Formation and migration of exoplanets

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Exoplanet formation and orbital evolution (WP 116 300)

Goals over a 5 – 10 year time scale:

- Develop formation and long-term dynamical evolution models that explain exoplanet population discovered by Kepler, K2, NGTS, CHEOPS, TESS, RV surveys, etc…

Future developments driven by improved disc models and deeper understanding of fundamental processes

- orbital architectures of multiplanet systems
- mean densities and bulk compositions
- influence of binary companions
- role played by formation environment
- influence of initial conditions
- post-main sequence phases

9 years and 1 month+ time scale:

- Make predictions for the PLATO planet population, and refine models according to discoveries
N-body simulations with migration, collisional growth and gas accretion onto planetary cores (Horry & Nelson 2012, Coleman & Nelson 2014)

**Model ingredients**

- Gravitationally interacting planetary embryos + planetesimals (Mercury-6, J. Chambers)

- Self-consistent thermally evolving 1D viscous disc model with stellar irradiation and dispersal through a photoevaporative disc wind (Dullemond et al 2011)

- Type I migration with corotation torques (Paardekooper et al 2011, Fendyke & Nelson 2014), and transition to type II migration when gap forms (Lin & Papaloizou 1986)

- Gas settling onto planetary cores – enhanced planetesimal capture (Inaba & Ikoma 2003)

- Gas accretion for cores with mass > 3 Earth masses (Movshovitz et al 2010)

- Simple chemical model that tracks ice-lines and planetary compositions through chemical tagging (Oberg et al 2012)

**Variation of parameters:**

Disc mass (1 – 5 MMSN)
Solids-gas ratio (1 or 2 x solar)
Planetesimal radii (1 or 10 km)
**Oligarchic growth**

- Formation of planetesimals followed by runaway growth to form planetary embryos
- Oligarchic/orderly growth of planetary embryos

**Question**
Can oligarchic growth, combined with a self-consistent disc model and the most up-to-date prescriptions for planet migration, lead to systems of planets similar to those observed?
Lindblad torque
Corotation torque

Type I migration of low mass planets

Type II migration of high mass planets
Gas accretion onto cores
(Movshovitz et al 2010)
Slow growth in a low mass disc: S111B
Kamikaze giants and late forming survivors: S521A
Comparing simulation results with observations

- Model leads to formation of super-Earth and Neptune-mass planets with intermediate orbital periods

- Adopting an inner boundary at 0.15 AU prevents formation of compact systems of super-Earths observed by Kepler (e.g. Kepler 11)

- The model fails to form any gas giants that survive - only two giant planets formed exterior to ~ 1 AU, due to rapid inward migration of cores when their masses \( m_p > 15 \, M_{\text{Earth}} \)
Conditions for giant planet formation and survival
Type II with slowing factor

Hydro simulation

N-body simulation

Semimajor axis versus time

Planet mass versus time

Mass versus semimajor axis
6 $M_\odot$ core – direct photoevaporation
Conclusions

• Corotation torques improve the survivability of planetary systems, but their saturation still leads to a significant loss of planets into the star.

• To form compact Kepler-like systems – probably require a migration stopping mechanism that operates at ~ few x 0.1 AU (transition between “dead zone” and fully active region in disc?)

• Planet formation simulations in low mass discs suggests that compact Kepler-like systems should be reproducible – with some fine-tuning

• Formation and survival of gas giants requires runaway gas accretion to initiate at ~ 10 AU - need to consider ways of allowing inward migration to weaken/stop at large distances from central star. Or need to slow down type II migration. Or…