Trapping dust particles in the outer regions of protoplanetary and transitional disks

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The Origins of Stars and their planetary systems
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Main Goals

How to overcome the meter-size barrier and explain the observed mm-grains in the outer regions of protoplanetary disks?

How is the dust evolution in a disk, where the gas density profile is determined by its interaction with a massive planet?
However, mm-size pebbles are observed in the outer regions of the disk (Natta et al. 2007; Ricci et al. 2010+...2012)
Particle traps

\[ v_{\phi,\text{gas}} = (1 + \eta) \, v_{\text{Kepler}} \]

\[ \eta \propto \frac{dP}{dr} \]

Trapping of dust particles in pressure maxima

Orbital Gas Velocity

Particle Traps
- Dead Zones
- Evaporation Front
- Giant Planets
- Zonal Flows

Super-Keplerian Velocity

Sub-Keplerian Velocity

\[ v_{\phi,\text{gas}} = (1 + \eta) \, v_{\text{Kepler}} \]

\[ \eta \propto \frac{dP}{dr} \]

Long-lived pressure bumps

Coagulation Model

Grains grow, crater and fragment due to radial drift, turbulent mixing and gas drag.

Pressure Bumps

Isothermal Disk

\[ \Sigma'(r) = \Sigma(r) \left( 1 + A \cos \left( 2\pi \frac{r}{L(r)} \right) \right) \]

\[ L(r) = f H(r) \quad H(r) = c_s \Omega^{-1} \]

- Effect of \( A \) and \( L(r) \).
- Comparison with mm-observations.
- Physical processes that may cause such long-lived pressure bumps.
- Future ALMA observations.

Fragmentation velocities based on laboratory experiments with ices (e.g. Blum & Wurm 2008)

\[ v_f \approx 10 \text{ms}^{-1} \]
Effect of the amplitude

\[ v_{\phi, \text{gas}} = (1 + \eta) \, v_{\text{Kepler}} \]

\[ \eta \propto \frac{dP}{dr} \]

\[ \eta > 0 \Rightarrow A_{\text{min}} = 0.1 \]

For \( A \sim 30\% \) the trapping of particles is effective.

\( \text{Pinilla et al. 2012} \)
Effect of the wavelength

With a shorter wavelength, the diffusion times becomes much more shorter.

\[ \nu = \alpha \frac{C_s^2}{\Omega} \quad \tau_\nu \propto \frac{\ell^2}{\nu} \]
Dust density distribution

\[ \text{St} \propto \frac{a \rho_s}{\Sigma} \]

\[ a_{\text{max}} \approx \frac{4 \Sigma}{3 \pi \alpha \rho_s} \frac{v_f^2}{c_s^2} \]

**DUST EVOLUTION IN A BUMPY GAS SURFACE DENSITY**

**AMPLITUDE 30%**

Pinilla et al. (2012)

Particles reach cm-mm sizes in the outer regions of the disk and they are retained for several million years.
Comparison with mm-observations

$L. \text{ Ricci's Talk}$

$F_v \propto \nu^{\alpha_{1-3\text{mm}}}$

If $\alpha_{1-3\text{mm}} \leq 3$
dust grain grow
to sizes $>1$ mm

Observations done by $L. \text{Ricci et al.}$ and obtained with mm interferometers (PdBI, CARMA, SMA, ATCA) for disks in Taurus, Ophiuchus star forming regions
Approach to zonal flows

Global 3D-simulations of a magnetized turbulent disk by *Uribe et al.* 2011

**Assumption:** quasi-steady state from MRI simulations (~1000 orbits) and they are long-lived perturbations
Transitional Disks

How is the dust evolution in a disk, where the gas density profile is determined by its interaction with a massive planet?
Transitional disks

S. Andrews’ talk

Williams & Cieza (2011)

Flared Disk
\[ \alpha = 10^{-3} \]

1000 orbits

Pressure Gradient

\[ r_{\text{gap}} \sim 5 \, r_{\text{Hills}} \]

\[ r_{\text{gap}} \sim 10 \, r_{\text{Hills}} \]

Dodson-Robinson et al (2011)
Zhu et al (2011)
Pinilla, Benisty & Birnstiel (submitted to A&A)
The case of LkCa15

Planet at $15.7 \pm 2.1$ AU with mass of $6 \, M_{\text{Jup}}$ to $15 \, M_{\text{Jup}}$

Kraus & Ireland (2011)
Ring shaped dust accumulation

Gaps formed by massive planets

Dust Evolution

Dust Evolution

Gap created by a 15M\textsubscript{jup} Planet
Flared Disk \& \( \alpha=10^{-3} \)

Pinilla et al (2012)

2D hydrodynamical simulation of a 15 M\textsubscript{jup} planet embedded in a disk, Using FARGO (Masset 2000)

Continuum model map for LkCa15.
Units are in Jy/beam.
Take home conclusions

Long-lived pressure bumps of ~25-30% of amplitude can explain the presence of observed mm-sized particles in the outer regions of disks.

Those pressure bumps may origin from MRI and future ALMA observations are very important to detect them and for understanding the impact on grain growth for planet formation.

Proper dust evolution modeling is needed for the interpretation of the shape of transitional disks with a possible embedded giant planet.

Measuring the spectral index of transitional disks with ALMA will help to test the idea that the ring structures are indeed particle traps.
Thank you for your attention

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