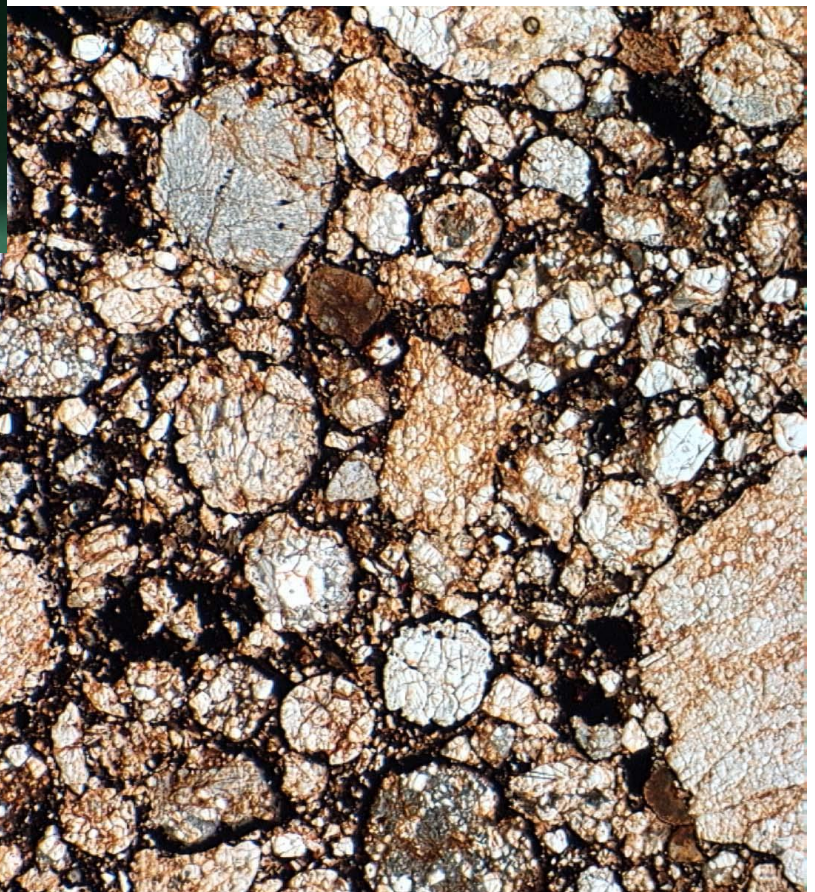


星・惑星系の形成過程 入門

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
7. 特論：隕石の起源と惑星形成

隕石

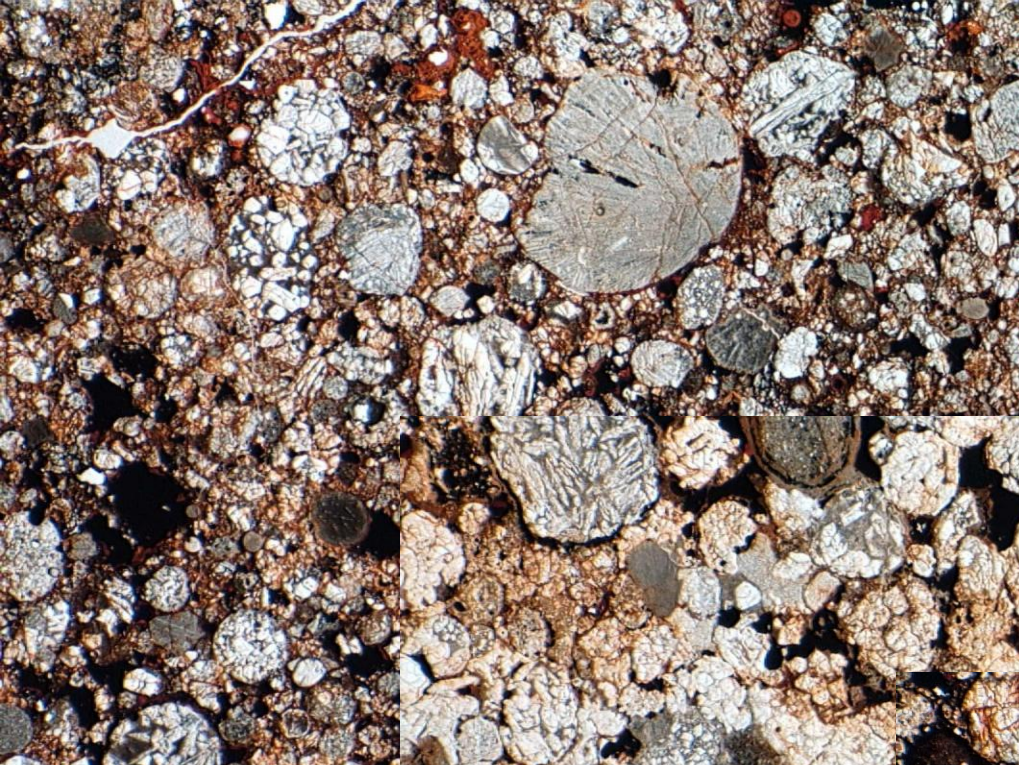


1mm

隕石

鉄隕石	5%
石鉄隕石	1%
石質隕石	
{ エイコンドライト	8%
{ コンドライト	86%
{ 普通コンドライト	90%
{ 炭素質コンドライト	4%
{ エンスタタイトコンドライト	2%
{ 他	4%

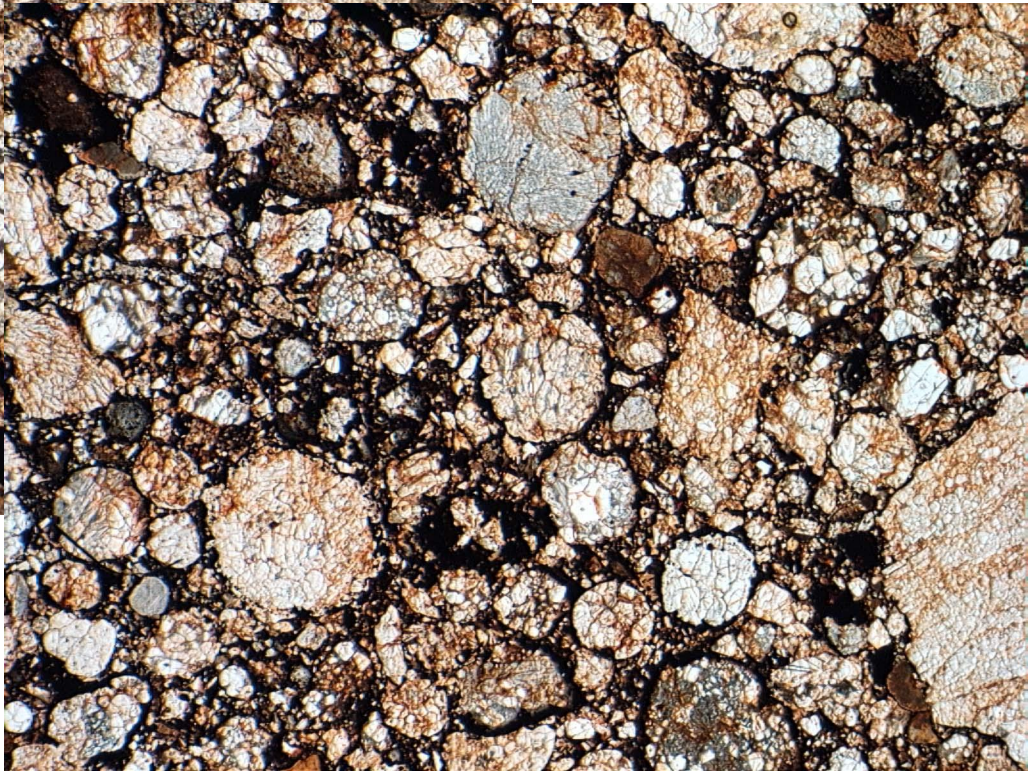
普通コンドライト



H

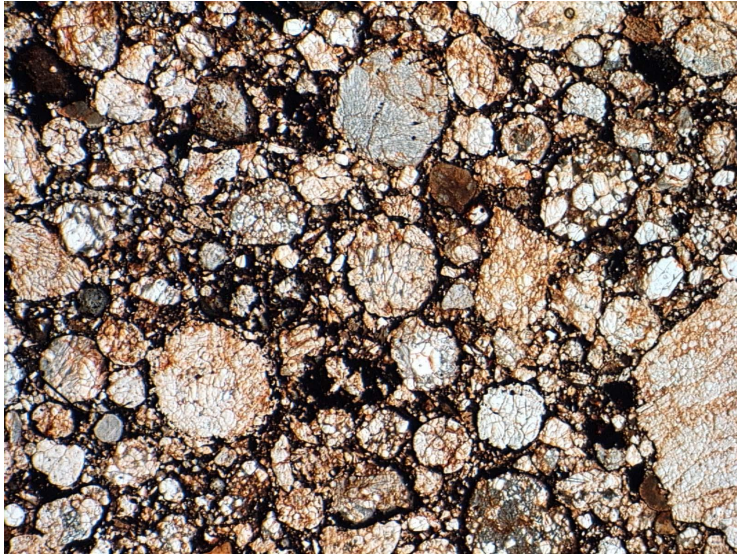


L



LL

コンドリュール



↔
1mm

“Flash Heating”による形成

- T タウリ型星期
時期 ~ 1 - 3 Myr after

CAI

期間 ~ 2 Myr

- 溶融 & 固化

前駆体 < 650 K

温度上昇 > 10^4 K/hr

最高温度 ~ 1600 -

2000 K

液体状態

継続時間 ~ 数分

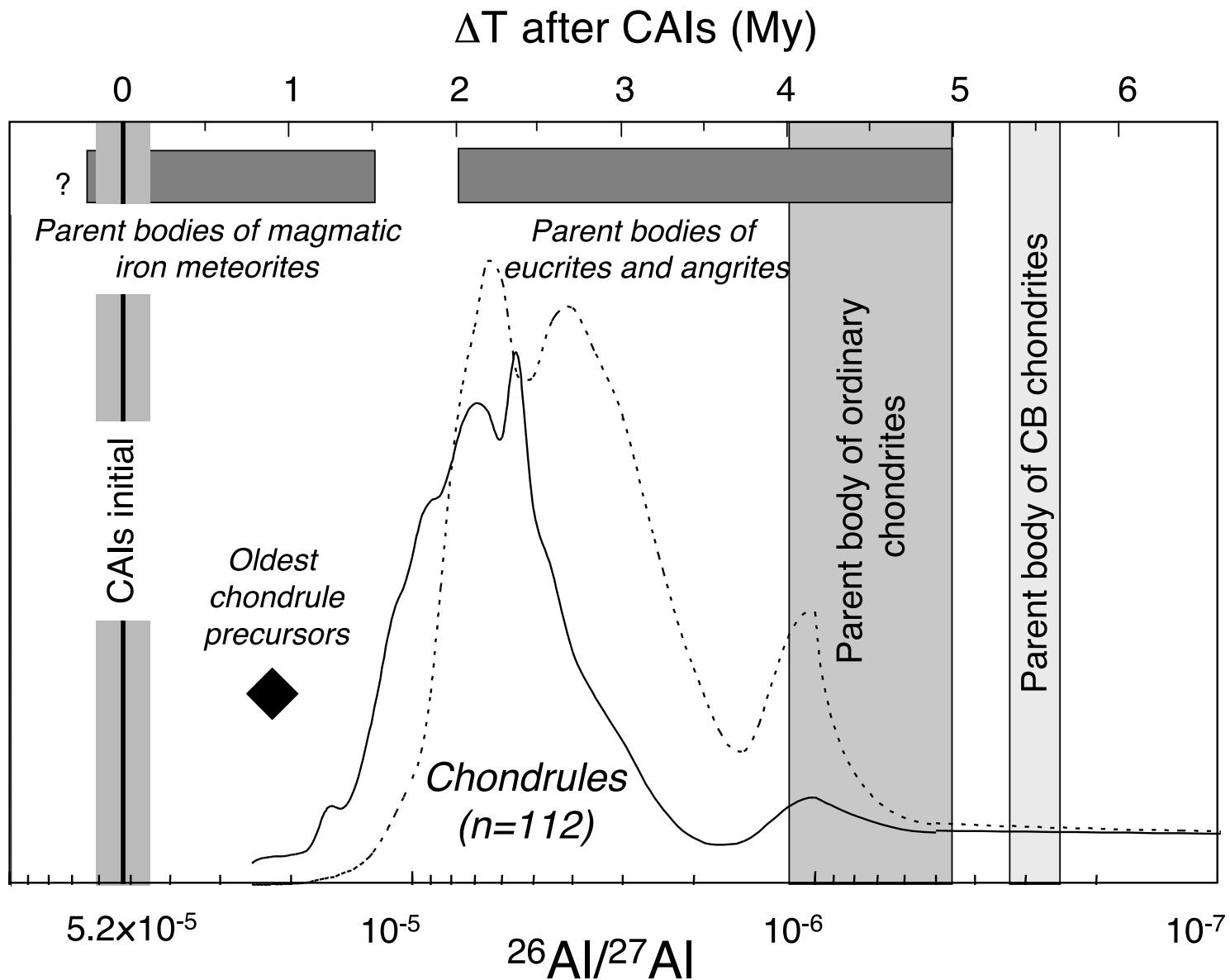
冷却 ~ 1 - 1000

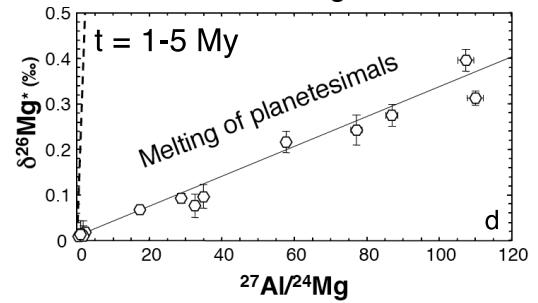
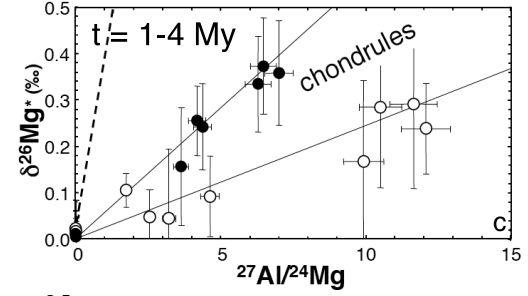
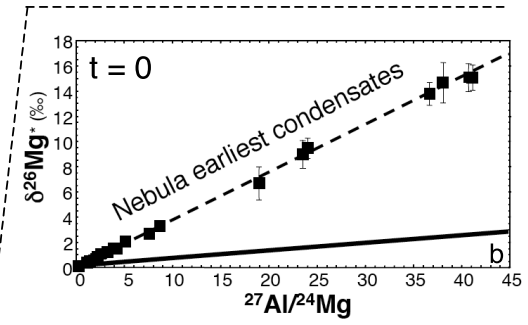
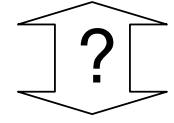
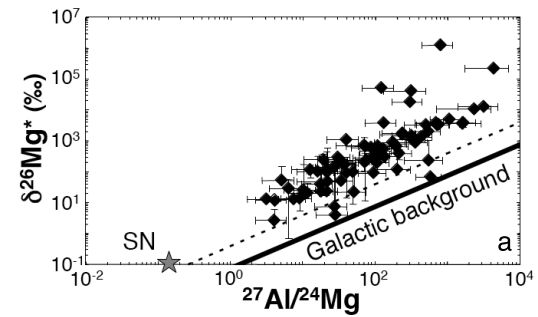
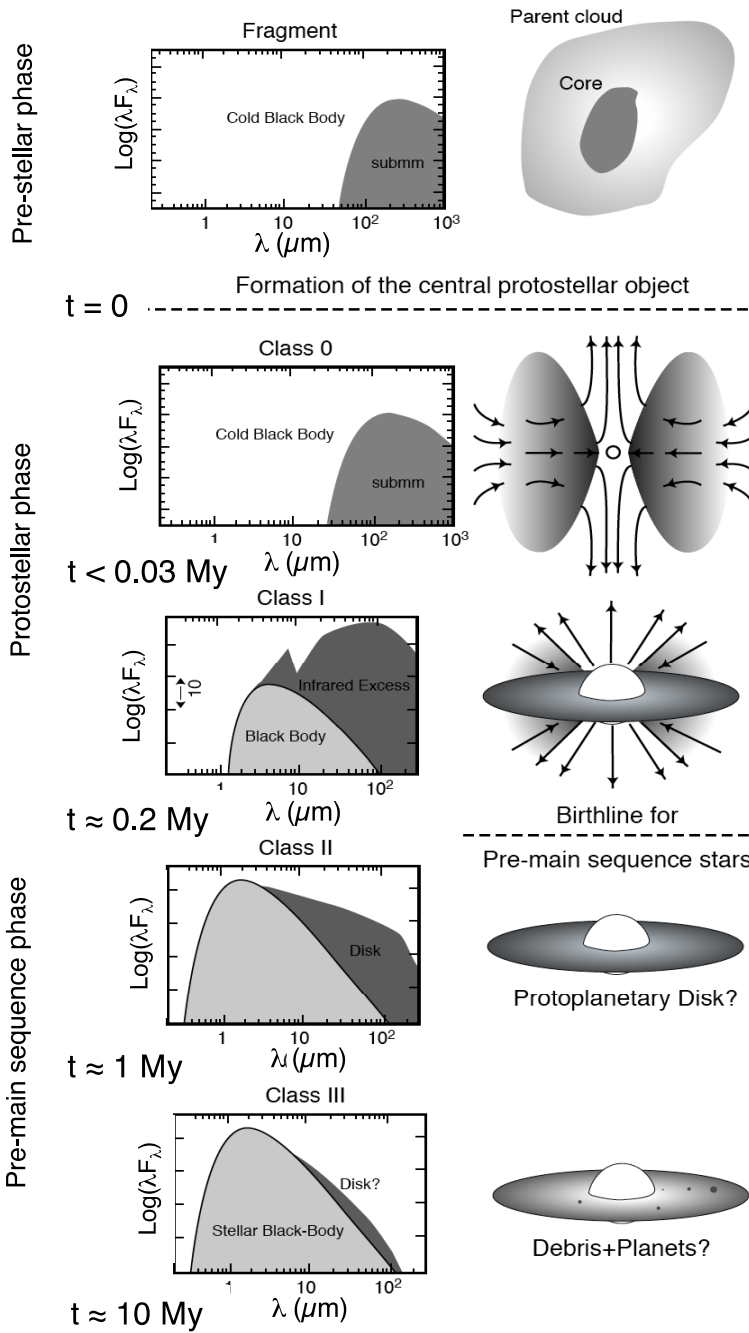
K/hr

- サイズ

0.1 - 1 mm

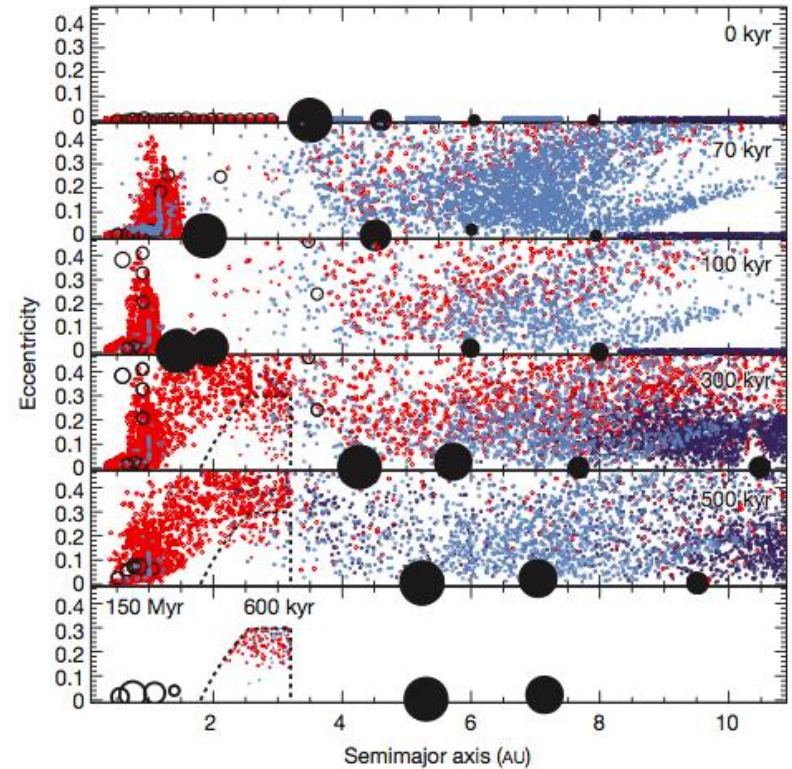
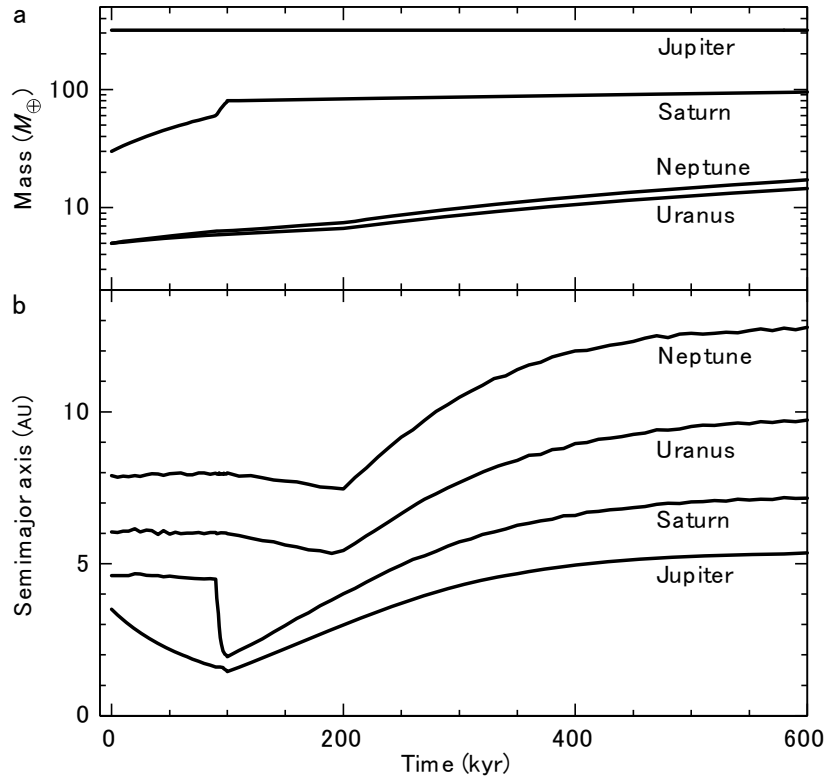
- 大量に存在 (up to 80%)





太陽系の形成に特化したモデル:

The Grand Tack Scenario (Morbidelli et al 2012)

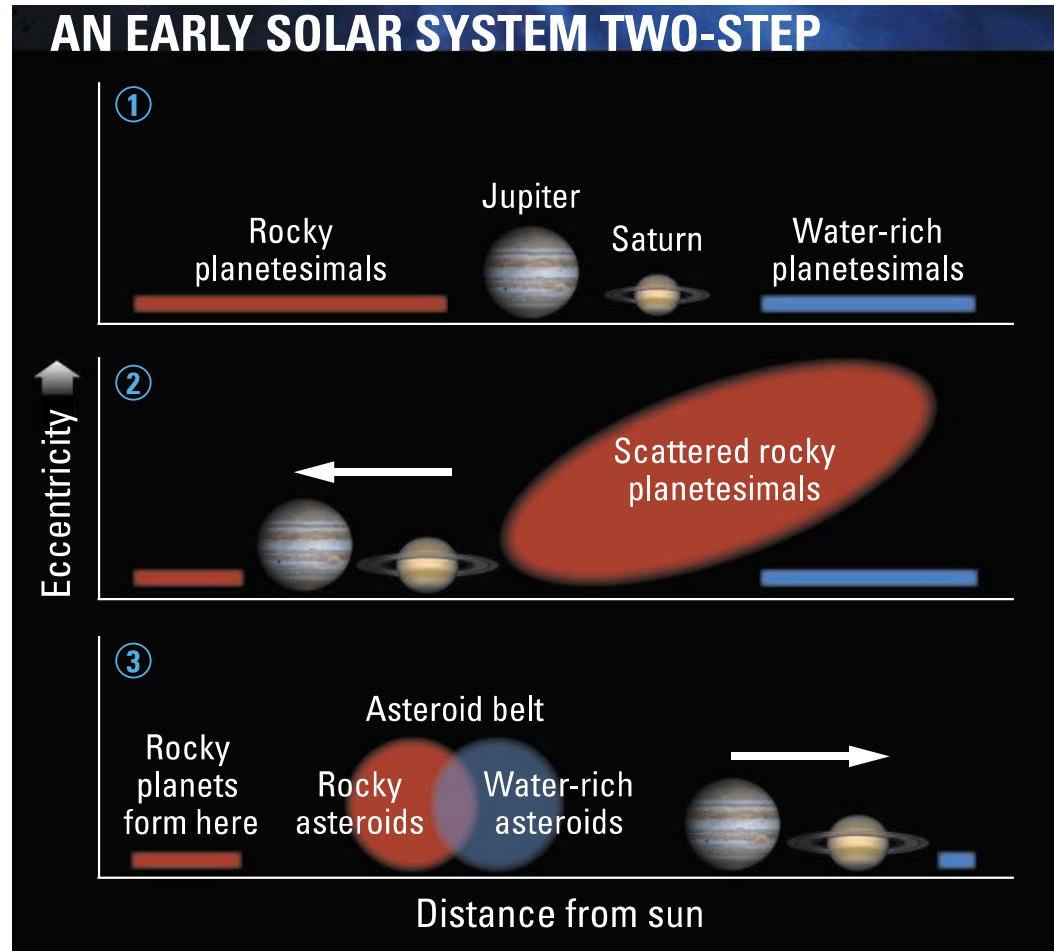


Walsh et al. 2011

- ガス惑星/氷惑星
- 地球型惑星
- 小惑星
- ...

井田：「局所形成」モデル

Walsh et al. 2011
(Kerr 2011)



コンドリュール形成モデル

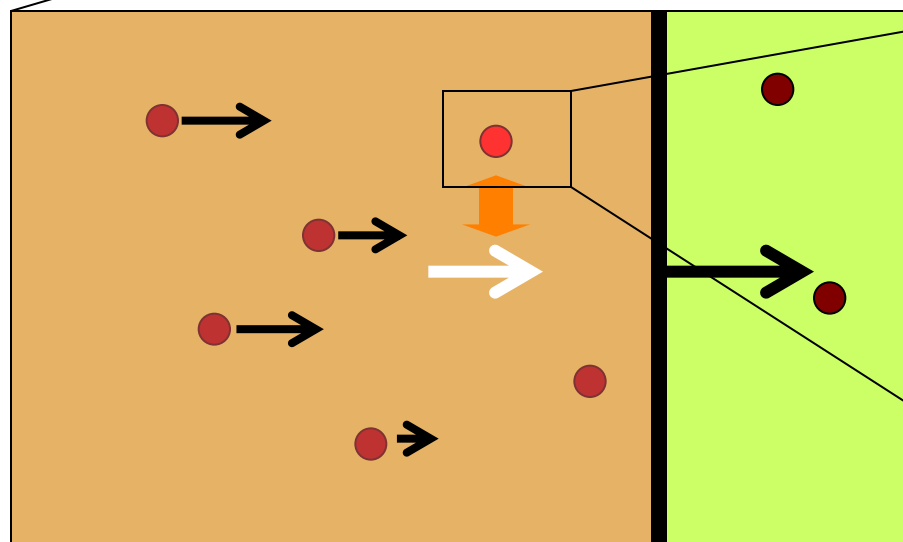
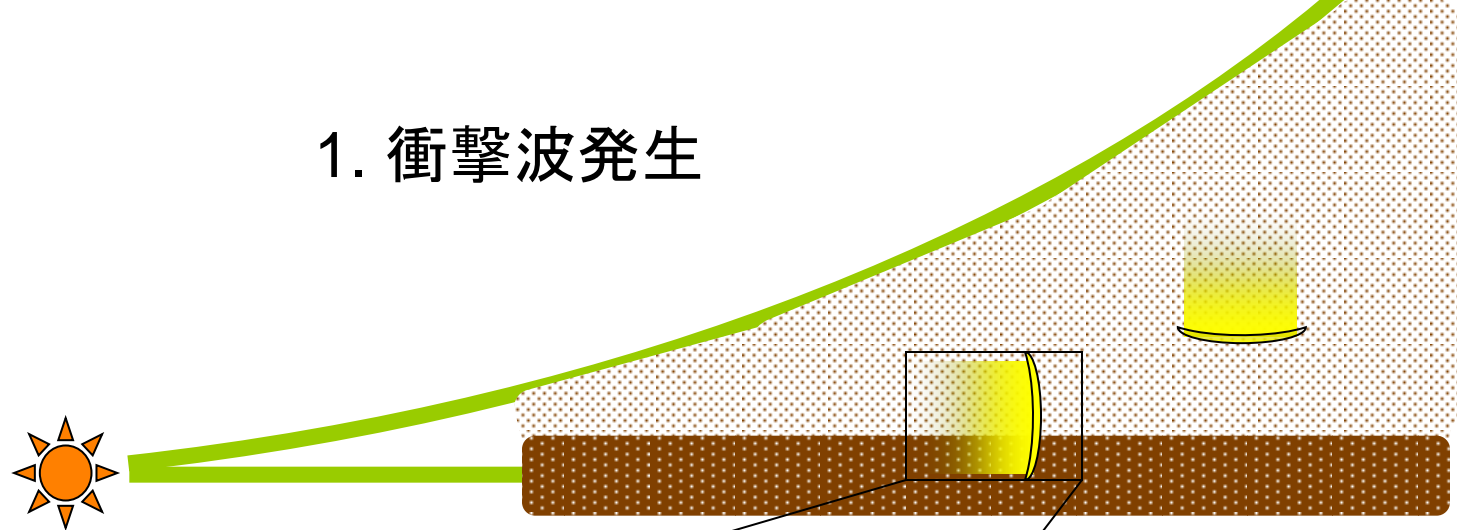
- 衝撃波加熱
- 雷加熱
- X-Windモデル
- ...

3. 衝撃波加熱仮説：コンドリュール形成

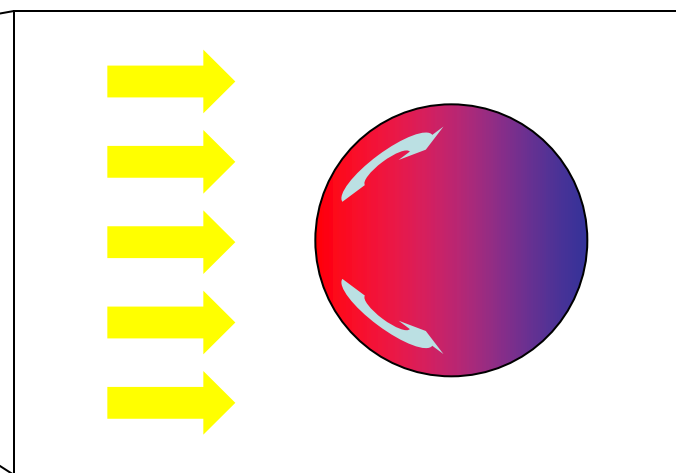
衝撃波加熱

1. 衝撃波の発生
2. 衝撃波内部での加熱機構
3. ダスト粒子内部の現象

1. 衝撃波発生

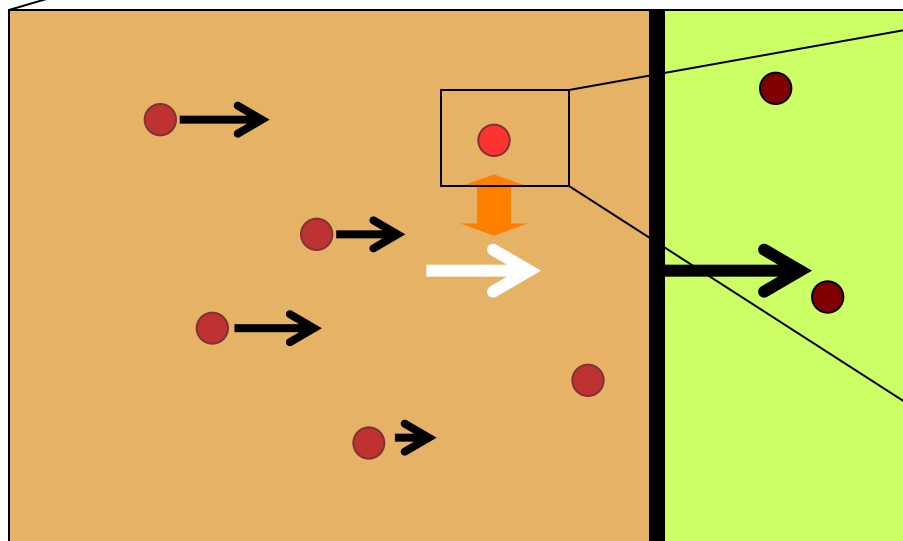
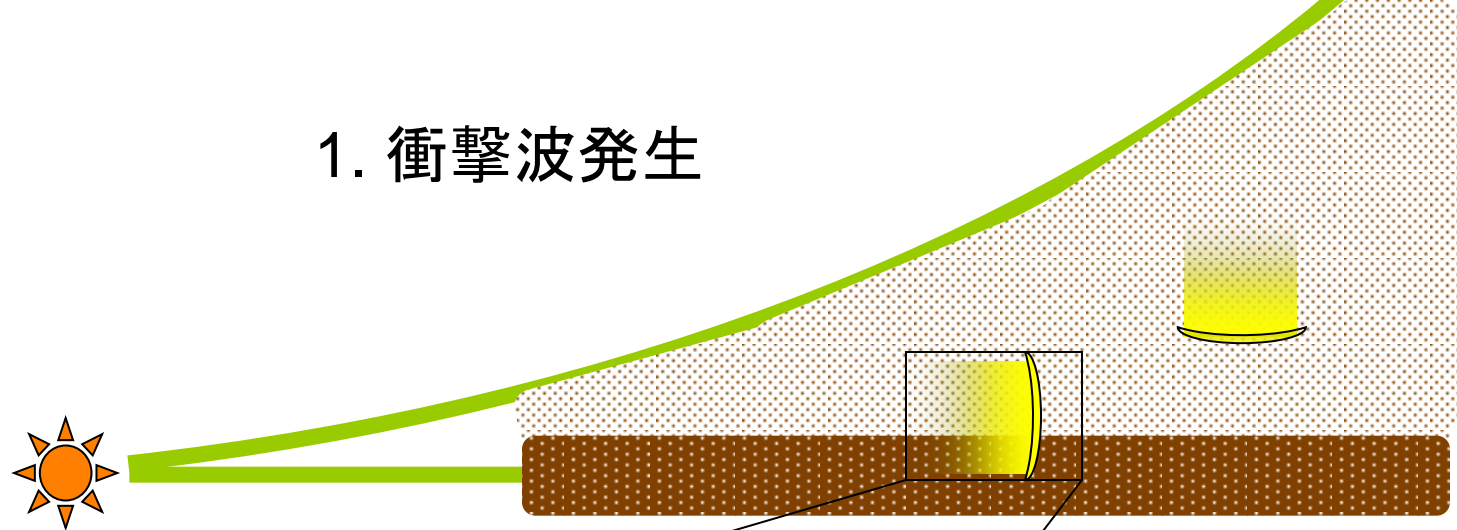


2. 衝撃波内部

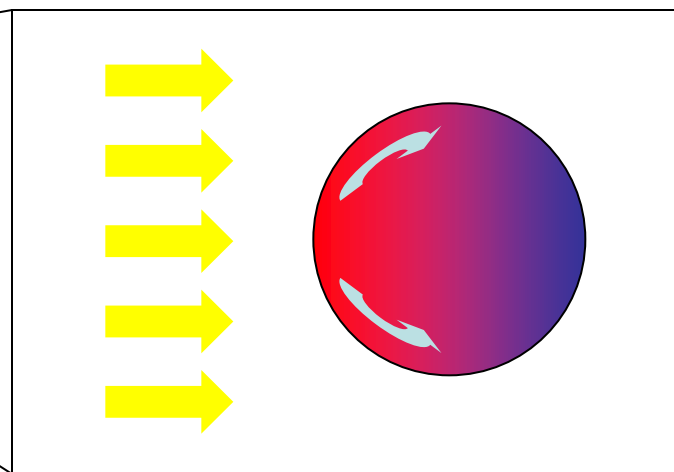


3. ダスト粒子内部

1. 衝撃波発生

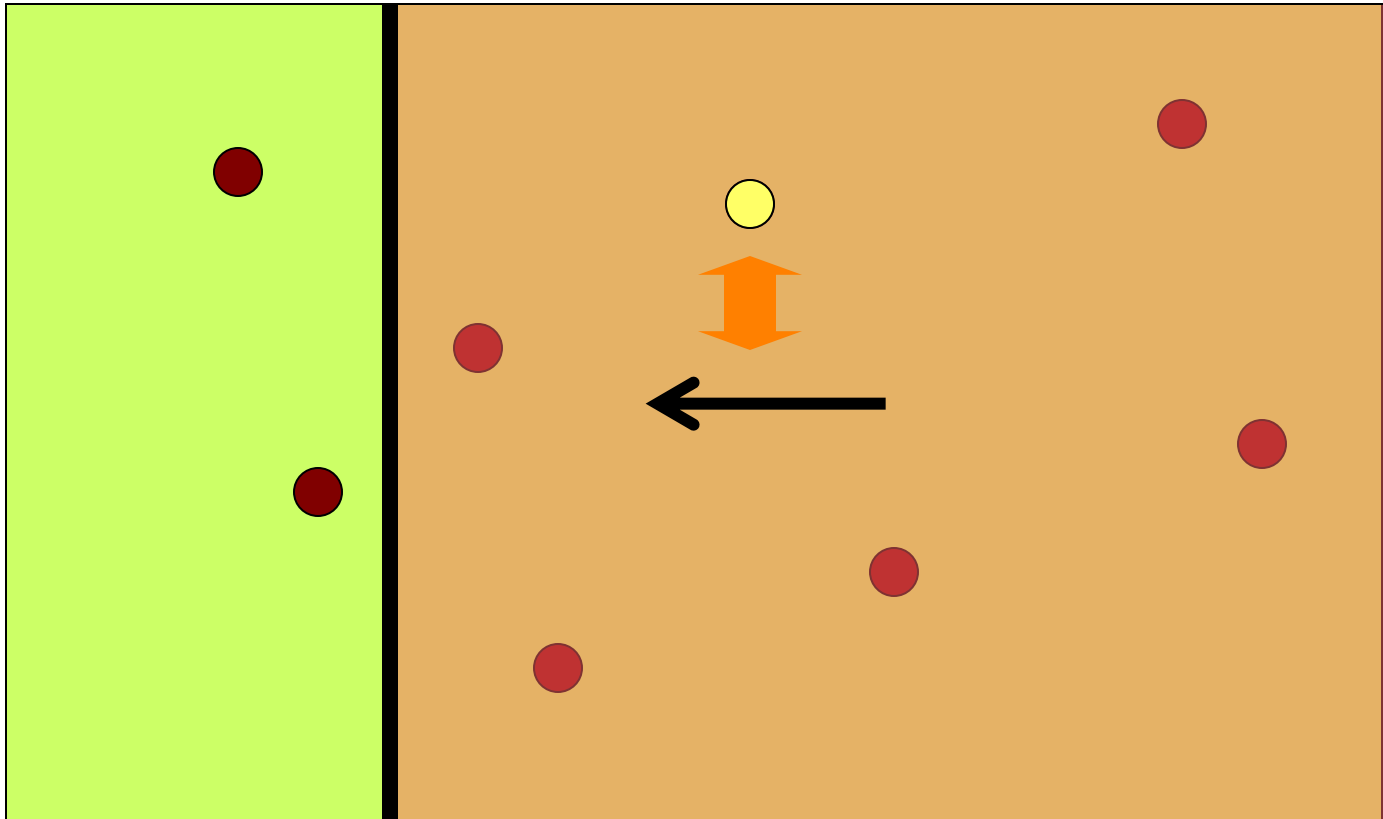


2. 衝撃波内部

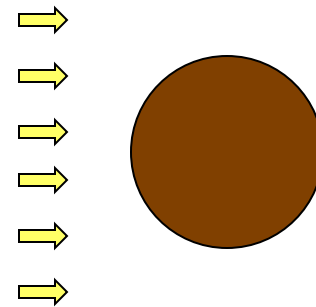


3. ダスト粒子内部

衝擊波加熱機構



簡単な見積もり



$$m_{\text{gr}} C_{\text{gr}} \frac{dT_{\text{gr}}}{dt} = \rho a^2 \frac{1}{2} r_{\text{gas}} V^3 - 4\rho a^2 s T_{\text{gr}}^4$$

最高温度到達時: $\frac{dT_{\text{gr}}}{dt} = 0$

$$\begin{aligned} \Rightarrow T_{\text{max}} &= \left(\frac{1}{2s} r_{\text{gas}} V^3 \right)^{1/4} \\ &= 1700 \left(\frac{n_{\text{gas}}}{10^{15} \text{ cm}^{-3}} \right)^{1/4} \left(\frac{V}{10 \text{ km s}^{-1}} \right)^{3/4} \text{ K} \end{aligned}$$

Basic Equations for Dust Particles:

$$m_{\text{gr}} \frac{dv_{\text{gr}}}{dt} = -\rho a_{\text{gr}}^2 \frac{C_D}{2} r v_{\text{rel}}^2$$

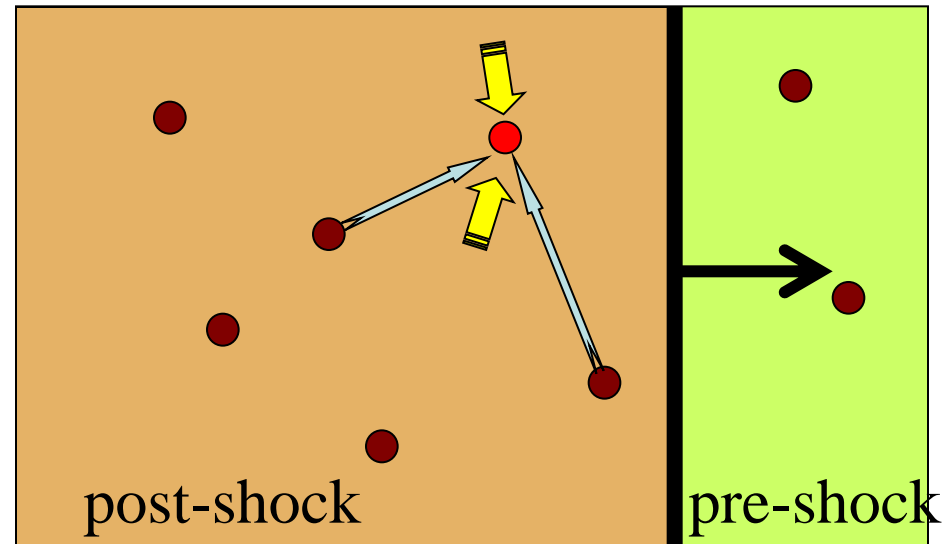
$$m_{\text{gr}} C_{\text{gr}} \frac{dT_{\text{gr}}}{dt} = -L_{\text{rad}} - L_{\text{evap}} + G_{\text{drag}} + G_{\text{rad,gas}} + G_{\text{rad,dust}}$$

$$r_{\text{gr}} \frac{da_{\text{gr}}}{dt} = -J_{\text{evap}}$$

radius a_{gr} : 0.01 μm – 1 cm

emissivity : size dependent

evaporation rate : pure forsterite



Basic Equations for Gas

$$\frac{1}{r} \frac{d}{dr} (rv) = 0$$

$$\frac{1}{r} \frac{d}{dr} (rv^2 + p) = 0$$

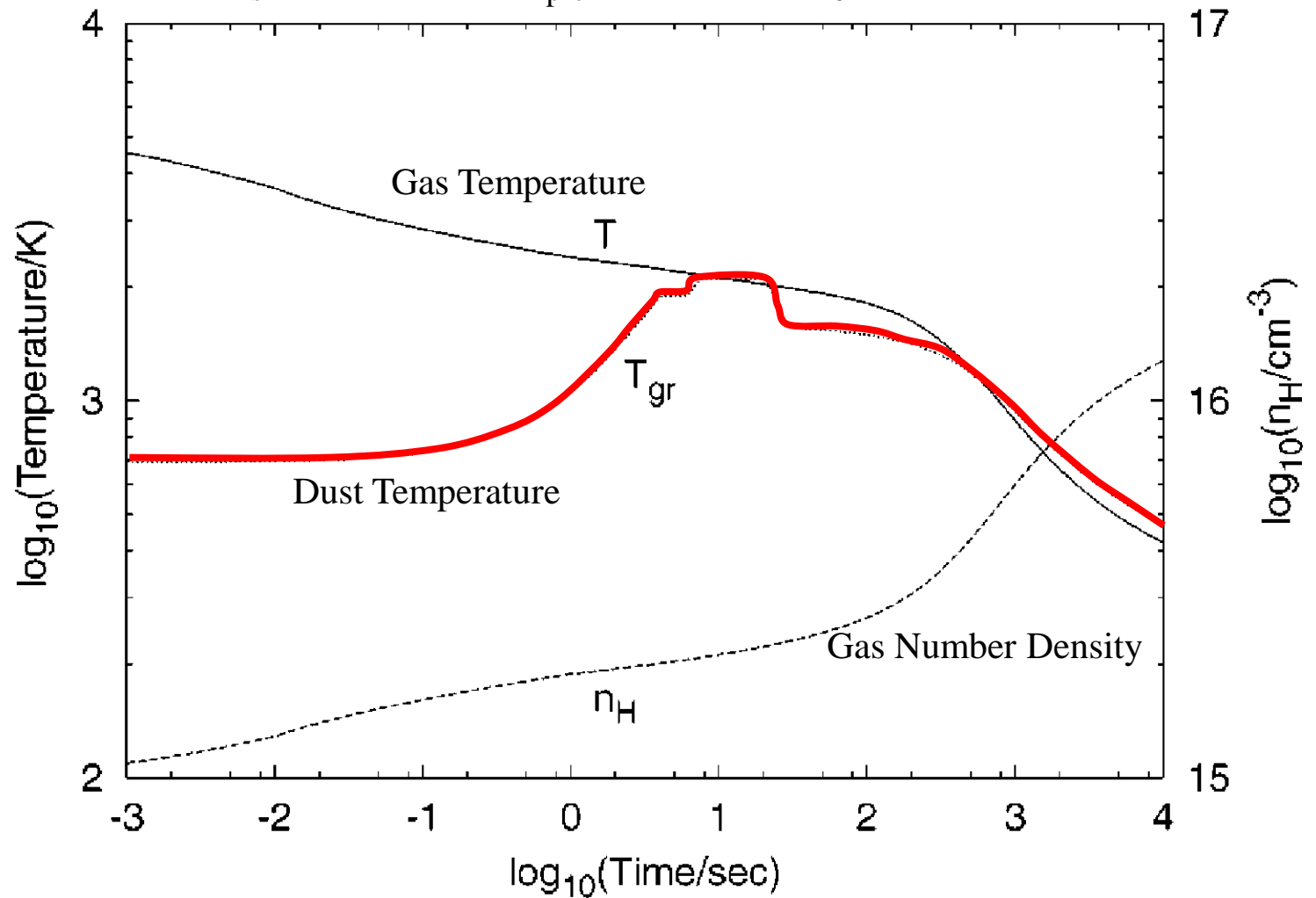
$$\frac{1}{r} \frac{d}{dr} \left(\frac{1}{2} rv^2 + E + P \right) = \sum \dot{m}_i$$

$$= G_{\text{H}_2\text{form}} - L_{\text{Ly}\alpha} - L_{\text{H}_2\text{diss}} - L_{\text{H}_2\text{O(V)}} - L_{\text{H}_2\text{O(R)}} - L_{\text{CO(V)}} - L_{\text{CO(R)}} - L_{\text{OH(R)}} - L_{\text{grain}}$$

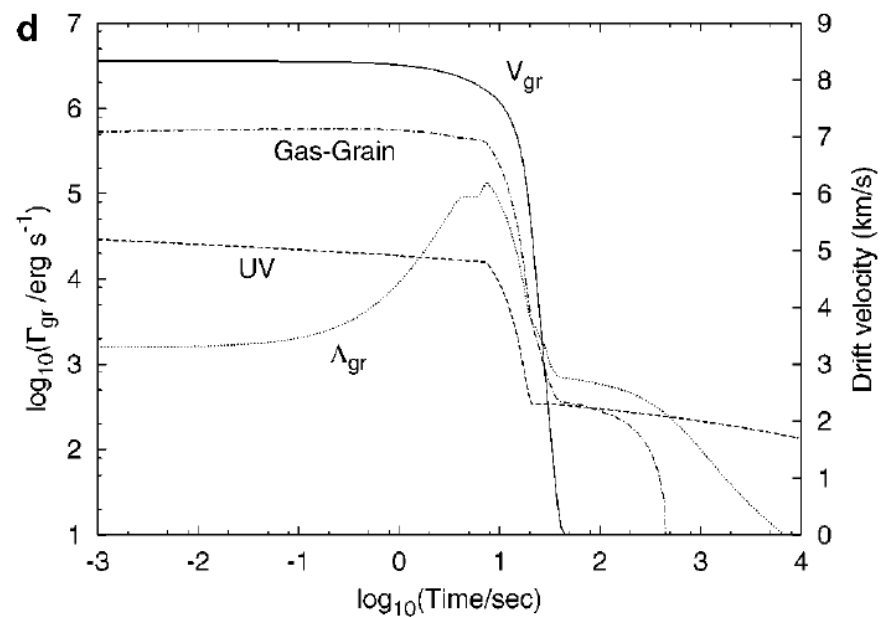
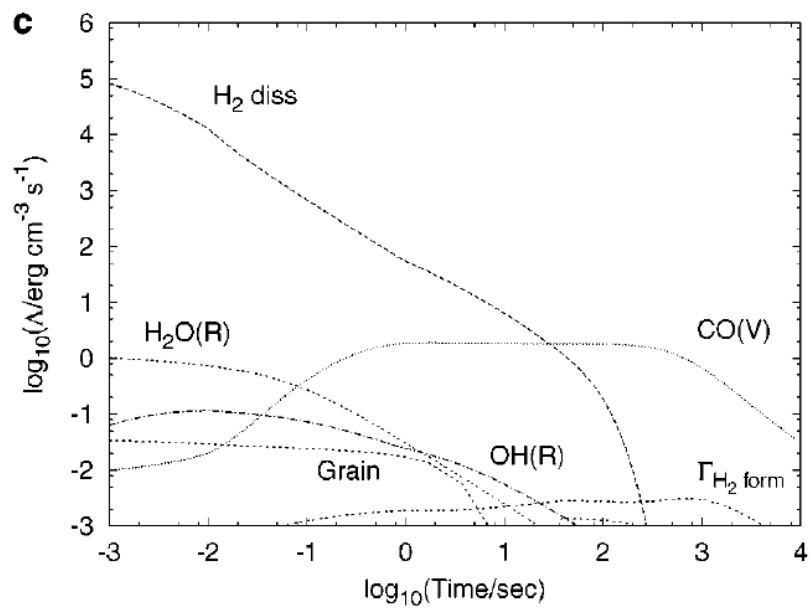
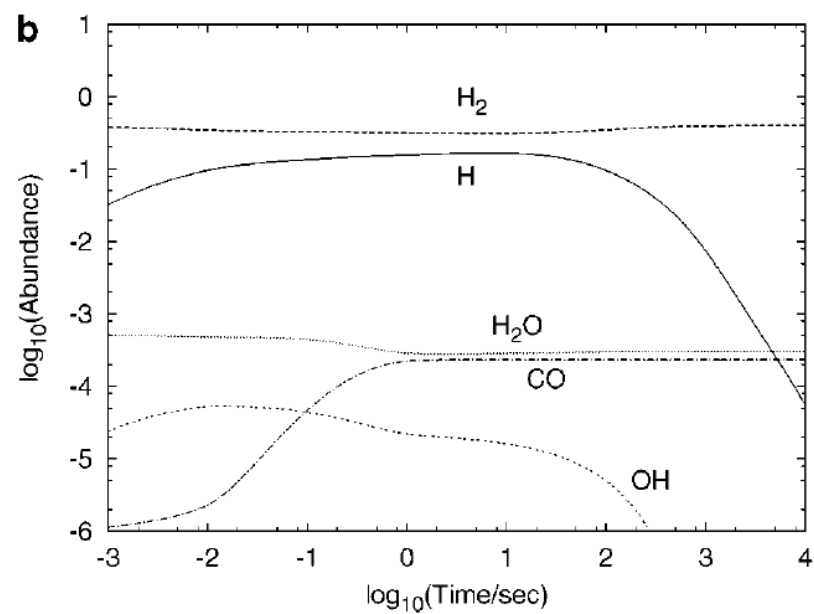
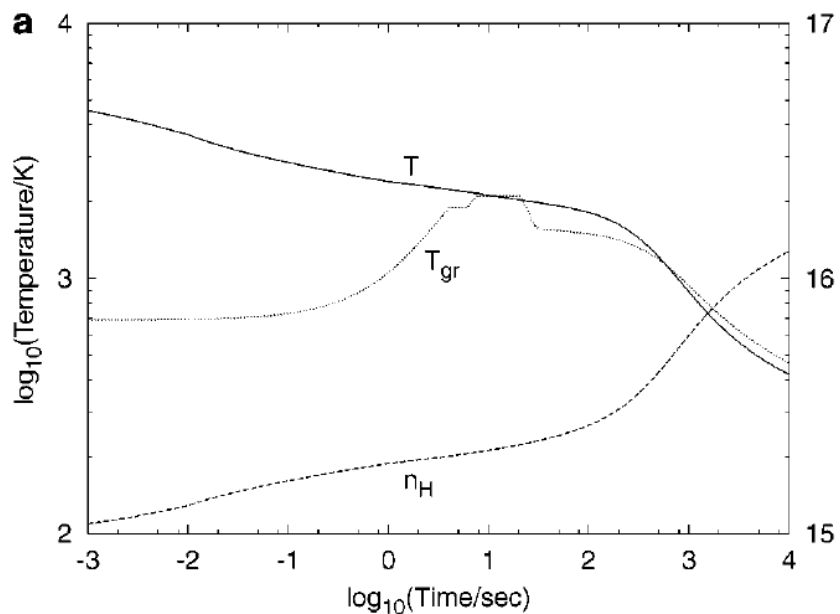
$$\frac{dy_i}{dt} = n_H \sum_{j=1}^{32} \dot{a}_{jk} y_j y_k + n_H^2 \sum_{l=1}^{32} \sum_{m=1}^{32} \sum_{n=1}^{32} \dot{a}_{lmn} y_l y_m y_n$$

Chemical Reactions : 32 species, 167 reactions

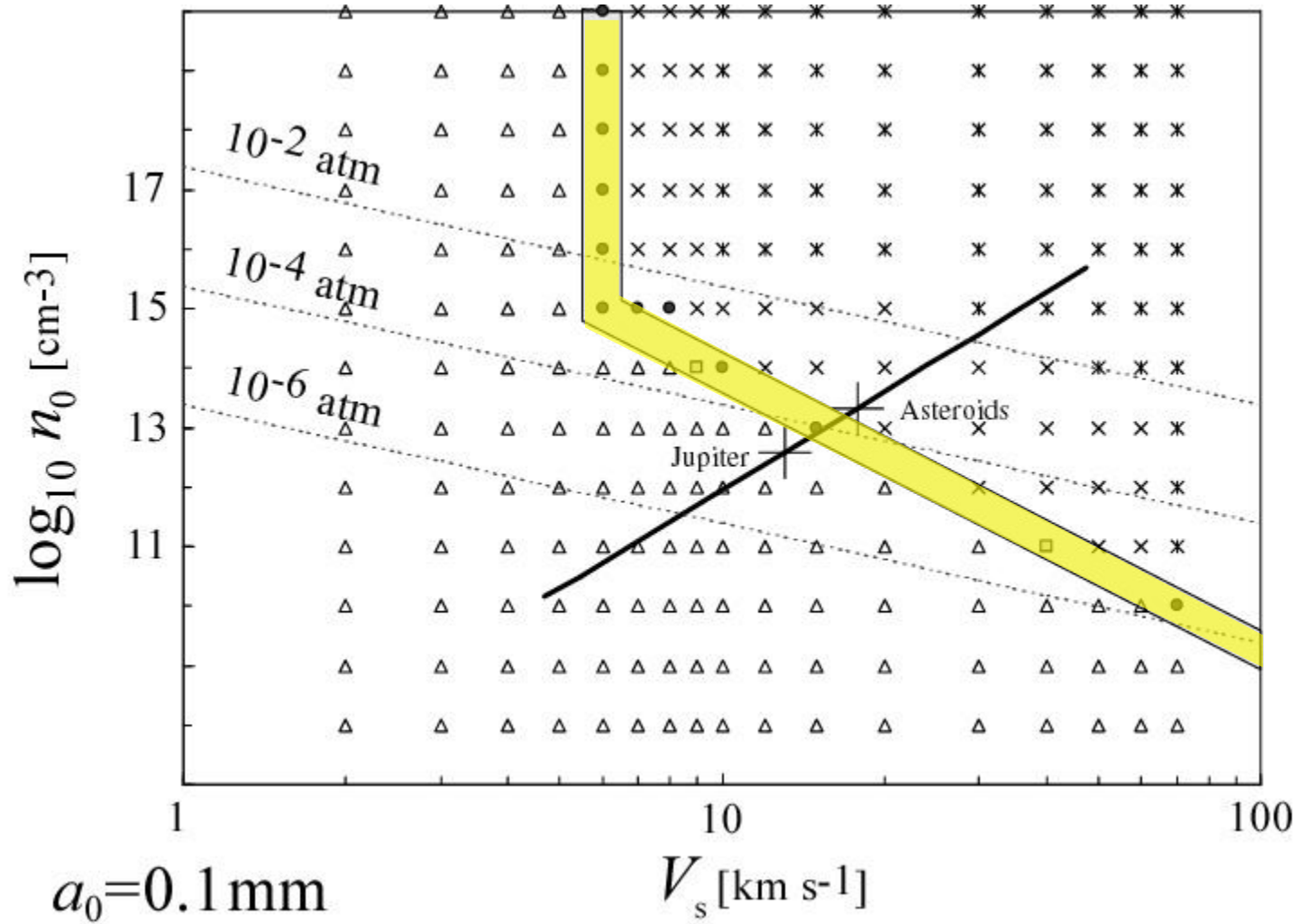
$$V_s = 10 \text{ km s}^{-1}, n_{\text{pre}} = 10^{14} \text{ cm}^{-3}, a_0 = 0.1 \text{ mm}$$



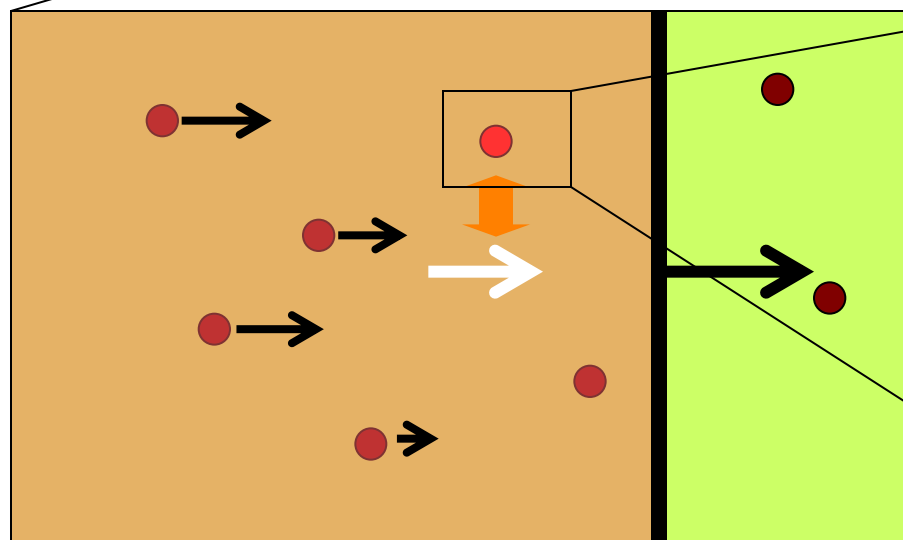
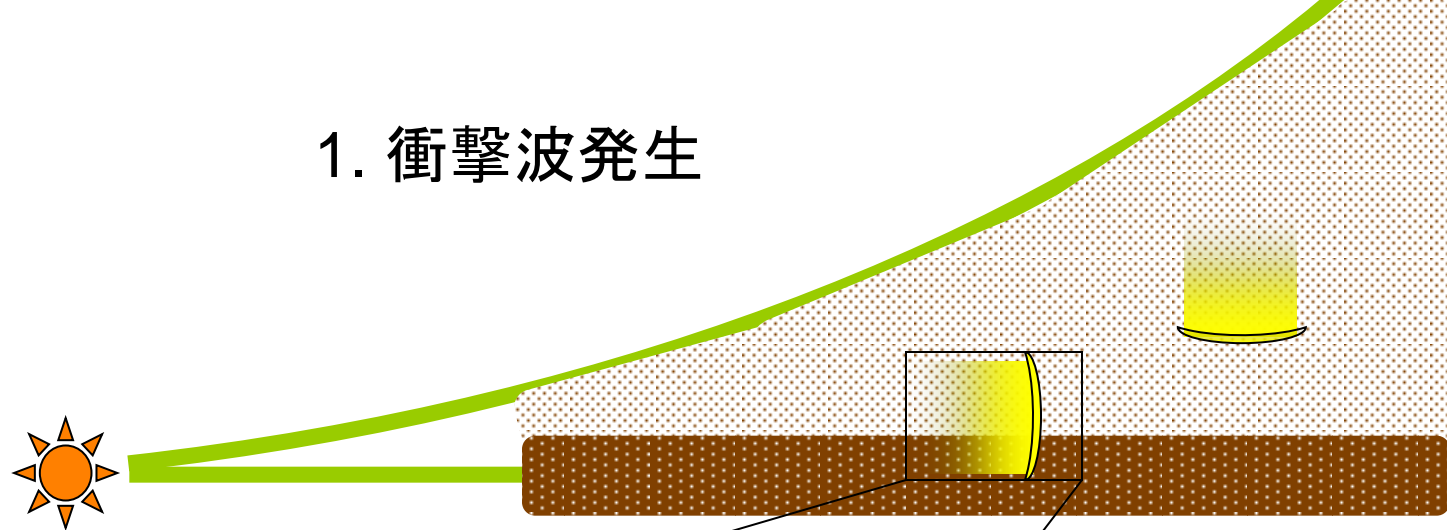
衝撃波後面の構造



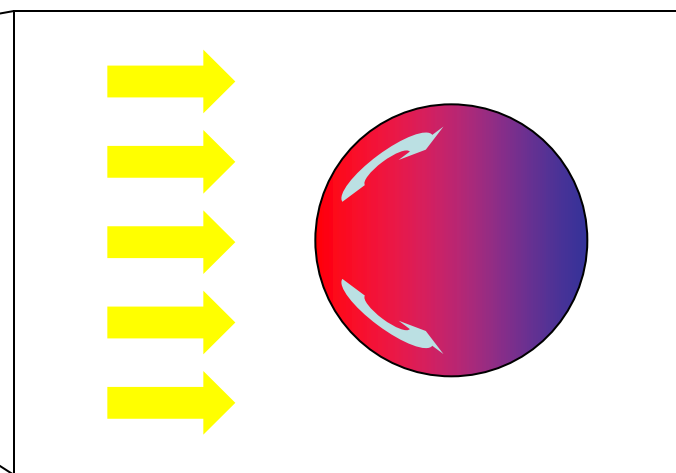
Chondrule Forming Shock Waves: Peak Temperature



1. 衝撃波発生



2. 衝撃波内部



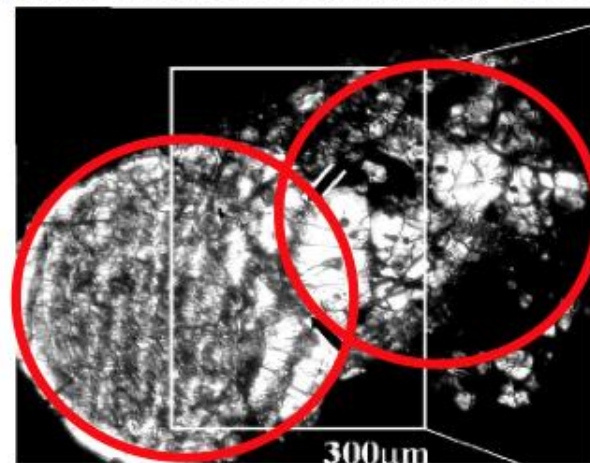
3. ダスト粒子内部

複合コンドリュール

- ▶二個以上のコンドリュールが付着
- ▶コンドリュール全体の**数%**存在

Akaki and Nakamura 2004

二つのコンドリュールが
溶融状態を経験中に衝突



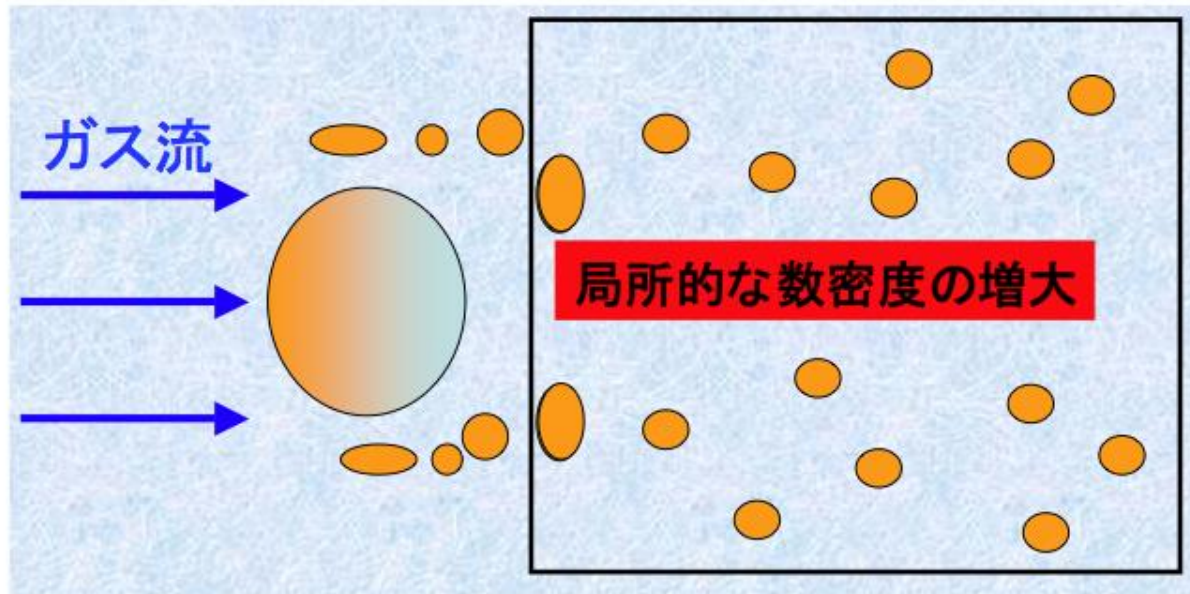
原始太陽系星雲中のダストの直接衝突は低頻度

(Sekiya and Nakamura 1996, Wasson et al. 1995, Gooding and Keil 1981)

分裂—衝突モデル

～複合コンドリュール形成の1モデル～

(Miura, Yasuda, and Nakamoto 2007)



衝突頻度

$$P_{\text{coll}} = n_e \sigma \Delta v t$$

~0.36

>>

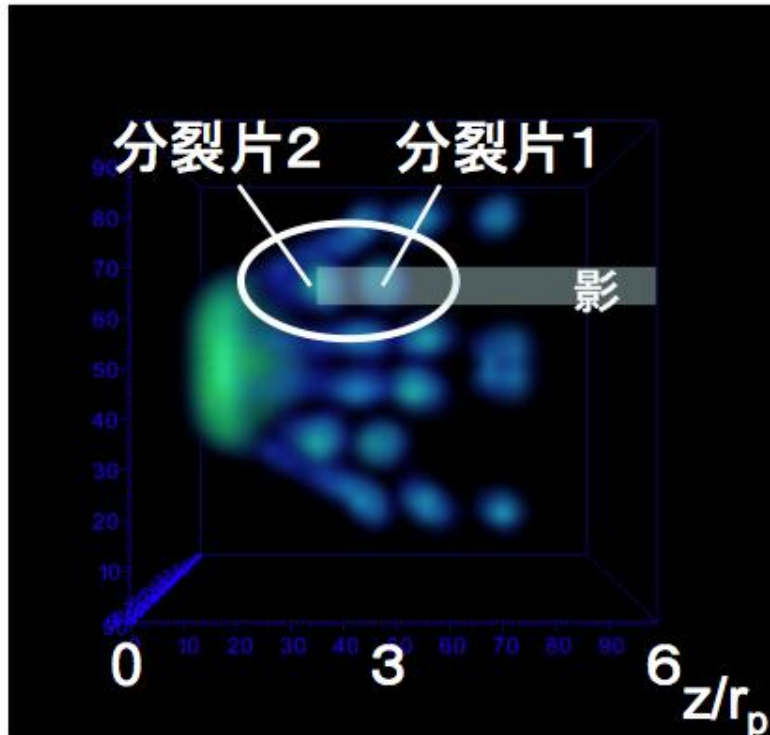
存在割合

$$\frac{\text{複合コンドリュールの数}}{\text{コンドリュールの数}}$$

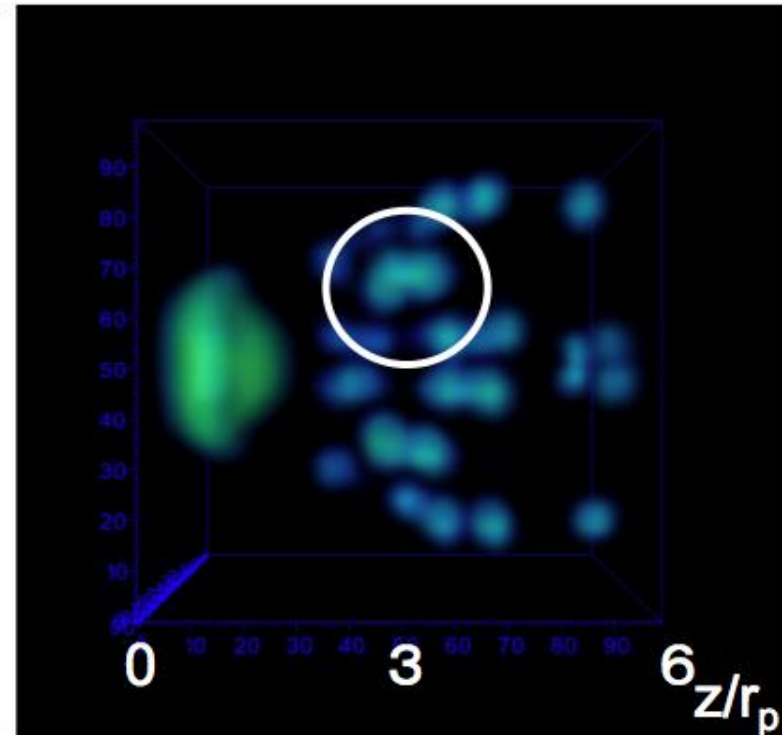
~0.05

分裂片同士の衝突

t = 0.0109sec



t = 0.0136sec

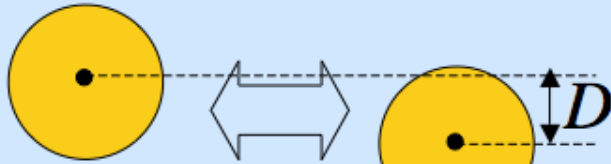


分裂片同士は確かに衝突する！

Miura, Yasuda, & Nakamoto (2008)

衝突付着条件

分裂片2 ($r_{e1} = 1.1\text{mm}$) 分裂片1 ($r_{e2} = 0.98\text{mm}$)



相对速度 ($\Delta v = 97\text{cm/s}$)

● Impact parameter

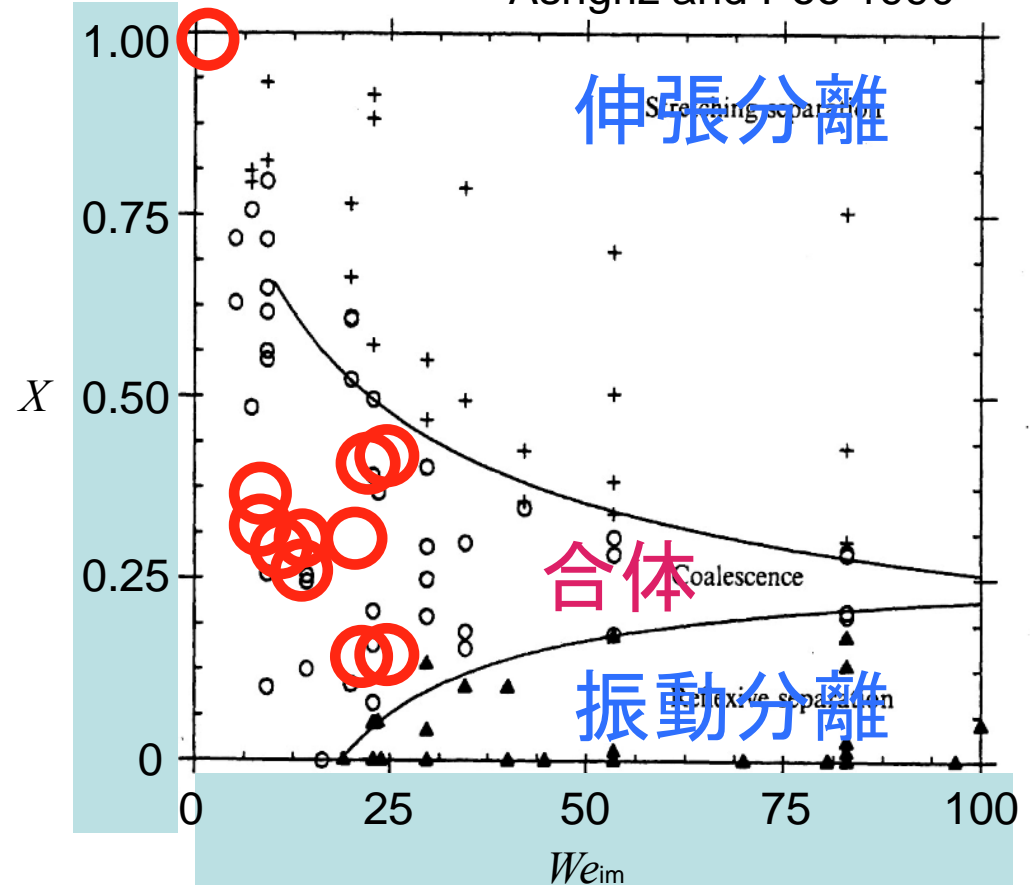
$$X \equiv \frac{D}{r_{e1} + r_{e2}} = \underline{0.29}$$

● Weber number

$$We_{im} = \frac{2r_{e2}\rho_{mat}\Delta v^2}{\gamma_s} = \underline{14.1}$$

ρ_{mat} : 分裂片の質量密度
($= 3\text{ g/cm}^3$)

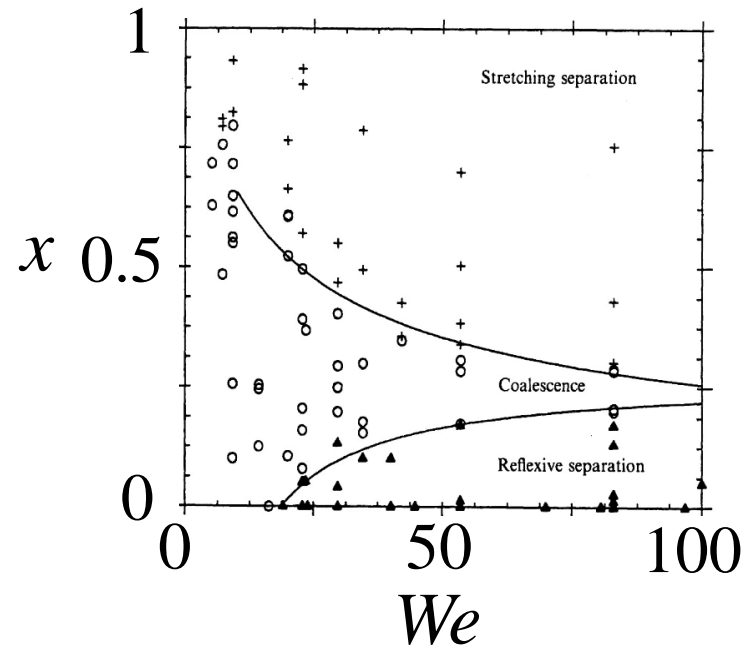
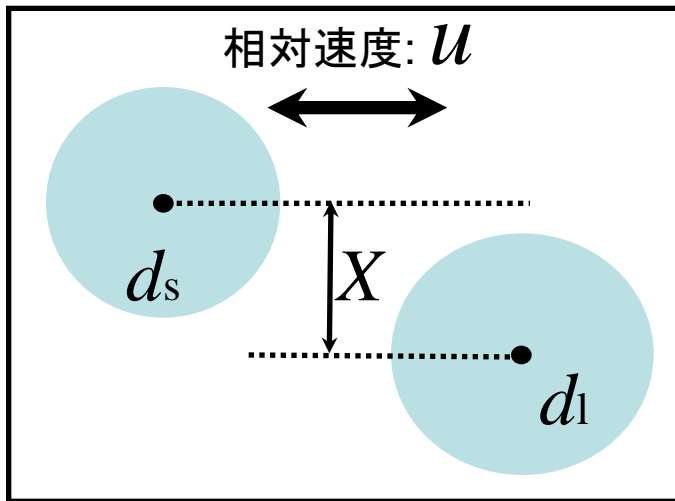
Ashgriz and Poo 1990



分裂片同士は
ほとんど付着。

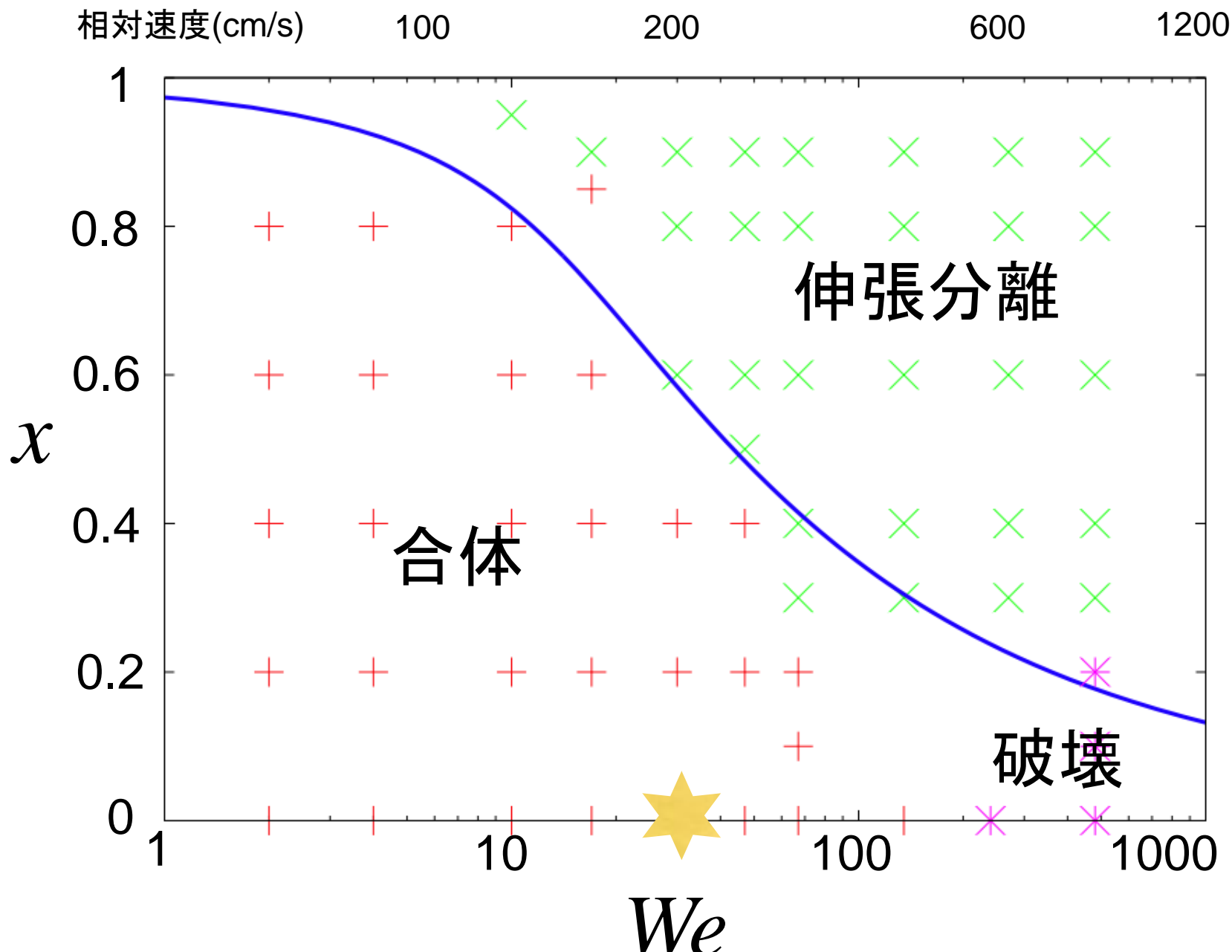
パラメータ

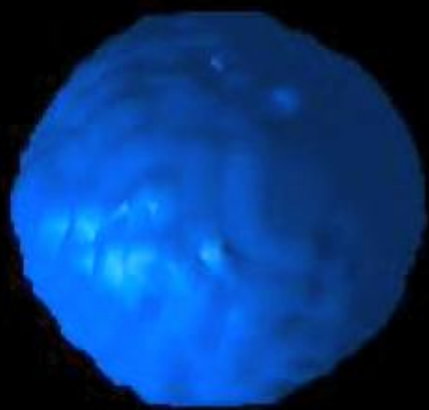
液滴の衝突実験 (水)
(Ashgriz and Poo 1990)



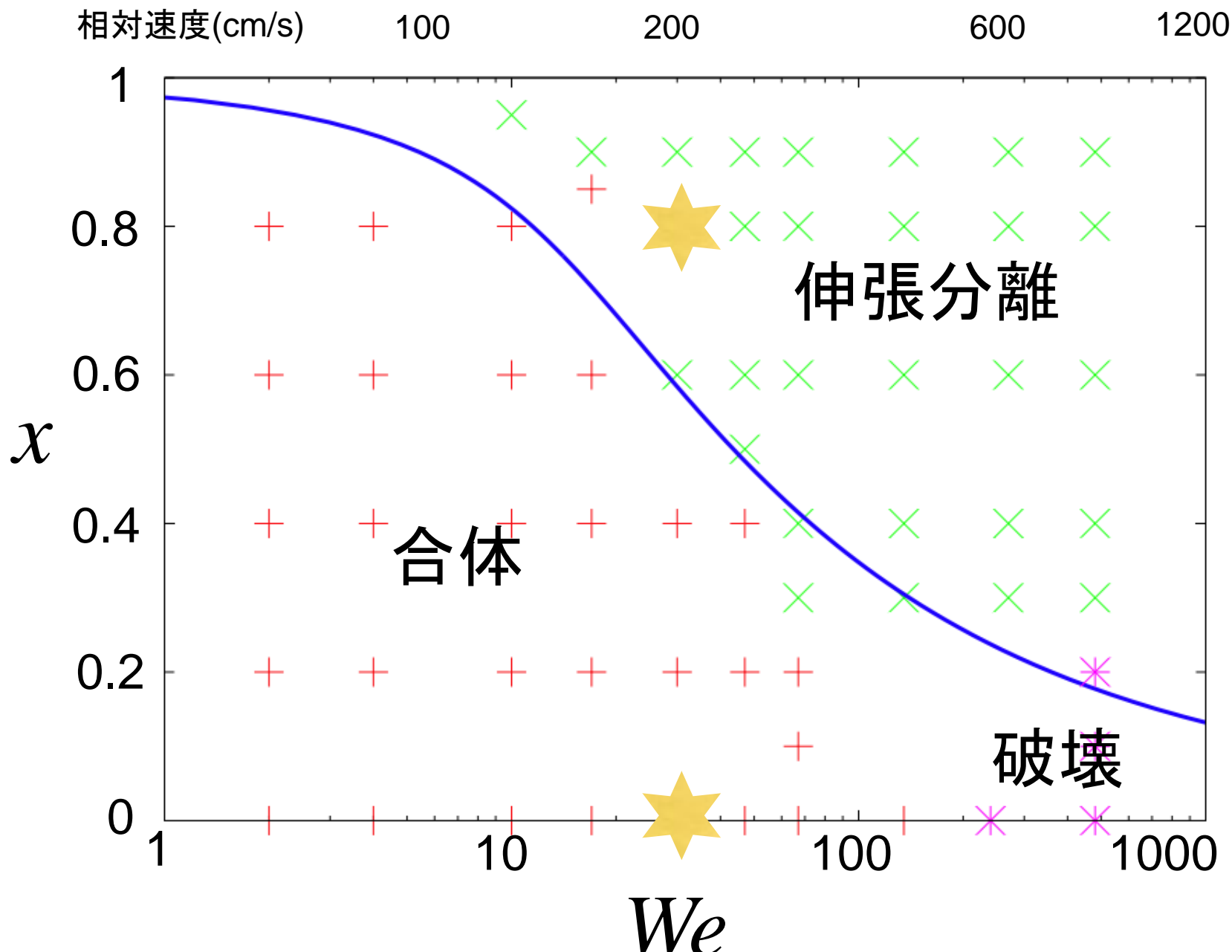
$$We = \frac{r v^2}{g/R} = \frac{\text{動圧}}{\text{表面張力}}$$

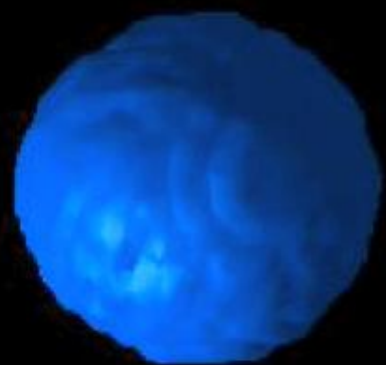
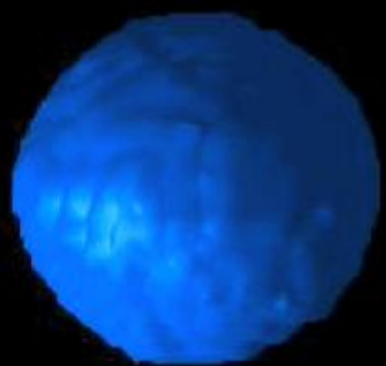
計算結果(ns1-n11)



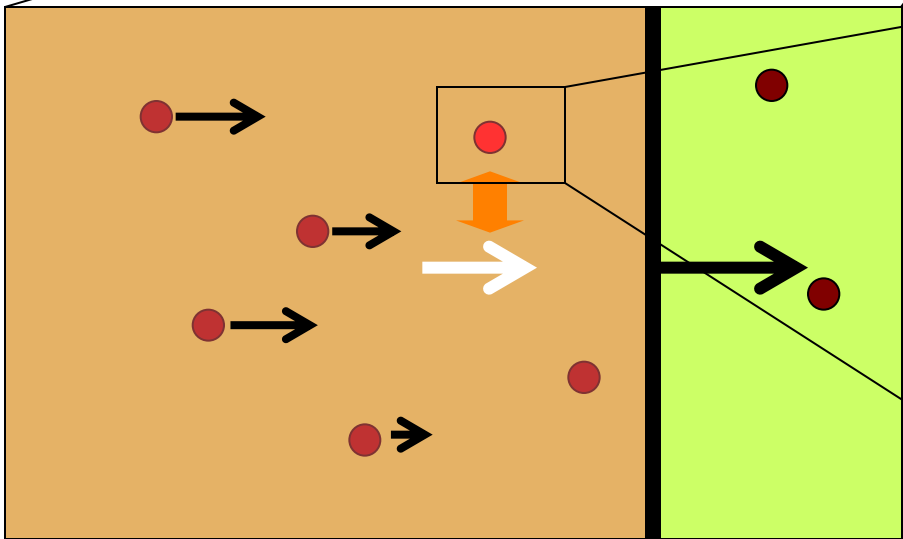
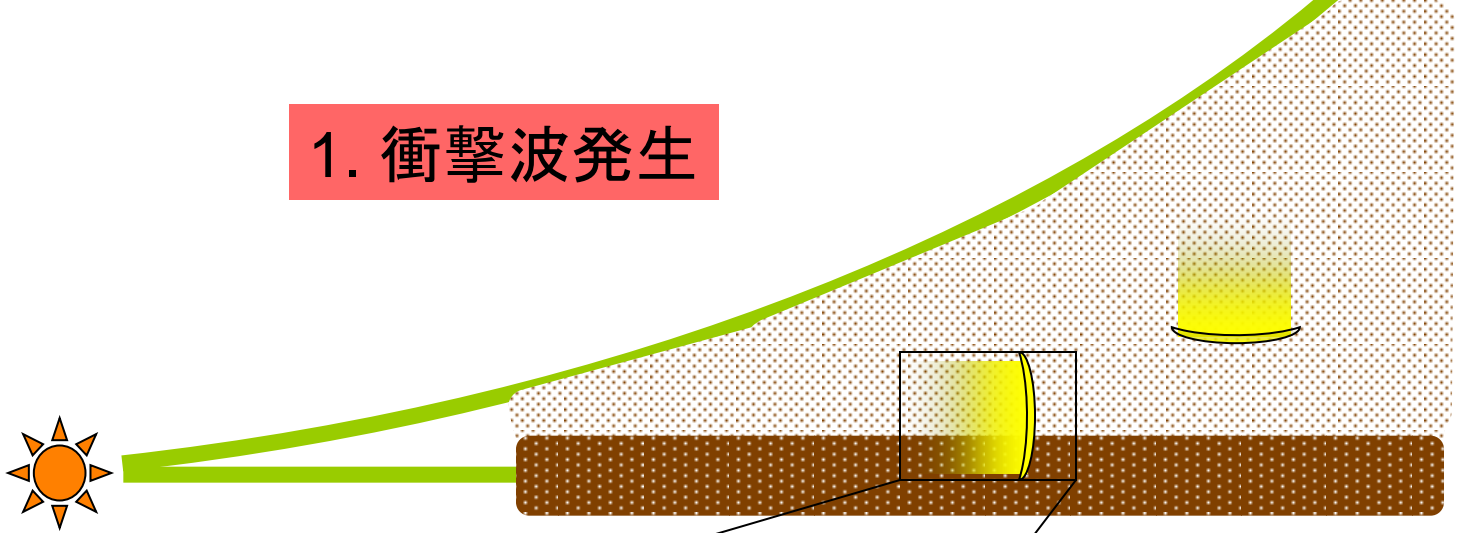


計算結果(ns1-n11)

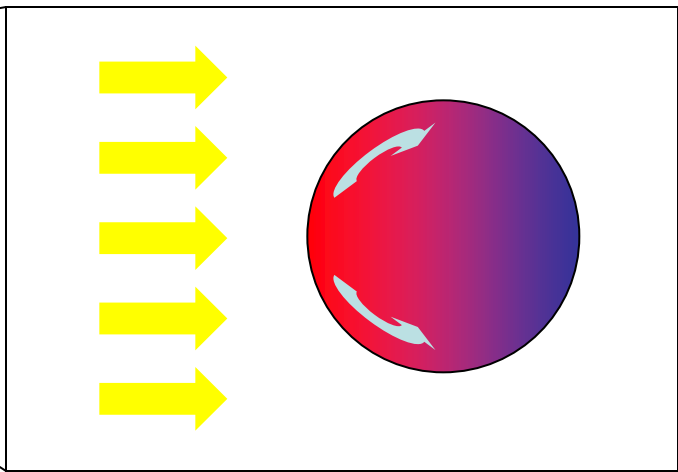




1. 衝撃波発生



2. 衝撃波内部



3. ダスト粒子内部

衝撃波の起源は何か？

- ・ 降着衝撃波

分子雲コアからの降着流による衝撃波

- ・ 自己重力円盤内密度波

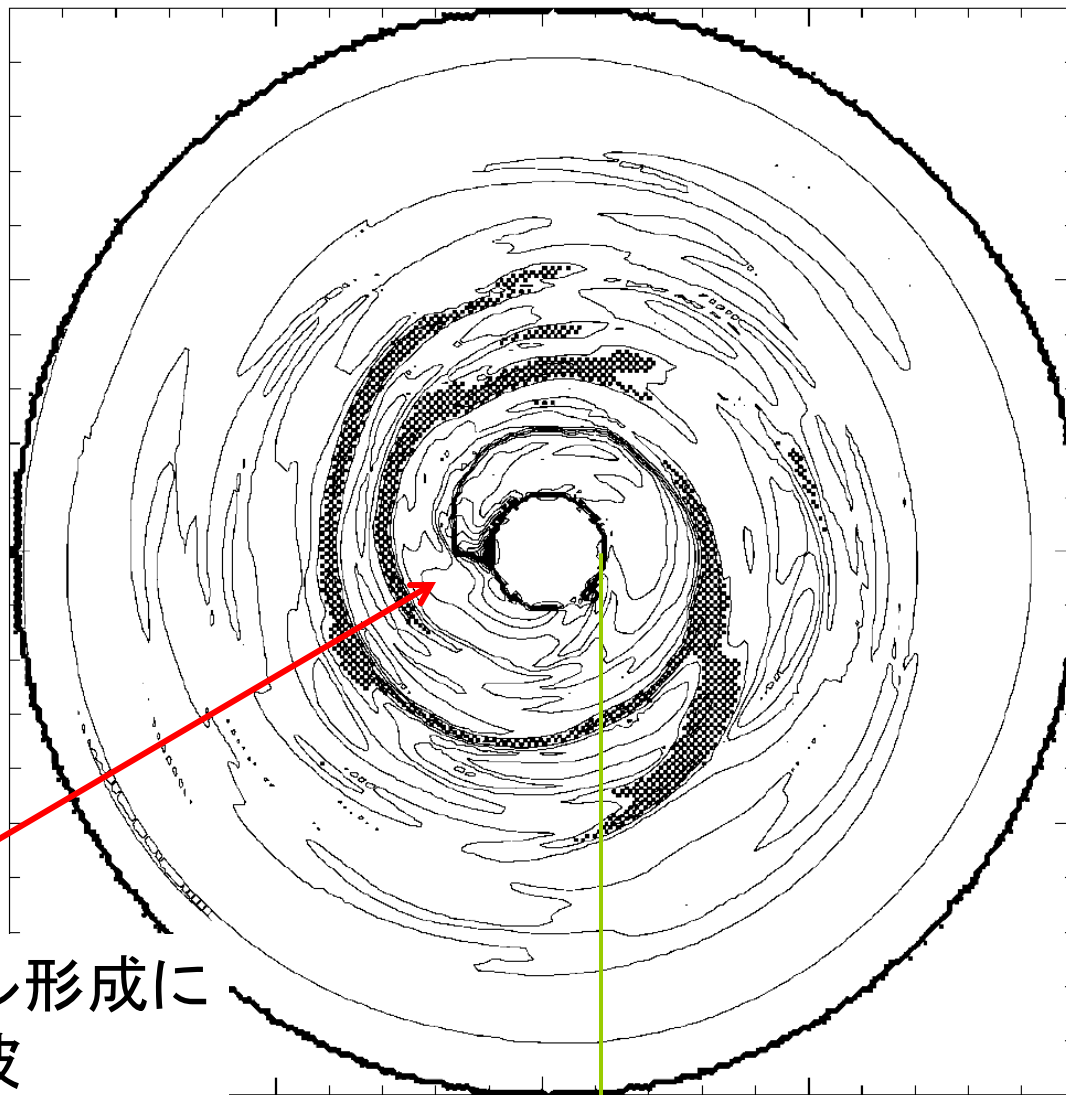
自己重力不安定なガス円盤内の密度波

- ・ 微惑星前面のバウショック

木星により大きなランダム運動を獲得した
微惑星前面に発生するバウショック

- ・ 星風による円盤上層衝撃波

X線フレアによる星風とそれによる衝撃波



コンドリュール形成に
適当な衝撃波

2AU

20AU

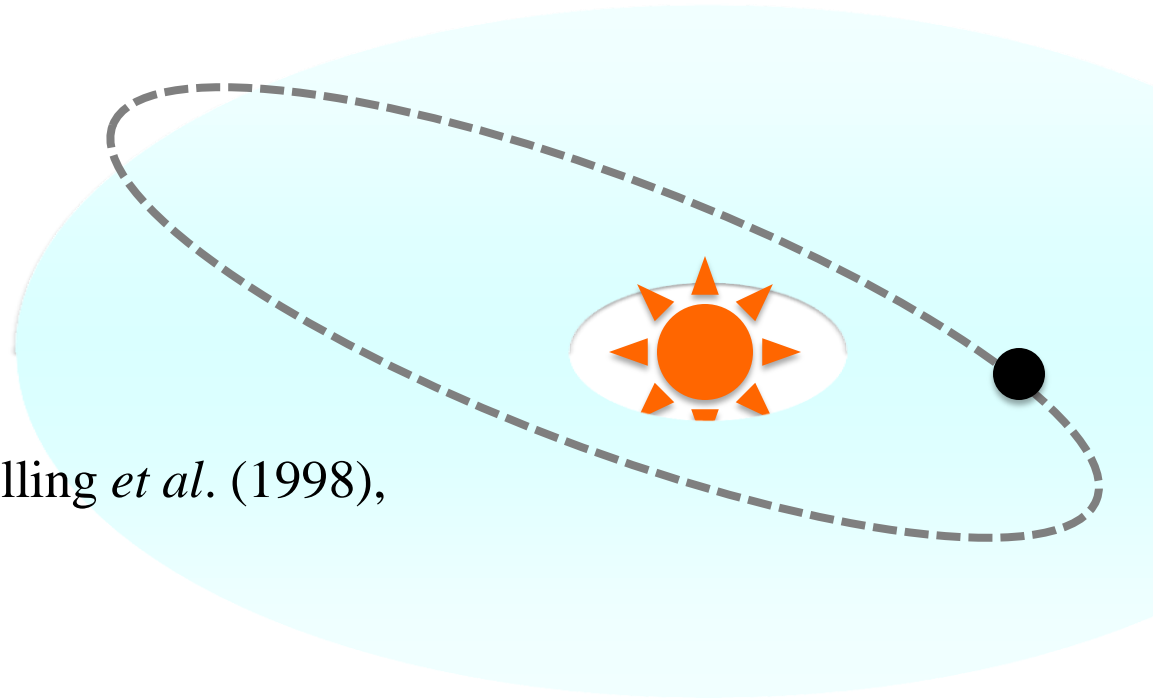
ショック源は何か

- コンドリュール前駆体を融かせるほど強い
- 数百万年にわたって起こる



微惑星まわりの バウショック

Hood (1998), Weidenschilling *et al.* (1998),
Ciesla *et al.* (2004)



木星による高速 微惑星形成と 微惑星前面の バウショック形成

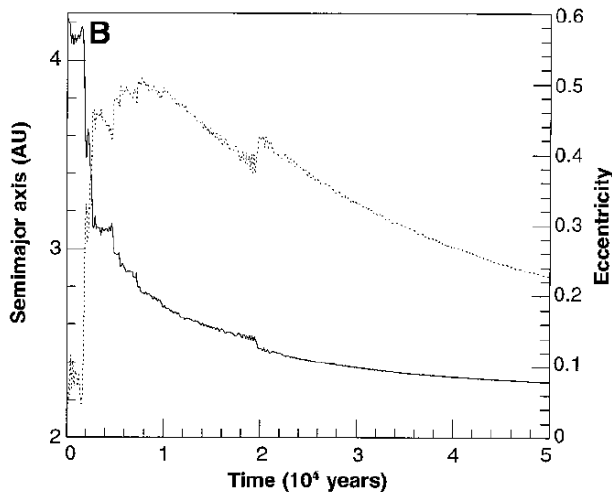
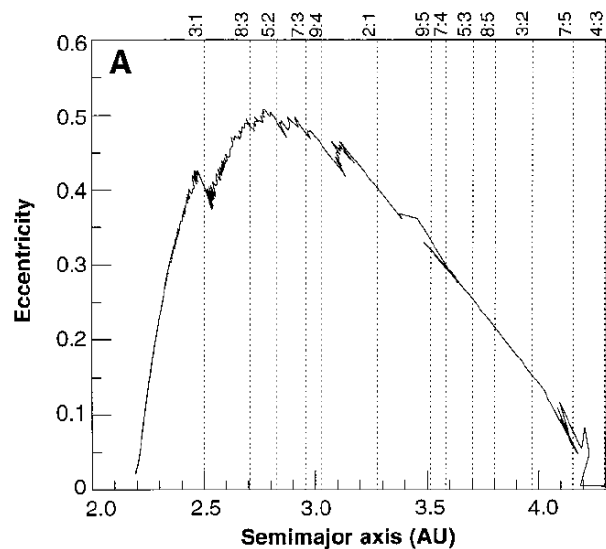
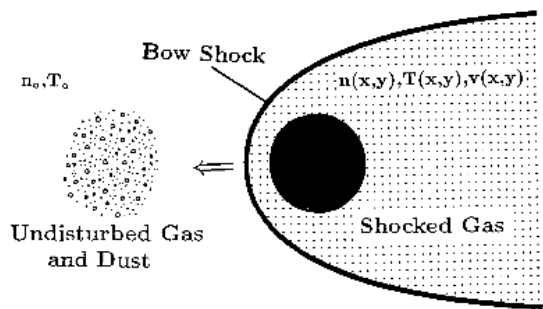


Fig. 1. (A) Eccentricity versus semimajor axis for a 100-km-diameter planetesimal started at 4.2 AU. Dashed lines mark the centers of major commensurability resonances, which overlap at eccentricities above 0.2 to 0.3 (27). **(B)** Semimajor axis (solid line) and eccentricity (dotted line) versus time for the planetesimal in (A). There is 3×10^5 years of slow orbital decay before encountering the resonance. Eccentricity

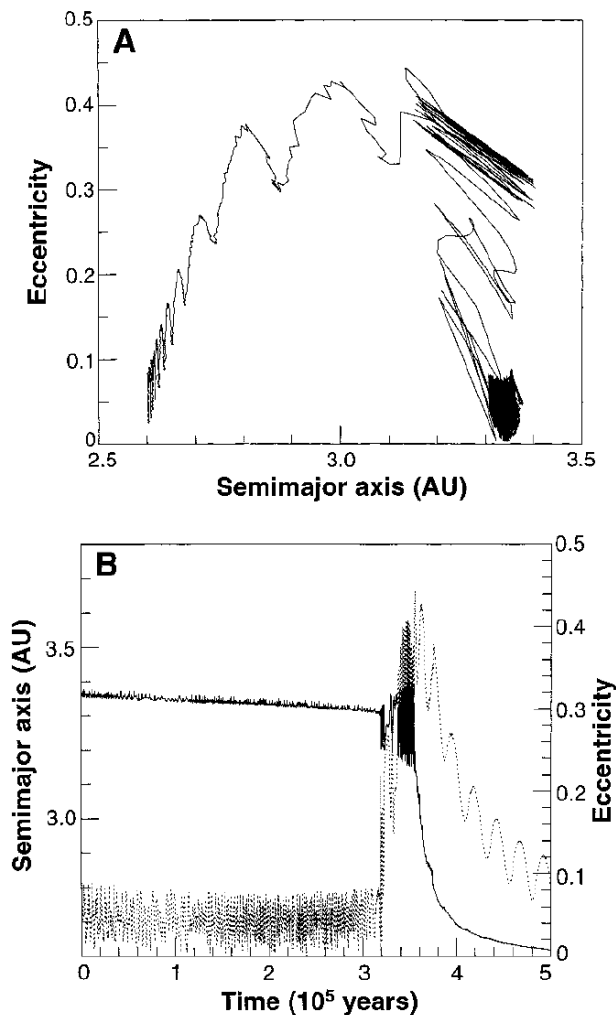
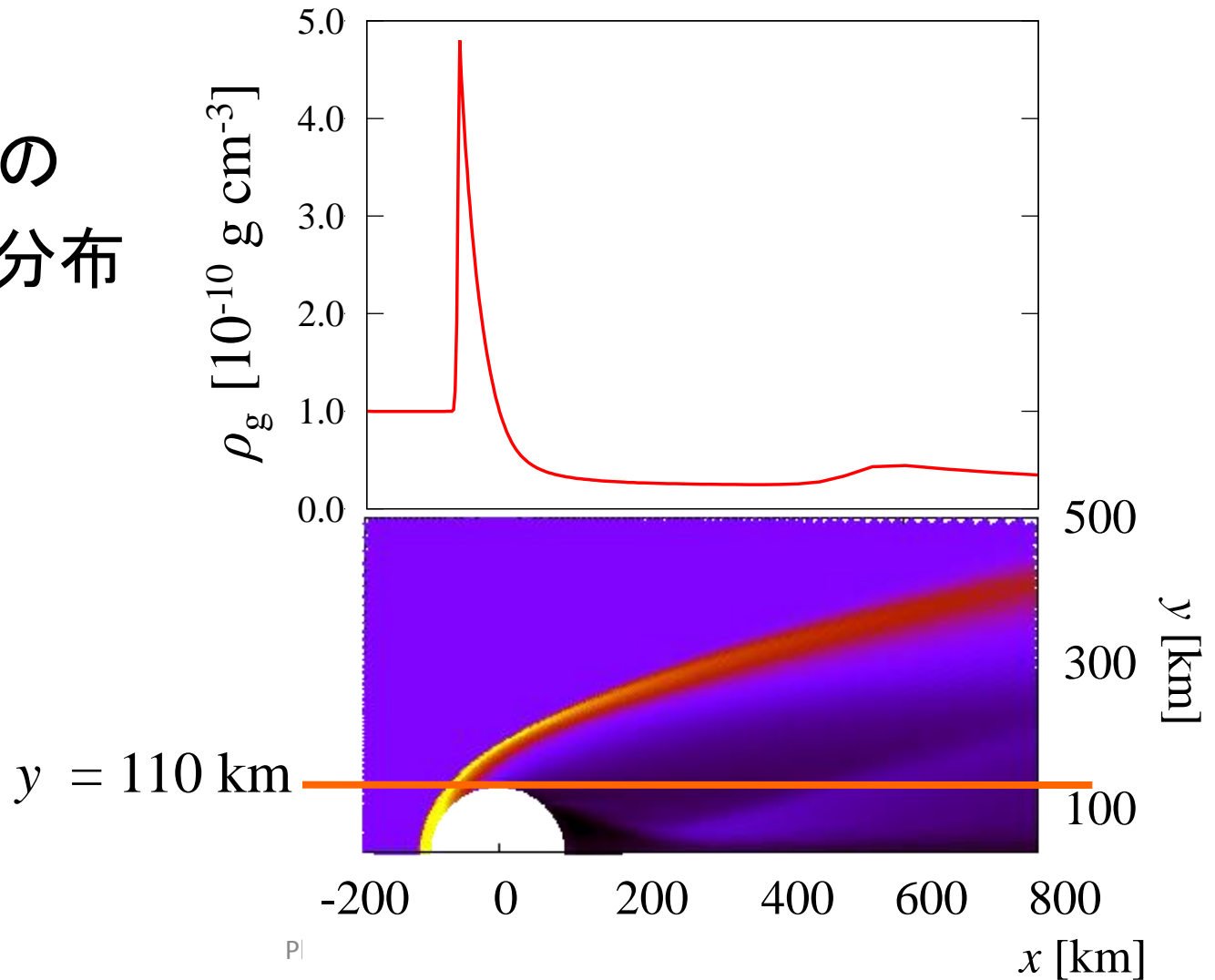


Fig. 2. (A) Eccentricity versus semimajor axis for a 100-km-diameter planetesimal started outside the 2:1 resonance. Jupiter is assumed to have its present eccentricity of 0.048. The planetesimal becomes trapped in the resonance until its eccentricity exceeds 0.3, then it escapes and is damped by drag. **(B)** Semimajor axis (solid line) and eccentricity (dotted line) versus time for the planetesimal in (A). There is 3×10^5 years of slow orbital decay before encountering the resonance. Eccentricity

【結果】

$y = 110$ km
直線上での
ガス密度分布

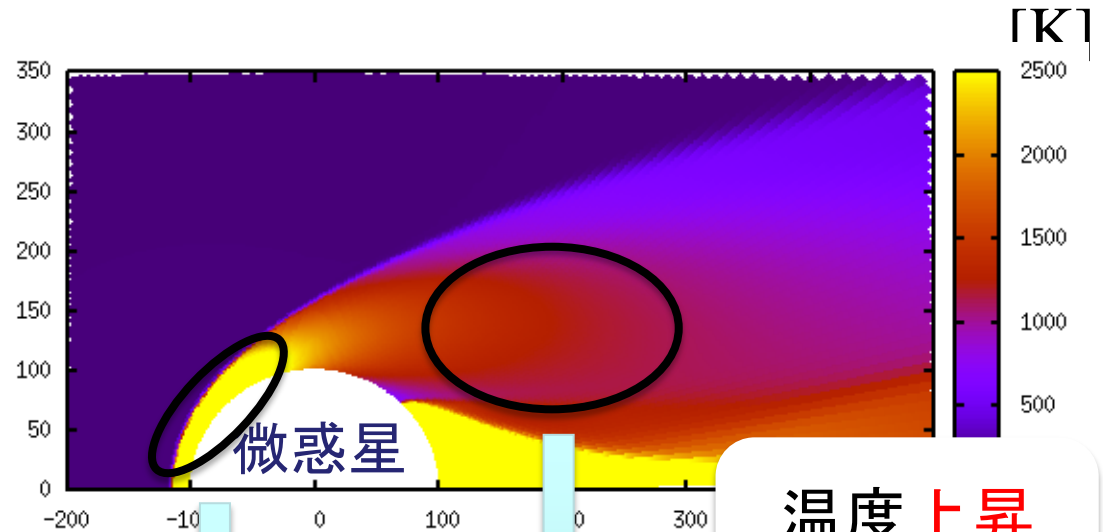


解離入り計算

$\rho=10^{-8} \text{ g/cm}^3$, $v=12 \text{ km/s}$ の場合

解離・再結合

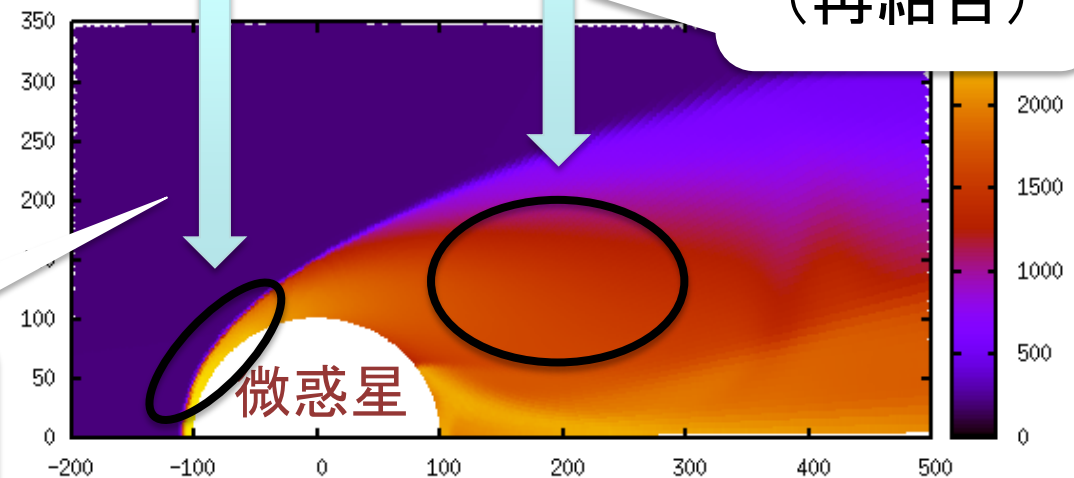
なし



解離・再結合

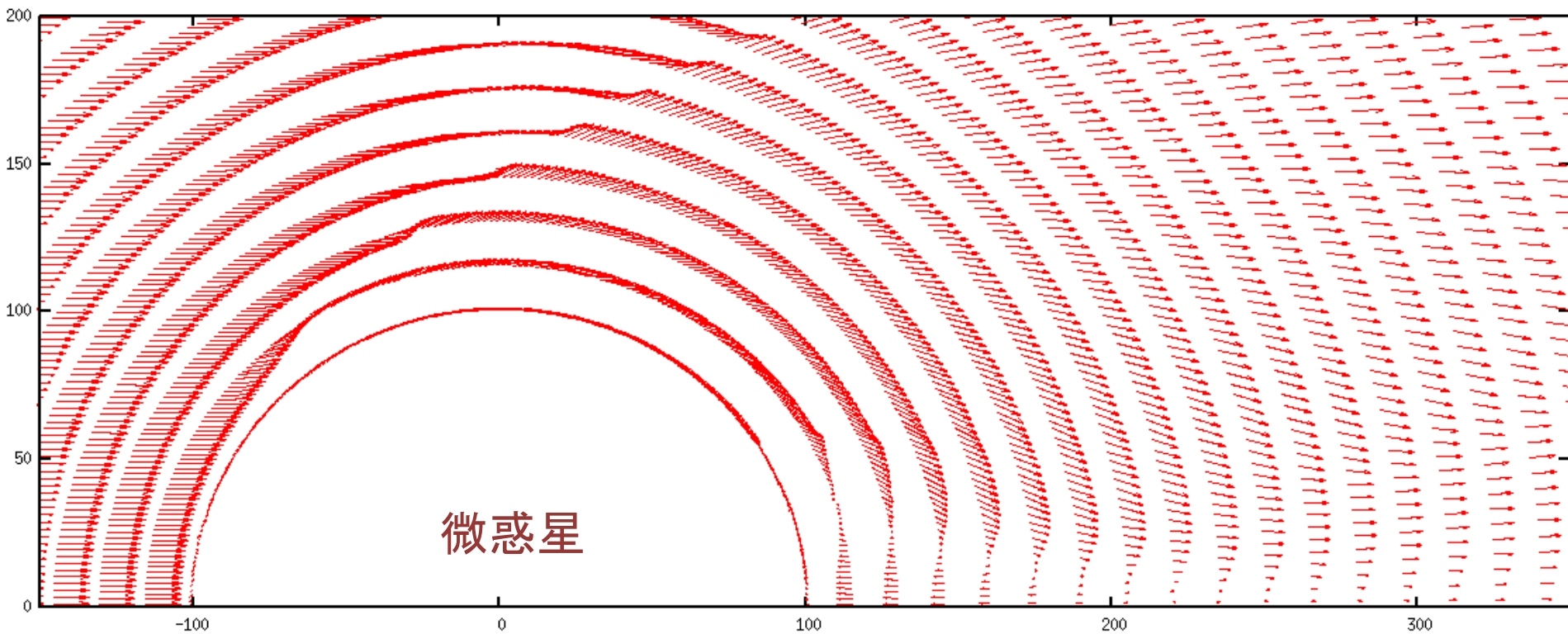
あり

低下
密度上昇
(解離)

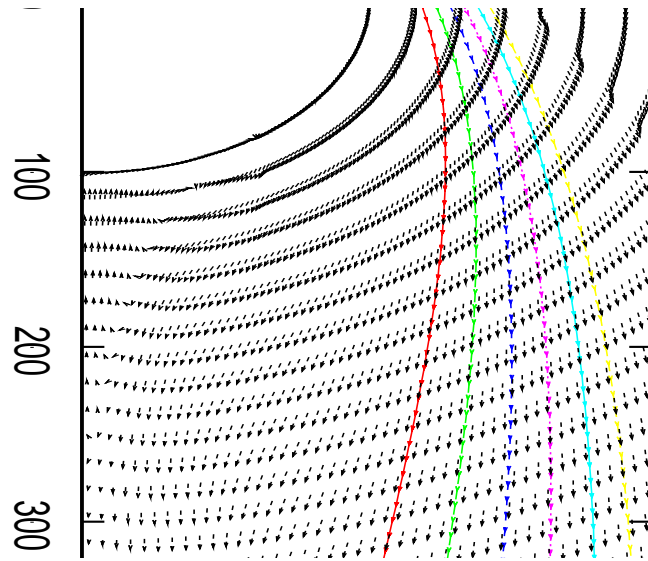


速度場（解離あり）

$\rho = 10^{-8} \text{ g/cm}^3$, $v = 12 \text{ km/s}$ の場
合



流線



バウショックに突入した粒子の熱履歴

- パラメータ

- $x_{\text{imp}} = 80 - 400 \text{ km}$

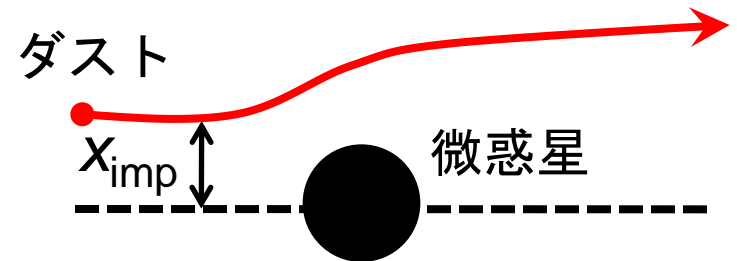
- $a = 0.1, 1, 10 \text{ mm}$

- 粒子に働く力

- ガス摩擦

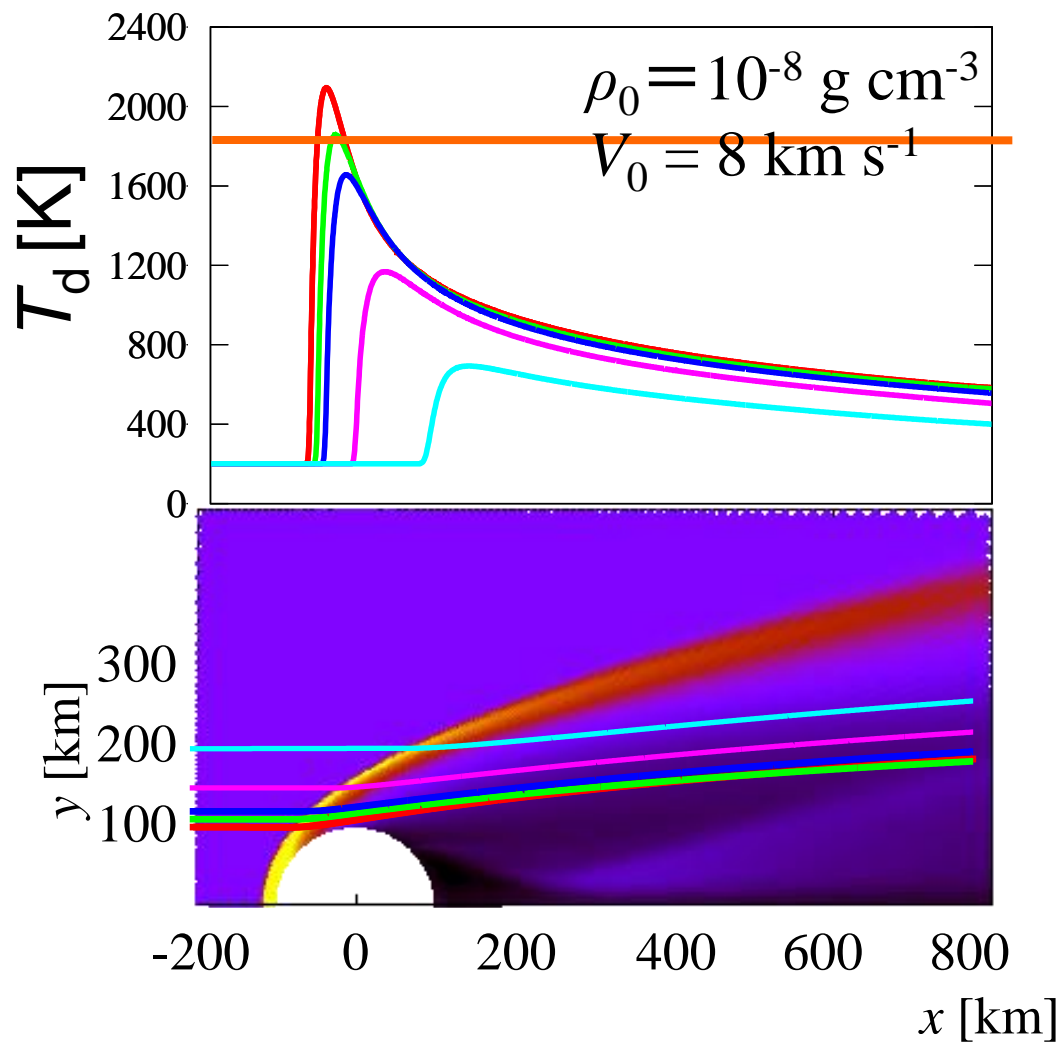
- 粒子の加熱と冷却

- ガス摩擦加熱、放射冷却



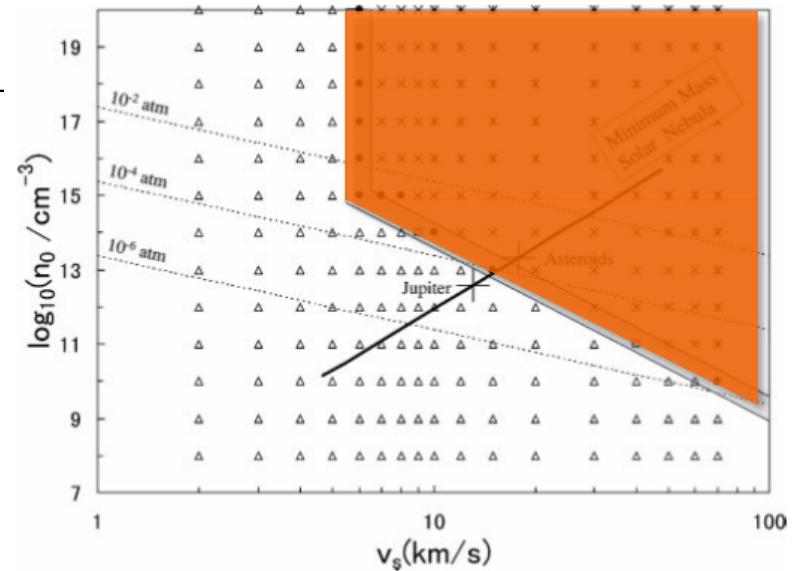
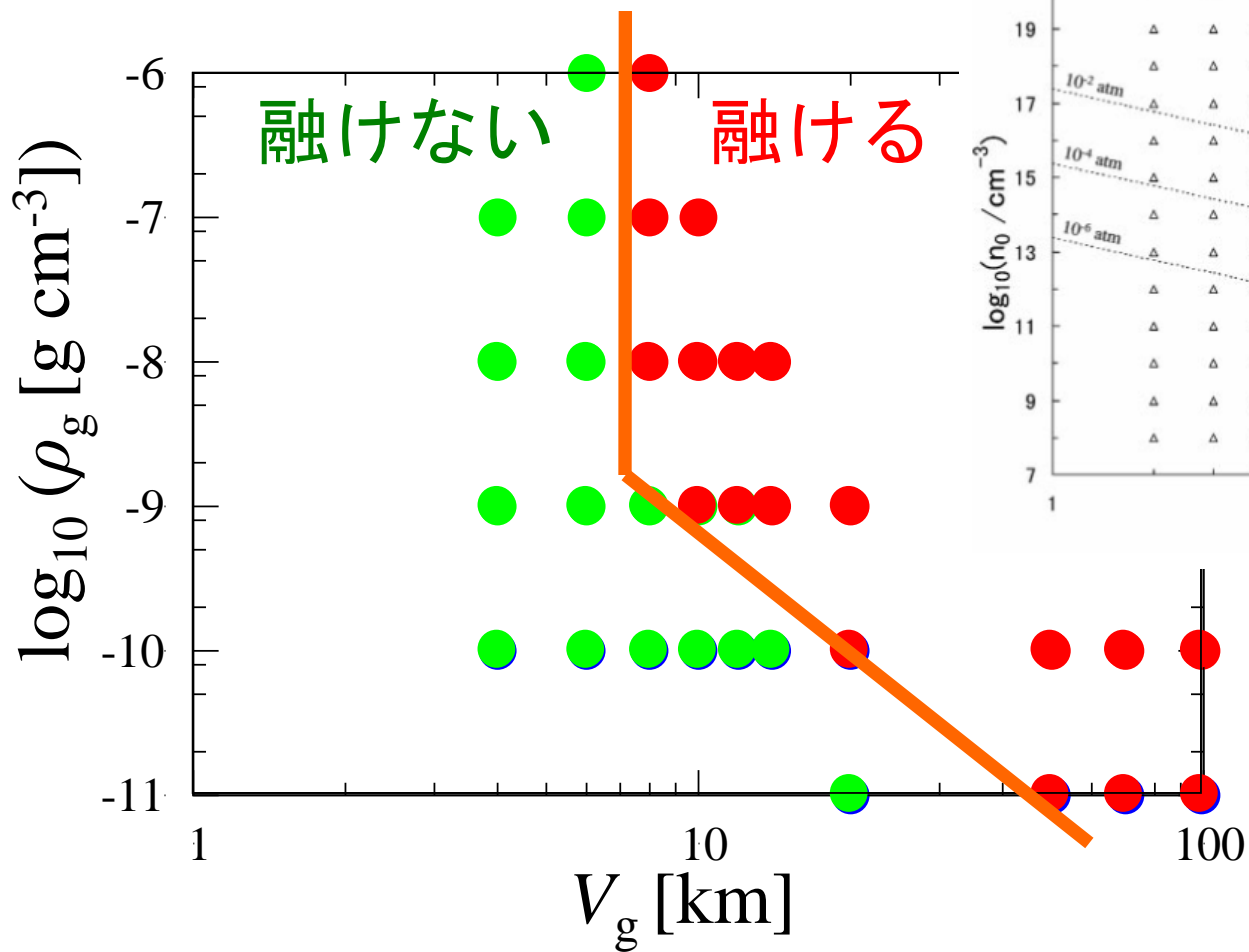
【結果】

- 軌跡に沿った粒子の温度



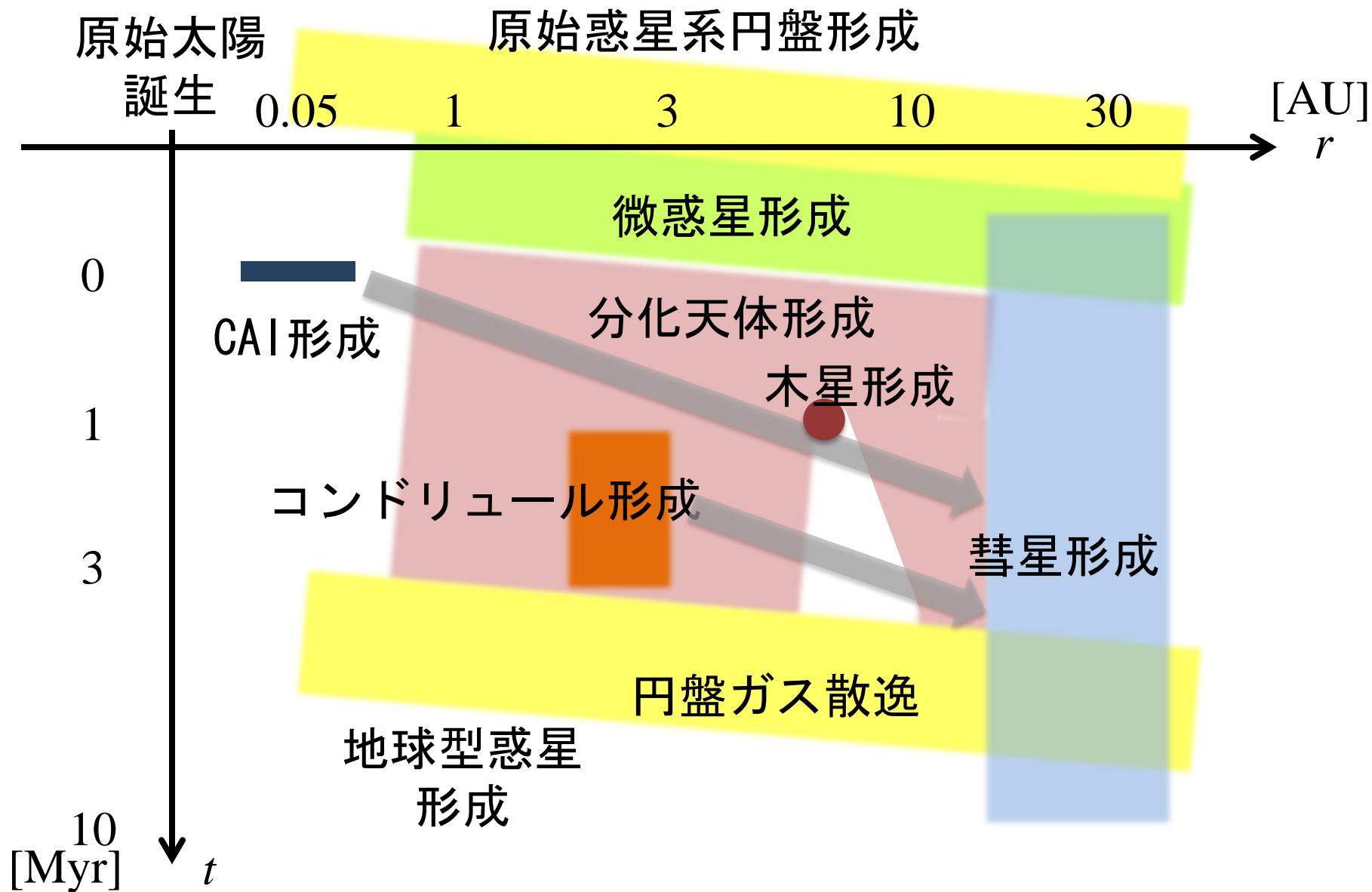
【結果】コンドリュール形成可能領域

- $V_g - \rho_g$ 空間でのコンドリュール形成可能領域



太陽系初期の進化

(中本 私見 2012)



課題

1. コンドリユール形成そのものを理解できるか
2. 惑星系形成の文脈中に、ただしく位置づけられるか

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