How to Build the Building Blocks of Planets

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Image: NASA
Outline

I) **Planet formation** and protoplanetary disks

II) The **formation of the building bricks of planets**
Outline

I) Planet formation and protoplanetary disks

II) The formation of the building bricks of planets
I) Planet Formation and Protoplanetary Disks

- **Disk properties** and definitions
- **Particle motion & evolution** in protoplanetary disks
- The **missing link** in planet formation
1) Planet Formation and Protoplanetary Disks

• Disk properties and definitions

• Particle motion & evolution in protoplanetary disks

• The missing link in planet formation
From a Molecular Cloud to a Disk

Figure 1.1: Cloud collapse to a disk. Gravity leads to collapse if the Jeans mass is reached, but rotation, i.e. centrifugal forces, prevent complete collapse. When the gas density becomes high enough such that the gas can be treated as a fluid, the pressure gradient and centrifugal force conspire to balance gravity and prevent the disk to contract further. At the highlighted equator in (a) a force balance is almost reached, denoted by bold arrows.

\[ M_{\text{disk}} \sim 1\%-10\% \ M_{\text{star}} \]

Size typically \( \sim 100 \ \text{AU} \)
The Scales

from ~1 µm

in ~30,000,000,000 km (~100 AU)

to ~13,000 km

or ~140,000 km
The Long Road From Dust to Planets

**Observable**

- **First growth phase**
  - Aggregation (=coagulation)

- **Final phase**
  - Gas is accreted
  - Gravity keeps/pulls bodies together

Covers 13 orders of magnitude in size = 40 (!!) orders of magnitude in mass

Credit: C. Dullemond
Turbulence Model

\[ \nu_{\text{turb}} = \alpha_t h_g c_s, \quad 0 \leq \alpha_t \leq 1 \quad (\text{Shakura & Sunyaev 1973}) \]

Typical values \( \alpha_t \approx 10^{-4} - 10^{-2} \)
(e.g. Turner+ 2014)
I) Planet Formation and Protoplanetary Disks

- Disk properties and definitions
- **Particle** motion & **evolution** in protoplanetary disks
- The missing link in planet formation
Grain Evolution Processes

Credit: Til Birnstiel; Sun+Earth: Dan Wiersema

1. Turbulence distributes particles vertically and radially
2. Growing particles sediment to the mid-plane of the disk
3. In the outer disk, particles of mm sizes drift quickly inwards
4. Particle collisions can have many different outcomes
   a) Sticking (= growth)
   b) Bouncing (= growth neutral)
   c) Fragmentation with net growth of the larger body
   d) Fragmentation
5. Volatile species condense or form on particle surfaces
   Particles sediment to the disk mid-plane and drift inward
6. In the hotter regions, volatiles are released back into the gas phase
7. Small fragments can be turbulently mixed up to the disk surface
   and can be carried away by disk winds
8. Accumulation of larger particles and planet formation
Example of a Protoplanetary Disk

www.youtube.com/watch?v=p_f6lWWc9jQ
Radial Drift Problem

$F_{\text{gravity}}$  $F_{\text{centrifugal}}$

towards star

$V_{\text{Kepler}}$

$F_{\text{gravity}}$  $F_{\text{centrifugal}}$  $F_{\text{pressure}}$

$V_{\text{gas}}$
Stokes Number

\[ \frac{t_{\text{stop}}}{t_{\text{orb}}} = t_{\text{stop}} \cdot \Omega_K \equiv St \quad \text{(Stokes number)} \]

\[ St << 1 \quad \text{i.e.} \quad \tau_{\text{fric}} \ll \tau_{\text{orb}} \]

\[ St \sim 1 \quad \text{i.e.} \quad \tau_{\text{fric}} \simeq \tau_{\text{orb}} \]

\[ St >> 1 \quad \text{i.e.} \quad \tau_{\text{fric}} \gg \tau_{\text{orb}} \]

It's (mostly) not size that matters - it's the Stokes number!
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Thanks to A. Morbidelli

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Typical Global Size Distribution

I: small particles resupplied by fragmentation

II: delivery of small particles by turbulent radial diffusion

III: growth + drift => top heavy size distribution, smeared out by turbulent radial diffusion

IV: lack of small particles remains
Drift is very fast!

Particles from \( \sim 100 \) AU drift into the star within \( \sim 10^4 \) years!!
Then, how do planets form?

1. Stop radial drift
2. Collect dust
3. Gravitational collapse to planetesimals
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• I) Planet formation and protoplanetary disks

• II) The formation of the building bricks of planets
II) Formation of the Building Bricks of Planets

- Particle trapping in pressure bumps and the toy model, leading questions of the project
- Planetesimal formation within our model
- Constrains on parameters for the Solar Nebula
II) Formation of the Building Bricks of Planets

- **Particle trapping** in pressure bumps and the toy model, leading questions of the project

- Planetesimal formation within our model

- Constrains on parameters for the Solar Nebula
Planetesimal planets = building blocks of planets

bound by gravity rather than molecular binding forces (e.g. Van der Waals): $>1 \text{ km}$ (Benz & Asphaug 1999)
Particle Trapping in Pressure Bumps

3.7. The planetesimal formation process

Figure 3.10: Schematic illustration of a pressure bump acting as a particle trap. At slightly larger radii than marked by the dashed line, the solids are drifting toward the local pressure maximum due to the positive pressure gradient, see (3.20). The stronger pressure gradient with a negative sign at slightly larger radii than the local pressure maximum causes higher inward orientated drift velocities. Thus, particles drift toward the location of the maximum from both sides, resulting in a rapid concentration of solids inside the \( P \)-bump. Larger arrows represent larger drift velocities \( v_{\text{drift}} \).

Streaming instability

If the accumulation of dust particles is large enough — more precisely when the dust-to-gas ratio reaches unity — the back reacting friction force from particles onto gas causes the gas to accelerate closer to the Keplerian speed, i.e. to the velocity of the particles. As a result, the particle clumps become less deficient in centrifugal acceleration and the particle clump drifts more slowly toward the star. Particles drifting with their unpected drift speed at slightly larger radii than the filament will catch up and pile up inside of the filament. This scenario is called the streaming instability [193], see also [83, 192], and the particle density in such filaments can reach \( \geq 1000 \) \( f_{\text{lg}} \) [4, 84]. To trigger strong particle concentration a threshold of approximately \( \frac{d}{g} \geq 0.015 \) is needed, which is roughly constant for particles with Stokes numbers from \( St = 0.03 \) to \( St = 0.3 \) [4]; particles below and above these numbers require a greater ratio [29, 193]. If the Hill density is reached, gravitational collapse can form planetesimals with typical sizes of around \( 100 \) km in diameter [97, 150].

It was shown [90] that boulders of radii \( 15 \text{ cm} \) to \( 60 \text{ cm} \) can form planetesimals very rapidly, i.e. within \( \geq 5 \) orbits, via efficient gravitational collapse in locally overdense regions in the mid-plane of circumstellar disks. This process is much faster than radial drift and thus offers a possible path to planetesimals in circumstellar accretion disks. The gravitational collapse of discrete solid objects forms clusters which are not able to contract further if there is not a mechanism to reduce the root mean square speed and hence dynamically cool the cluster. Two mechanisms can be important:

1. The drag force cooling occurs because of the partial dissipation of the kinetic energy exchanged between the solid objects and the gas.
2. Additionally, collisional cooling appears due to the transfer of kinetic energy into heat and deformation energy during the inelastic collisions between the boulders.

Collisional cooling is not required for the gravitational collapse, but can allow it to occur in less massive disks. Different boulder sizes, despite their different aerodynamical properties and drift behaviors, can participate in the same collaps. Radial variation in boulder drift speeds [195] or photoevaporation of gas [170] may allow the solids to gas ratio to increase from \( 0.01 \) to \( 0.03 \) and generate strong clumping.

Collapse can occur without magnetorotational turbulence, however, it can support the mid-plane layers to be able to collapse. It was found that gas heating does not prevent collapse.

3.7.3. Remarks

Growth to particles with Stokes numbers sufficient large enough to decouple from the gas is crucial to allow particle concentration as discussed above. Coagulation and particle concentration are a coupling each other: clumping of particles lead to higher collision rates and the outcomes in turn determine the

Idea: Whipple 1972
Condition for Planetesimal Formation

Thanks to Hubert Klahr & Andreas Schreiber

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Rapid planetesimal formation in turbulent circumstellar discs

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\(^3\)CITA, University of Toronto, Canada

Credit: Johansen, Oichi, MacLow, Klahr, Henning & Youdin, 2007, Nature
Can coagulation cross the streaming regime?
Column/Surface Density

\[ \Sigma = \int_{-\infty}^{\infty} \rho \, dz \]
Leading Questions

• Where and when do planetesimals form? How does the surface density profile look like, $\Sigma_p(r)$?
• Can we exclude certain parameter ranges of our model for the Solar Nebula?
The Planetesimal Model

- $0 < \varepsilon < 1$: efficiency parameter
- $d(r)$: trap distance
- $M_t$: trapped mass within 1 trap lifetime
- $m_p$: planetesimal mass

Dust+gas evolution
Birnstiel+ 2010
II) Formation of the Building Bricks of Planets

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Comments on Simulations

• Saturation/stagnation around 1 Myr
• Viscously evolving disk (dispersal)
• No...
  – photoevaporation (sink term for the gas)
  – planetesimal collisions ($2^{nd}$ generation planetesimals)
  – pebble accretion (Ormel & Klahr 2010)
Typical Evolution, $\alpha_t = 10^{-3}$, $M_{\text{disk}} = 0.05M_\odot$, $r_c = 35$AU, $\epsilon = 0.1$

Drift Barrier
Fragmentation Barrier
$\text{St} = 1$ (fastest drifting particles)
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Results (1), small & light

\[ r_c = 20 \, \text{AU}, \quad M_{\text{disk}} = 0.02 \, M_\odot \]

\[ \Sigma_p \, [\text{g cm}^{-2}] \]

\[ \Sigma_d(r, t_0) \]

distance to the star \( r \) [AU]
Results (1), small & light

$r_c = 20 \text{ AU}, \ M_{\text{disk}} = 0.02 \ M_{\odot}$

$\Sigma_p [\text{g cm}^{-2}]$

$\alpha_t = 10^{-2}, \ \varepsilon = 0.1$
$\alpha_t = 10^{-2}, \ \varepsilon = 0.8$
$\alpha_t = 10^{-3}, \ \varepsilon = 0.1$
$\alpha_t = 10^{-3}, \ \varepsilon = 0.8$

distance to the star $r \ [\text{AU}]$
Results (2), small & heavy

$r_c = 20 \text{ AU}, \; M_{\text{disk}} = 0.05 \, M_\odot$

- $\Sigma_d(r, t_0)$
- $\alpha_t = 10^{-2}, \; \epsilon = 0.1$
- $\alpha_t = 10^{-3}, \; \epsilon = 0.1$
- $\alpha_t = 10^{-3}, \; \epsilon = 0.8$

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Results (3), large & light

\[ r_c = 35 \text{ AU}, \quad M_{\text{disk}} = 0.02 M_\odot \]

\[ \Sigma_p \text{ [g cm}^{-2}] \]

\[ \alpha_t = 10^{-2}, \quad \varepsilon = 0.8 \]
\[ \alpha_t = 10^{-3}, \quad \varepsilon = 0.8 \]
Results (4), large & heavy

$r_c = 35 \text{ AU}, \ M_{\text{disk}} = 0.05 \ M_\odot$

$\Sigma_p [\text{g cm}^{-2}]$

$\Sigma_d(r, t_0)$

$\alpha_t = 10^{-2}, \ \epsilon = 0.1$

$\alpha_t = 10^{-2}, \ \epsilon = 0.8$

$\alpha_t = 10^{-3}, \ \epsilon = 0.1$

$\alpha_t = 10^{-3}, \ \epsilon = 0.2$

distance to the star $r$ [AU]
Conclusion

Strong turbulence ($\alpha_t \approx 0.01$) for the Solar Nebula stays in harsh contradiction with our findings

Smaller disks ($r_c < 20$ AU?) seem to help
Outlook

- **Pebble accretion** (Ormel & Klahr 2010), mm-cm sized particles onto planetesimals

- **Planetesimal-planetesimal interactions** (leading to fragmentation & growth), N-Body

- Experiment with **trap formation** time and **check other model parameters**, fit the outer disk

Credit: Kouji Kanba
Summary

• Novel model: planetesimals via pebble trapping, directly linked to pebble flux

• Difficult to get a radial planetesimal profile with $\alpha_t \approx 10^{-2}$ allowing the formation of our planets in the Solar System

• Further physics has to be included (ptes-ptes collisions, photoevaporation, pebble accretion, temperature model, trap formation model...)

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