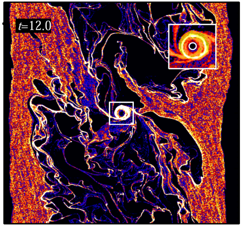
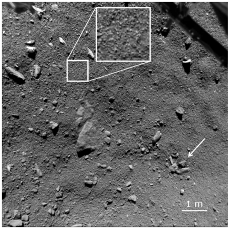
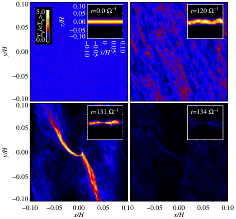
Lecture 3: Recent topics







"NBI summer School on Protoplanetary Disks and Planet Formation"

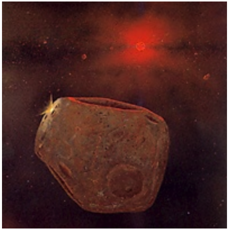
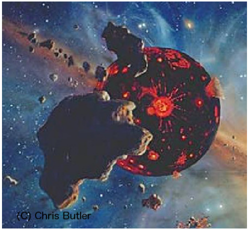
August 2015

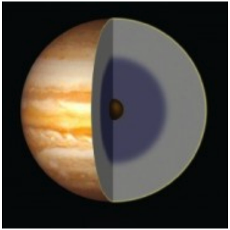
Anders Johansen (Lund University)

Topics

1. Wide-orbit exoplanets
2. Pebble accretion
3. Size distribution of asteroids
4. Nice model
5. Grand Tack model
6. Population synthesis with pebbles
7. Chondrule accretion

Classical core accretion scenario



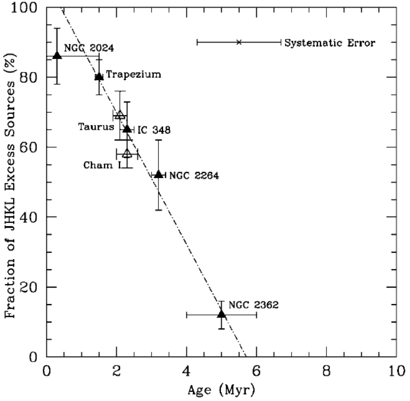
1. Dust grains and ice particles collide to form km-scale planetesimals
2. Large protoplanet grows by run-away accretion of planetesimals
3. Protoplanet attracts hydrostatic gas envelope
4. Run-away gas accretion as $M_{\mathrm{env}} \approx M_{\mathrm{core}}$
5. Form gas giant with $M_{\mathrm{core}} \approx 10 M_{\oplus}$ and $M_{\mathrm{atm}} \sim M_{\mathrm{Jup}}$

(*Safronov*, 1969; *Mizuno*, 1980; *Pollack et al.*, 1996)

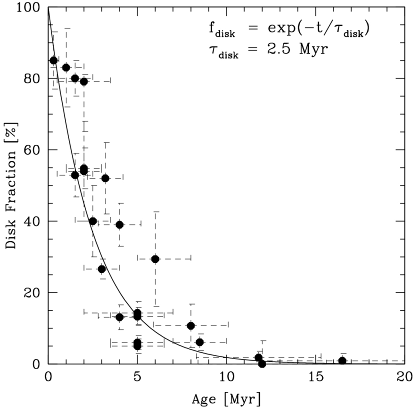
All steps must happen within 1–3 Myr while there is gas orbiting the star

Life-times of protoplanetary discs

- Stars in a star-forming region are pretty much the same age
- Compare *disc fraction* between regions of different age



(*Haisch et al.*, 2001)



(*Mamajek*, 2009)

⇒ Protoplanetary discs live for 1–3 Myr

Core formation time-scales

- The size of the protoplanet relative to the Hill sphere:

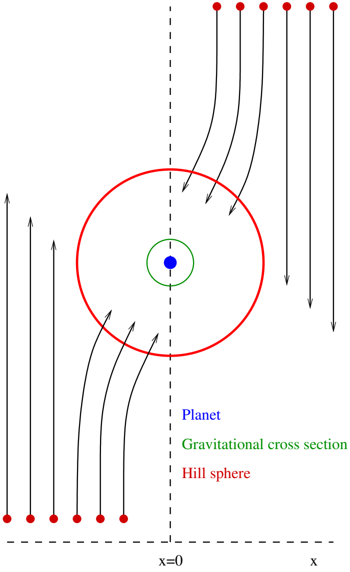
$$\frac{R_{\rm p}}{R_{\rm H}} \equiv \alpha \approx 0.001 \left(\frac{r}{5\,\rm AU}\right)^{-1}$$

- Maximal growth rate by gravitational focussing

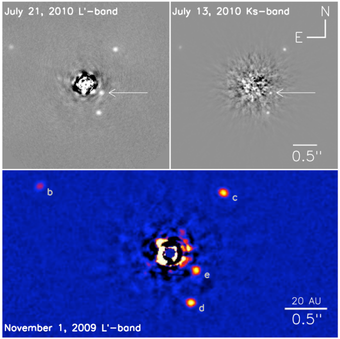
$$\dot{M} = \alpha R_{\rm H}^2 \mathcal{F}_{\rm H}$$

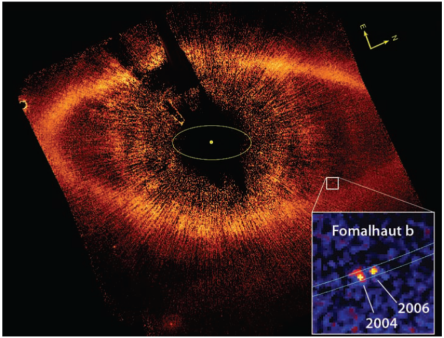
$\Rightarrow$ Only 0.1% (0.01%) of planetesimals entering the Hill sphere are accreted at 5 AU (50 AU)

$\Rightarrow$ Time to grow to 10 $M_\oplus$ is
$\sim$10 Myr at 5 AU
$\sim$50 Myr at 10 AU
$\sim$5,000 Myr at 50 AU



Directly imaged exoplanets





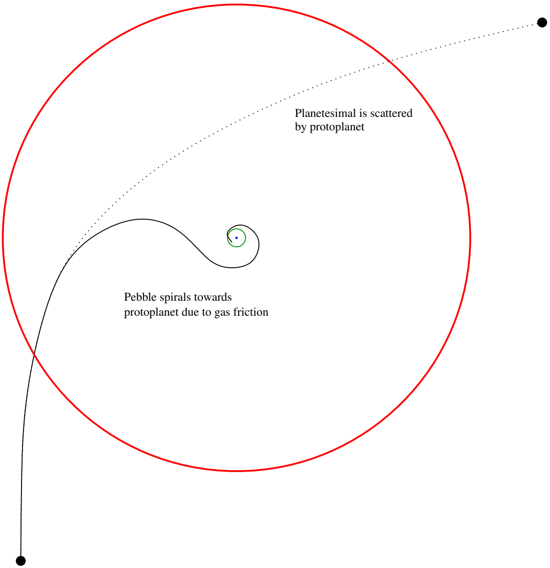
(*Marois et al.*, 2008; 2010)

(*Kalas et al.*, 2008)

- HR 8799 (4 planets at 14.5, 24, 38, 68 AU)
- Fomalhaut (1 controversial planet at 113 AU)

$\Rightarrow$ No way to form the cores of these planets within the life-time of the protoplanetary gas disc *by standard core accretion*

Pebble accretion



- Most planetesimals are simply scattered by the protoplanet
- Pebbles spiral in towards the protoplanet due to gas friction

$\Rightarrow$ Pebbles are accreted from the entire Hill sphere

- Growth rate by planetesimal accretion is

$$\dot{M} = \alpha R_{\mathrm{H}}^2 \mathcal{F}_{\mathrm{H}}$$

- Growth rate by pebble accretion is

$$\dot{M} = R_{\mathrm{H}}^2 \mathcal{F}_{\mathrm{H}}$$

Relevant parameters for pebble accretion

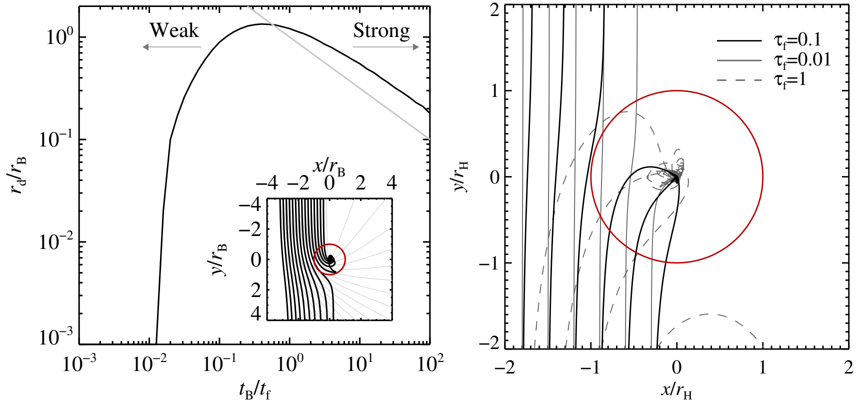
- Hill radius $R_{\rm H} = [GM/(3\Omega^2)]^{1/3}$
  Distance over which the gravity of the protoplanet dominates over the the tidal force of the central star

- Bondi radius $R_{\rm B} = GM/(\Delta v)^2$
  Distance over which a particle with approach speed Δv is significantly deflected by the protoplanet (in absence of drag)

- Sub-Keplerian speed Δv
  Orbital speed of gas and pebbles relative to Keplerian speed

- Hill speed $v_{\rm H} = \Omega R_{\rm H}$
  Approach speed of gas and pebbles at the edge of the Hill sphere

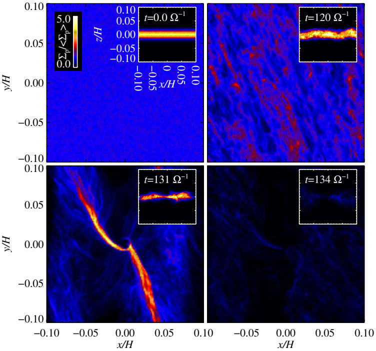
Pebble accretion regimes

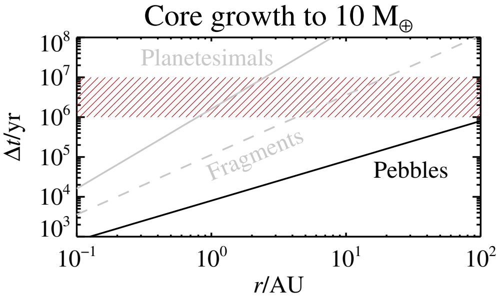


Two main pebble accretion regimes: (*Lambrechts & Johansen*, 2012)

1. Bondi regime (when $\Delta v \gg v_{\rm H}$)
   Particles pass the core with speed Δv, giving $\dot{M} \propto R_{\rm B}^2 \propto M^2$
2. Hill regime (when $\Delta v \ll v_{\rm H}$)
   Particles enter Hill sphere with speed $v_{\rm H} \approx \Omega R_{\rm H}$, giving $\dot{M} \propto M^{2/3}$

Time-scale of pebble accretion





$\Rightarrow$ Pebble accretion speeds up core formation by a factor 1,000 at 5 AU and a factor 10,000 at 50 AU

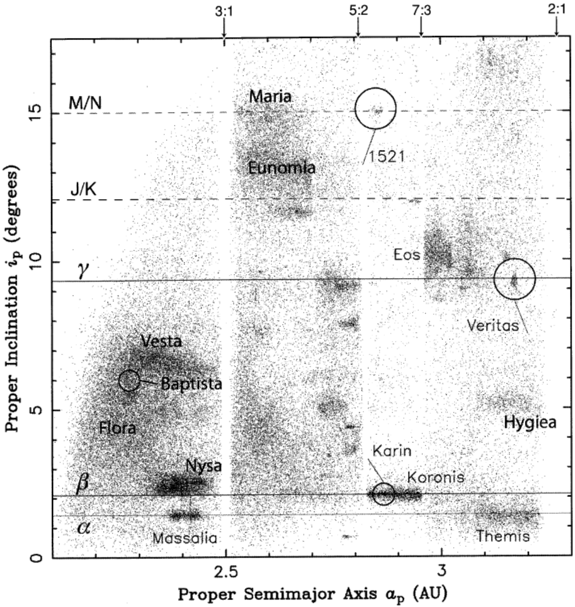
(*Ormel & Klahr*, 2010; *Lambrechts & Johansen*, 2012; *Nesvorny & Morbidelli*, 2012)

$\Rightarrow$ Cores form well within the life-time of the protoplanetary gas disc, even at large orbital distances

- Requires large planetesimal seeds to accrete in Hill regime, consistent with planetesimal formation by gravitational collapse

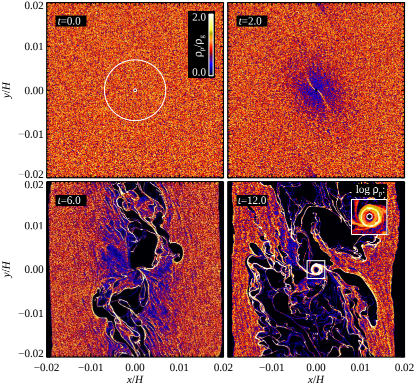
The asteroid belt

- 1–2 million asteroids larger than 1 km in main belt between Mars and Jupiter
- Total mass is only 0.0005 M_{E}
- Interpolation between terrestrial planets and giant planets gives 2.5 M_{E} in the primordial asteroid belt between 2 and 3 AU
- Asteroid belt depleted by resonances with Jupiter



Growth of asteroids by pebble accretion

Put large (500 km) planetesimal in an ocean of pebbles:

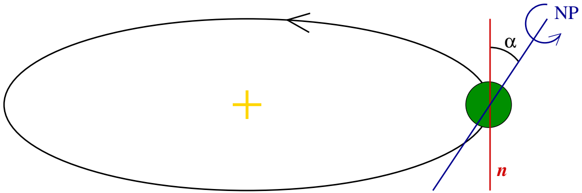


⇒ Prograde accretion disc forms around the protoplanet
(*Johansen & Lacerda*, 2010)

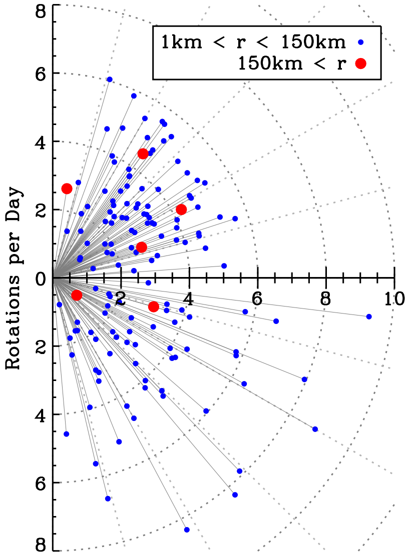
Asteroid rotation

- The majority of large asteroids have axial tilt $\alpha < 90^\circ$
- Called "direct" or "prograde" rotation

Body	α
Ceres	2^o
2 Pallas	60^o
3 Juno	50^o
4 Vesta	29^o
5 Astraea	33^o
6 Hebe	42^o

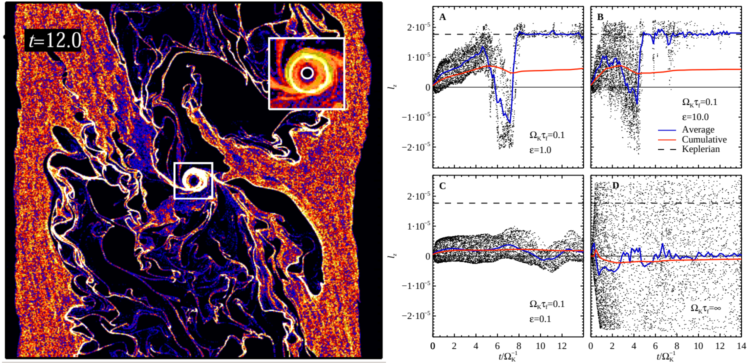


Asteroid poles



- Plot of asteroid pole axes
  (from *Johansen & Lacerda*, 2010)
- Largest asteroids have a *tendency* to rotate prograde (1-2 σ)
- ... but there is a very large scatter
- The two large retrograde asteroids, 2 Pallas and 10 Hygiea, are actually spinning on the side
- Planetesimal accretion yields slow, retrograde rotation (*Lissauer & Kary*, 1991)
- Prograde spin can also arise from random effect of large impacts (*Dones & Tremaine*, 1993) or due to collisions between planetesimals within the Hill sphere (*Schlichting & Sari*, 2007)

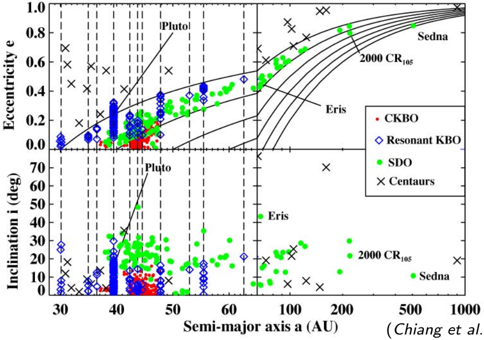
Primordial spin of planetesimals



- Prograde rotation with $P \approx (5 \ldots 10)\,\mathrm{h}$ induced for particles between centimeters and a few meters
- Spin can be randomised later in giant impacts

$\Rightarrow$ Predict that pristine Kuiper belt objects formed by gravitational collapse should have prograde spin

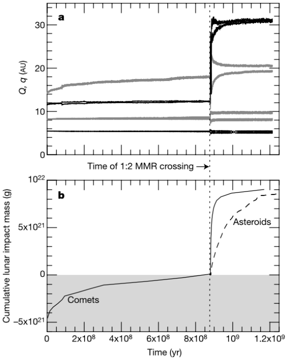
Orbits of Kuiper belt objects

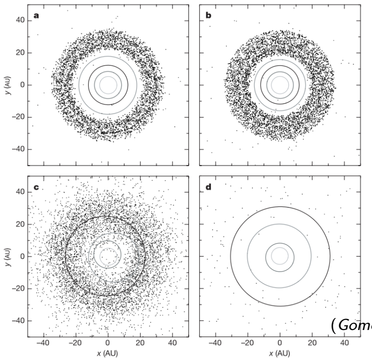


(*Chiang et al.*, 2007; *de Pater & Lissauer*, 2010)

- Kuiper belt objects reside beyond the orbit of Neptune
- Pluto trapped in 3:2 resonance with Neptune – result of outwards migration of Neptune
- Scattered disc objects have high *e* and perihelion between 33 and 40 AU
- Centaurs have perihelion within 30 AU – source of Jupiter family comets
- Classical KBOs have low *e* and semimajor axes between 37 and 48 AU – future target of New Horizons

Nice model

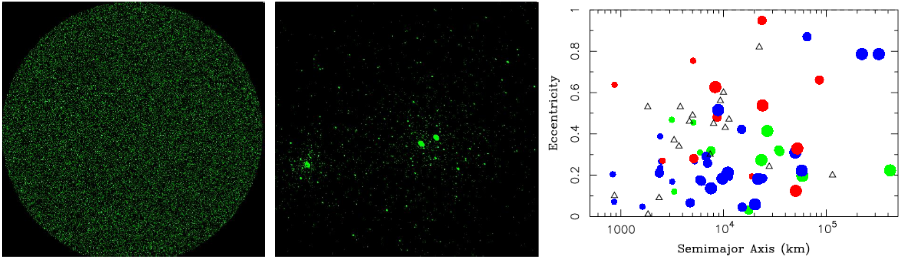




(*Gomes et al.*, 2005)

- Pluto's resonant orbit with Neptune is explained by trapping during the migration of Neptune through a primordial, massive Kuiper belt (*Malhotra*, 1993, 1995)
- Planetesimals scattered inwards by N, U and S are ejected from the Solar System by J, leading to a net outwards migration of the three outer giants
- As Jupiter and Saturn cross their 2:1 mean motion resonance, the orbits of Uranus and Neptune are excited and the primordial Kuiper belt is depleted (*Tsiganis et al.*, 2005)
- Explains modern architecture of the Kuiper belt and Late Heavy Bombardment of the terrestrial planets and the Moon (*Gomes et al.*, 2005)

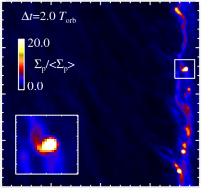
Kuiper belt binaries

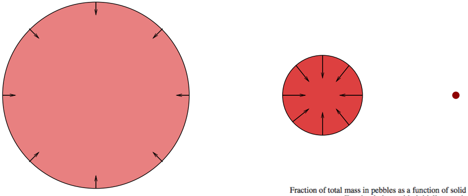


(*Nesvorny et al.*, 2010)

- At least 30% of 100-km classical KBOs are binaries (*Noll et al.*, 2008)
- *Nesvorny et al.* (2010) modelled gravitational collapse of particle clumps to explain why binary KBO can have similar colors
- Found good statistical agreement in orbital parameters between simulations and observed KBO binary systems
- Almost no binaries in scattered disc – ionised by close encounters?

Cloud collapse to pebble piles



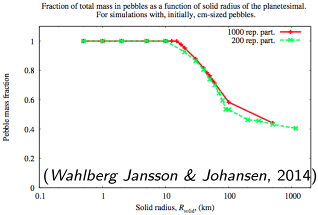


- Simulate cloud collapse in 0-D collision code
  (*Wahlberg Jansson & Johansen*, 2014)
- High collision rates ⇒ Rapid energy dissipation ⇒ Contraction to solid density

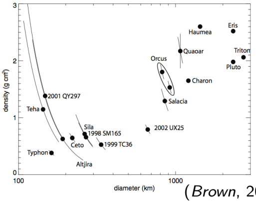
⇒ High pebble fraction after collapse

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

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

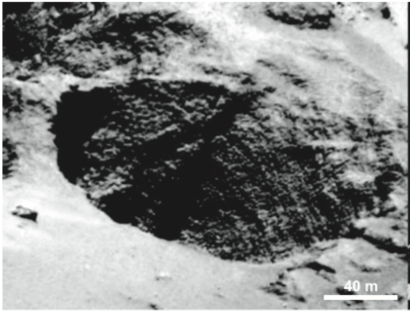


(*Wahlberg Jansson & Johansen*, 2014)

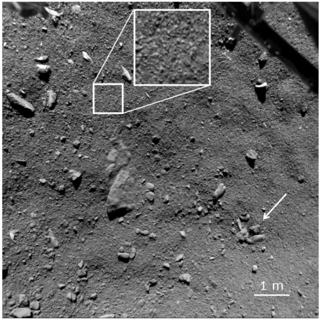


(*Brown*, 2013)

Goosebumps on 67P



(*Sierks et al.*, 2015)



(*Mottola et al.*, 2015)

- The Rosetta mission arrived at the comet 67P/Churyumov-Gerasimenko in 2014
- Orbiter will follow 67P beyond perihelion
- Structures in deep pits resemble goosebumps (*Sierks et al.*, 2015)
- Could be the primordial pebbles from the solar protoplanetary disc
- But meter-sized pebbles hard to explain in light of radial drift
- Philae's first landing site shows characteristic particle scale of cm in smooth terrains (*Mottola et al.*, 2015)

Pebbles in the media!

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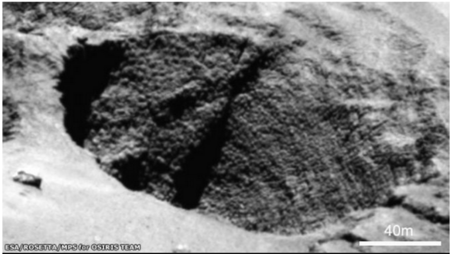
Science & Environment

Rosetta: 'Goosebumps' on 'space duck' hint at comet formation

By Jonathan Amos
Science correspondent, BBC News

22 January 2015 | Science & Environment

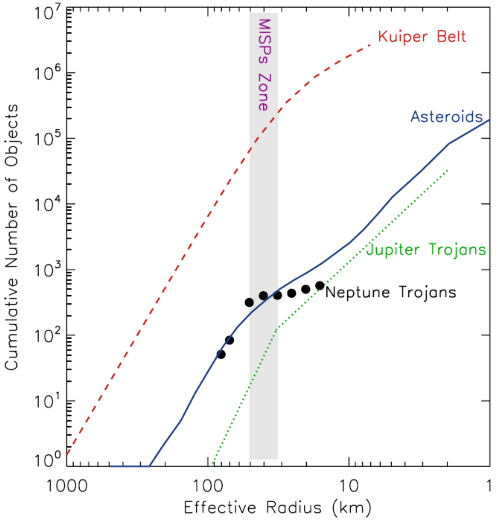


A fascinating texture: Comet 67P's "goosebumps" have a preferred scale of about 3m

"We could be looking at the fundamental building blocks of our Solar System" - Colin Snodgrass, the Open University

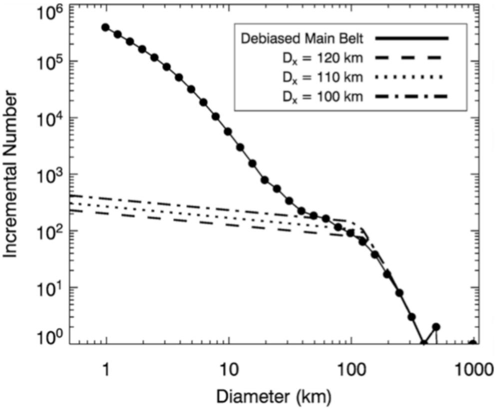
Missing intermediate-size planetesimals

- *Sheppard & Trujillo* (2010) searched for Neptune Trojans
- Sensitive to planetesimals larger than 16 km
- Found no Trojans with radius less than 45 kilometers
- Dubbed them *the missing intermediate-size planetesimals* (MISPs)



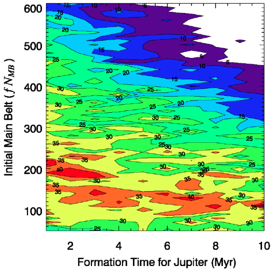
Asteroid size distribution

- Differential size distribution of asteroids shows several bumps
- Can be used to infer the degree of depletion and collisional grinding in the asteroid belt
- Divide the history of the asteroid belt into an early *accretion* phase followed by an extended *depletion* phase
- *Bottke et al.* (2005a,b) evolved the asteroid belt over billions of years, starting from a size distribution which matches the current one for bodies larger than 120 km in diameter

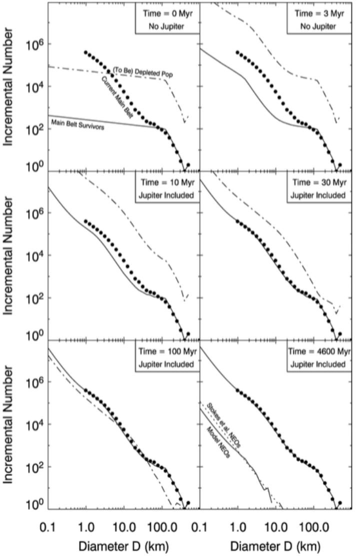


Evolution of asteroid size distribution

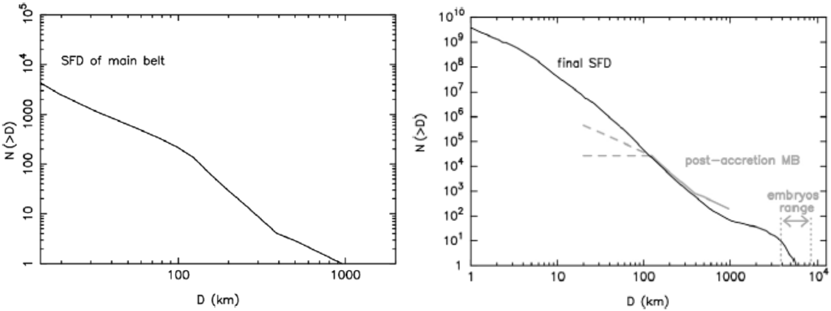
- Depletion factor of 100–200 gives good fit to observed size distribution after 4600 Myr of evolution
- Also satisfies the two constraints: (i) Vesta only has a single large crater and (ii) there are only 9 large asteroid familes
- Observed size distribution of large asteroids is a fossil of the size distribution at the end of the accretion phase



(*Bottke et al.*, 2005)

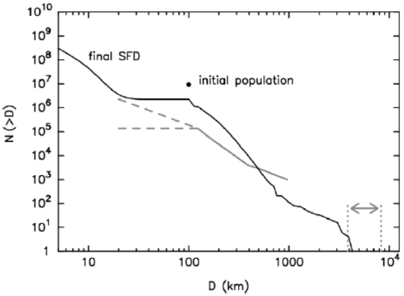


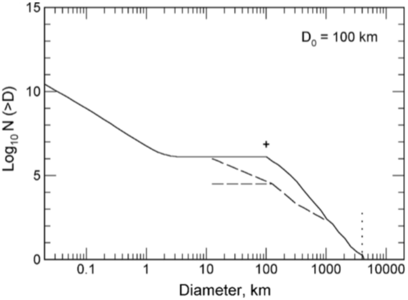
Accretion phase of asteroids



- Size distribution of asteroids shows distinct bumps at $D = 120$ km and at $D = 350$ km
- The first bump must be primordial (*Bottke et al.*, 2005)
- Starting accretion phase with km-sized planetesimals produces way too many asteroids with $D < 100$ km (*Morbidelli et al.*, 2009)

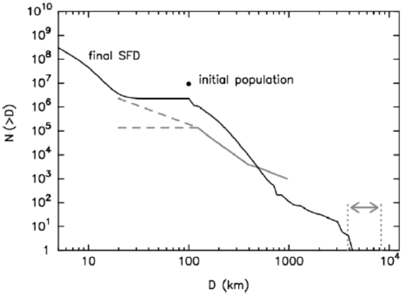
Starting from planetesimals with $D = 100$ km

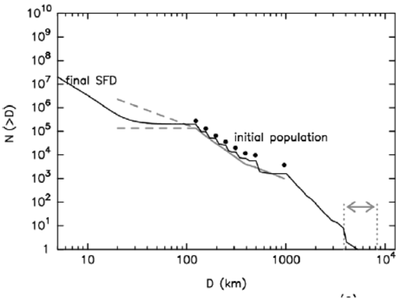




- Starting with planetesimals with $D = 100$ km produces very few fragments during the accretion stage
- But the resulting size distribution is too steep for $D > 100$ km
  (*Morbidelli et al.*, 2009; *Weidenschilling*, 2011)

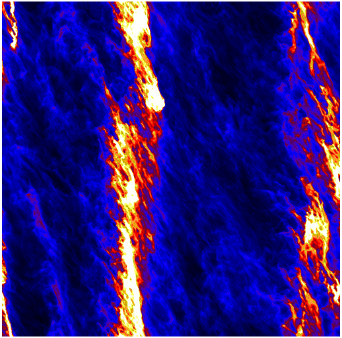
Asteroids are born big

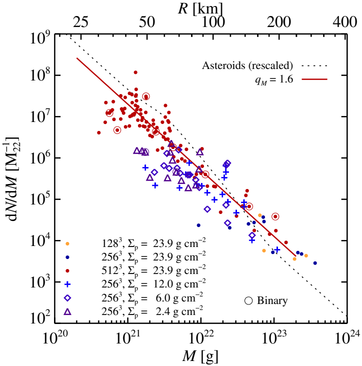




- The best results are obtained by setting the birth size distribution of asteroids equal to the current observed size distribution of large asteroids
- Asteroids are born BIG (*Morbidelli et al.*, 2009)
- Can we connect birth sizes to planetesimal formation models?

Birth sizes of planetesimals



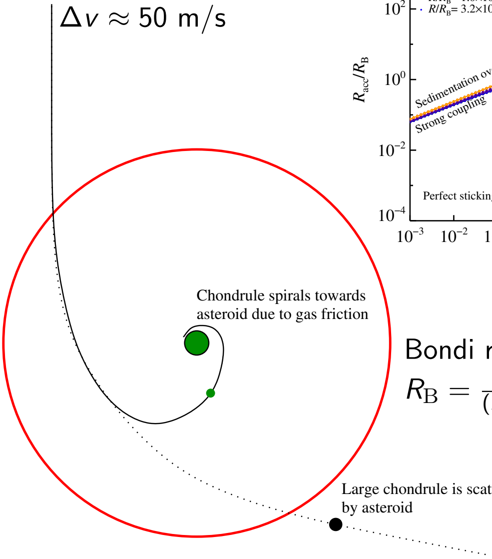


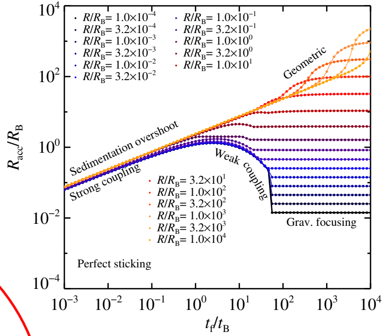
- Streaming instability leads to concentration of pebbles and to planetesimal formation
- Higher resolution yields smaller and smaller planetesimals
- Powerlaw in $\mathrm{d}N/\mathrm{d}M \propto M^{-q}$ with $q \approx 1.6$ (*Johansen et al.*, 2015)
- Most of the planetesimals are small but most mass is in the largest bodies
- Birth sizes of planetesimals show no sign of a bump at 50 km radii

Chondrules

- Primitive meteorite parent bodies contain a large fraction of 0.1-1-mm-sized chondrules (formed over the first 3 million years)
- Ordinary chondrites contain up to 80% of their mass in chondrules
- What role did chondrules play in asteroid formation and growth?

Bondi accretion of chondrules





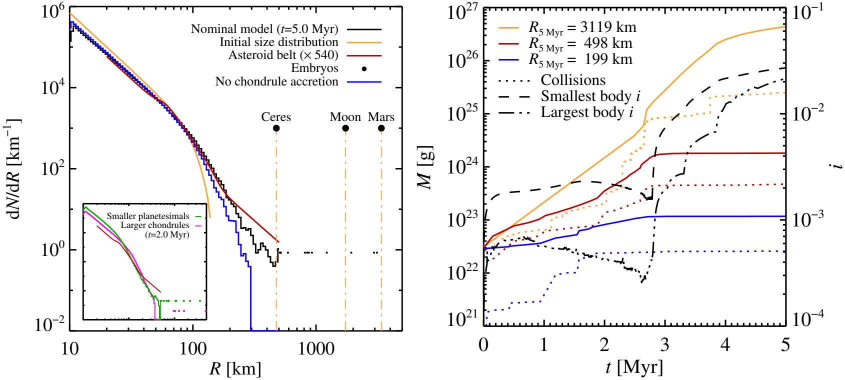
Bondi radius:

$$R_B = \frac{GM}{(\Delta v)^2}$$

$$\dot{M} = \pi f_B^2 R_B^2 \rho_c \Delta v \propto R^6$$

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

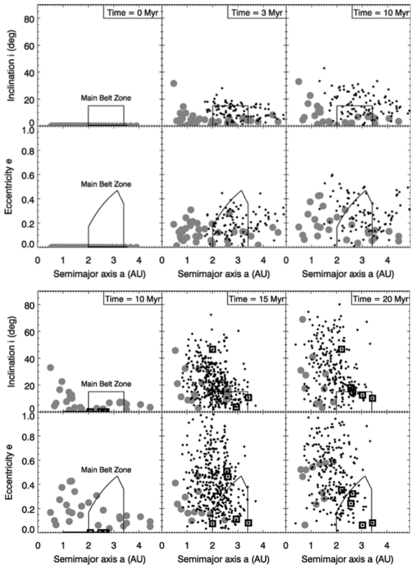
Asteroid sizes after chondrule accretion



- Chondrule accretion reproduces both the bump at $R = 120$ km and the steep size distribution up to $R = 200$ km (*Johansen et al.*, 2015)
- Embryos with sizes between the Moon and Mars are also formed by rapid chondrule accretion
- Direct planetesimal accretion contributes only a minor amount of mass to the embryos and the largest asteroids

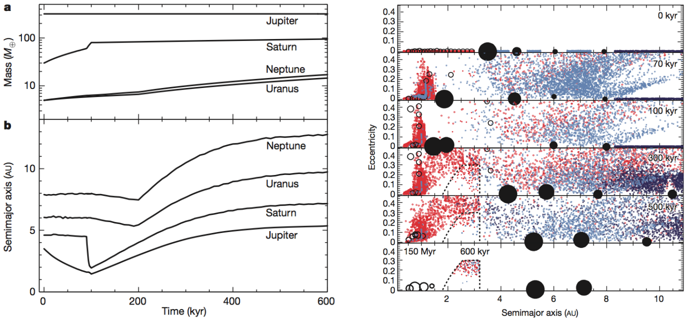
Embryos in the asteroid belt

(*Bottke et al.*, 2005)



- Both planetesimal accretion and chondrule accretion models produce embryos in the asteroid belt
- The embryos excite the eccentricities and inclinations of asteroids to their high values (*Wetherill*, 1991; *Petit et al.*, 2001)
- Embryos also scattered asteroids to Jupiter resonances
- Embryos entirely removed from the asteroid belt by perturbation from Jupiter

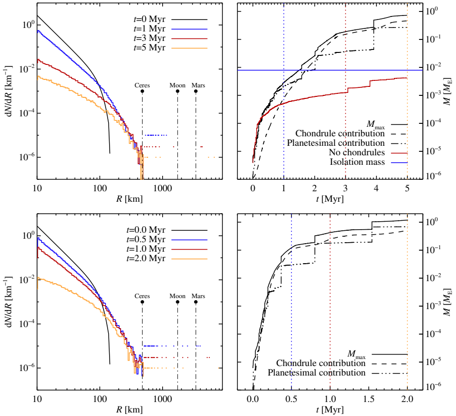
The Grand Tack scenario



(*Walsh et al.*, 2011)

- The small mass of Mars (11% of Earth's) is hard to explain in terrestrial planet formation models
- Jupiter could have migrated sufficiently far in to perturb the embryos in the terrestrial planet formation region
- As Jupiter and Saturn come to share a gap, they migrate outwards together (the Grand Tack scenario of *Walsh et al.*, 2011)
- Best alternative to embedded embryos model for asteroid stirring, particularly if one is concerned about Mars' small size

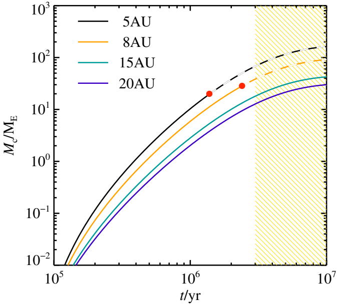
Terrestrial planet formation with chondrules

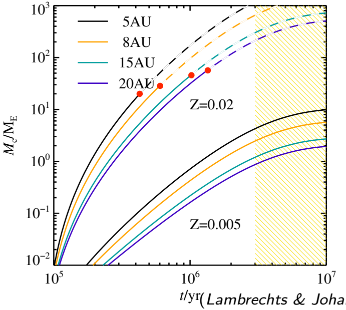


(*Johansen et al.*, 2015)

- Chondrule accretion leads to rapid formation of Mars-sized embryos in the terrestrial planet formation region
- Planetesimal accretion nevertheless more important than in the asteroid belt
- Larger chondrules are accreted more efficiently

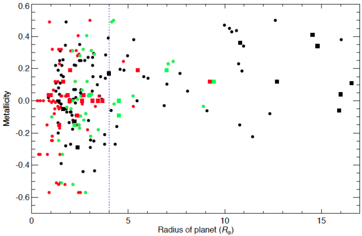
From planetesimals to planets





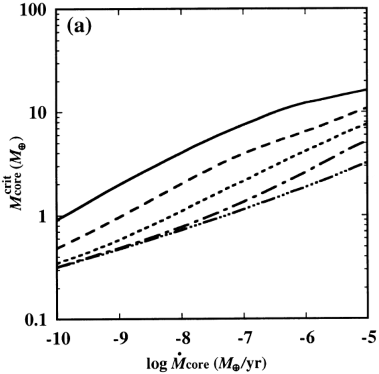
(*Lambrechts & Johansen*, 2014)

- The largest planetesimals accrete the remaining pebbles and grow to planets in the next 1–5 Myr
- Growth depends strongly on the amount of heavy elements in the protoplanetary disc ($Z = 0.01$ in the Sun's photosphere)
  (*Lambrechts & Johansen*, 2014)
- Gas-giant planets like Jupiter form if Z is high, in agreement with exoplanet surveys

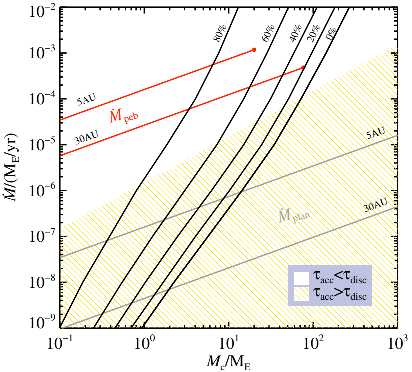


(*Buchhave, Latham, Johansen, et al.*, 2012)

The critical core mass



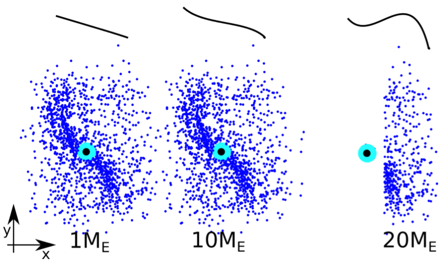
(*Ikoma et al.*, 2000)

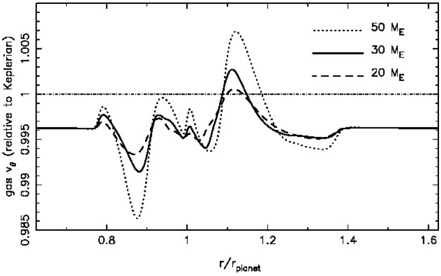


(*Lambrechts, Johansen, & Morbidelli*, 2014)

- The critical core mass for envelope collapse increases when the accretion rate increases
- Planetesimal accretion rates at 5–10 AU yield core masses of 10-20 Earth masses – but the growth rate is too low to compete with gas dissipation
- Pebble accretion rates yield very high critical core masses of 100–200 Earth masses – in disagreement with measured core masses

Halting pebble accretion

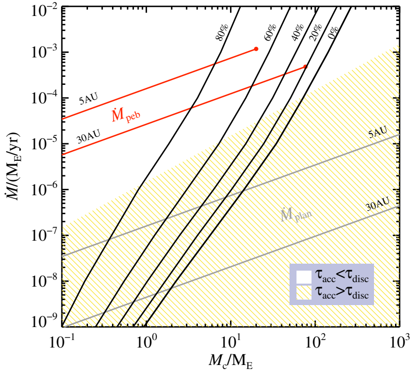


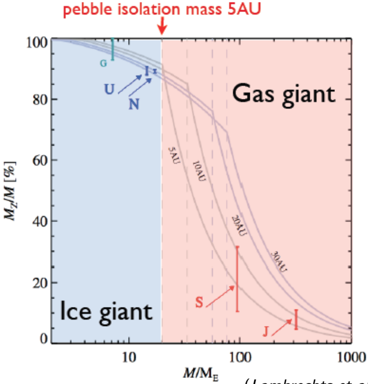


- Pebble accretion is stopped when the protoplanet grows massive enough to carve a gap in the pebble distribution
- Gap formation known for Jupiter-mass planets (*Paardekooper & Mellema*, 2006)
- *Lambrechts et al.* (2014) demonstrate that pebble accretion is stopped already at 20 $M_\oplus$ at 5 AU, with isolation mass scaling as

$$M_{\rm iso} = 20 \left(\frac{r}{5{\rm AU}} \right)^{3/4} M_\oplus$$

The critical core mass revisited

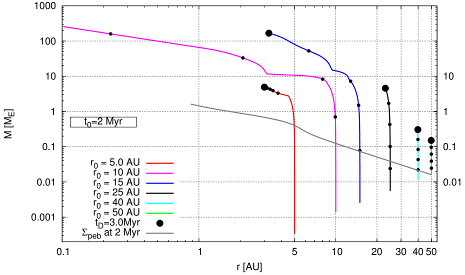


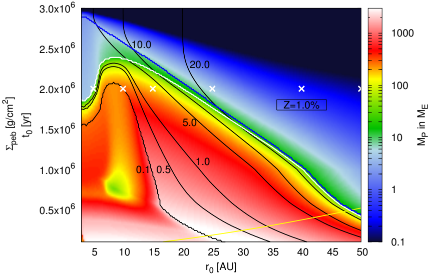


(*Lambrechts et al.*, 2014)

- Protoplanets grow at the pebble accretion rate until pebble accretion is halted *abruptly*
- The envelope is then *supercritical* and collapses onto the core
- Gives an excellent fit to Jupiter's and Saturn's heavy elements (*Lambrechts et al.*, 2014)
- Gas giants in wide orbits must have large cores masses (50-100 $M_{\rm E}$)
- Explains dichotomy between ice giants and gas giants

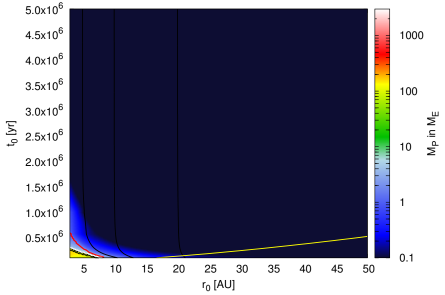
Including planetary migration





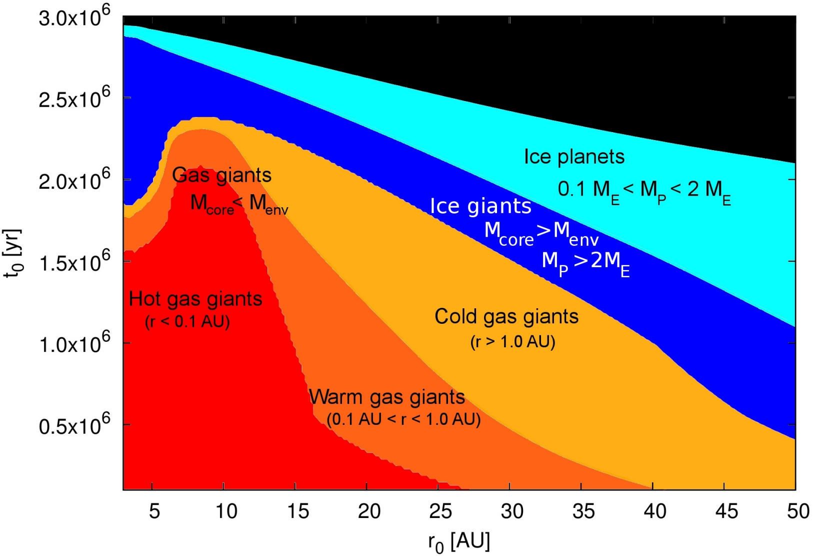
- Pebble accretion combined with protoplanetary disc evolution and planetary migration (*Bitsch, Lambrechts, & Johansen*, 2015)
- Jupiter analogue forms late (after 2 Myr) and far out (beyond 15 AU)
- Migrates into 3 AU orbit while growing to 300 $M_{\rm E}$
- Growth tracks can be bundled into a growth map
- Early formed planets migrate to become hot and warm Jupiters
- Formation after 2 Myr yields a range of planetary classes

Growth map with planetesimal accretion



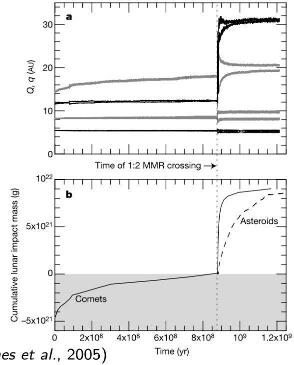
- Accretion of planetesimals can not form cores within 5 Myr, even if planetesimal surface density enhanced by factor 8 (*Bitsch et al.*, 2015)
- Hard to form Jupiter at 5 AU due to the slow accretion rate and the high migration rate

Emergence regions of planetary classes

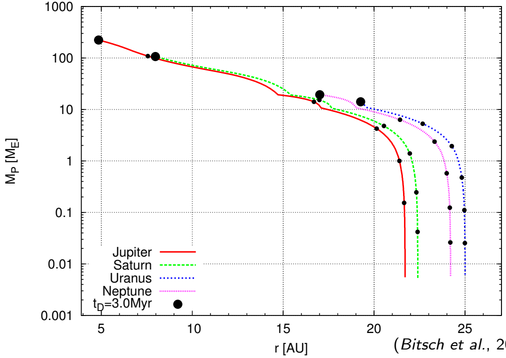


(*Bitsch et al.*, 2015)

Reaching the initial conditions for the Nice model



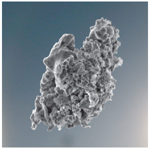
(*Gomes et al.*, 2005)

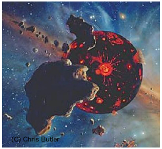


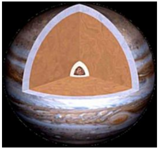
(*Bitsch et al.*, 2015)

- In the Nice model the giant planets orbit initially in a compact configuration
- Natural consequence of planetary migration combined with rapid pebble accretion
- Orbital architecture of the Nice model can be explained if the planetary embryos emerge after 1.5–2 Myr in initial orbits between 20 and 25 AU
- What happened to the embryos that formed closer to the Sun?

Summary





- Models and experiments of dust coagulation / fragmentation / bouncing are very advanced now
- Ice condensation may be another necessary ingredient for efficient formation of pebbles
- Particle clumping by streaming instabilities / pressure bumps / vortices is by now a robust phenomenon studied by several groups with independent codes
- Pebble accretion is very efficient at growth from planetesimals to planets – the full importance of this new growth mechanism is still being explored
- Asteroid belt and Kuiper belt may be sculpted by gravitational collapse, pebble accretion *and* planetesimal collisions