Accelerated planetesimal growth in self-gravitating protoplanetary discs

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Planet formation theories

- **Gravitational instability** (Boss 2000):
  - Requires extreme conditions
    - Massive discs (maybe possible)
    - Very fast cooling \( t_{\text{cool}} < 3 \Omega^{-1} \), Gammie 2001, Rice et al. 2003
  - Produces only very massive planets \( (M > 5M_{\text{Jupiter}}) \)

- **Core accretion** (Pollack et al. 1996):
  - Growth of planetesimals from small dust grains
  - Problems:
    - sticking efficiency ?
    - long formation timescales (longer than disc lifetime?)
    - planetesimal migration
Dust migration: gas drag

- Gas supported by pressure: in a smooth, power-law disc moves in sub-Keplerian orbits
- Dust grains: move in Keplerian orbits
- Gas drag causes the grains to migrate toward regions of high pressure (inwards) Weidenschilling 1977
- Metre-sized particles drift rapidly inwards (on a timescale of \(~ 10^3\) yrs)
Self-gravitating discs

- Early phases of star formation: disc mass can be large (Lin & Pringle 1990)
- Even in T Tauri phase disc masses up to $> 0.1 \, M_\ast$ (Natta et al. 2003)
- Fragmentation unlikely, but still gravitational instability can develop a spiral structure
  - Angular momentum transport ($\alpha \sim 0.05$) (Lodato & Rice, MNRAS 2004)
  - Strong influence on the dynamics of small planetesimals
SPH simulations of gas-planetesimal interaction

- Modified SPH code to include "planetesimals"
  - Treated as "test" particles that move under the influence of gravity and drag force only
  - No back-reaction on the gas

- Modelled a 2-component (gas+planetesimals) disc
  - Same initial density profile ($\rho_p/\rho=0.01$)
  - Single sized planetesimal disc (50 cm, 1000 cm, no drag)
  - Massive disc ($M_{\text{disc}}=0.25M_*, R_{\text{out}}=25$ au, Lodato & Rice 2004)
  - Initially pure gas evolution: (include heating and cooling!)
Surface density enhancement $\sim 5$

1000 cm

Surface density enhancement $> 50!$

50 cm
Planetesimal density enhancement

- The density of the planetesimal disc is greatly enhanced
- What fraction of the planetesimals reach high densities during the evolution?

![Diagram showing the distribution of densities and time evolution of densities.](image)
Implications for planetesimal growth

• Enhanced collision rate:
  – for the 50 cm case, collision rate up by 2 orders of magnitude

• Gravitational instability in the planetesimal disc?
  – Mass within a smoothing length can be comparable to Jeans mass
Summary

• We have considered the combined effect of gas self-gravity and drag on the dynamics of a planetesimal.
• For metre-sized planetesimal, we find large density enhancements along the spiral arms.
• This could have significant effects on the growth of planetesimal by:
  – Enhancing the collision rate *(significant processing even before the T Tauri phase?)*
  – Enhancing the possibility of gravitational instability
    (note that this is NOT the Boss mechanism but the Goldreich & Ward 1973! Furthermore we are not affected by vertical shear instability, Weidenschilling & Cuzzi 1993)
Remaining issues

- Include the planetesimals' self-gravity and the back-reaction on the gas (important when $\rho_p \sim \rho$)
- Consider a distribution of sizes for the planetesimals (e.g., Mizuno et al. 1988, Mathis 1977)
- How do the results change for different gas disc masses (e.g., do the relevant planetesimal size change)?