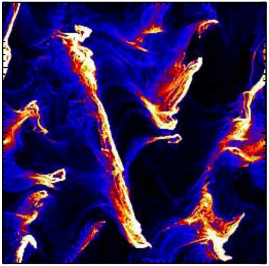
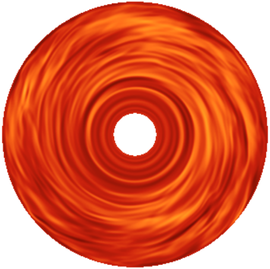
How migrating geese and falling pens inspire planet formation





Anders Johansen

Common Seminar, Department of Astronomy and Theoretical Physics

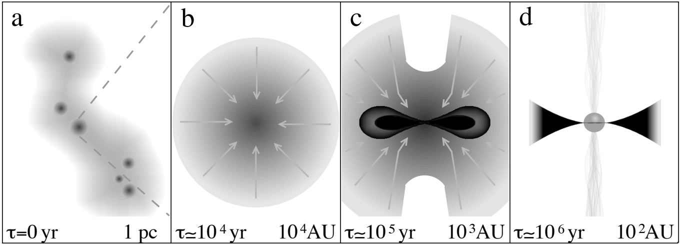
Lund University, November 2010

About me

- Biträdande universitetslektor (*associate senior lecturer*) since May 2010
- Theorist working on planet formation and the dynamics of Keplerian discs
- Main scientific interests are exoplanets, hydrodynamics, turbulence, and supercomputing
- Master's programme coordinator in astrophysics

Formation of stars and discs

- The four stages of star formation:



(Lada & Wilking 1984; Adams, Lada, & Shu 1987)

a Dense regions of molecular clouds collapse under their own gravity

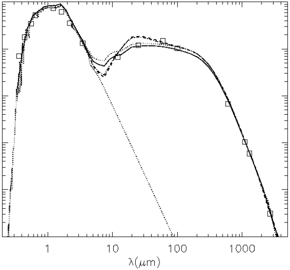
b Star forms in the centre, gaining material from the collapse

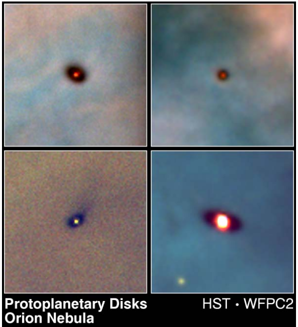
c A several hundred AU circumstellar disc forms around the star because of angular momentum conservation and cooling

d Envelope is emptied and the Keplerian accretion disc feeds gas to the star

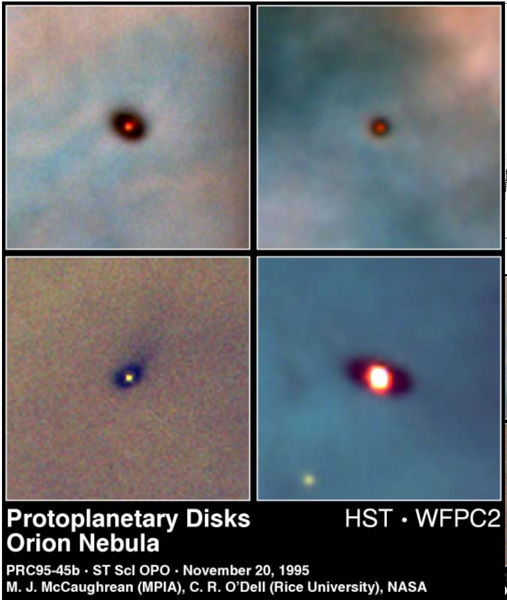
Protoplanetary discs

- Strong infrared flux evidence of the presence of cold dust in orbit around the star
- Discs in the Orion nebula, as seen by the Hubble space telescope
- Disc masses from $0.001 M_\odot$ to $1 M_\odot$
  (Beckwith et al. 1990)
- Typical sizes of hundreds of AU
- Life-times of approximately 1–5 million years
  (Haisch et al. 2001)





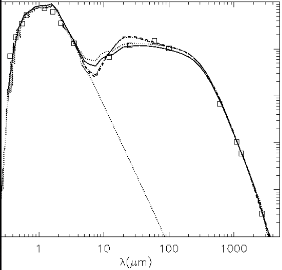
Protoplanetary discs

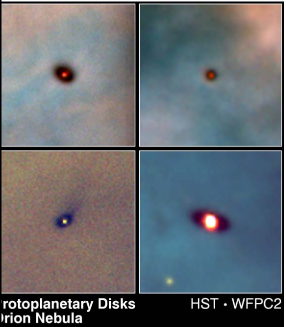


Protoplanetary Disks
Orion Nebula

HST • WFPC2

PRC95-45b · ST ScI OPO · November 20, 1995
M. J. McCaughrean (MPIA), C. R. O'Dell (Rice University), NASA





rotoplanetary Disks
rion Nebula

HST • WFPC2

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

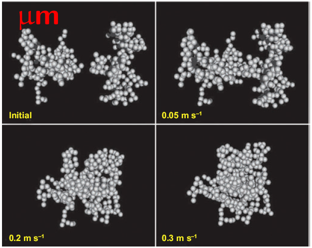
1. Dust to planetesimals
   μm → cm: contact forces during collision lead to sticking
   cm → km : ???
2. Planetesimals to protoplanets
   km → 1,000 km: gravity (run-away accretion)
3. Protoplanets to planets
   Gas giants: $10\ M_\oplus$ core accretes gas ($< 10^7$ years)
   Terrestrial planets: protoplanetes collide (10^7–10^8 years)

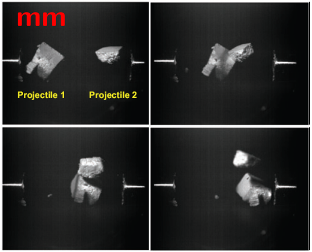
Recipe for making planets?

- Hydrogen and Helium (98,5%)
- Dust and ice (1,5%)
- Coagulation (dust growth)

⇒ Planets?

(Paszun & Dominik)





(Blum & Wurm 2008)

Recipe for making planets?

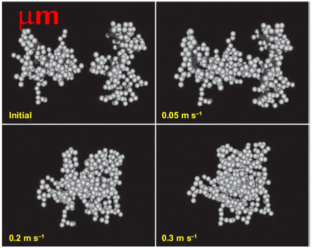
- Hydrogen and Helium (98,5%)
- Dust and ice (1,5%)
- Coagulation (dust growth)

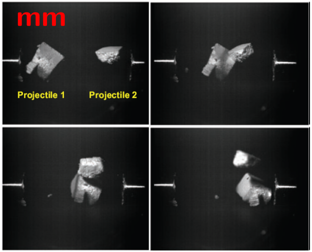
⇒ Planets? *No*

"Meter barrier"

- Growth to mm or cm, but not larger
- The problem: *small dust grains stick readily with each other – sand, pebbles, and rocks do not*

(Paszun & Dominik)



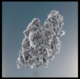


(Blum & Wurm 2008)

Miracle needed

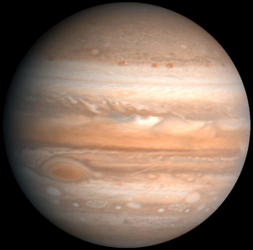
Overview of planets

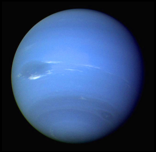
Protoplanetary discs



Dust grains

Pebbles





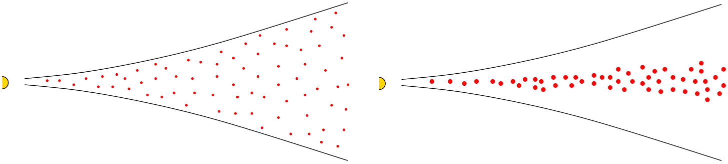
Gas giants and ice giants

Terrestrial planets

Dwarf planets

+ Countless asteroids and Kuiper belt objects
+ Moons of giant planets
+ More than 500 exoplanets

Sedimentation



- Pebbles and rocks *sediment* to the mid-plane of the disc
- Further growth frustrated by high-speed collisions ($>$1–10 m/s) which lead to erosion and bouncing
- Layer not dense enough for gravitational instability

⇒ **Need some way for particle layer to get dense enough to initiate gravitational collapse**

Particle dynamics

Gas accelerates solid particles through drag force:

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

Particle velocity

Gas velocity

The friction time is *(Weidenschilling 1977)*

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

$a_\bullet$: Particle radius

$\rho_\bullet$: Material density

c_s: Sound speed

ρ_g: Gas density

(valid for particles smaller than the mean free path)

Important nondimensional parameter in protoplanetary discs:

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

At $r = 5$ AU in MMSN we have $a_\bullet/\mathrm{m} \sim 0.3\Omega_\mathrm{K}\tau_\mathrm{f}$.

Terminal velocity approximation

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

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

- 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

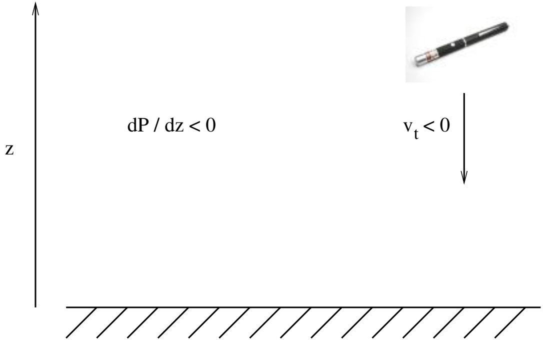
$$\frac{\mathrm{d}(\mathbf{v}-\mathbf{u})}{\mathrm{d}t} = -\frac{1}{\tau_{\mathrm{f}}}(\mathbf{v}-\mathbf{u}) + \frac{1}{\rho}\boldsymbol{\nabla}P = 0$$

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

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

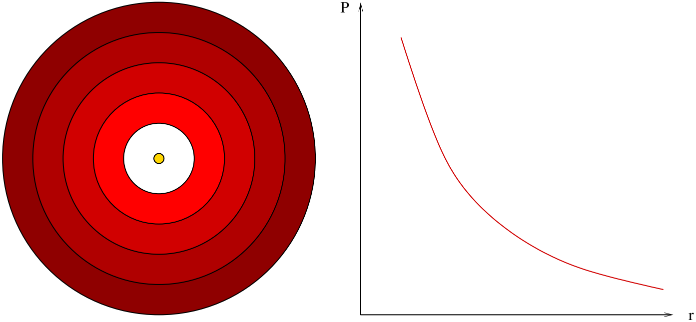
⇒ **Particles move towards the direction of higher presure**

Object falling in Earth's atmosphere



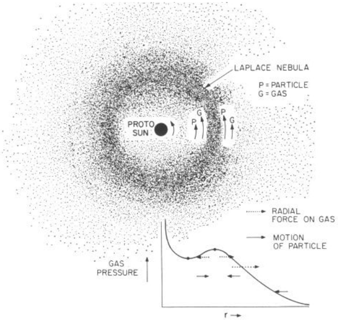
- Laser pen falls to the ground because of gravity
- But we can reinterpret this as the pen seeking higher gas pressure
- Obviously this analogy is more useful in protoplanetary discs...

Radial pressure gradient



- The disc is hotter and denser close to the star
- Particles drift through the disc with up to 100 m/s (seeking the higher pressure)
- Ice particles sublimate when temperatures rise above freezing (a few AU from the star)

Pressure bumps



EFFECT OF GAS PRESSURE GRADIENT ON PARTICLE MOTION

Fig. 1.

(Figure from Whipple 1972)

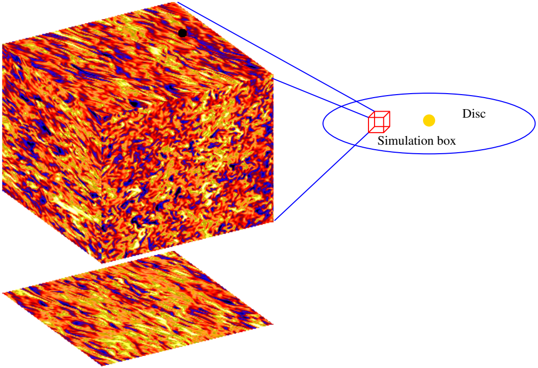
- Particles seek the point of highest pressure

$\Rightarrow$ Particles get trapped in *pressure bumps*

- Achieve high enough density for gravitational instability and planetesimal formation

Magnetorotational instability

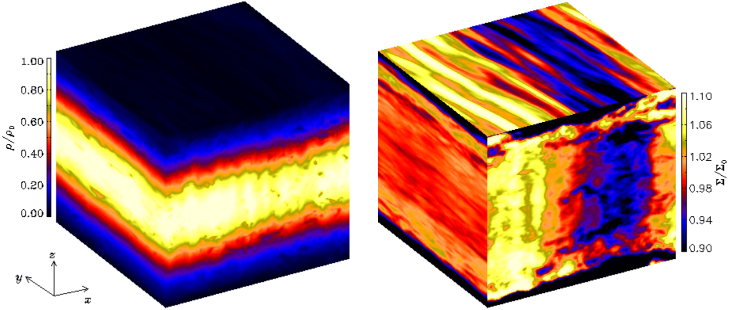
- Magnetorotational instability likely source of turbulence and accretion in protoplanetary discs *(Balbus & Hawley 1991)*



- *Pencil Code* – an international open-source numerical code for grid magnetohydrodynamics and dust particles

⇒ `http://www.nordita.org/software/pencil-code/`

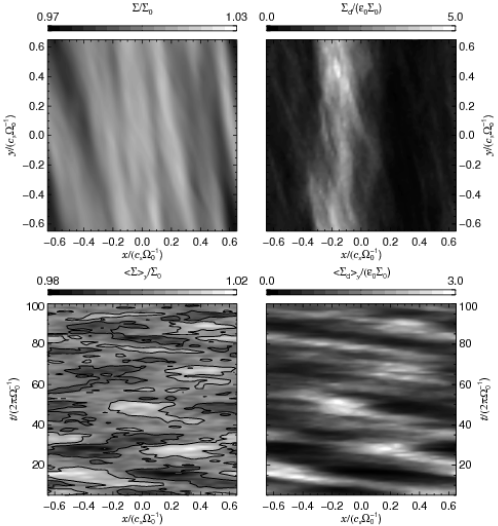
High-pressure regions



(Johansen, Youdin, & Klahr 2009)

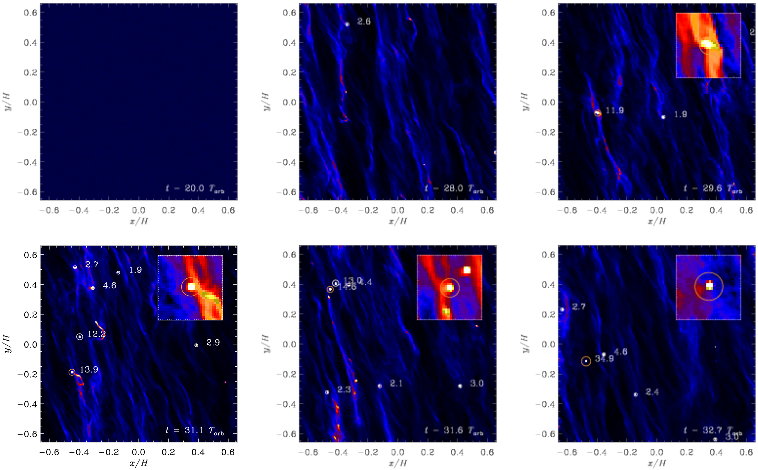
- Gas density shows the expected vertical stratification
- Gas column density shows presence of large-scale pressure fluctuations with variation only in the radial direction
- Pressure fluctuations of order 10%

Particle trapping



- Strong correlation between high gas density and high particle density *(Johansen, Klahr, & Henning 2006)*

Forming protoplanets in pressure bumps

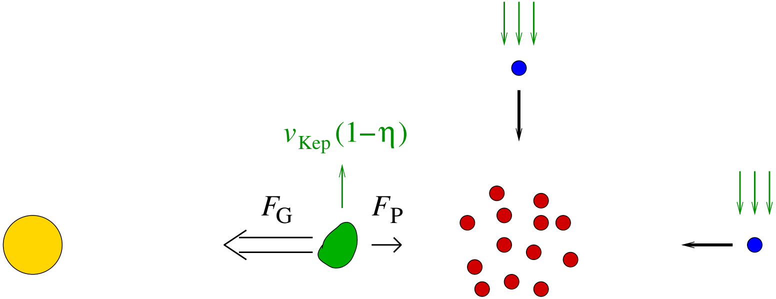


(Johansen et al. 2007, Nature)

(Johansen et al. 2010, A&A submitted)

Streaming instability

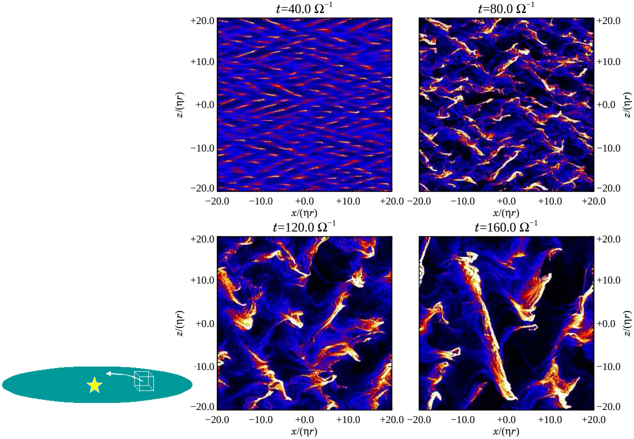
- Gas orbits slightly slower than Keplerian
- Particles lose angular momentum due to headwind
- Particle clumps locally reduce headwind and are fed by isolated particles



- Johansen, Henning, & Klahr (2006); Youdin & Johansen (2007); Johansen & Youdin (2007)
- Youdin & Goodman (2005): “Streaming instability”

Clumping

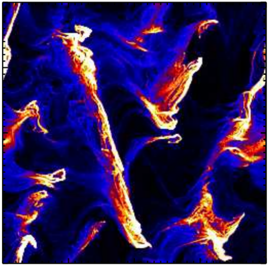
Linear and non-linear evolution of radial drift flow of meter-sized boulders:



Strong clumping in non-linear state of the streaming instability

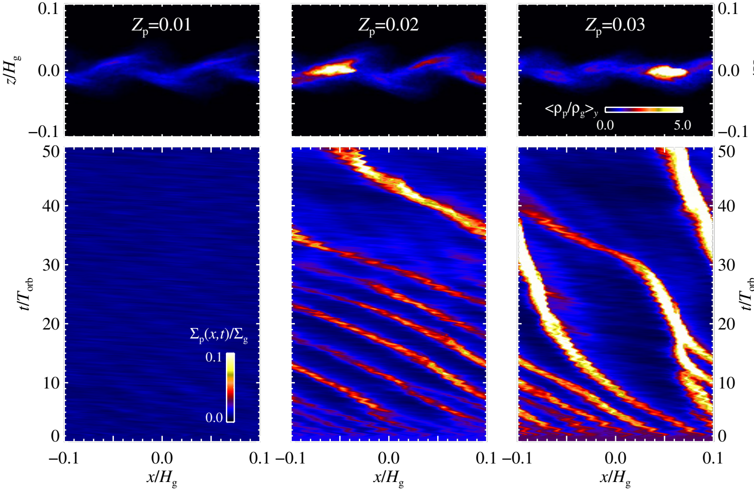
(Youdin & Johansen 2007, Johansen & Youdin 2007)

Why clump?



Dependence on pebble abundance

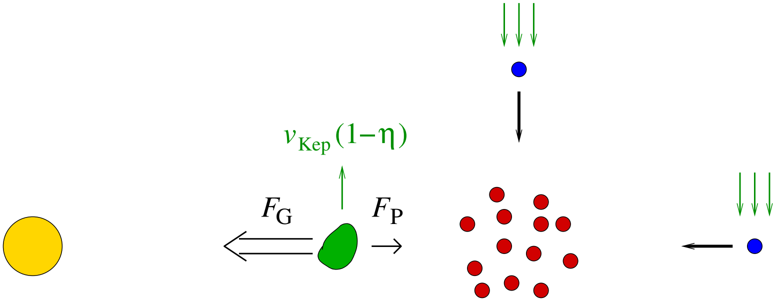
- Particles sizes 3–12 cm at 5 AU, 1–4 cm at 10 AU
- Increase pebble abundance $\Sigma_{\rm par}/\Sigma_{\rm gas}$ from 0.01 to 0.03



(Johansen, Youdin, & Mac Low 2009)

Why is “metallicity” important?

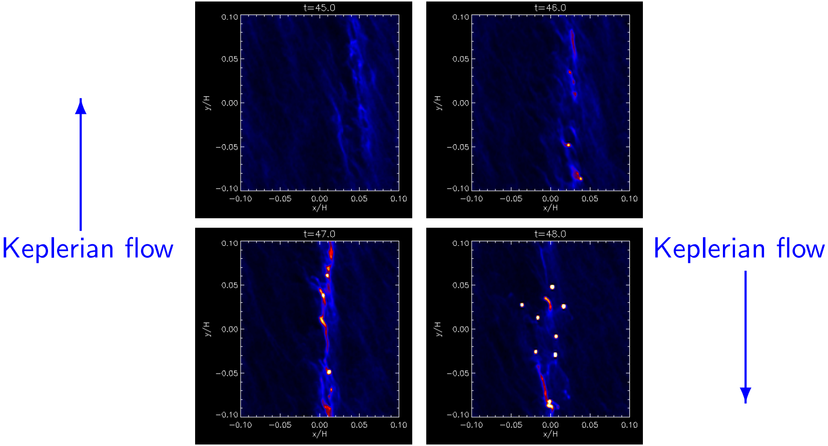
- Gas orbits slightly slower than Keplerian
- Particles lose angular momentum due to headwind
- Particle clumps locally reduce headwind and are fed by isolated particles



- *Clumping relies on particles being able to accelerate the gas towards Keplerian speed*

Planetesimal formation movie

Time is in Keplerian orbits (1 orbit $\approx$ 10 years)



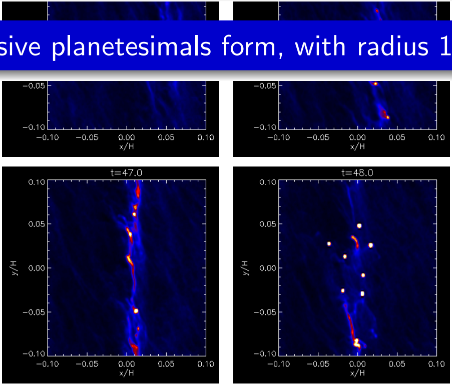
Johansen, Youdin, & Mac Low (2009)

Planetesimal formation movie

Time is in Keplerian orbits (1 orbit ≈ 10 years)

Collapse happens much faster than the radial drift time-scale

Very massive planetesimals form, with radius 100–200 km



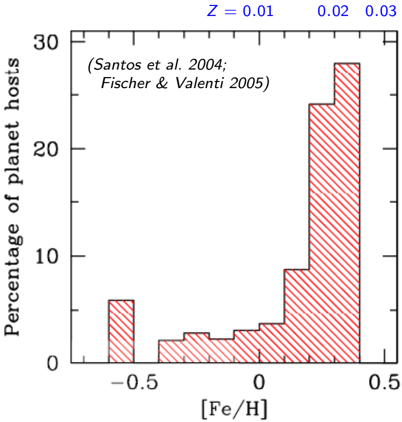
Keplerian flow

Keplerian flow

Johansen, Youdin, & Mac Low (2009)

Metallicity of host star

- First planet around solar-type star discovered in 1995 *(Mayor & Queloz 1995)*
- Today more than 500 exoplanets known
- Exoplanet probability increases sharply with metallicity of host star

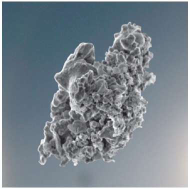

(Santos et al. 2004; Fischer & Valenti 2005)

⇒ Planetesimal formation shows similarly strong dependence on metallicity *(Johansen et al. 2009)*

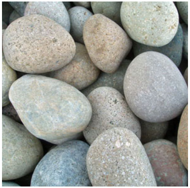
⇒ *Planetesimal formation stage may hold important clues to why the solar system formed when it did*

The "clumping scenario" for planetesimal formation

1. Dust growth by coagulation to a few cm



2. Spontaneous clumping in high-pressure regions and through streaming instabilities



3. Gravitational collapse to 100-1000 km radius planetesimals