Formation of the Solar System

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Standard theory: Accretion inside a proto-planetary disk

From \( \mu \text{m} \) grains to Mm planets: 14 orders of magnitude to grow!

1) Condensation
2) Sedimentation
3) Aggregation, coagulation;
4) gravitation

Minimum Mass Solar Nebula:
Spread the masses of the planets around their present orbits

(Hayashi, 1981; Weidenschilling 1977):

\[
\Sigma (r) = 1.7 \times 10^4 \ (r / 1 \text{ AU})^{-3/2} \ \text{kg.m}^{-2}
\]

Typical PPD:

Radius = \(~\) a few 100 AU

\( \text{H/r} = 0.05 \times (r / 1 \text{ UA})^{1/4} \)
\( T(r) = 150 \text{K} \times (1 \text{ UA} / r) \)

Life-time = \(~\) 5 Myrs
Mass = \(~\) Star mass / 100
Migration ?


« The properties of the Main Asteroid Belt [...] show that Jupiter never orbited in this region. [...] The existence of a 'cold' population [in the Kuiper Belt] excludes the passage of a massive planet through that zone. [...] There is almost no room for type II migration in the Solar System. »

Conclusion: Jupiter and Saturn probably avoided migration by entering in resonance (Morbidelli & Crida 2007; Masset & Snellgrove 2001; see also Crida 2009).
The « grand Tak » scenario

Jupiter migrated inward down to 1.5 AU ! Then, caught in resonance by Saturn, it migrated back out to ~5 AU. (Walsh, Morbidelli, Raymond, O'Brien, Mandell, 2011)

This grand tak:
- truncates the inner disk of planetesimals and embryos at ~1 AU, explaining the small mass of Mars (Hansen 2009)
- explains the repartition of the S-(dry) and C-(hydrous) type asteroids in the MAB.
- brings the 4 giant planets in a fully resonant configuration, in agreement with ... (Morbidelli, Tsiganis, Crida et al. 2007)
After the proto-planetary disk dissipated, the giant planets were on circular orbits, in a compact configuration, surrounded by a massive disk of planetesimals.

A late global instability explains:

- their present orbits (Tsiganis et al. 2005)
- the Late Heavy Bombardment (Gomes et al. 2005)
- the Trojans of Jupiter and N. (Morbidelli et al. 2005)
- Hildas and D-type asteroids (Botke et al. 2008)
- the irregular satellites (Nesvorny et al. 2007)
- the Kuiper Belt structure (Levison et al. 2007)
The mid-sized moons of Saturn formed from the spreading of the (before massive) rings beyond the Roche limit. This explains:
- their young surfaces
- their ice-dominated composition, and random silicate cores
- the Mass – Distance distribution

-> planetary formation is still at play in the Solar System!
Charnoz, Salmon, Crida (2010),
Charnoz, Crida, Castillo-Rogez et al. (2011)
Conclusions and open questions

Planets do not orbit now where they formed.
( => You can't build a Minimum Mass Solar Nebula. )

Resonances are observed = consequence of migration.

Which constrains on planetary formation models?
(e.g. Planet Population Synthesis should consider resonances ...)

Late global instabilities (after gas dispersal) could be common.
Do they explain the observed eccentricities?

Which consequences for observations/detections?