衛星系の形成
周惑星ガス円盤への固体物質供給

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衛星系とは？

- 惑星周りを回る複数の天体から成る系
- ガス惑星に普遍的に存在
- 規則衛星 と 不規則衛星
  - 規則衛星：
    - ほぼ円軌道・惑星赤道面内
    - → 周惑星円盤からの形成を示唆

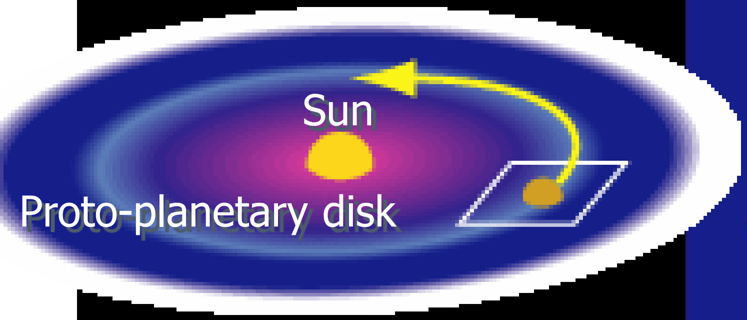
Jupiter and Galilean satellites

Satellites of outer planets

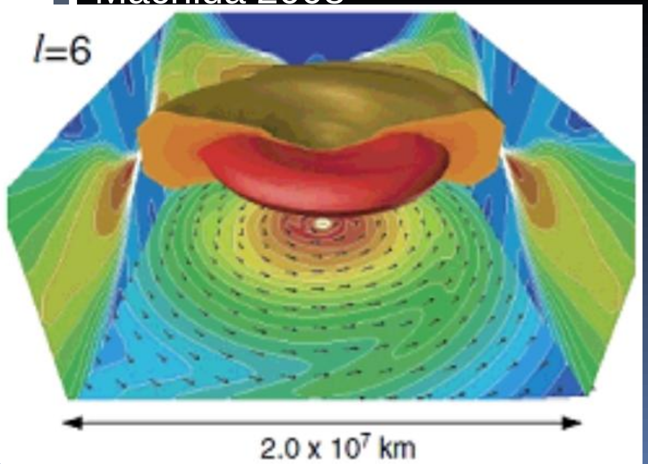
周惑星円盤の構造

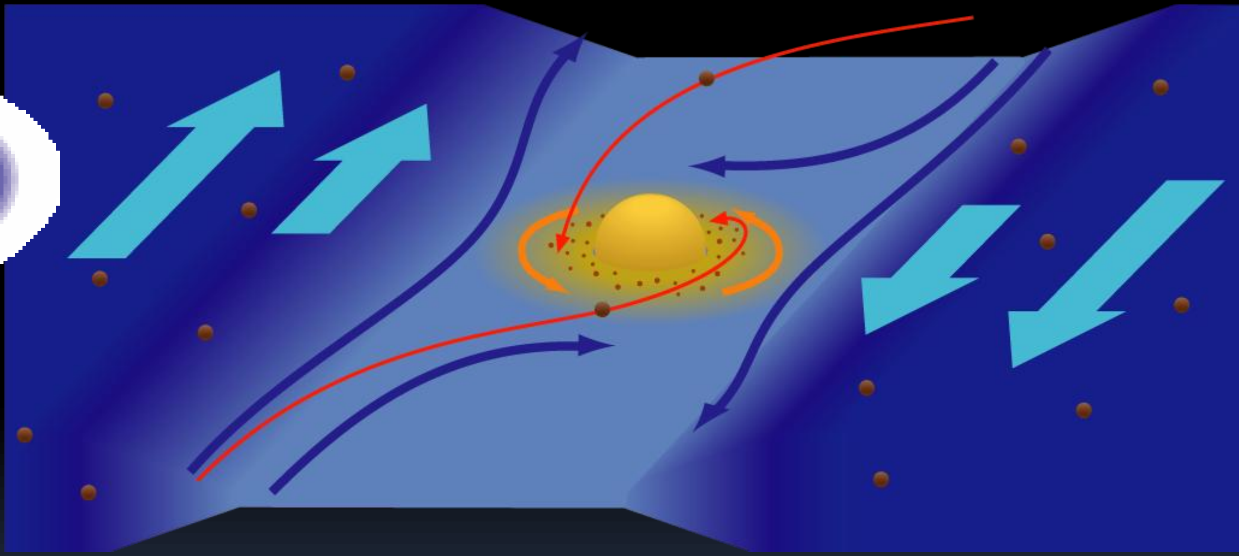
近年の数値流体力学計算 (e.g., Tanigawa and Watanabe 2002)

→ 周惑星円盤の具体的描像



- Machida 2008





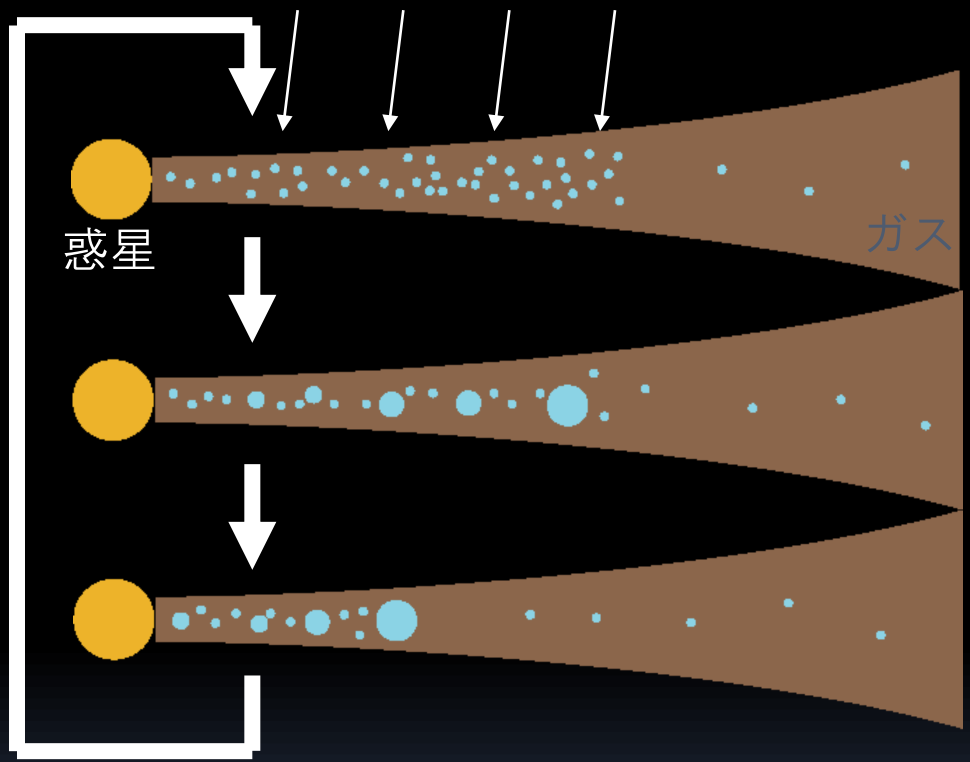
ガス円盤は形成

→ 固体成分は？

過去の研究

- Traditional model
  - Closed disk model with the “Minimum Mass Sub-Nebula”
  - Several severe problems
    - Temperature, accretion time, type I migration …
- Canup and Ward model (2002, 2006)
  - Open disk model based on the knowledge of gas accretion flow onto gas giant planets
    - Solid material is steadily supplied to circum-planetary disks
    - $M_{satellites} / M_{planet}$ is consistent with the real systems

Canup and Ward モデル



定常的な物質供給

外側から成長

大きく成長すると内側へ移動

内側の衛星を一掃

物質の供給が終わるまで繰り返す

現在の衛星系は、この輪廻の最終世代

過去の研究

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    - Solid material is steadily supplied to circum-planetary disk
    - $M_{satellites}$ / M_{planet} is consistent with the real systems.
  - Assumptions
    - Solid material is supplied uniformly on the disks.
      - -> Unknown
- In any case, disk models were given by assumptions.

本研究の目的

周惑星円盤構造を、復元的にではなく演繹的に決定する

微惑星が周惑星ガス円盤へ侵入した時に受けるガス抵抗により捕獲・供給されるメカニズムを考え、固体物質供給率・分布を求める。

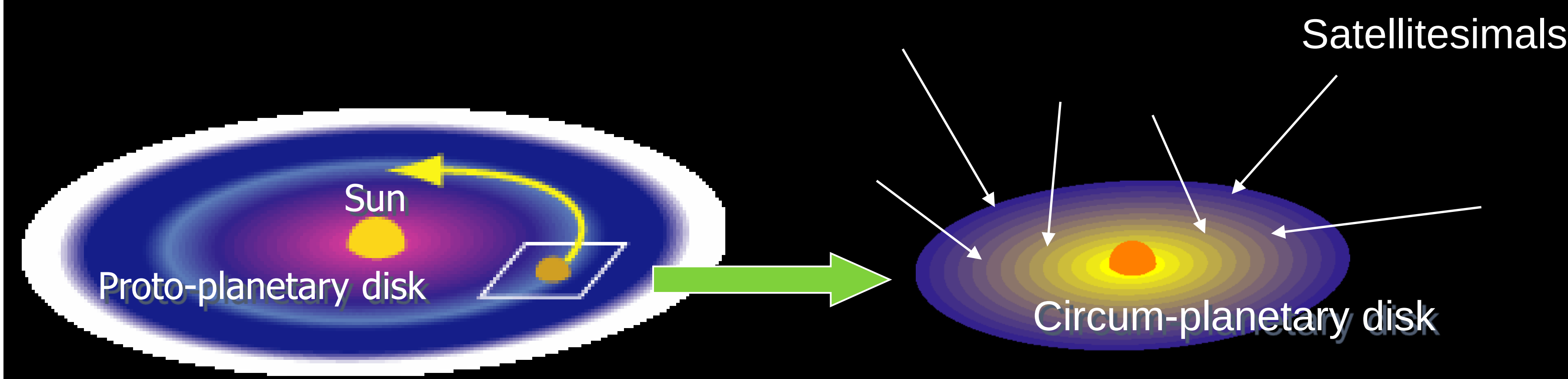
２種類の供給様式

- 小さいサイズ（＜ m-size ）
  - ガス降着流に乗って供給
- 大きいサイズ（＞ m-size ）
  - ガス降着流とは独立だが、ガス抵抗の影響あり

ここでは、大きいサイズについての解析的見積もり

Analytical estimation

Setting



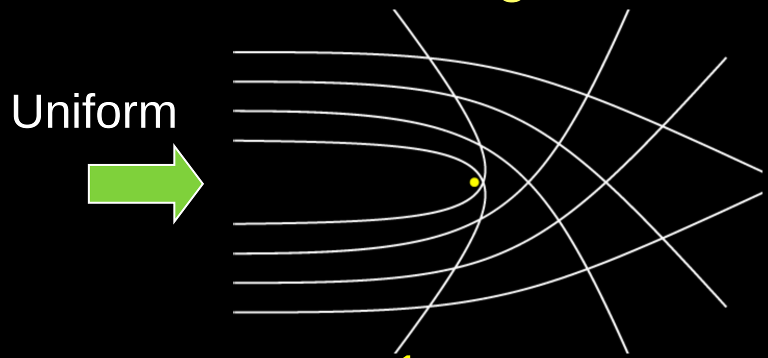
Captured by gas drag with the disk gas

- Assumptions
  - Gas disks are axisymmetric and power-law surface density distribution
  - Incident angle of satellitesimals is uniform
  - Ignore the effect of the central star

Capturing process

Before

Gravitational focusing



→ $r_{min} \propto r^{-1}$ (centered near the planet)

Critical radius to be captured

$$R_c \propto m^{-1/3(p+1)} \qquad \Sigma_{gas} = \Sigma_{gas,0} \left(\frac{r}{r_0}\right)^{-p}$$

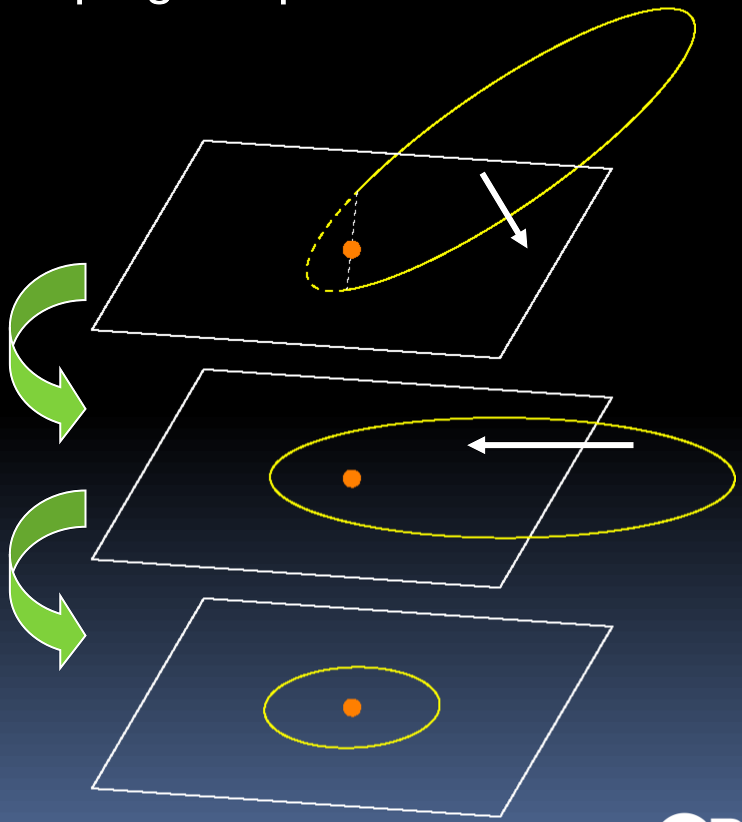
Dissipation energy due to gas drag

||

Energy necessary to be captured by the gravitational potential

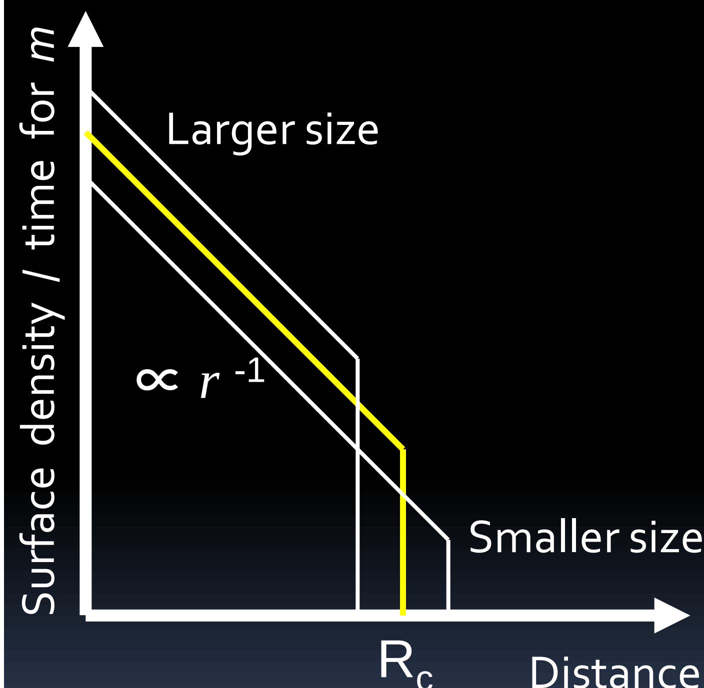
After

Eccentricity and inclination decrease with keeping the pericenter



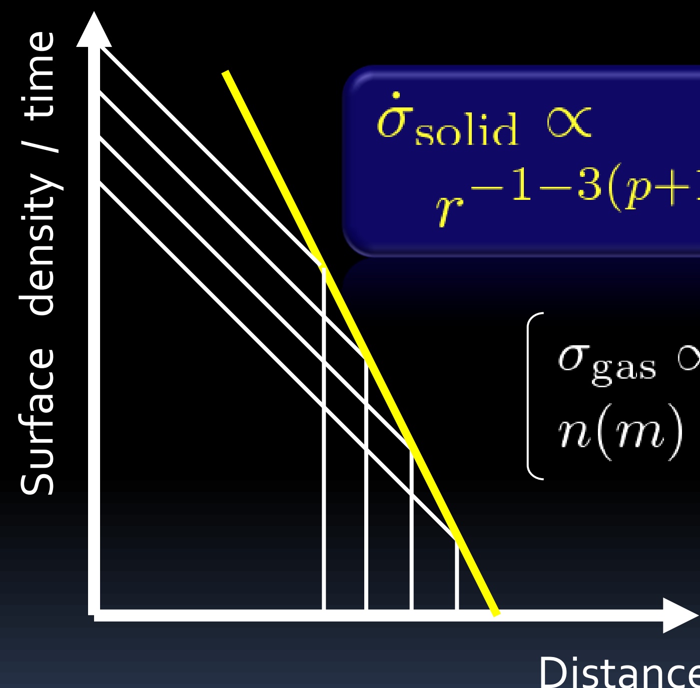
Supplying rate of solid material

For a single size swarm



(Rc = Critical radius to be captured)

For a power-law size distribution



$$\dot{\sigma}_{\rm solid} \propto r^{-1-3(p+1)(2-s)}$$

$$\begin{cases} \sigma_{\rm gas} \propto r^{-p} \\ n(m) \propto m^{-s} \end{cases}$$

A typical case (p=1, s=11/6)

$$\dot{\sigma}_{\rm solid} \propto r^{-2}$$

面密度供給率の値

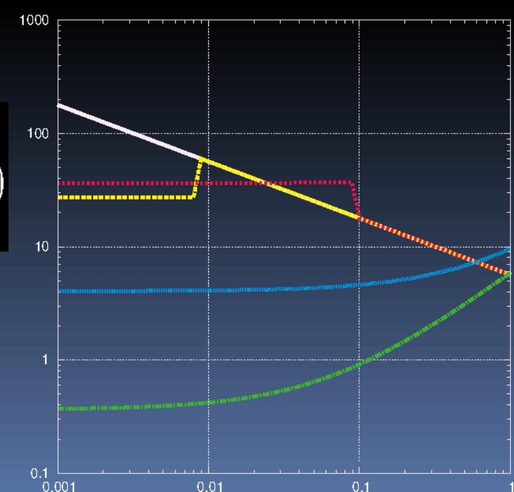
$$\dot{\sigma}(\tilde{r}) = \frac{1}{2\pi}\left(\frac{9\pi}{128}C_{\mathrm{D}}^{3}(A(i))^{3}\right)^{2-\alpha}\left(\frac{\sigma_{\mathrm{g},0}^{3}}{\rho_{\mathrm{s}}^{2}m_{\mathrm{max}}}\right)^{2-\alpha}\left(\frac{\Sigma_{\mathrm{d}}}{\Omega_{\mathrm{K}}^{-1}}\right)\tilde{r}^{-1-3(p+1)(2-\alpha)}\frac{d}{d\tilde{r}}P_{\mathrm{col}}(\tilde{r}),$$

$$A(i) = \frac{2(3-2\sqrt{2}\cos i)^{1/2}}{3\sin i}(\sqrt{2}-\cos i)$$

典型的には（α＝11/6, a=5AU）

$$\dot{\sigma}(r) \sim 10^{3}\,\mathrm{g\,cm^{-2}\,yr^{-1}}\left(\frac{\sigma_{\mathrm{g},0}}{10^{3}\mathrm{g\,cm^{2}}}\right)^{1/2}\left(\frac{m_{\mathrm{max}}}{10^{18}\mathrm{g}}\right)^{-1/6}\left(\frac{\Sigma_{\mathrm{d}}}{10\mathrm{g\,cm^{-2}}}\right)\left(\frac{\rho_{\mathrm{s}}}{1\mathrm{g\,cm^{-3}}}\right)^{-1/3}\left(\frac{r}{10R_{\mathrm{J}}}\right)^{-2}$$

$$\frac{d}{d\tilde{r}}P_{\mathrm{col}}(\tilde{r})$$



Migration due to gas drag?

- After circularization with short timescale, objects slowly spiral toward the planets by gas drag

Migration velocity due to the gas drag with disk gas:

$$v_{r,\mathrm{s}} = -2\eta\Gamma v_{\mathrm{K}}$$

$$\Gamma = \frac{\tau_{\mathrm{K}}}{\tau_{\mathrm{stop}}} \qquad \eta \sim \left(\frac{c}{v_{\mathrm{K}}}\right)^2$$

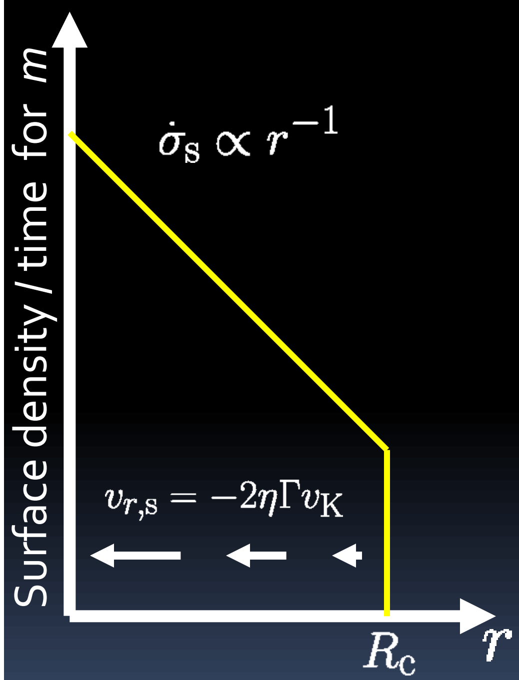
→ How about the steady state distribution?

Steady state distribution

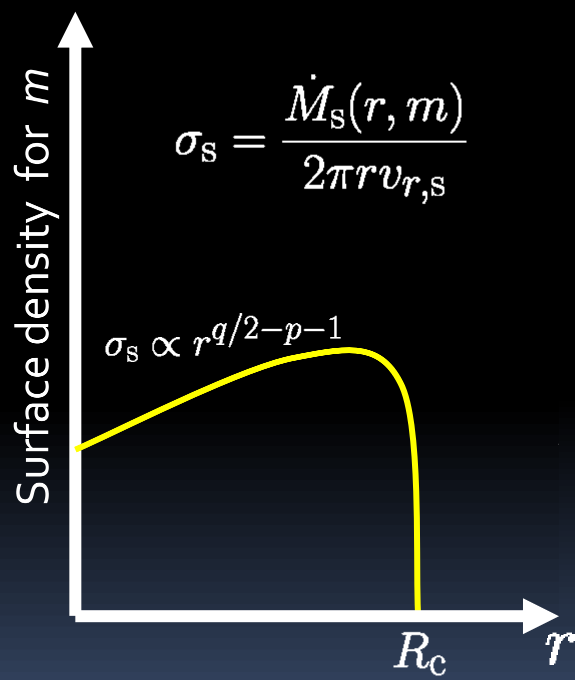
considering radial migration due to gas drag

For a single size swarm

Supplying rate



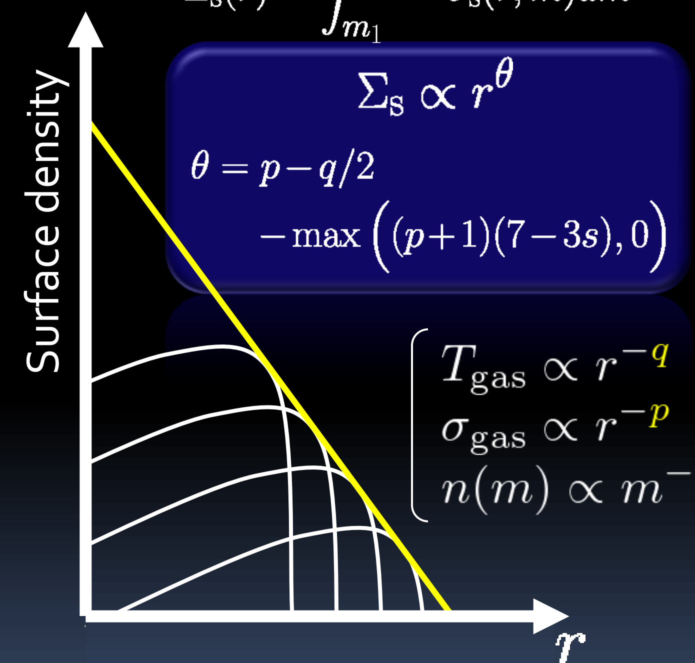
Steady state distribution



$$\dot{M}_{\rm s}(r,m) = \int_r^{R_{\rm c}} 2\pi r' \dot{\sigma}_{\rm s}(r',m)dr'$$

For a power-law size distribution

$$\Sigma_{\rm s}(r) = \int_{m_1}^{m_{\rm c}(r)} \sigma_{\rm s}(r,m)dm$$



p =1, q =1/2, s =11/6:

$$\Sigma_{\rm s} \propto r^{-9/4}$$

実際には...

- ガス抵抗による動径方向の移動に比べ、成長の方が速い

⟶ 動径方向の移動は無視できる

⟶ 供給率の空間分布 $\dot{\sigma}_{\mathrm{solid}}$ のみが重要

動径方向の移動を考慮した定常分布が実現されるケースは少ない（ダスト／ガス比が著しく小さいときのみ）

Test orbital calculations for captured satellitesimals

Basic equations

Equation of motion

$$\frac{d\tilde{\boldsymbol{v}}}{d\tilde{t}} = -\nabla\tilde{\Phi}_{\rm hill} - 2\boldsymbol{e}_z \times \tilde{\boldsymbol{v}} + \tilde{\boldsymbol{a}}_{\rm drag}$$

Hill's potential $\tilde{\Phi}_{\rm hill} = -\frac{3}{\tilde{r}} - \frac{3}{2}\tilde{x}^2 + \frac{1}{2}\tilde{z}^2 + \frac{9}{2}$

Gas drag term

$$\tilde{\boldsymbol{a}}_{\rm drag} = -\frac{3}{8}C_{\rm D}\left(\frac{\rho_{\rm g}}{\rho_{\rm s}}\right)\tilde{r}_{\rm s}^{-1}\Delta\tilde{u}\Delta\tilde{\boldsymbol{u}}$$

(Only inside the Hill's sphere)

Hydrostatic equilibrium in *z*-direction and axisymmetric

$$\rho_g(r,\ z) = \rho_0 r_{\rm AU}^p \exp\left(-\frac{z^2}{2h_g^2}\right)$$

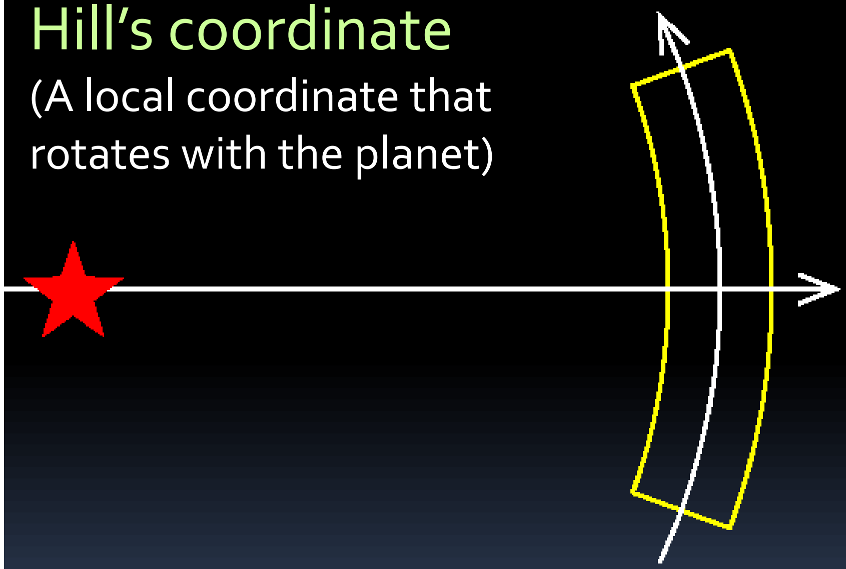
$$\Omega_g(r,\ z) = \Omega_{\rm K,mid}\left[1 + \frac{1}{2}\left(\frac{h_g}{r}\right)^2\left(p + q + \frac{q}{2}\frac{z^2}{h_g^2}\right)\right]$$

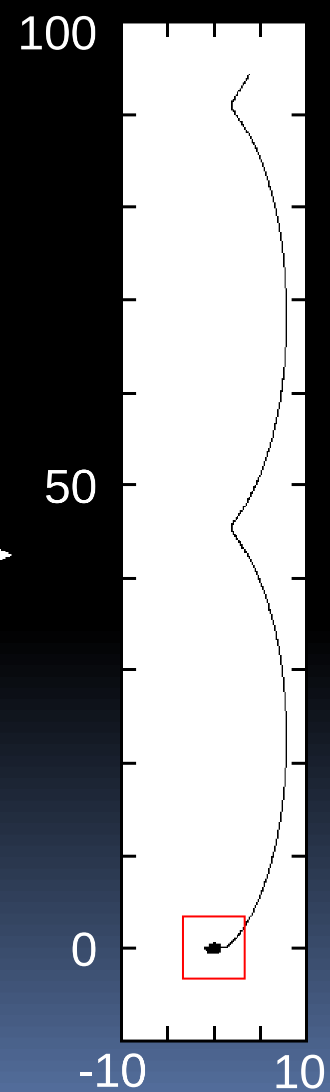
$$c^2(r) = c_0^2 r_{\rm AU}^q$$

Example orbits

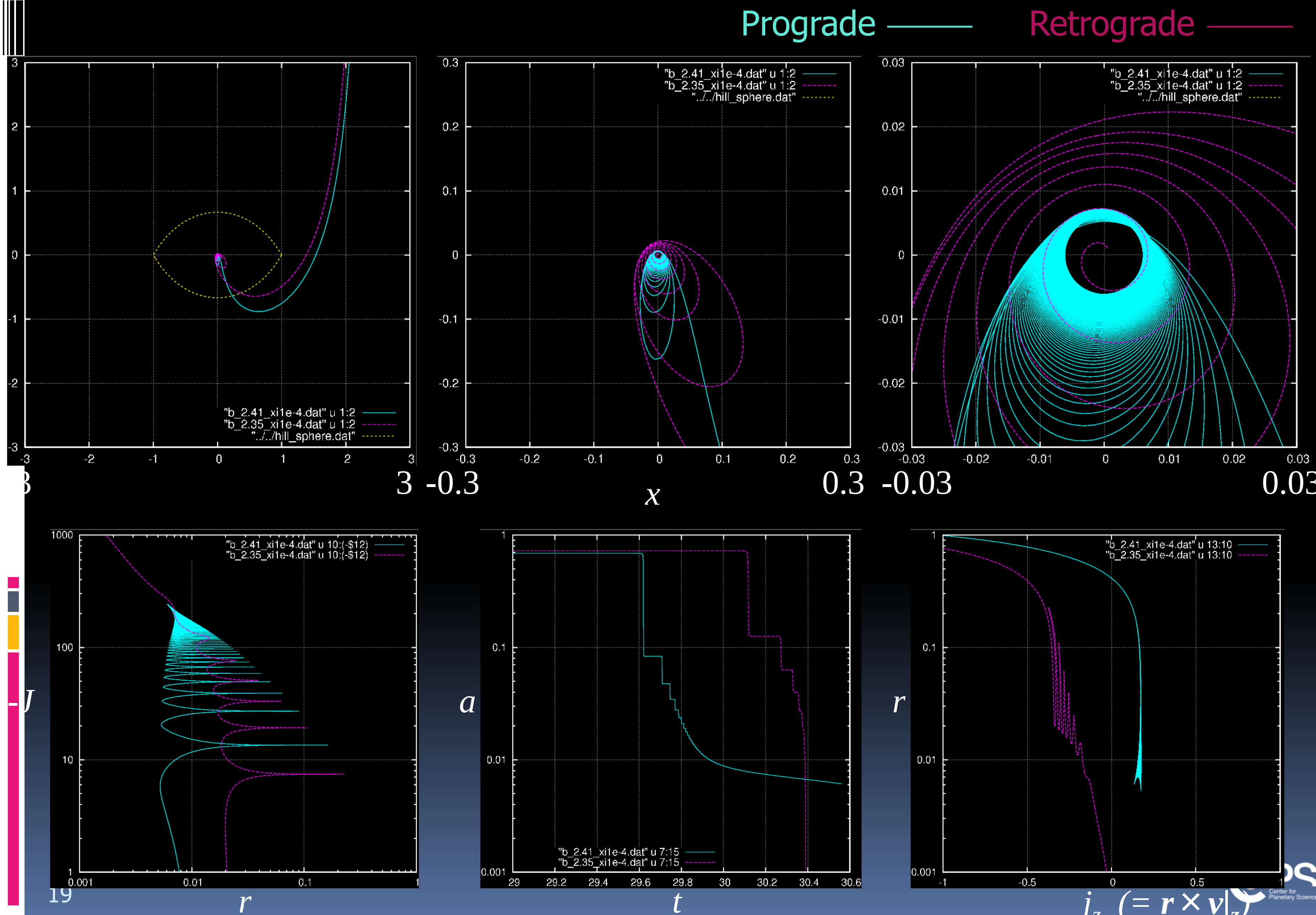
Hill’s coordinate

(A local coordinate that rotates with the planet)





Example orbits (e=i=0, b=2.35, 2.41)



まとめ

- 周惑星円盤への固体供給
  - 周惑星円盤とのガス抵抗による微惑星捕獲メカニズムを考察
  - 解析的見積もり
    - 固体物質の供給率分布

$$\dot{\sigma}_{\rm solid} \propto r^{-1-3(p+1)(2-s)}$$ *cf.* $\sigma_{\rm gas} \propto r^{-p}$

Typical case
$\dot{\sigma}_{\rm solid} \propto r^{-2}$ for m – km size（s=11/6）
$\dot{\sigma}_{\rm solid} \propto r^{-1}$ for larger than 1km size（s=8/3）

    - ガス抵抗による動径方向移動を考慮した定常面密度

$$\sigma_{\rm solid} \propto r^{p-q/2-3(p+1)(7/3-s)}$$

Typical case
$\sigma_{\rm solid} \propto r^{-9/4}$ for m – km size（s=11/6）
$\sigma_{\rm solid} \propto r^{3/4}$ for larger than 1km size（s=8/3）

    - ガスと固体の面密度勾配は<u>一般に異なる</u>
      - ガス／ダスト比が惑星からの距離の関数

CPS Center for Planetary Science