Planet formation with Gaia

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Observational view of planet formation

- Protoplanetary discs
- Dust grains
- Pebbles
- Gas giants and ice giants
- Terrestrial planets
- Minor bodies
Detection of exoplanets

Exoplanets are mainly found via indirect methods where the presence of the planet is inferred from its effect on the host star:

1. *Radial velocity method* (gives minimum mass)
2. *Transit method* (gives radius)

⇒ Today we know of several thousand exoplanets

- *Gaia* will detect 10,000s of Jupiter-mass planets by *astrometry* ([Casertano et al., 2008; Perryman et al., 2014](#))
- Sensitive out to 3 AU orbits in nominal 5-year mission
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 $M_{\text{env}} \approx M_{\text{core}}$
5. Form gas giant with $M_{\text{core}} \approx 10M_\oplus$ and $M_{\text{atm}} \sim M_{\text{Jup}}$

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

All steps must happen within 1–3 Myr while there is gas orbiting the star
Core formation time-scales

- The size of the protoplanet relative to the Hill sphere:
  \[
  \frac{R_p}{R_H} \equiv \alpha \approx 0.001 \left( \frac{r}{5 \text{ AU}} \right)^{-1}
  \]

- Maximal growth rate:
  \[
  \dot{M} = \alpha R_H^2 \mathcal{F}_H
  \]

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

⇒ Time to grow to 10 $M_\oplus$ is
  - \(~10\) Myr at 5 AU
  - \(~50\) Myr at 10 AU
  - \(~5,000\) Myr at 50 AU
Planetesimal accretion versus pebble accretion

- Most planetesimals are simply scattered by the protoplanet

- Pebbles spiral in towards the protoplanet due to gas friction

⇒ Pebbles are accreted from the entire Hill sphere

- Growth rate by planetesimal accretion is
  \[ \dot{M} = \alpha R_H^2 F_H \]

- Growth rate by pebble accretion is
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⇒ Pebble accretion speeds up core formation by a factor 1,000 at 5 AU and a factor 10,000 at 50 AU
(Lambrechts & Johansen, 2012; also Ormel & Klahr, 2010; Morbidelli & Nesvorny, 2012)

⇒ Cores form well within the life-time of the protoplanetary gas disk, even at large orbital distances

⇒ Population synthesis with pebble accretion
Planetary systems

- Protoplanets grow to planets by pebble accretion over 1–3 Myr \((\text{Lambrechts & Johansen, 2012; Ormel & Klahr, 2010; Lambrechts, Johansen, & Morbidelli, 2014})\)

- Growth depends strongly on the amount of heavy elements in the protoplanetary disc \((Z = 0.01 \text{ in the Sun's photosphere})\) \((\text{Lambrechts & Johansen, 2014})\)

- Gas-giant planets like Jupiter form if \(Z\) is high, in agreement with exoplanet surveys \((\text{Buchhave, Latham, Johansen, et al., 2012, Nature})\)
Migration and wide-orbit planets

Planets migrate towards the star due to gravitational torques from gas disc

Type I migration becomes much less severe if growth rate is high

Cores starting at 5 and 8 AU grow to gas giants at 2 and 3 AU

Direct imaging has revealed several wide-orbit planetary companions to young stars

HR 8799 has gas-giant planets at 15, 24, 38 and 68 AU

The critical core mass is $50 \, M_E$ at large orbital distances
Results from *Kepler* satellite show that solar-type stars are very often orbited by super-Earths in close orbits.

- Systems of super-Earths are flat to within a few degrees (*Lissauer et al.*, 2011; *Tremaine & Dong*, 2012; *Johansen et al.*, 2012)
- Super-Earths are rarely accompanied by giant planets
How do gas giants affect the formation of super-Earths?

- Super-Earths in close orbits are rarely accompanied by giant planets.

- Possible that the formation or migration of the gas giant prevents the accumulation of further planets.

⇒ Formation of small planets and large planets is coupled.

⇒ Knowing 10,000 gas-giant planets in 1-3 AU orbits from Gaia could tell lots about the conditions for forming smaller planets.