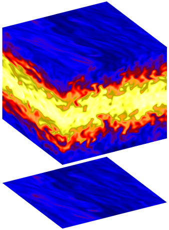
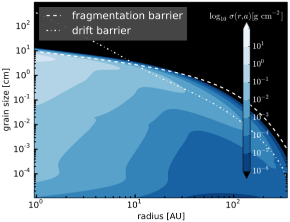
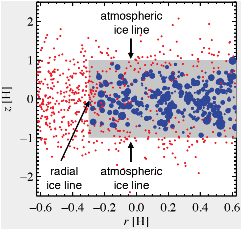
Lecture 1: Dust evolution





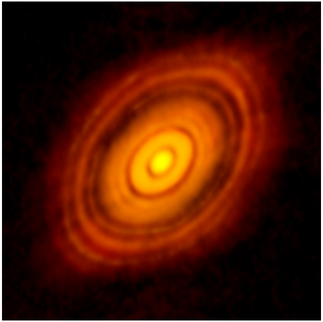


"NBI summer School on Protoplanetary Disks and Planet Formation"

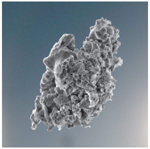
August 2015

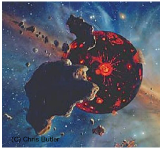
Anders Johansen (Lund University)

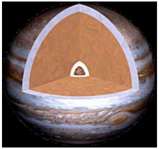
Conditions for planet formation



- Young stars are orbited by turbulent protoplanetary discs
- Disc masses of 10^{-4}–10^{-1} $M_\odot$
- Disc life-times of 1–10 million years





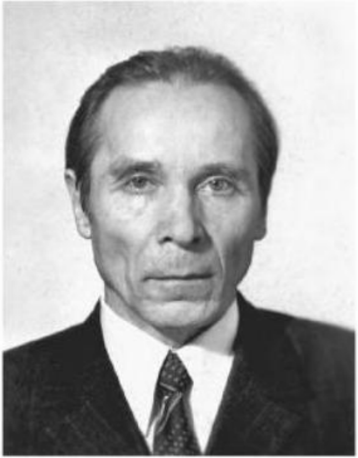


Planet formation paradigm

Planetesimal hypothesis:

Planets form in protoplanetary discs around young stars from dust and ice grains that stick together to form ever larger bodies

- Viktor Safronov (1917-1999): "father" of the planetesimal hypothesis
- "Evolution of the Protoplanetary Cloud and Formation of the Earth and the Planets" (1969, translated from Russian)



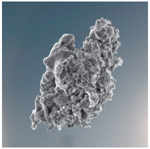
The three steps of planet formation

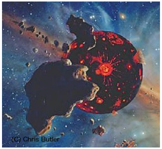
Planetesimal hypothesis of Safronov 1969:

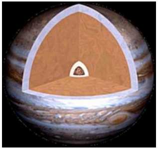
Planets form in protoplanetary discs around young stars from dust and ice grains that stick together to form ever larger bodies

1. Dust to planetesimals
   μm → km: contact forces during collision lead to sticking
2. Planetesimals to protoplanets
   km → 1,000 km: gravity (run-away accretion)
3. Protoplanets to planets

Gas giants:	10 $M_\oplus$ core accretes gas	($< 10^7$ years)
Terrestrial planets:	protoplanets collide	(10^7–10^8 years)

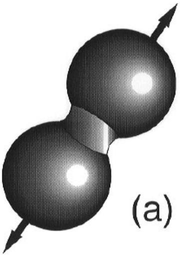


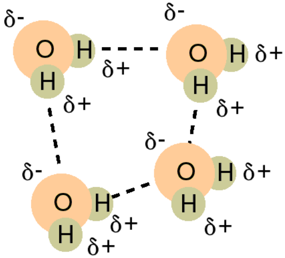


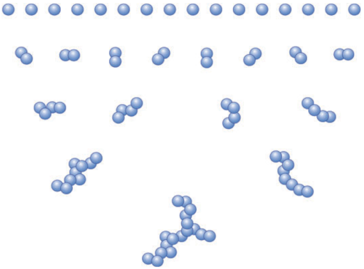
Sticking

- Colliding particle stick by the same forces that keep solids together (van der Waals forces such as dipole-dipole attraction)

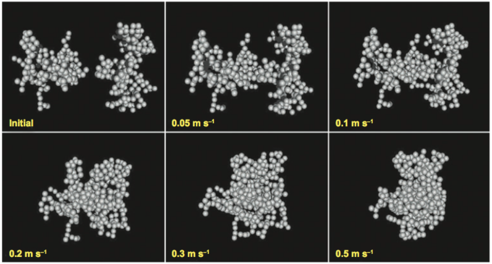




Dust growth



(*Blum & Wurm*, 2008)

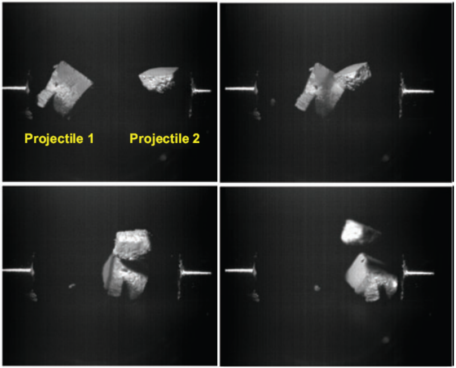


(*Paszun & Dominik*, 2006)

- Dust growth starts with μm-sized *monomers*
- Growth of dust aggregates by hit-and-stick
- Dust aggregates compactify in mutual collisions

Bouncing

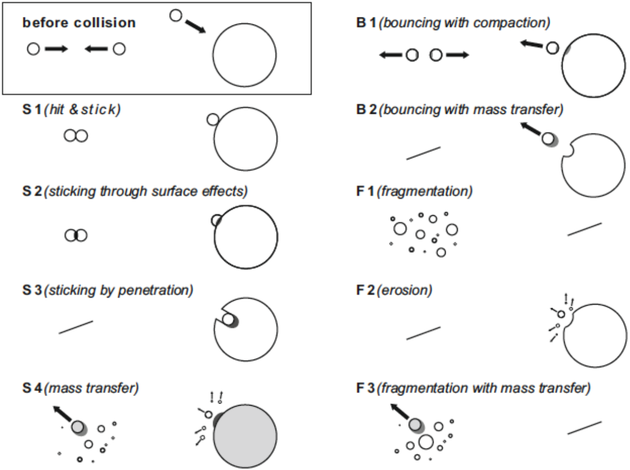
- Laboratory experiments used to probe sticking, bouncing and shattering of particles (labs e.g. in Braunschweig and Münster)
- Collisions between equal-sized macroscopic particles lead mostly to bouncing:



- Experimental result presented in *Blum & Wurm* (2008)

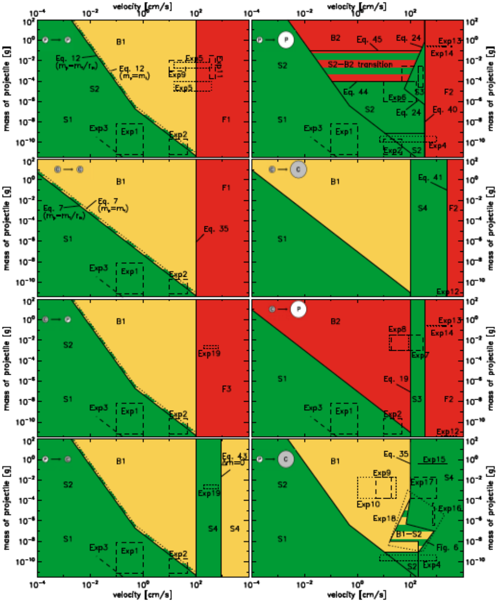
Collision regimes

- *Güttler et al.* (2010) compiled experimental results for collision outcomes with different particle sizes, porosities and speeds



Collision outcomes

- *Güttler et al.* (2010) →
- Generally sticking or bouncing below 1 m/s and shattering above 1 m/s
- Sticking may be possible at higher speeds if a small impactor hits a large target



Drag force

Gas accelerates solid particles through drag force: (*Whipple*, 1972; *Weidenschilling*, 1977)

$$\frac{\partial \boldsymbol{v}}{\partial t} = \ldots - \frac{1}{\tau_\mathrm{f}}(\boldsymbol{v} - \boldsymbol{u})$$

Particle velocity

Gas velocity

In the Epstein drag force regime, when the particle is much smaller than the mean free path of the gas molecules, the friction time is

$$\tau_\mathrm{f} = \frac{R\rho_\bullet}{c_\mathrm{s}\rho_\mathrm{g}}$$

R: Particle radius

$\rho_\bullet$: Material density

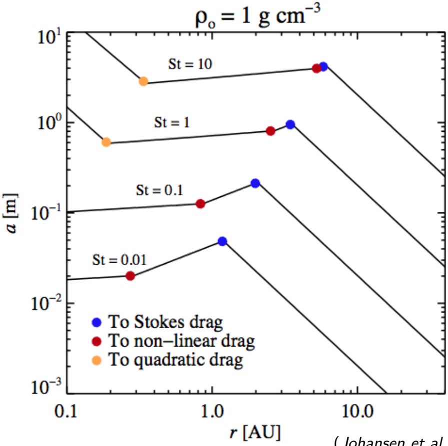
c_s: Sound speed

ρ_g: Gas density

Important nondimensional parameter in protoplanetary discs:

$\Omega_\mathrm{K}\tau_\mathrm{f}$ (*Stokes number*)

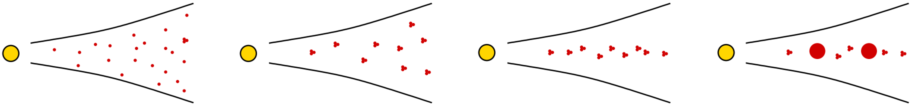
Particle sizes



(*Johansen et al.*, 2014, Protostars & Planets VI)

- In the Epstein regime $\mathrm{St} = \frac{\sqrt{2\pi} R \rho_\bullet}{\Sigma_\mathrm{g}}$
- Other drag force regimes close to the star yield different scalings with the gas temperature and density (*Whipple*, 1972)

Sedimentation



- Dust grains coagulate and gradually decouple from the gas
- Sediment to form a thin mid-plane layer in the disc
- Planetesimals form by self-gravity in dense mid-plane layer
- Turbulent diffusion prevents the formation of a very thin mid-plane layer

Diffusion-sedimentation equilibrium

Diffusion-sedimentation equilibrium:

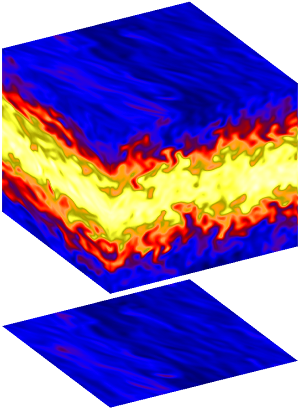
$$\frac{H_{\mathrm{dust}}}{H_{\mathrm{gas}}} = \sqrt{\frac{\delta}{\Omega_{\mathrm{K}} \tau_{\mathrm{f}}}}$$

H_{dust} = scale height of dust layer

H_{gas} = scale height of gas

δ = turbulent diffusion coefficient, like α-value ($D = \delta H c_{\mathrm{s}}$)

$\Omega_{\mathrm{K}} \tau_{\mathrm{f}}$ = Stokes number, proportional to radius of solid particles



(*Johansen & Klahr*, 2005)

Derivation of diffusion-sedimentation equilibrium

- The flux of dust particles in the vertical direction is

$$\mathcal{F}_z = \rho_\mathrm{p} v_z - D\rho_\mathrm{g} \frac{\mathrm{d}(\rho_\mathrm{p}/\rho_\mathrm{g})}{\mathrm{d}z} \, .$$

- Here we have assumed *Fickian diffusion* where the diffusive flux is proportional to the concentration $\epsilon = \rho_\mathrm{p}/\rho_\mathrm{g}$.
- In diffusion-sedimentation equilibrium we have $\mathcal{F} = 0$,

$$\epsilon v_z - D \frac{\mathrm{d}\epsilon}{\mathrm{d}z} = 0 \, .$$

- We use the terminal velocity expression $v_z = -\tau_\mathrm{f} \Omega_\mathrm{K}^2 z$ to obtain

$$\frac{\mathrm{d} \ln \epsilon}{\mathrm{d}z} = -\frac{\tau_\mathrm{f} \Omega_\mathrm{K}^2 z}{D}$$

- The solution is

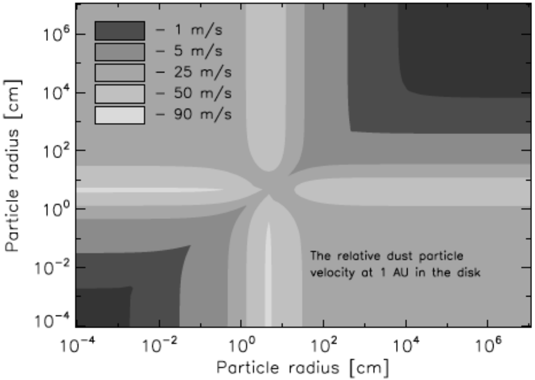
$$\epsilon(z) = \epsilon_\mathrm{mid} \exp[-z^2/(2H_\epsilon^2)]$$

- with

$$H_\epsilon^2 = \frac{D}{\tau_\mathrm{f} \Omega_\mathrm{K}^2} = \frac{\delta H^2 \Omega_\mathrm{K}}{\tau_\mathrm{f} \Omega_\mathrm{K}^2} \qquad \Rightarrow \qquad \frac{H_\epsilon^2}{H^2} = \frac{\delta}{\Omega_\mathrm{K} \tau_\mathrm{f}}$$

Turbulent collision speeds

- Turbulent gas accelerates particles to high collision speeds:



(*Brauer et al.*, 2008; based on *Weidenschilling & Cuzzi*, 1993)

⇒ Small particles follow the same turbulent eddies and collide at low speeds

⇒ Larger particles collide at higher speeds because they have different trajectories

Terminal velocity approximation

- Equation of motion of particles ($\boldsymbol{v}$) and gas ($\boldsymbol{u}$)

$$\begin{aligned} \frac{\mathrm{d}\boldsymbol{v}}{\mathrm{d}t} &= -\boldsymbol{\nabla}\Phi - \frac{1}{\tau_{\mathrm{f}}}(\boldsymbol{v} - \boldsymbol{u}) \\ \frac{\mathrm{d}\boldsymbol{u}}{\mathrm{d}t} &= -\boldsymbol{\nabla}\Phi - \frac{1}{\rho}\boldsymbol{\nabla}P \end{aligned}$$

- Particles do not care about the gas pressure gradient since they are very dense
- Subtract the two equations from each other and look for equilibrium

$$\frac{\mathrm{d}(\boldsymbol{v} - \boldsymbol{u})}{\mathrm{d}t} = -\frac{1}{\tau_{\mathrm{f}}}(\boldsymbol{v} - \boldsymbol{u}) + \frac{1}{\rho}\boldsymbol{\nabla}P = 0$$

- In equilibrium between drag force and pressure gradient force the particles have their *terminal velocity* relative to the gas

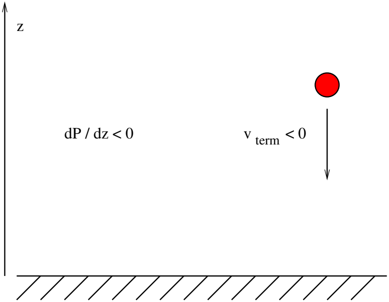
$$\delta\boldsymbol{v} = \tau_{\mathrm{f}}\frac{1}{\rho}\boldsymbol{\nabla}P$$

$\Rightarrow$ **Particles move towards the direction of higher pressure**

Ball falling in Earth's atmosphere

$$\boldsymbol{v}_{\rm term} = \tau_{\rm f} \frac{1}{\rho} \boldsymbol{\nabla} P$$

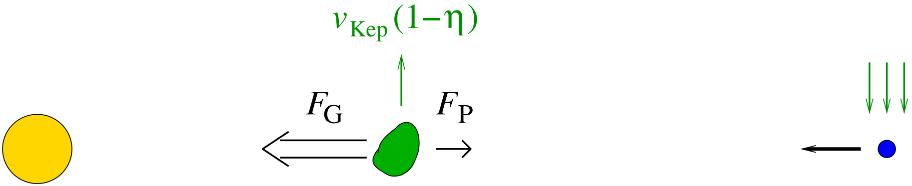
- Ball falling in Earth's atmosphere:



- Pressure is falling with height, so $\mathrm{d}P/\mathrm{d}z < 0$ and thus $v_{\rm term} < 0$

$\Rightarrow$ *Ball is seeking the point of highest pressure*

Radial drift



- Disc is hotter and denser close to the star
- Radial pressure gradient force mimics decreased gravity $\Rightarrow$ gas orbits slower than Keplerian
- Particles do not feel the pressure gradient force and want to orbit Keplerian
- Headwind from sub-Keplerian gas drains angular momentum from particles, so they spiral in through the disc
- Particles sublimate when reaching higher temperatures close to the star

Sub-Keplerian motion I

- Balance between gravity, centrifugal force and pressure gradient force:

$$0 = -\frac{GM_\star}{r^2} + \Omega^2 r - \frac{1}{\rho}\frac{\partial P}{\partial r}$$

- If we can ignore pressure gradients, then we recover the Keplerian solution

$$\Omega = \sqrt{\frac{GM_\star}{r^3}} \equiv \Omega_\mathrm{K}$$

- We can use Ω_K to rewrite the original expression as

$$\Omega^2 r - \Omega_\mathrm{K}^2 r = \frac{1}{\rho}\frac{\partial P}{\partial r}$$

Sub-Keplerian motion II

- Balance between gravity, centrifugal force and pressure gradient force:

$$\Omega^2 r - \Omega_{\mathrm{K}}^2 r = \frac{1}{\rho}\frac{\partial P}{\partial r}$$

- Write pressure as $P = c_{\mathrm{s}}^2 \rho$

$$\Omega^2 r - \Omega_{\mathrm{K}}^2 r = \frac{c_{\mathrm{s}}^2}{P}\frac{r}{r}\frac{\partial P}{\partial r} = \frac{c_{\mathrm{s}}^2}{r}\frac{\partial \ln P}{\partial \ln r}$$

- Use $H = c_{\mathrm{s}}/\Omega_{\mathrm{K}}$ and get

$$\Omega^2 r - \Omega_{\mathrm{K}}^2 r = \frac{H^2 \Omega_{\mathrm{K}}^2}{r}\frac{\partial \ln P}{\partial \ln r}$$

- Divide equation by $\Omega_{\mathrm{K}}^2 r$

$$\left(\frac{\Omega}{\Omega_{\mathrm{K}}}\right)^2 - 1 = \frac{H^2}{r^2}\frac{\partial \ln P}{\partial \ln r}$$

Sub-Keplerian motion III

- Balance between gravity, centrifugal force and pressure gradient force:

$$\left(\frac{\Omega}{\Omega_{\mathrm{K}}}\right)^2 - 1 = \frac{H^2}{r^2}\frac{\partial \ln P}{\partial \ln r}$$

- The left-hand-side can be expanded as

$$\begin{aligned}
\left(\frac{\Omega}{\Omega_{\mathrm{K}}}\right)^2 - 1 &= \left(\frac{v}{v_{\mathrm{K}}}\right)^2 - 1 \\
&= \left(\frac{v_{\mathrm{K}} - \Delta v}{v_{\mathrm{K}}}\right)^2 - 1 \\
&= (1 - \Delta v/v_{\mathrm{K}})^2 - 1 \\
&= 1 - 2\Delta v/v_{\mathrm{K}} + (\Delta v/v_{\mathrm{K}})^2 - 1 \\
&\approx -2\Delta v/v_{\mathrm{K}} \quad \text{for} \quad \Delta v \ll v_{\mathrm{K}}
\end{aligned}$$

Sub-Keplerian motion IV

- Balance between gravity, centrifugal force and pressure gradient force:

$$-2\Delta v/v_\mathrm{K} = \left(\frac{H}{r}\right)^2 \frac{\partial \ln P}{\partial \ln r}$$

$$\Delta v = -\frac{1}{2}\left(\frac{H}{r}\right)^2 \frac{\partial \ln P}{\partial \ln r} v_\mathrm{K} \equiv \eta v_\mathrm{K}$$

- Use $H/r = (c_\mathrm{s}/\Omega_\mathrm{K})/(v_\mathrm{K}/\Omega_\mathrm{K}) = c_\mathrm{s}/v_\mathrm{K}$ to obtain the final expression

$$\Delta v = -\frac{1}{2}\frac{H}{r}\frac{\partial \ln P}{\partial \ln r} c_\mathrm{s}$$

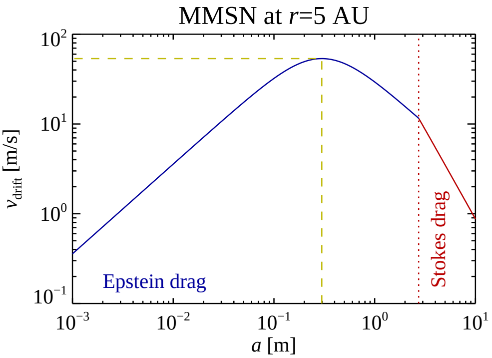
- Particles do not feel the global pressure gradient and want to orbit Keplerian $\Rightarrow$ headwind from the sub-Keplerian gas

Radial drift

Balance between drag force and head wind gives radial drift speed
(Adachi et al. 1976; Weidenschilling 1977)

$$v_{\mathrm{drift}} = -\frac{2\Delta v}{\Omega_{\mathrm{K}}\tau_{\mathrm{f}} + (\Omega_{\mathrm{K}}\tau_{\mathrm{f}})^{-1}}$$

for Epstein drag law $\tau_{\mathrm{f}} = a\rho_\bullet/(c_{\mathrm{s}}\rho_{\mathrm{g}})$



- MMSN $\Delta v \sim 50 \ldots 100$ m/s
- Drift time-scale of 100 years for particles of 30 cm in radius at 5 AU

Column density in the Minimum Mass Solar Nebula

- Spread rock and ice in the solar system planets evenly over the distance to the neighbouring planets
- Assume rock and ice represent ≈1.8% of total material ⇒ original gas contents (*Kusaka, Nakano, & Hayashi*, 1970; *Weidenschilling*, 1977b; *Hayashi*, 1981)

$$
\begin{aligned}
\Sigma_{\rm r}(r) &= 7\,{\rm g\,cm^{-2}} \left(\frac{r}{\rm AU}\right)^{-3/2} \quad {\rm for} \quad 0.35 < r/{\rm AU} < 2.7 \\
\Sigma_{\rm r+i}(r) &= 30\,{\rm g\,cm^{-2}} \left(\frac{r}{\rm AU}\right)^{-3/2} \quad {\rm for} \quad 2.7 < r/{\rm AU} < 36 \\
\Sigma_{\rm g}(r) &= 1700\,{\rm g\,cm^{-2}} \left(\frac{r}{\rm AU}\right)^{-3/2} \quad {\rm for} \quad 0.35 < r/{\rm AU} < 36
\end{aligned}
$$

- Total mass of Minimum Mass Solar Nebula

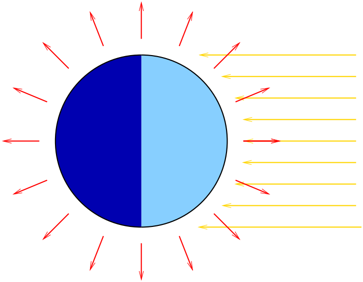
$$
M = \int_{r_0}^{r_1} 2\pi r \Sigma_{\rm r+i+g}(r) {\rm d}r \approx 0.013 M_\odot
$$

Temperature in the Minimum Mass Solar Nebula

- Much more difficult to determine the temperature in the solar nebula
- Several energy sources: solar irradiation, viscous heating, irradiation by nearby stars
- Simplest case: only solar irradiation in optically thin nebula

$$F_\odot = \frac{L_\odot}{4\pi r^2}$$

$$P_\mathrm{in} = \pi \epsilon_\mathrm{in} R^2 F_\odot \qquad P_\mathrm{out} = 4\pi R^2 \epsilon_\mathrm{out} \sigma_\mathrm{SB} T_\mathrm{eff}^4$$



$$T_\mathrm{eff} = \left[\frac{F_\odot}{4\sigma_\mathrm{SB}}\right]^{1/4}$$

$$T = 280\,\mathrm{K} \left(\frac{r}{\mathrm{AU}}\right)^{-1/2}$$

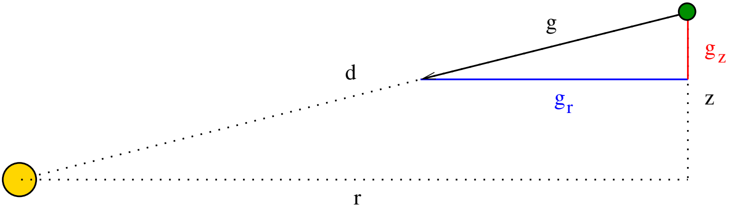
Vertical gravity

Radial density structure of MMSN

$$\Sigma(r) = 1700\,\mathrm{g\,cm^{-2}}\,r^{-1.5}$$

- What about the vertical structure?

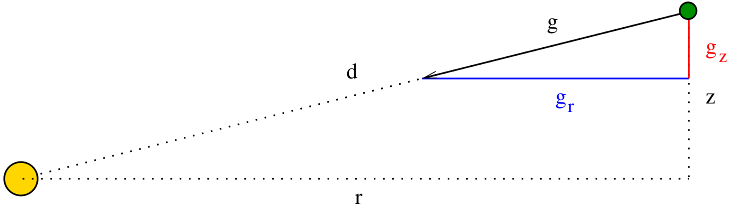
$\Rightarrow$ Hydrostatic equilibrium between gravity and pressure



- The distance triangle and the gravity triangle are *similar triangles* $\Rightarrow$ $g_z/g = z/d$

$$g_z = g\frac{z}{d} = -\frac{GM_\star}{d^2}\frac{z}{d} \approx -\frac{GM_\star}{r^3}z = -\Omega_\mathrm{K}^2 z$$

Hydrostatic equilibrium structure



- Equation of motion for fluid element at height z over the disc mid-plane:

$$\frac{\mathrm{d}v_z}{\mathrm{d}t} = -\Omega_{\mathrm{K}}^2 z - \frac{1}{\rho}\frac{\mathrm{d}P}{\mathrm{d}z}$$

- For constant temperature T we can write $P = c_{\mathrm{s}}^2 \rho$ (isothermal equation of state with sound speed c_{s}=const)
- Look for hydrostatic equilibrium solution:

$$0 = -\Omega_{\mathrm{K}}^2 z - c_{\mathrm{s}}^2 \frac{1}{\rho}\frac{\mathrm{d}\rho}{\mathrm{d}z}$$

Scale height

- Hydrostatic equilibrium condition:

$$0 = -\Omega_{\rm K}^2 z - c_{\rm s}^2 \frac{\mathrm{d} \ln \rho}{\mathrm{d} z}$$

- Rewrite slightly and introduce *scale height* $H = c_{\rm s}/\Omega_{\rm K}$:

$$\frac{\mathrm{d} \ln \rho}{\mathrm{d} z} = -\frac{\Omega_{\rm K}^2}{c_{\rm s}^2} z = -\frac{z}{H^2}$$

- Solution in terms of $\ln \rho$:

$$\ln \rho = \ln \rho_0 - \frac{z^2}{2H^2}$$

- Solution in terms of ρ:

$$\rho(z) = \rho_0 \exp\left[-\frac{z^2}{2H^2}\right]$$

Mid-plane density

Vertical density structure of protoplanetary disc

$$\rho(z) = \rho_0 \exp\left[-\frac{z^2}{2H^2}\right]$$

- $\rho_0 = \rho(r, z = 0)$ is the mid-plane gas density
- Problem: we only know the column density. Connection between Σ and ρ_0 comes from definite integral

$$\begin{aligned}\Sigma &= \int_{-\infty}^{\infty} \rho(z)\mathrm{d}z = \rho_0 \int_{-\infty}^{\infty} \exp[-z^2/(2H^2)]\mathrm{d}z \\ &= \sqrt{2}H\rho_0 \int_{-\infty}^{\infty} \exp[-\zeta^2]\mathrm{d}\zeta = \sqrt{2\pi}H\rho_0\end{aligned}$$

- This yields the mid-plane density

$$\rho_0 = \frac{\Sigma}{\sqrt{2\pi}H}$$

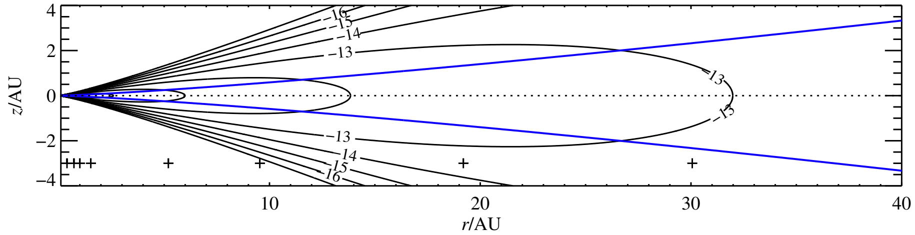
Minimum Mass Solar Nebula overview

- As a starting point for planet formation models we can use the Minimum Mass Solar Nebula model of *Hayashi* (1981):

$$
\begin{aligned}
\Sigma(r) &= 1700\,\mathrm{g\,cm^{-2}} \left(\frac{r}{\mathrm{AU}}\right)^{-3/2} \\
T(r) &= 280\,\mathrm{K} \left(\frac{r}{\mathrm{AU}}\right)^{-1/2} \\
\rho(r,z) &= \frac{\Sigma(r)}{\sqrt{2\pi}H(r)} \exp\left[-\frac{z^2}{2H(r)^2}\right] \\
H(r) &= \frac{c_\mathrm{s}}{\Omega_\mathrm{K}} \qquad \Omega_\mathrm{K} = \sqrt{\frac{GM}{r^3}} \\
c_\mathrm{s} &= 9.9 \times 10^4\,\mathrm{cm\,s^{-1}} \left(\frac{2.34}{\mu}\frac{T}{280\,\mathrm{K}}\right)^{1/2} \\
H/r &= \frac{c_\mathrm{s}}{v_\mathrm{K}} = 0.033 \left(\frac{r}{\mathrm{AU}}\right)^{1/4}
\end{aligned}
$$

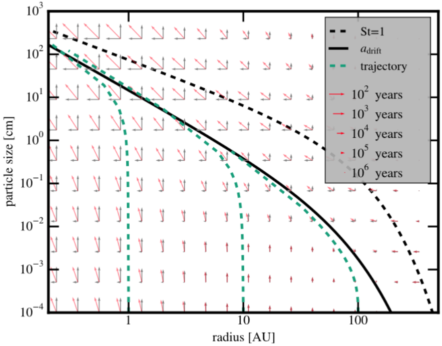
Minimum Mass Solar Nebula density

- Density contours in Minimum Mass Solar Nebula:

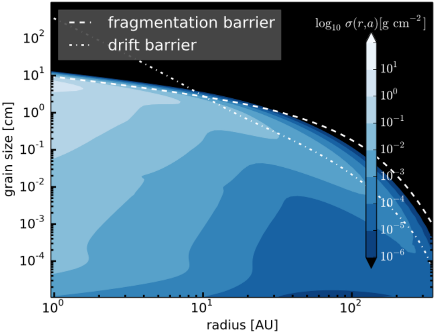


- Mid-plane gas density varies from 10^{-9} g/cm^3 in the terrestrial planet formation region down to 10^{-13} g/cm^3 in the outer nebula
- Blue line shows location of $z = H$
- Aspect ratio increases with r, so solar nebula is slightly *flaring*

Drift-limited growth



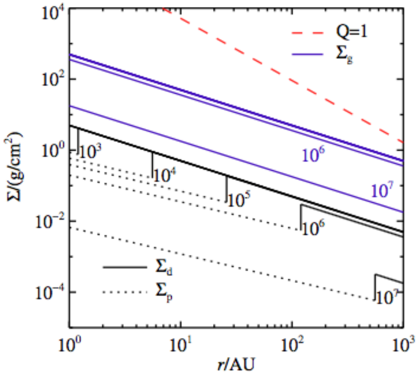
(*Birnstiel et al.*, 2015)

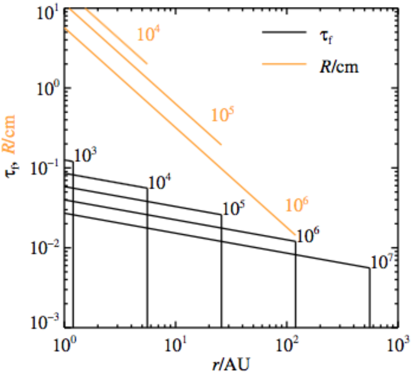


(*Testi et al.*, 2014)

- Particles in the outer disc grow to a characteristic size where the growth time-scale equals the radial drift time-scale (*Birnstiel et al.*, 2012)
- Growth time-scale $t_{\rm gr} = R/\dot{R}$, drift time-scale $t_{\rm dr} = r/\dot{r}$
- Yields dominant particle Stokes number $\mathrm{St} \approx \frac{\sqrt{3}}{8}\frac{\epsilon_{\rm p}}{\eta}\frac{\Sigma_{\rm p}}{\Sigma_{\rm g}}$, with $\epsilon_{\rm p} \sim 1$ the sticking efficiency (*Lambrechts & Johansen*, 2014)
- Here the pebble column density can be obtained from the pebble mass flux through $\dot{M}_{\rm p} = 2\pi r v_r \Sigma_{\rm p}$

Radial pebble flux





- The pebble mass flux can be calculated from the pebble formation front that moves outwards with time (*Lambrechts & Johansen*, 2014)
- The final Stokes number is $\sim$ 0.1 inside 10 AU and $\sim$ 0.02 outside of 10 AU
- The drift-limited solution shows a fundamental limitation to particle growth
- Inclusion of bouncing and fragmentation results in even smaller particle sizes

Radial drift barrier

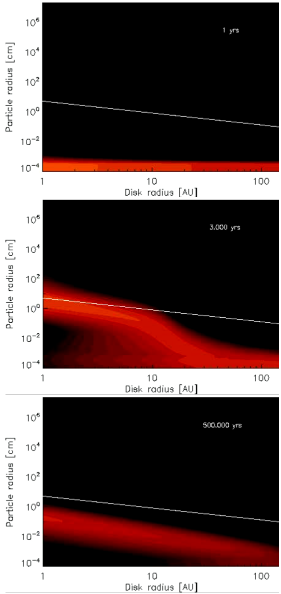
- Coagulation equation of dust particles can be solved by numerical integration

- We start with μm-sized particles and let the size distribution evolve by sticking and fragmentation

- The head wind from the gas causes cm particles to spiral in towards the star

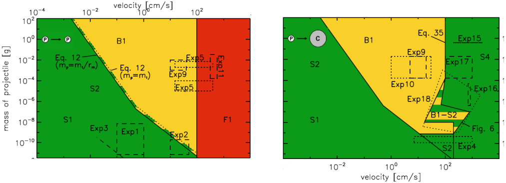
$\Rightarrow$ All solid material lost to the star within a million years (*radial drift barrier*)

- Inclusion of particle fragmentation worsens the problem in the inner disc (*fragmentation barrier*)

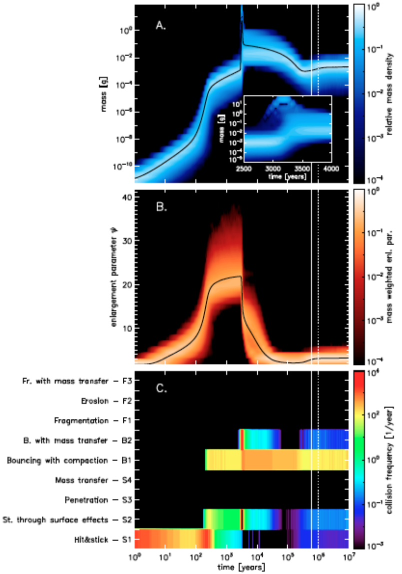


(*Brauer et al.*, 2008)

Bouncing barrier



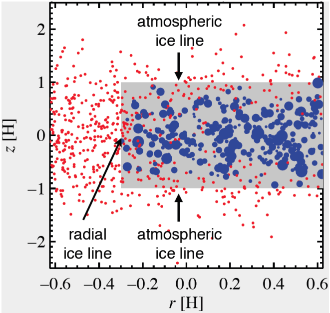
(*Zsom et al.*, 2010)

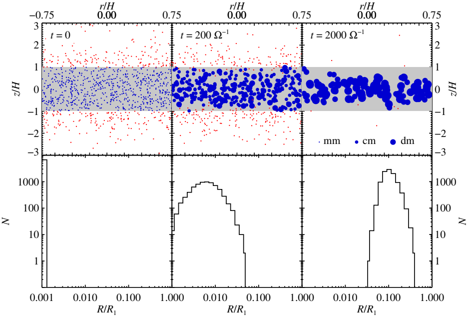


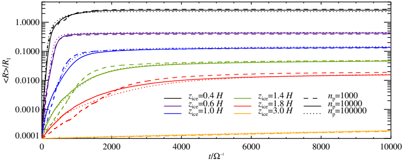
- Collisions between dust aggregates can lead to sticking, bouncing or fragmentation (*Güttler et al.*, 2010)
- Sticking for low collision speeds and small aggregates
- Bouncing prevents growth beyond mm sizes (*bouncing barrier*)
- Further growth may be possible by mass transfer in high-speed collisions (*Windmark et al.*, 2012) or by ice condensation (*Ros & Johansen*, 2012), but stops at radial drift barrier

Growth by ice condensation

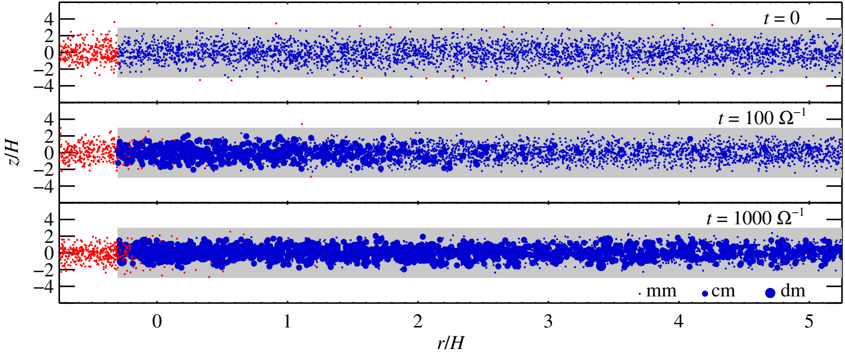
- Near ice lines pebbles can form like hail stones (*Ros & Johansen*, 2013)
- The water ice line has both radial and vertical components
- The atmospheric ice line is ~ 3 scale-heights from the mid-plane and ice particles are rarely lifted so high







Radial iceline



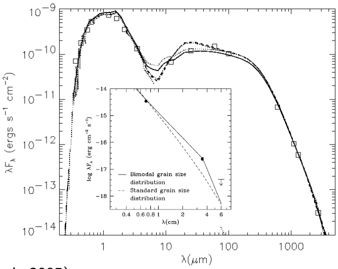
- The radial ice-line feeds vapour directly into the mid-plane

⇒ Growth to dm-sized ice balls

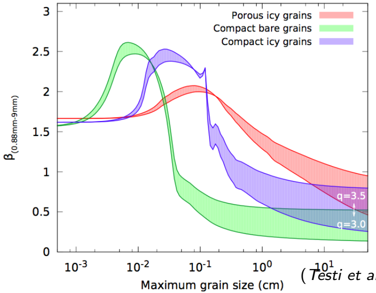
⇒ Turbulent diffusion mixes growing pebbles in the entire cold region

⇒ Future models of coagulation *and* condensation could yield large enough particle sizes for streaming instabilities to become important

Observed dust growth in protoplanetary discs



(*Wilner et al.*, 2005)

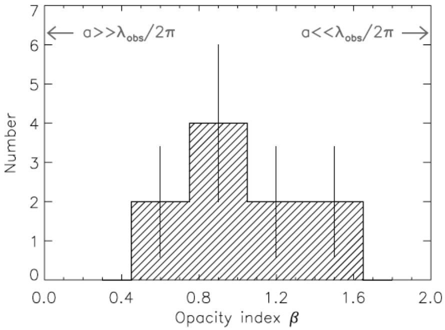


(*Testi et al.*, 2014)

- Dust opacity as a function of frequency $\nu = c/\lambda$:
  - $\kappa_\nu \propto \nu^2$ for $\lambda \gg a$
  - $\kappa_\nu \propto \nu^0$ for $\lambda \ll a$
- $F_\nu \propto \nu^\alpha \propto \kappa_\nu B_\nu \propto \kappa_\nu \nu^2 \propto \nu^\beta \nu^2$
- By measuring α from SED, one can determine β from $\beta = \alpha - 2$
- Knowledge of β gives knowledge of dust size

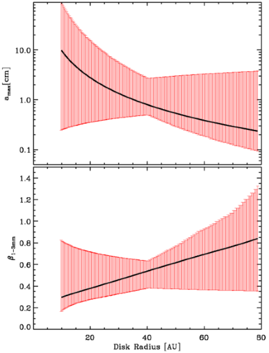
Opacity index

- *Rodmann et al.* (2006) observed 10 low-mass pre-main-sequence stars in the Taurus-Auriga star-forming region
- All had $\beta \sim 1$, indicating growth to at least millimeters
- Agrees well with expectation from drift-limited growth



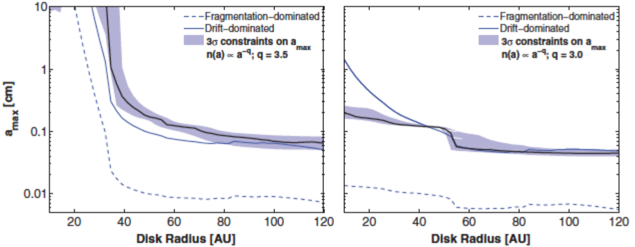
- The disc around TW Hya contains 0.001 $M_\odot$ of cm-sized pebbles (*Wilner et al.*, 2005) and more than 0.05 $M_\odot$ of gas (*Bergin et al.*, 2013)

Pebbles in protoplanetary disks



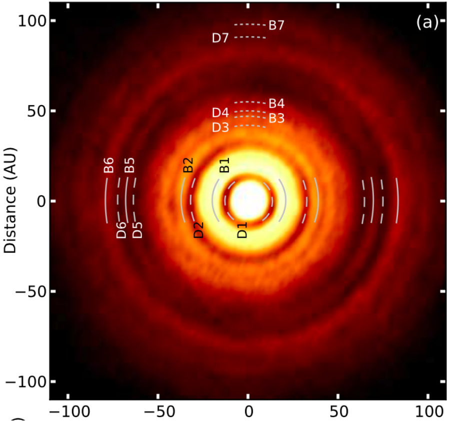
(*Trotta et al.*, 2013)

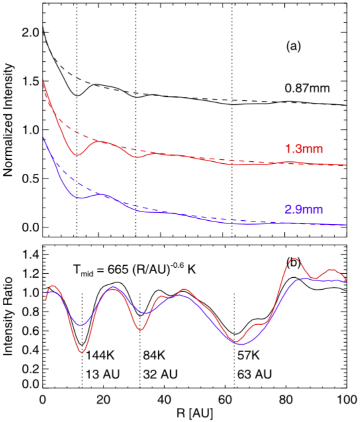
(*Perez et al.*, 2012)



- Many nearby protoplanetary disks observed in mm-cm wavelengths show opacity indices below $\beta = 2$ ($\kappa_\nu \propto \nu^\beta$)
- Typical pebble sizes of mm in outer disk and cm in inner disk
- *Protoplanetary disks are filled with pebbles*

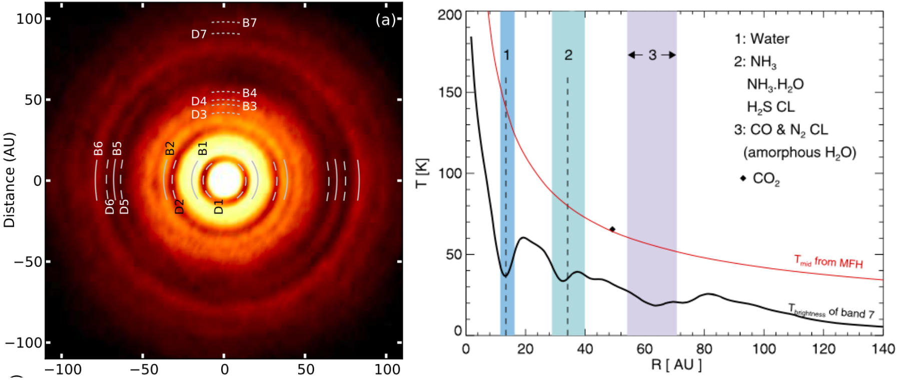
Pebbles in HL Tau





- This beautiful ALMA image of HL Tau was published in 2015 (*ALMA Partnership*, 2015)
- Emission at mm wavelengths comes mainly from mm-sized pebbles
- Dark rings have been interpreted as density depressions caused by the presence of planets (*Dipierro et al.*, 2015)

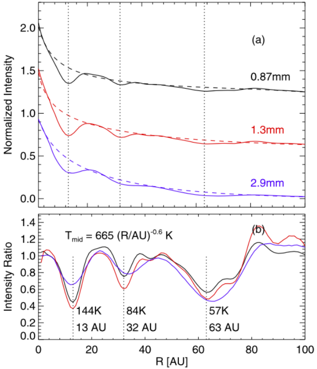
Dark rings and ice lines

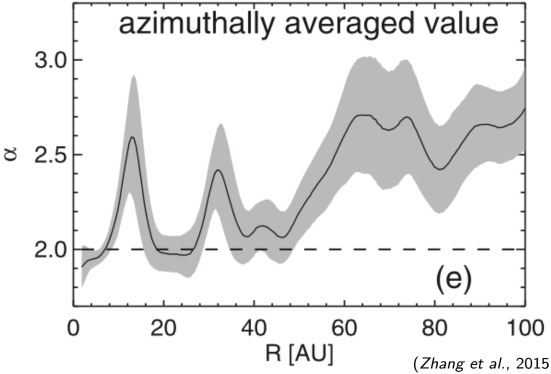


(*Zhang et al.*, 2015)

- The dark rings have also been proposed to coincide with ice lines of major volatile species (H_2O, NH_3, CO) (*Zhang, Blake, & Bergin*, 2015)

Opacity index

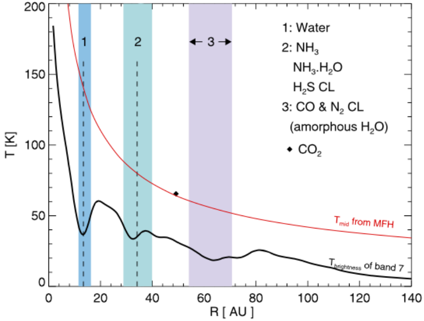


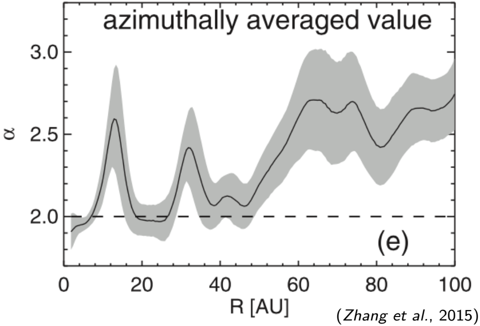


(*Zhang et al.*, 2015)

- The opacity index α is ~ 2.5 outside of 50 AU, consistent with mm particles
- The two inner dark rings have $\alpha \sim 2.5$, while the bright regions have $\alpha \sim 2$
- Direct interpretation is that mm particles dominate the opacity in the dark rings and cm particles in the bright areas
- In that case we need to evoke smaller column densities in the dark rings to explain the weaker emission there

Two-component model of HL Tau emission





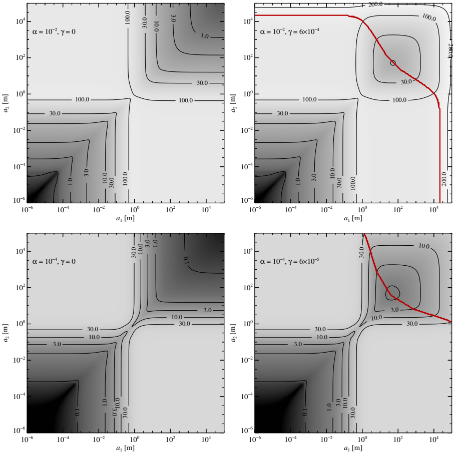
(*Zhang et al.*, 2015)

- Alternatively, lack of emission in the dark rings explained by particle growth
- Two particle size components: 10% mm particles and 90% cm particles
- The large particles yield $\alpha \sim 2$ in the inner disc
- In the dark rings the large particles have grown to 10 cm or larger and hence the (weak) emission is dominated by the mm grains with $\alpha \sim 2.5$

$\Rightarrow$ Particle growth by condensation or enhanced sticking outside of ice lines

- Protoplanetary disc are efficient pebble factories

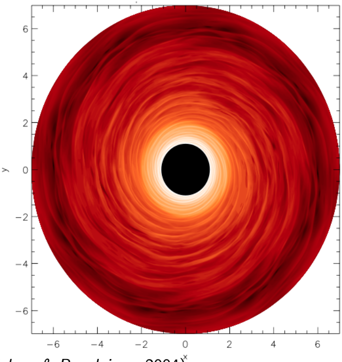
Collision speeds



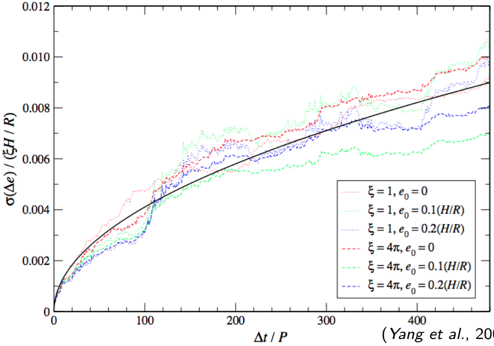
(*Johansen et al.*, 2014)

- Collision speeds are given by a combination of brownian motion, gas turbulence, differential drift and gravitational torques from the turbulent gas

Turbulent density fluctuations

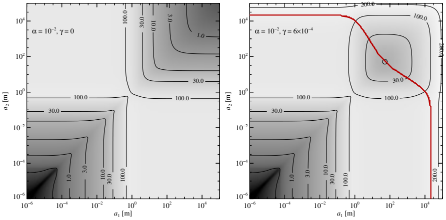


(*Nelson & Papaloizou*, 2004)

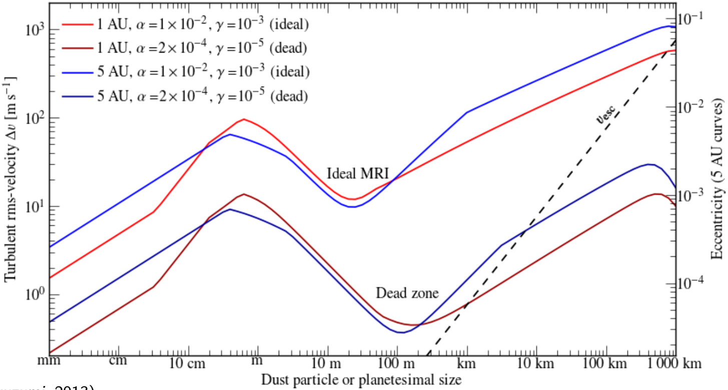


(*Yang et al.*, 2009)

- Torques from turbulent gas excite the eccentricities of embedded planetesimals
- Eccentricity grows like a random walk
- Equilibrium reached when growth time-scale is equal to gas drag time-scale



Gravitational torques

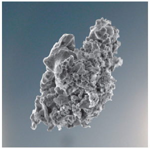


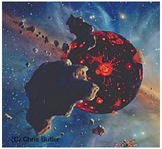
(*Ormel & Okuzumi*, 2013)

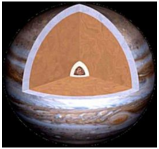
- Torques from the turbulent gas excite high collision speeds for pre-planetesimals (sizes larger than 10 m)
- High collision speeds prevent accretion (*Ida et al.*, 2008)
- Run-away accretion only when $v_{\rm esc}$ higher than $v_{\rm col}$ (*Ormel & Okuzumi*, 2013)

$\Rightarrow$ Need some way to form large planetesimals directly from pebbles

Summary of dust growth





- Dust aggregates grow efficiently by sticking and ice condensation
- Direct growth to planetesimal sizes hampered by bouncing and fragmentation
- Radial drift limits the particle size to between mm and cm even for perfect sticking
- Protoplanetary discs are very efficient pebble factories
- Torques from the turbulent gas induces catastrophic collision speeds for pre-planetesimals larger than 10 m in size
- Need some way to form planetesimals directly from pebbles