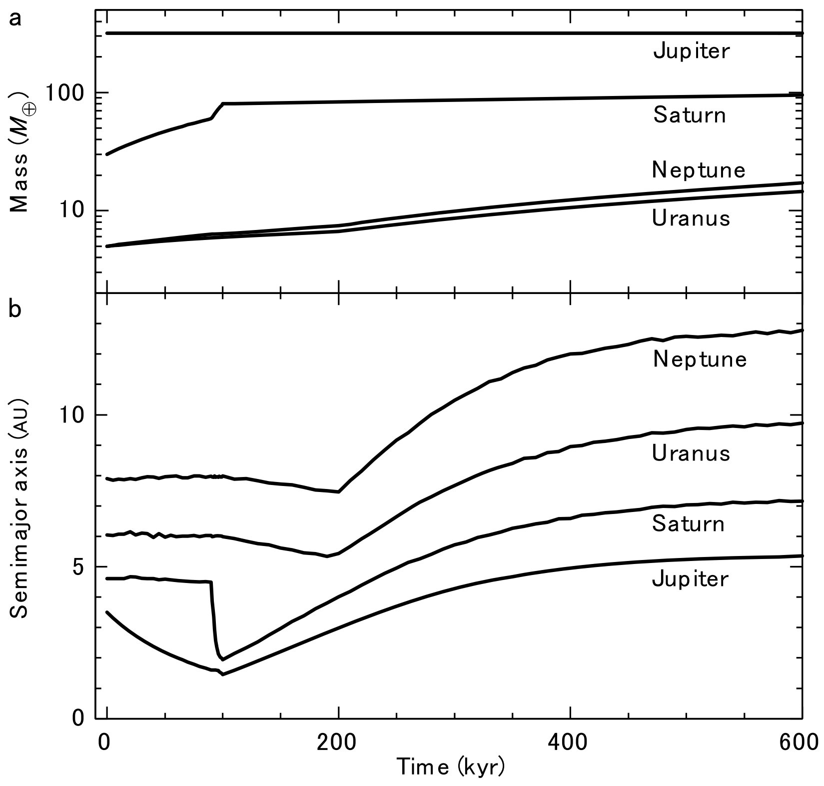


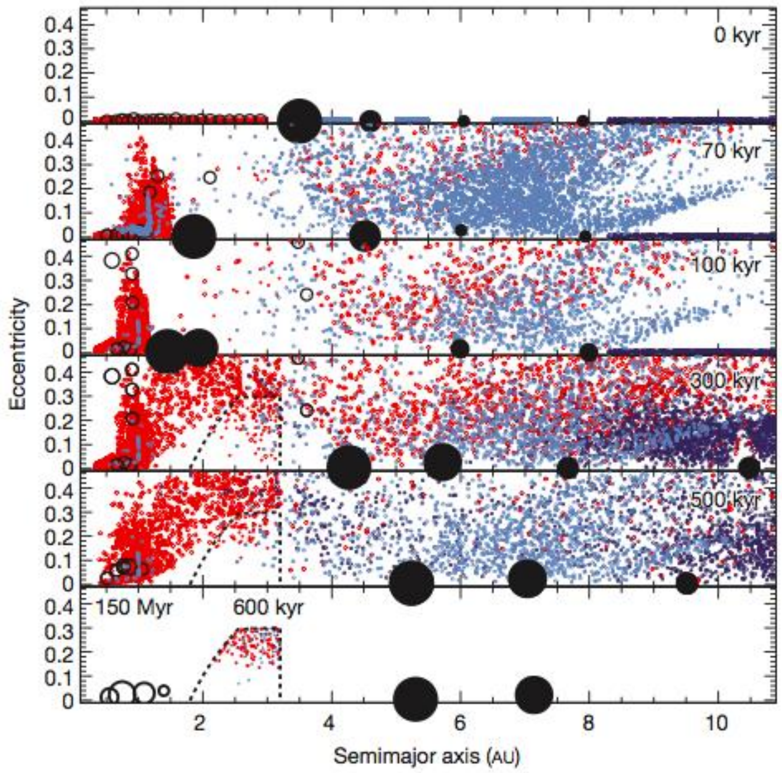
FIG. 9.—Theoretically predicted distribution based on the core accretion model for gas giant planets (for the range of parameters we used, see text). Cores are truncated by $M_{c,\rm iso}$. Gas accretion is truncated by (*a*) $M_{g,\rm iso}$, (*b* and *c*) $M_{g,\rm th}$, and (*d*) $M_{g,\rm vis}$. We adopt $\Delta a_g = 2r_{\rm H}$ in (*a*), the critical Hill radius $r_{{\rm H},c}$ being h and $1.5h$ in (*b*) and (*c*), respectively, and $\alpha = 10^{-3}$ in (*d*). The green filled circles and the blue crosses represent rocky and icy planets with gaseous envelopes less massive than their cores. The green and blue open circles represent gas-rich rocky and icy planets with gaseous envelopes that are 1–10 times more massive than their cores. The red filled circles represent gas giants with envelopes more massive than 10 times their cores. For comparison, we also plot observational data of extrasolar planets in (*d*). The dashed ascending lines correspond to radial velocity amplitude of 100 (*upper line*), 10 (*middle line*), and 1 m s^{-1} (*lower line*), assuming the host star mass is 1 $M_\odot$.


exoplanet.eu, 2012-9-7
木星
海王星
地球
惑星質量 [地球質量]
Planetary Mass, Mjup
中心星からの距離 [AU]
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}

太陽系の形成に特化したモデル：

The Grand Tack Scenario (Morbidelli et al 2012)

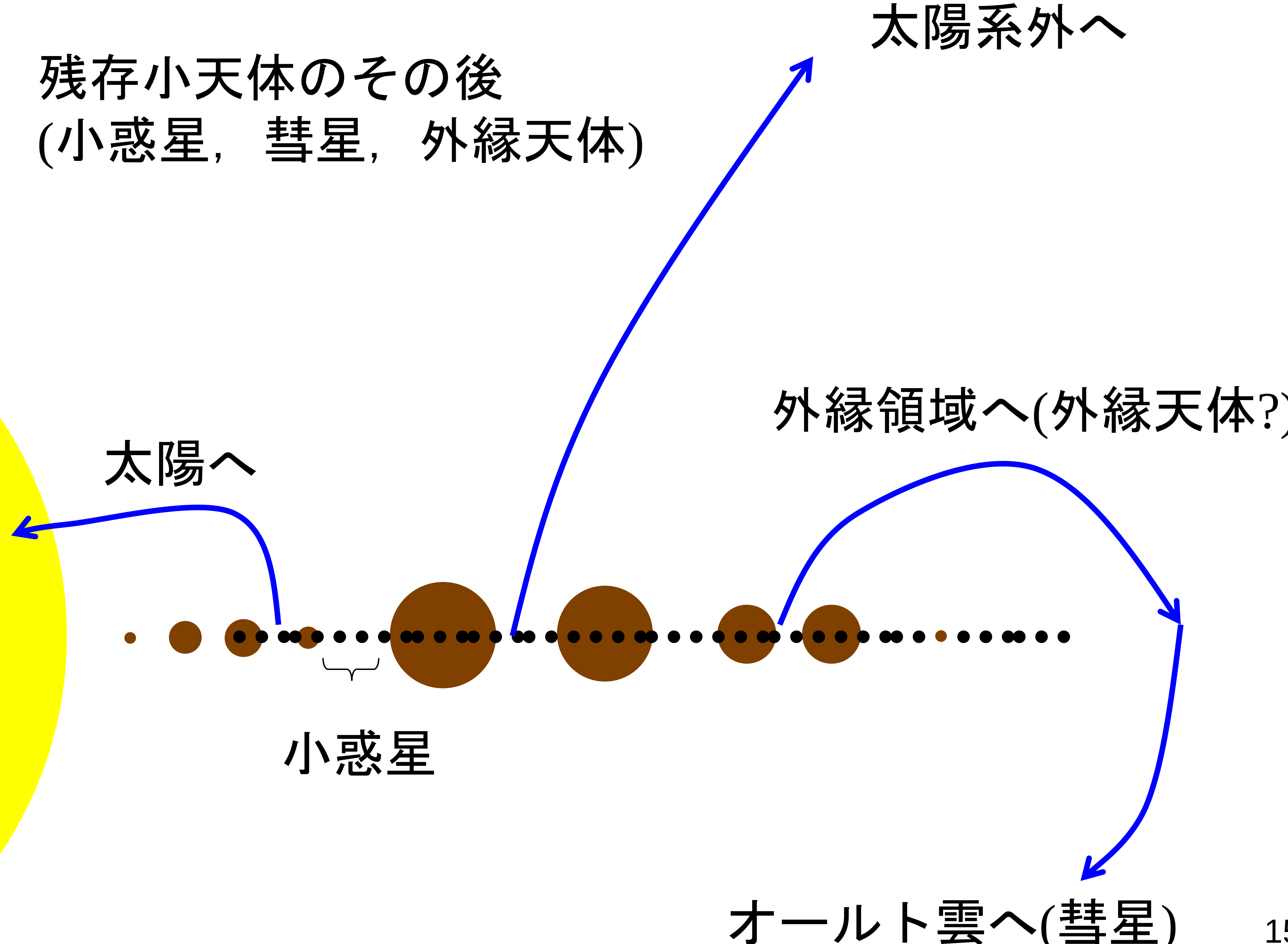




Walsh et al. 2011

- ガス惑星/氷惑星
- 地球型惑星
- 小惑星
- …

残存小天体のその後
(小惑星，彗星，外縁天体)



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