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Migration

- Migration regimes
- Time scale for massive planet formation
- Observational signatures

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Migration

- Gravitational perturbation from planet
  - Exchange of angular momentum with gas or particle disk
- Change in orbit - migration
- Perturbation to the disk surface density
  - Described as Type I / Type II migration depending on whether perturbation is weak / strong
Migration regimes

Slowly increase $M_p$ - compute the response of a 2D laminar disk

- **Type I** - small effect on disk, ~Earth masses
- **Type II** - gap opening at ~Jupiter mass

Displayed in an almost corotating frame
Type I migration and planet formation

Is Type I migration important for:
- Assembling giant planet cores $M \sim 20 M_{\text{Earth}}$
- Terrestrial planet formation $M \ll M_{\text{Earth}}$

Rate can be calculated analytically:
- Net torque $T \propto M_p^2 t_{\text{migrate}} M_p^{1/3}$

\[
\frac{v_{\text{migrate}}}{v_{\text{Kepler}}} = 3q \frac{r_p^2 h}{M^* r_p^{1/2}}
\]

$q = M_p / M^*$
$h / r$ is disk thickness

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For a minimum mass Solar Nebula profile:

\[ v_{migrate} \sim 1 \times \left( \frac{M_p}{M_\oplus} \right) \text{ cm/s} \quad \text{VERY FAST!} \]

Analytic estimate in agreement with simulations by Bate et al. (2003)

No reason to believe that Type I migration doesn’t occur
Critical core mass ~20 M_{Earth}

Migration matters for giant planet cores

Hourigan & Ward 84
Alibert et al. 04

\[ q = \frac{m_p}{m_*} \]

- Time scale of 1 Myr
- Migration time scale of 50 Myr (10 x disk)
Type I migration: laminar disks

- Expect fast growth up to isolation mass
- At isolation in same disk model, Type I rate matters at all radii
- Turbulent disk: scattering off fluctuations will dominate Type I rate at low enough masses
- Diffusive migration regime - planet will random walk in a
- Simulations:
Could reduce core mass + formation time scales (Rice & Armitage 2003)
Important for terrestrial planet formation??

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Type II migration

- Coupled evolution of planet + disk
- Inward at small $r$, outward at large $r$
- Uncertainty: poorly known disk physics

- How lossy is the planet formation process?
Can exclude *in situ* formation only for the small fraction of hot Jupiters: $T_{\text{disk}} > 1600 \text{K}$
Is Type II migration common?

- Expect Type II migration if:
  - Planets form significantly prior to gas dispersal
    \[ M_{\text{disk}} \left( t_{\text{form}} \right) \geq M_p \]
  - Disk evolves (accretion)

- Can we find evidence for migration in the statistical distribution of extrasolar planets: \( N(M_p, a, e, [\text{Fe/H}]...) \)?

- Models: *Trilling et al. (1998); Armitage et al. (2002); Trilling, Lunine & Benz (2002); Ida & Lin (2004a,b)*
- Distribution of planets with orbital radius is consistent with a maximal migration model:
  - Planets form at `large’ radii ~5 au
  - Migrate inward
  - Swallowed by star, unless stranded during migration by disk dispersal
- Raw census of extrasolar planets in $dN / d\log(a)$
- Selection effects + multiple surveys
- Cumming et al. (1999); Udry et al. (2003); Jones et al. (2004)
Distribution of planets with $M > M_J$ only
Predicted distribution from migration only - Armitage et al. (2002)
Not unique - may be able to identify better signatures using extra information from host star metallicity

Observationally and theoretically, planet formation via core accretion becomes much easier at higher [Fe/H] or $\frac{p}{s}$.

If we assume that [Fe/H] differences are the main source of variations in $\frac{p}{s}(r)$, present host metallicity tells us how quickly cores formed at different radii.
Schematically:

- Core forms quickly: substantial migration
- Core forms just as the gas is about to be lost: little or no migration

Lower envelope of planets in [Fe/H] - a plane defines a sample of objects predicted to suffer less than average migration
Criticalmetallicity curve depends upon planet formation model (e.g. amount of Type I migration) + surface density profile of disk.

No Type I migration: Rice & Armitage ‘05

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Simple core accretion models (cf Ida & Lin 04) including slow Type I migration of the core

- Measurement of critical [Fe/H] as f(a) from large planet samples at a ~ few au could constrain core accretion models
Summary

- Stochastic migration of very low mass bodies from scattering off turbulent fluctuations

- Type I migration rate is fast - will impact growth of giant planet cores

- Expect Type II migration to be common - future observations may confirm statistical clues that it really happened