Planet migration with gravitationally unstable gaps

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Last time

- Massive planet & massive disc
- Planet migrates *outwards*
Outline

Part I:
- Review of instability
- Numerical results
- A fiducial case
- Discussion and future work

Part II:
- Validating the use of 2D discs
Gravitational instability in structured discs

- Level of self-gravity (SG) usually measured by Toomre $Q$:

$$Q \equiv \frac{c_s \kappa}{\pi G \Sigma}$$

- Locally Toomre unstable if $Q \lesssim 1$. 
Gravitational instability in structured discs

- Level of self-gravity (SG) usually measured by Toomre $Q$:
  \[ Q \equiv \frac{c_s \kappa}{\pi G \Sigma} \]

- Locally Toomre unstable if $Q \lesssim 1$.

- Discs can be unstable if it has radial structure. An important quantity is the vortensity profile $\eta$:
  \[ \eta \equiv \frac{\kappa^2}{2\Omega \Sigma} \]

- Instabilities associated with $\min(\eta)$ or $\max(\eta)$.
Application to planetary gaps

$Q_0$ parameterises disc models (inversely proportional to disc mass).

- Gap GI first suggested by Meschiari & Laughlin (2008)
- Explicitly confirmed by Lin & Papaloizou (2011a)
Application to planetary gaps

- Global instability associated with $\max(\eta)$, equivalent to $\max(Q)$ for gaps.

\[ t = 30.0 P_0 \]

- Disturbances inside the gap edge
The co-orbital region

\[ r \]

\[ 2.5r_h \]
The co-orbital region

\[ r \]

\[ 2.5r_h \]

low $\Sigma$ gap

higher $\Sigma$ edge
The co-orbital region

\[ r \]

\[ 2.5r_h \]
Numerical experiments

- 2D self-gravitating disc-planet simulations

- Three disc masses: \( M_d/M_\ast = 0.06, 0.07, 0.08 \)
  \( (Q_o = 2.0, Q_o = 1.7, Q_o = 1.5) \)

- 2-Jupiter mass planet \( (M_p/M_\ast = 0.002) \) initially at \( r = 10 \)

- Domain \( r = [1, 25] \), resolution \( N_r \times N_\phi = 1024 \times 2048 \) (28 cells per Hill radius)
Unstable gaps & migration

- \( \log \left[ \Sigma / \Sigma(t = 0) \right] \) plotted
Unstable gaps & migration

![Graph showing torque over time with unstable gaps for different Q values]
Unstable gaps & migration

![Graph showing migration with unstable gaps](image)

- $Q_o = 1.5$
- $Q_o = 1.7$
- $Q_o = 2.0$

$t/\text{orbits}$

$r_p(t)$
Gap evolution

- Gap is more shallow with increasing instability
The $Q_0 = 1.7$ case
Passage of spiral arms

- Instability sends material to the planet for interaction
Passage of spiral arms

Show movie
Co-orbital torques

$Q_0 = 1.7$

$Q_0 = 2.0$

Torque

$(r-r_p)/r_h$
Discussion & future work

- Migration in massive discs: Baruteau et al. (2011); Michael et al. (2011)
- Migration of stars in black hole accretion discs (e.g. McKernan et al., 2011)
- Parameter study
Three-dimensional discs

- All previous works on gap stability use 2D disc models (Lin & Papaloizou, 2010, 2011a,b)
- Verify with counterpart 3D simulations
- ZEUS-MP code: add planet and boundary potential solver
Vortex-induced migration

- Lin & Papaloizou (2010): vortex formation at gap edges in low viscosity discs
- Non-monotonic migration: discrete jumps in orbital radius
Vortex-induced migration

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Vortex modes in 3D self-gravitating discs

- Lin & Papaloizou (2011b): more vortices with increasing SG, and
- Resisted vortex merging with increasing SG
Vortex modes in 3D self-gravitating discs

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- Top: $Q_\omega = 4.0$, bottom $Q_\omega = 8.0$. 
Vertical structure

- Relative density perturbation in $R - z$ plane

50.00 orbits, $\phi/2\pi = 0.126$

- Top: relative to non-SG background, bottom: relative to SG background
Gravitational instability of gaps

- Lin & Papaloizou (2011a): global spirals attached to gaps in massive discs
Outward migration induced by GI inside gap

\[ \frac{a}{e} \text{ (solid)} \]

\[ \frac{t}{\text{orbits}} \]

0.00
0.02
0.04
0.06
0.08
0.10
10.0
10.2
10.4
10.6
10.8
11.0
20
40
60
80
100
120

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Conclusions & future work

- Checked that 2D results persist in 3D
- Vertical boundary conditions
- Self-gravitational collapse of a disc vortex
- Gravitational stability of planetary wakes
- All future simulations will have SG as standard
- Documentation for code modifications
References