AST SPECIAL TOPICS: EXOPLANETS
MISC. LECTURE NOTES: SPRING 2015

INSTRUCTORS: JOEL KASTNER & MICHAEL RICHMOND

Week(s) 5 (and 6?): 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
  - 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
- so perhaps for Jupiter, Saturn lots of disk gas left after envelope collapse...whereas for Uranus, Neptune, very little left after envelope collapse
- 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 Fig. 1. *Students are encouraged to pick some aspect of this complex problem for a final project.*

(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 slide 41*)
- Stability to perturbations parameterized through Toomre Q:
$$Q = \frac{c\kappa}{\pi G \Sigma}$$
where c is 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.
- Conditions are most favorable for small Q in massive disks
- Conditions for small Q are also favorable in outer regions of massive disks
- GI models predict rapid planet formation may occur at large radii... *both predictions supported by HL Tau disk image (age of system < 1 Myr)?*: `https://public.nrao.edu/news/pressreleases/planet-formation-alma`

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