Disc-Planet Interactions during Planet Formation

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Talk Outline

• Protoplanets in laminar protostellar discs:
  Low mass planets – type I
  Corotation torques - type III
  High mass planets – type II

• Protoplanets in turbulent discs:
  Dead-zones
  Low mass planets
  Planetesimals
  High mass planets

• Effect of a “migrating Jupiter” on terrestrial planet formation

• Conclusions
Low mass planets – type I

- Planet generates spiral waves in disc at Lindblad resonances
- Gravitational interaction between planet and spiral wakes causes exchange of angular momentum
- Wake in outer disc is dominant (pressure support shifts resonant locations) – inward migration
- Migration time scale ~ 70,000 yr for $m_p=10 \ M_{\text{earth}}$
- Giant planet formation time $\gtrsim 1 \ \text{Myr}$

QuickTime™ and a YUV420 codec decompressor are needed to see this picture.
Evidence for type I migration

• Recently discovered short-period low mass planets:
  13 planets with $m \sin i < 40 \text{M}_{\text{Earth}}$
  (e.g. HD69830 - 3 planets Lovis et al 2006)

• All disc models agree
  $T > 1500 \text{K}$ within 0.1AU
  - dust sublimes
  - planets must form further out and migrate in

• Type I migration does occur!
  - but probably more slowly than predicted by basic theory
Stopping/slowing type I migration

- MHD Turbulence (see later)
- Planet-planet scattering (Cresswell & Nelson 2006) - migration stops if $e > H/r$
- Corotation torques may slow/stop planet migration (Masset et al 2006)
- Strong magnetic field (Terquem 2002; Fromang, Terquem & Nelson 2005)
- Opacity variations: sharp transition in density and temperature (Menou & Goodman 2002)
- Eccentric disks (Papaloizou 2002)
- Planet enters cavity due to transition from ‘dead-zone’ to ‘live zone’ - planet trap (Masset et al. 2005)
Low mass planetary swarms

- Consider a swarm consisting of between 5 - 20 low mass interacting planets.
- Question: can interaction within the swarm maintain an eccentric population and prevent type I migration?
- Answer: No!
- Outcomes:
  - Initial burst of gravitational scattering
  - Collisions (~1 per run)
  - "Stacked" mean motion resonances
  - Inward migration in lockstep
  - Exotic planet configurations: Horseshoe and tadpole systems (sometimes in MMR with each other)
May be detected by COROT or KEPLER
Corotation torques – type III

Corotation torques arise from horseshoe region

Intermediate mass planets may undergo type III migration (Masset & Papaloizou 2003)
Can corotation torques slow type I?

(Masset, D’Angelo & Kley 2006)
3D simulations with evolving planets

Viscous discs

Inviscid discs

Questions: Dead-zones? Does corotation torque operate in turbulent disc?

\[ \Sigma = \text{constant} \]
\[ H/r = 0.05 \]
\[ \alpha = 0.005 \]

\[ \Sigma = \text{constant} \]
\[ H/r = 0.05 \]
\[ \alpha = 0.0 \]
High mass protoplanets

- When planets grow to ~ Jovian mass they open gaps:
  
  (i) The waves they excite become shock waves when $R_{\text{Hill}} > H$
  
  (ii) Planet tidal torques exceed viscous torques

- Inward migration occurs on viscous evolution time scale of the disk
• Inward migration occurs on time scale of ~ few $\times 10^5$ year
• Jovian mass planets remain on ~ circular orbits
• Heavier planets migrate more slowly than viscous rate due to their inertia
• A 1 $M_J$ planet accretes additional 2 – 3 $M_J$ during migration time of ~ few $\times 10^5$ yr
Eccentricity Evolution

- Disc interaction can cause both growth and damping of $e$ due to interaction at ELRs, CRs, and COLRs
- So far simulations show damping for Jovian mass planets
- For $M_p > 5 \, M_{\text{Jup}}$ can get disc eccentricity growth
  - planet eccentricity growth? (Kley & Dirksen 2005)

- Origin of exoplanet eccentricities: planet-planet scattering? Simulations tend to generate too many high $e$ planets (Rasio & Ford; Papaloizou & Terquem 2003; Laughlin & Adams 2004)
Evidence for type II migration

- Existence of short period planets (Hot Jupiters)
- Resonant multiplanet systems: GJ876 – 2:1
Planets in turbulent discs

- Magnetorotational instability
  $\Theta \Rightarrow$ vigorous turbulence in discs
  (Balbus & Hawley 1991; Hawley, Gammie & Balbus 1996, etc…)

- Necessary ingredients:
  (i) Weak magnetic field
  (ii) $d\Omega / dR < 0$
  (iii) Sufficient ionisation:
    $X(e^-) \sim 10^{-12}$
  (iv) $Re_m > 100$

Dust free disc $\sim$ 50 % of matter turbulent
Dusty disc $\sim$ 1 % of matter turbulent

Ilgner & Nelson (2006a,b,c)
Cylindrical disc models

- Models computed using 3D MHD code NIRVANA
- Cylindrical discs – no vertical component of gravity
- Equation of state - locally isothermal
- Disc thickness – $H/R=0.07$
- Assume ideal MHD
\[ T_m = \frac{B_r B_\phi}{4\pi} \]

\[ T_R = \rho \delta v_r \delta v_\phi \]

\[ \alpha = \frac{T_R - T_m}{P} \]
Low mass protoplanets

What is effect of turbulence on embedded protoplanets?
Fluctuating torques – suggest stochastic migration
$Mp = 10$ Earth masses
100 metre sized planetesimals

- 100 m sized objects dominated by fluctuations in disc gravity
- Instead of inward drift undergo `random walk’ on time scales ~ 100 orbits
- Icy 100m sized objects fragment if $v < 14$ m/s
- $v \approx 120$ m/s for $e=0.01$ at 5 AU
- Destructive collisions are likely outcome
- Runaway growth slows down
High Mass Planets

- $5$ and $3 \, M_{\text{Jupiter}}$ protoplanets
- Form gaps and migrate inward on time scale $\sim 10^5 \, \text{yr}$

*QuickTime™ and a YUV420 codec decompressor are needed to see this picture.*
Vertically stratified models

\[ H/R = 0.1 \]
Initial net flux toroidal field
Disc height \( \sim 4.5 \) scale heights
\( \alpha \sim 4 \times 10^{-3} \)

Consider \( mp=1 \) and 10 Earth masses
Stochastic torque amplitude $\sim 1/10$ cylindrical disc value: 
$M_{\text{disc}} \sim 1/2$ cylindrical model 
$(\delta \rho/\rho)_{\text{stratified}} \sim 1/2 (\delta \rho/\rho)_{\text{unstratified}}$
Disc vertical thickness acts to soften stochastic torques 
Stochastic torques scale as $(H/R)^2$ ?
Softening due to stratification
Migration distance $\sim 1/10$ obtained in cylindrical runs
Eccentricity growth < e growth obtained in cylindrical discs
But still large enough to disrupt planetesimals and slow runaway growth
mp=10 Earth mass planets

Need to perform longer simulations with thinner discs
Terrestrial Planet Formation During Giant Planet Migration

- N-body simulations performed (Fogg & Nelson 2005)
- **Initial conditions:** inner disk undergoing different stages of `oligarchic growth’
- Giant planet migrates through inner planet-forming disc
- General outcomes:
  (i) massive terrestrial planets can form interior to migrating giant
  (ii) significant outer disk forms from scattered planetesimals and embryos
  (iii) terrestrial planets can form in outer disc
Accretion in an oligarch and planetesimal disk, initially consisting of 0.025 $M_\oplus$ oligarchs and 0.0025 $M_\oplus$ planetesimal clusters between 0.4 - 2.7 AU and 0.1 $M_\oplus$ oligarchs and 0.01 $M_\oplus$ planetesimal clusters between 2.7 - 4.0 AU.

Disk mass: 3MMSN; Gas $\alpha = 2 \times 10^{-3}$
Nominal start time: 0.5 Myr.
Run time = 100000 years.
Nominal start time: 0.5 Myr.
0.5 M_\odot giant appears and starts to migrate @ 100000 years.
Run time = 120000 years.
Nominal start time: 0.5 Myr.
0.5 M_j giant appears and starts to migrate @ 100000 years.
Run time = 140000 years.

scenario 1a
Nominal start time: 0.5 Myr.
0.5 $M_\odot$ giant appears and starts to migrate @ 100000 years.
Run time = 200000 years.
Inner regions of Scenario la @ runtime = 206000 years

4.035 M_Ε
Conclusions and Future Directions

• Low mass planets migrate rapidly in laminar discs
• Multiple low mass planet systems display: inward resonant migration, horseshoe and trojan systems - observable by COROT or KEPLER?
• Turbulence modifies type I migration and may prevent large-scale inward migration for some planets
• Turbulence increases velocity dispersion of planetesimals and may lead to destructive collisions and quenching of runaway growth
• Stochastic forces experienced by planets in vertically stratified discs lower in amplitude due to finite disc thickness
• Terrestrial planets probably form in “hot Jupiter” systems