AST SPECIAL TOPICS: EXOPLANETS
MISC. LECTURE NOTES: SPRING 2018

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WEEKS 10 AND 11: GIANT (AND TERRESTRIAL) PLANET FORMATION & PLANET-DISK INTERACTIONS

- Giant planet formation: overview of D'Angelo, Durison, & Lissauer chapter in *Exoplanets* (p. 319), supplemented by selected M. Wyatt slides ("4. planet formation")
- Again, planets form in disks (see *Wyatt slide 6*). Two "competing" models: (1) *core accretion* and (2) *gravitational instability*

  (1) **Core accretion** begins w/ terrestrial-planet-formation-like process — buildup of planetesimals from dust — and is followed by accretion of gaseous envelope from protoplanetary disk.

  - Dust grains coagulate into larger particles (*Wyatt slide 7*), which settle to disk midplane (*Wyatt slide 9*)
  - Grain coagulation process may be accelerated if grains develop "mantles" (coatings) of volatile ices (H_2O, CO)...hence observers are in hot pursuit of evidence for "snow lines" in disks
  - cm-sized particles eventually (somehow!) aggregate into km-size bodies: *planetesimals* (*Wyatt slides 10, 11*)
  - >km-sized planetesimals are compacted by their own gravity; can transition from "orderly growth," sweeping up disk material along orbit, to "runaway growth" phase, involving gravitational focusing (*Wyatt slide 17*)
  - Planetesimals grow into *embryos* via pair-wise collisions (*Wyatt slide 20*); larger embryos — Wyatt uses accepted term "oligarchs," but I prefer Big Mamma planetesimals — tend to sweep up all smaller planetesimals in their orbital region. *Terrestrial planet formation: no need to read further; stop here.*
  - When escape velocity from surface of embryo exceeds local thermal speed of disk gas, the gas can accrete onto the embryo — we would then call

this embryo a giant planet *core*, and the accreted gas begins to form an atmosphere, and eventually, its *envelope* (*Wyatt slide 24*)

- If protoplanet's radiation trapping becomes efficient, then it can't inhibit further accretion; pressure no longer balances gravitational force, and the envelope contracts rapidly → envelope "collapse;" happens when $M_c \approx M_e$ (*Wyatt slide 24*)
- Above "feedback loop" facilitates rapid accretion; planet is now in "runaway accretion" phase, regulated only by available disk gas in its vicinity. *Speculation (beware):* perhaps for Jupiter, Saturn lots of disk gas left in their vicinities after envelope collapse, resulting in gas giants for which $M_c << M_e$; whereas for Uranus, Neptune, very little disk gas left in their vicinities after envelope collapse, resulting in "ice giants" for which $M_c \sim M_e$.
- Even if they open a large gap in disk as a consequence of runaway accretion, giant planets can migrate, so can continue to slurp up additional disk gas (*Wyatt slide 26*).
- Kley & Nelson's ARAA review, "Planet-Disk Interaction and Orbital Evolution" (Kley & Nelson 2012, ARAA, 50, 211), `http://www.annualreviews.org/doi/pdf/10.1146/annurev-astro-081811-125523` is an excellent, very dense review of planet migration theory & simulations. We will just discuss/ponder Fig. 1 and briefly review the three main types of planet migration in disks:

  Type I migration: Applies to low-mass planet in a relatively massive disk. Planet's mass is too small to affect disk dynamically; in particular, the planet cannot open a disk gap. Migration is then determined by the competition between (a) *Lindblad torques* caused by resonance-driven disk spiral density waves and (b) *corotation torques* caused by disk material that is (nearly) corotating with the planet. Bottom line: complicated & messy math! Can result in either inward or outward migration.

  Type II migration: Applies to massive planets that are capable of opening gaps in disks. A gap forms because, quoting Kley & Nelson, "material inside (outside) the planet loses (gains) angular momentum and recedes from the planet. Consequently, the material appears to be pushed away from the location of the planet and a gap begins to open in the disk." Lindblad and corotation torques now no longer matter. Instead, "the planet is coupled to the viscous evolution of the disk." My translation: the disk slowly accretes onto the central star, and the planet goes along for the ride!

Type III migration: "Runaway" migration whose rate increases due to the effects of the migration itself on the disk. This sounds like a feedback loop, which it is. Can be inward or outward.

- See §2.4.3 of Kley & Nelson for a planet formation/migration scenario that invokes all three of the above migration types...but not in I–II-III order!

(2) **Gravitational instability** (GI) models of giant planet formation in dusty molecular disks were developed via analogy to star formation in dusty molecular clouds: gas-phase fragmentation of the disk into bound clumps (Boss 1997).

- GIs build out of local perturbations in steady-state disk conditions (density, temperature) (*Wyatt slides 41–43*)
- Stability to perturbations parameterized through Toomre Q:

  $$Q = \frac{c\kappa}{\pi G \Sigma}$$

  where $c = (\gamma kT/\mu m_H)^{1/2}$ is the local sound speed, κ is oscillation frequency of a test particle or parcel of gas about its equilibrium position — for a disk, $\kappa = \Omega$, i.e., the Keplerian angular velocity — and Σ is local surface density.
  If $Q < 1$ *then the disk is locally unstable to collapse.*
- Note that this condition implies one wants a cool disk with a high surface density. So conditions are most favorable for small Q in massive disks; conditions for small Q are even favorable in outer regions of massive disks. So...
- GI models predict planet formation (a) should occur rapidly and (b) may occur at large radii.
- Both of the foregoing predictions are supported by ALMA images of very young disks, like HL Tau (whose age is likely < 1 Myr):
  `http://www.almaobservatory.org/en/press-release/revolutionary-alma-image-reveal`
  Caveat: There are other mechanisms that could explain gaps in disks: snow lines, density waves, magnetic fields(!)...

TABLE 1. **Comparison: giant planet formation models**

	Core Accretion	Gravitational Instability
Timescale	Myr ($10^4 - 10^5$ orbital periods)	kyr (tens of orbital periods)
Disk masses	MMSN ($M_d \sim 0.01 M_\odot$) enough?	massive ($M_d \gtrsim 0.1 M_\odot$)
planet formation regions	a few AU to tens of AU	can extend to hundreds of AU