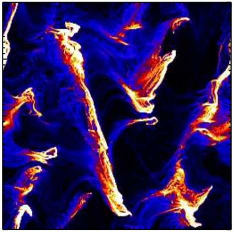
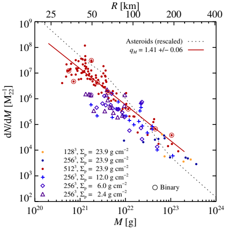
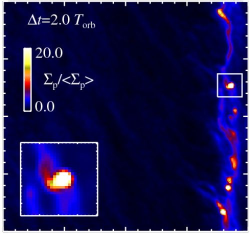
How gas turbulence influences planet formation







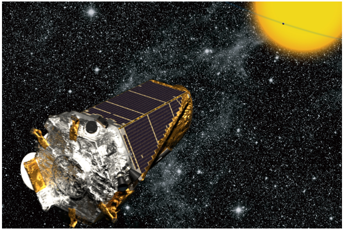
Anders Johansen (Lund University)

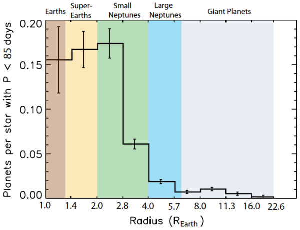
"Non-ideal MHD, Stability, and Dissipation in Protoplanetary Disks"

Copenhagen, August 2014

LUND UNIVERSITY · erc European Research Council · VETENSKAPSRÅDET THE SWEDISH RESEARCH COUNCIL · Knut och Alice Wallenbergs Stiftelse · PRACE

Exoplanets



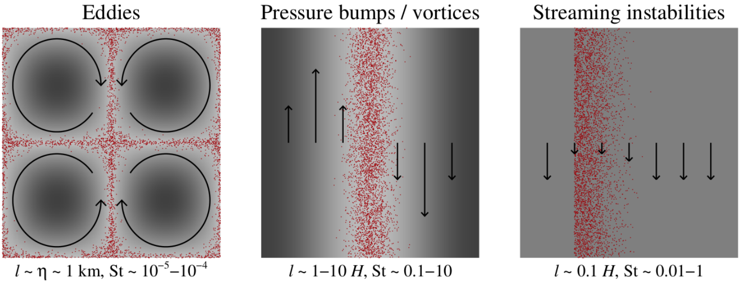


In the first 16 months the *Kepler* satellite detected 2321 planet candidates:

- 253 Earth-sized ($R \leq 1.25 R_\oplus$)
- 712 Super-Earth-sized ($1.25 R_\oplus < R \leq 2 R_\oplus$)
- 1078 Neptune-sized ($2 R_\oplus < R \leq 6 R_\oplus$)
- 207 Jupiter-sized ($6 R_\oplus < R \leq 15 R_\oplus$)
- 71 Super-Jupiter-sized ($15 R_\oplus < R$)

$\Rightarrow$ Nature is *very* efficient at converting dust to planets...
... despite radial drift barrier, bouncing barrier, fragmentation barrier, etc

Particle concentration

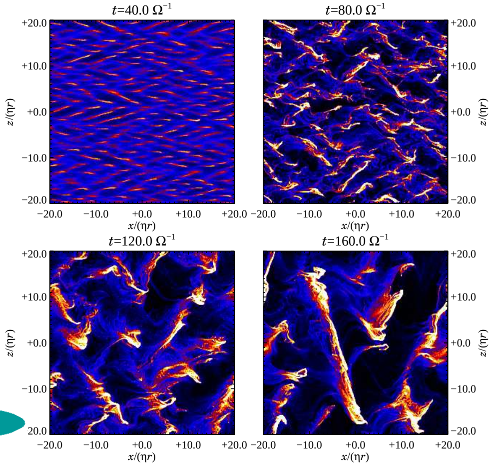


Three ways to concentrate particles: (*Johansen et al.*, 2014, arXiv:1402.1344)

- Between small-scale low-pressure eddies
  (*Squires & Eaton*, 1991; *Fessler et al.*, 1994; *Cuzzi et al.*, 2001, 2008; *Pan et al.*, 2011)
- In pressure bumps and vortices
  (*Whipple*, 1972; *Barge & Sommeria*, 1995; *Klahr & Bodenheimer*, 2003; *Johansen et al.*, 2009a)
- By streaming instabilities
  (*Youdin & Goodman*, 2005; *Johansen & Youdin*, 2007; *Johansen et al.*, 2009b; *Bai & Stone*, 2010a,b,c)

Streaming instability

Linear and non-linear evolution of radial drift flow:



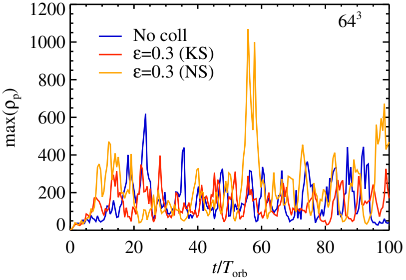
Strong clumping in non-linear state of the streaming instability

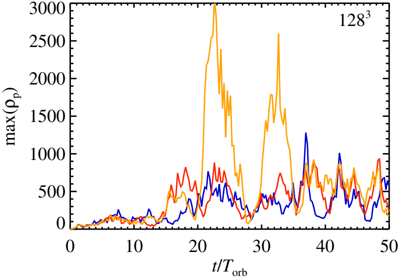
(Johansen & Youdin 2007; Bai & Stone 2010a)

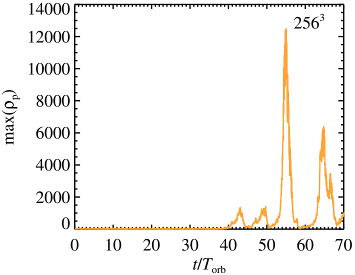
Particle density

- Maximum density increases with increasing resolution
  (Johansen, Lithwick, & Youdin 2012)
- Particle density up to 10,000 times local gas density
- Criterion for gravitational collapse: $\rho_\mathrm{p} \gtrsim 100\rho_\mathrm{g}$

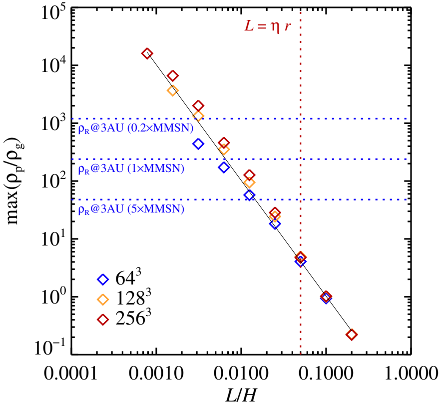
$\Rightarrow$ Gravitational contraction to form planetesimals

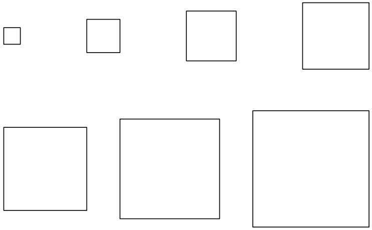






Scale-by-scale convergence



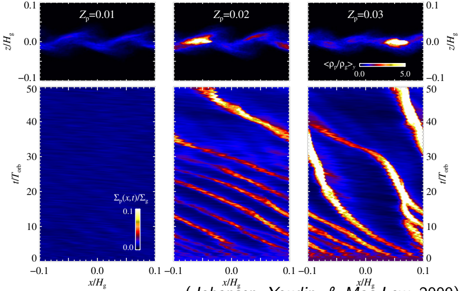


- Plot shows maximum density over a given scale (averaged over time)
- Points for 64^3, 128^3 and 256^3 almost on top of each other

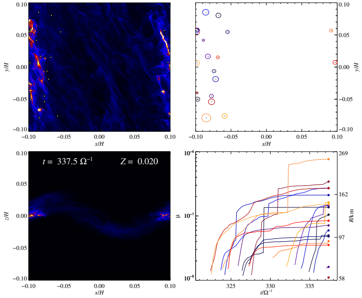
$\Rightarrow$ Streaming instability clumping converges scale-by-scale

- Increasing the resolution increases the maximum density because we resolve filamentary structures better

Gravitational collapse

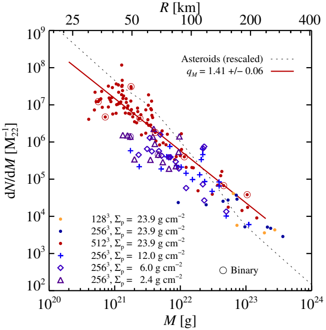


(*Johansen, Youdin, & Mac Low*, 2009)

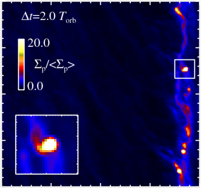


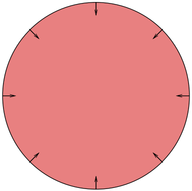
- Particle concentration by streaming instabilities reach at least 10,000 times the gas density
- Filaments fragment to bound *pebble clumps*, with contracted radii 25-200 km (*Johansen, Mac Low, Lacerda, & Bizzarro*, submitted)

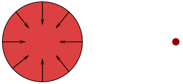
⇒ Initial Mass Function of planetesimals



Cloud collapse to pebble piles





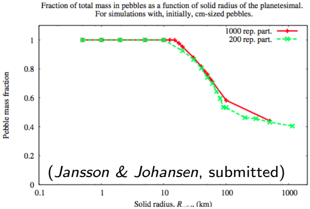


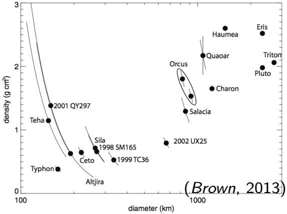
- Simulate cloud collapse in 0-D collision code
  (*Jansson & Johansen*, submitted)
- High collision rates ⇒ Rapid energy dissipation ⇒ Contraction to solid density

⇒ High pebble fraction after collapse

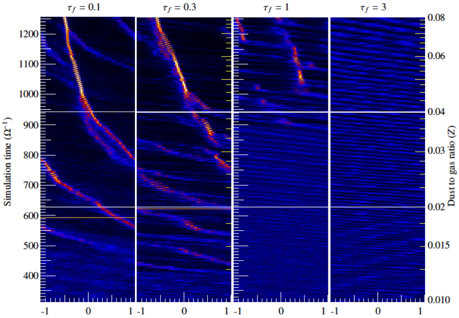
⇒ Predict that comets like 67P/ Churyumov-Gerasimenko are pebble piles

- Large Kuiper belt objects likely lost their porosity by gravitational compression





Concentrating chondrules



- Typical particle sizes considered for the streaming instability are of size 10 cm (when scaled to the asteroid belt)
- Meteorites contain up to 80% mass in *chondrules* of sizes 0.1–1 mm (e.g. *Krot et al.*, 2009)

⇒ Smaller particles can be concentrated at higher metallicity (*Carrera, Johansen, & Davies*, in preparation)

- Metallicity increase by photoevaporation or drifting particles? (*Alexander et al.*, 2006; *Alexander & Armitage*, 2007)

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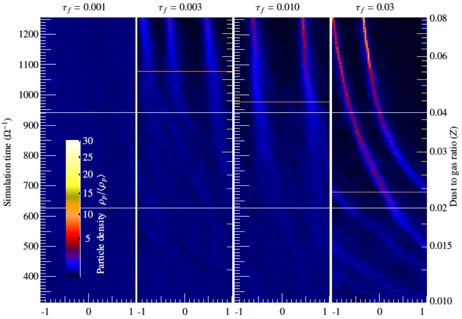

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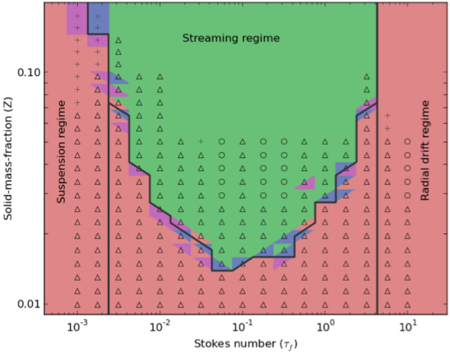

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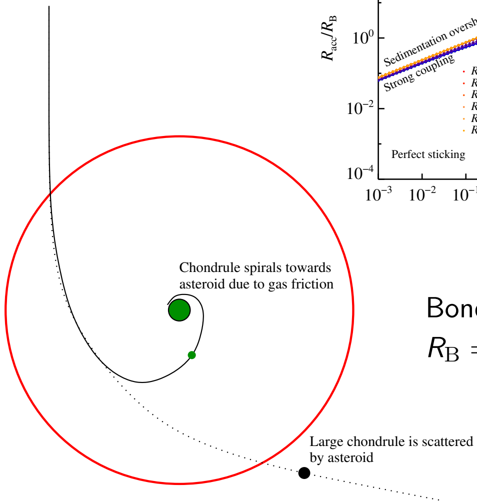
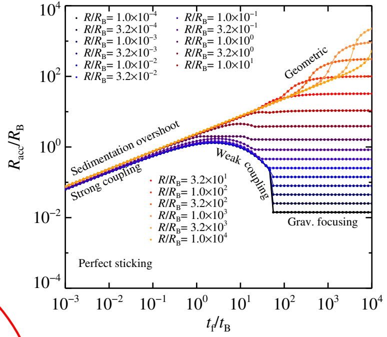
Chondrule accretion

$\Delta v \approx 50$ m/s





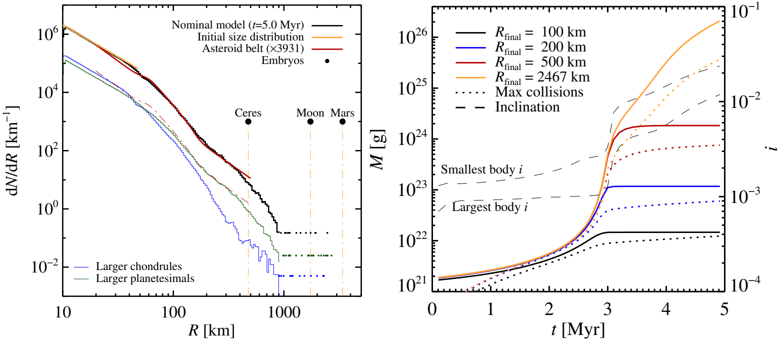
Bondi radius:

$$R_{\rm B} = \frac{GM}{(\Delta v)^2}$$

$$\dot{M} \propto R_{\rm B}^2 \propto R^6$$

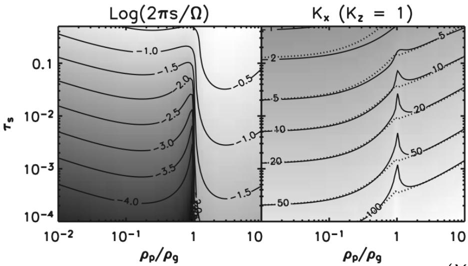
(*Johansen & Lacerda*, 2010; *Ormel & Klahr*, 2010; *Lambrechts & Johansen*, 2012)

Planetesimal growth by chondrule accretion



- The birth sizes of planetesimals forming by streaming instabilites have most mass in the largest bodies and most number in the smallest
- Formed during an epoch when the asteroid belt was icy?
- Chondrule accretion over 5 Myr gives same size distribution as asteroids plus Moon- to Mars-sized embryos (*Johansen, Mac Low, Lacerda, & Bizzarro, submitted*)
- Variation in the parameters gives different realisations of the asteroid belt

To stream or not to stream



(*Youdin & Goodman*, 2005)

- Sedimentation-diffusion equilibrium gives particle layer density

$$\rho_{\rm p} = Z\rho_{\rm g}\sqrt{\frac{{\rm St}+\delta}{\delta}}$$

- Streaming instability requires sedimentation to $\rho_{\rm p} \sim \rho_{\rm g}$, hence $\delta \lesssim Z^2\,{\rm St}$

$\Rightarrow$ Ice particles of mm-cm sizes can sediment for $\delta \sim 10^{-4}$ at 10-100 AU

$\Rightarrow$ Chondrules in the asteroid belt require $\delta \lesssim 10^{-6}$

? Streaming instability may piggy back on pressure bumps and vortices if δ is too high for sedimentation