Particle Trapping at Planet-Induced Gap Edges and Vortices

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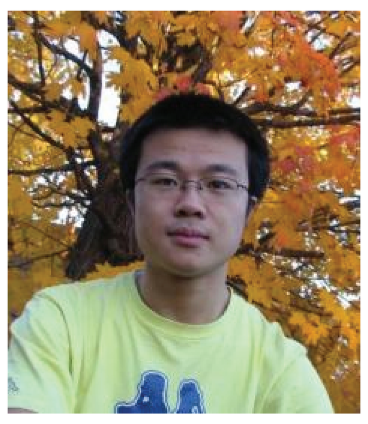
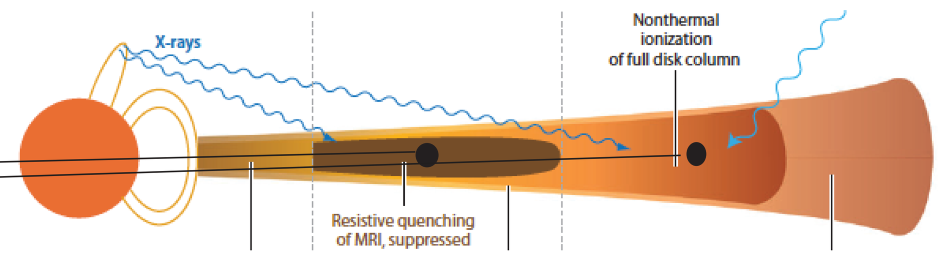


We use numerical simulations to perform a systematic study on the dynamics of dust particles in protoplanetary disks under the influence of a planet in disks. Dust particles in viscous disks (representing turbulent regions in disks) and inviscid hydro disks (``dead zone'') have been simulated separately using our newly developed Two-Fluids FARGO and ATHENA+Particle codes. For inviscid 3-D disks, we found that a low mass planet (8 $M_\oplus$) open almost unnoticeable gaps in gas which can still lead to significant dust piling up at gap edges. Sharp gap edges carved out by a massive planet are unstable to the formation of vortices, which can efficiently trap particles with a wide range of sizes (at least 4 orders of magnitude in our cases). Thus gaps and vortices in particle disks should be very common if there are planets in the ``dead zones''.

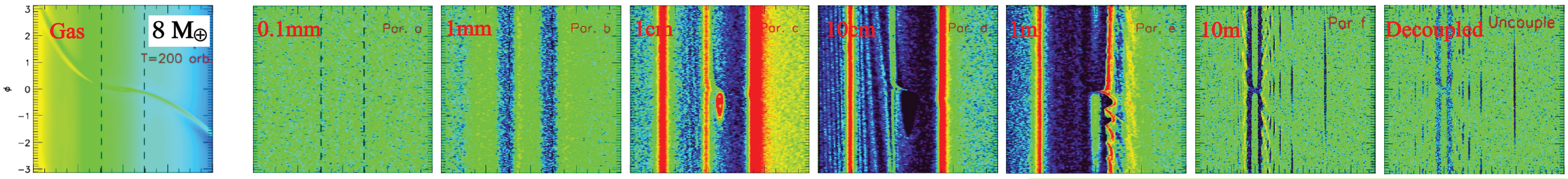
For viscous disks, the dust features are significantly smoothed out by the parameterized turbulent diffusion, and small dust particles can follow the accreting gas flowing to the inner disk. Thus, the so-called ``dust filtration'' mechanism by the gap edges can differentiate big and small dust particles. MHD simulations are developed to understand the gap opening and particle concentration in realistic turbulent disks.

Introduction:

A realistic protoplanetary disk has a layered accretion structure (Fig. 1). Both the inner disk and the outer disk are MRI turbulent, while in the region between ~AU to 10s of AU only the disk surface is MRI turbulent and the midplane is quiescent (the ``dead zone''). We ask how planets affect dust particles in 1) the dead zone and 2) the turbulent regions.



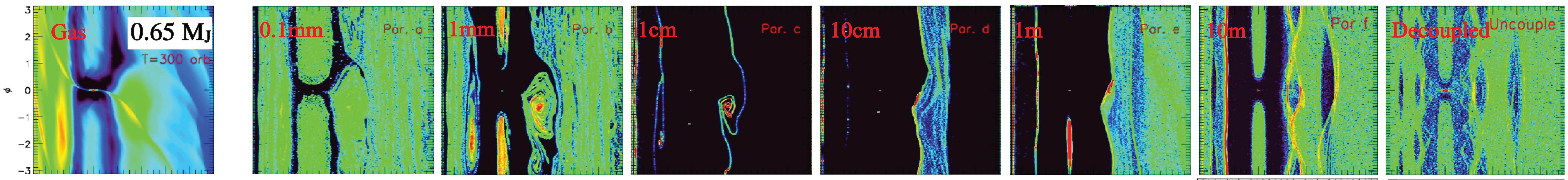
Dust Particles in Inviscid Disks (``dead zone'') with Planets



With the presence of a low mass planet, two shallow gaseous gaps start to open on each side of the planet at the distance where the nonlinear spiral wake steepens to shocks. We find that although these gaps may be barely visible in the gaseous disk after several hundred orbits the gaps are very prominent in dust disks since the shallow gaps in the gas change the drift speed of dust particles leading to particles' piling up at the gap edge. Particles also concentrate at the coorbital region of the planet.

The gas and dust surface densities in the R-Φ plane with a 8 $M_\oplus$ planet at 20 AU. For dust particles, the ratio between the dust and gas surface densities are shown.

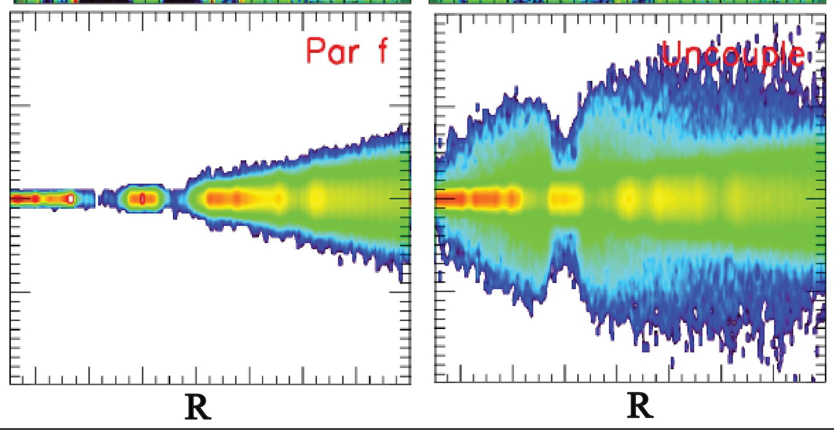
For big particles, the particle dynamic nature starts to be revealed since particles eccentricity cannot be damped within one orbit by gas drag (e.g. 1m). Particles having the same eccentricity collectively form ``ripples'' in the disk, similar to Saturn's ring. For almost fully decoupled particles (e.g. 10m), eccentric orbits at the mean motion resonances become apparent.



A massive planet can quickly induce sharp gap edges, which are unstable to the formation of vortices. Eventually these vortices merge into one single vortex, which can last more than several hundred orbits until the end of our simulations. The vortex can effectively trap dust particles. We find that the vortex is intrinsically 2-dimensional having no strong vertical motion, and thus particles settle to the midplane in the vortex without being stirred to the atmosphere. In our simulations, particles with 0.02<Ts<20 have significant concentration within the vortex within one hundred orbits.

The gas and dust surface densities in the R-Φ plane with a 0.65 M_J planet at 20 AU. Dust distributions in the R-Z planet for 10 m and decoupled particles are shown on the right.

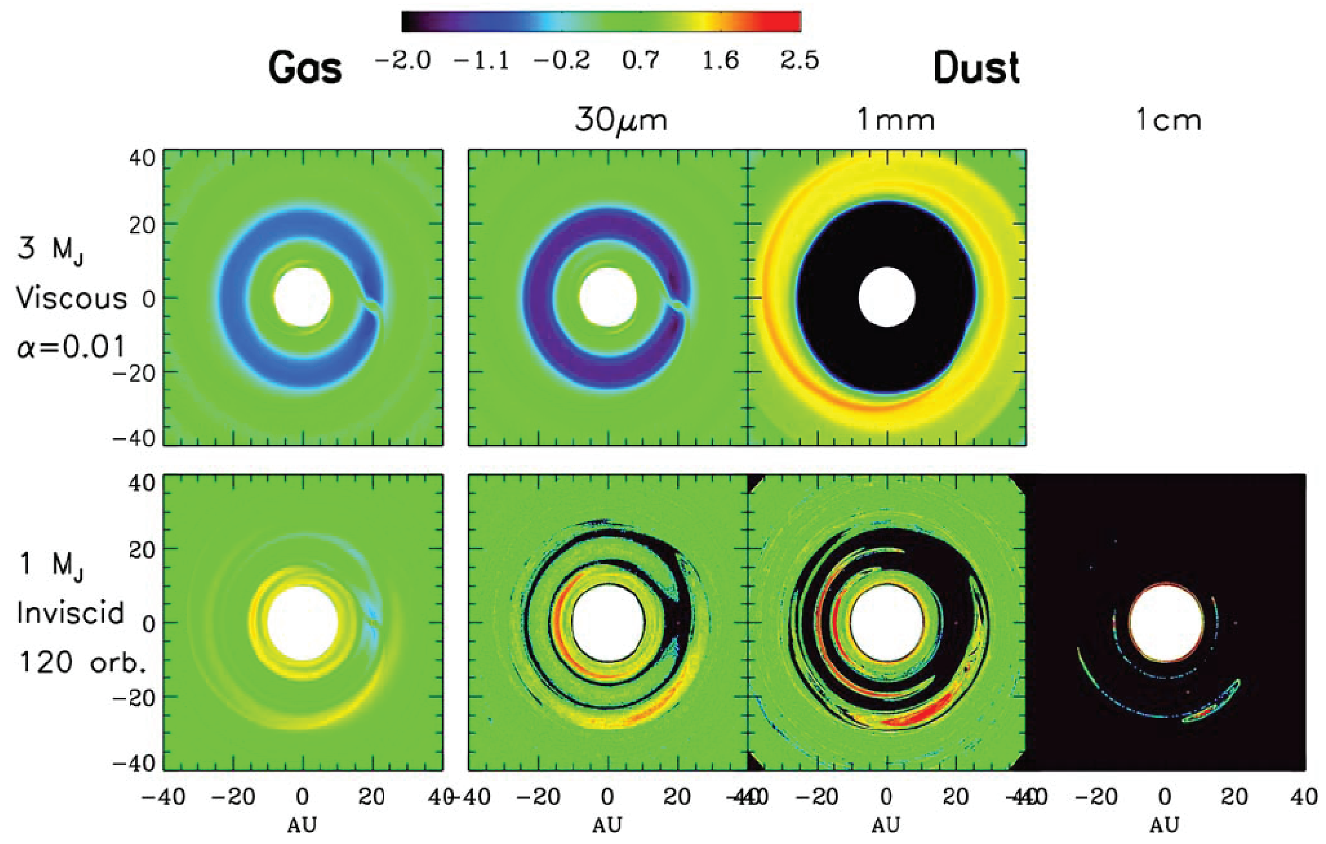
Not only the particle eccentricity but also the inclination angle can be excited by the planet if gas drag is small. The right panels show that the disk is significantly puffed up close to the planet.



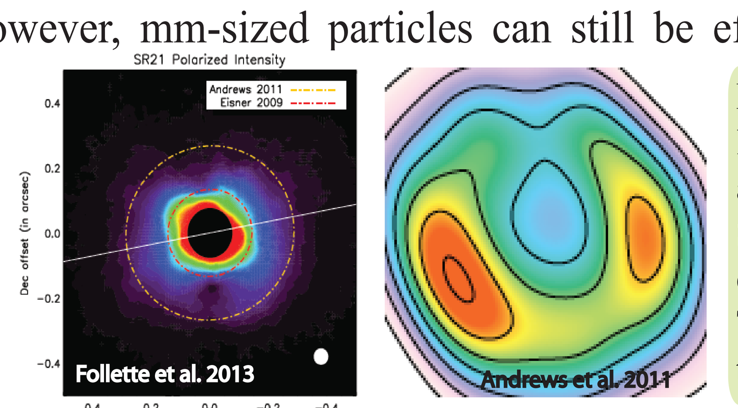
Dust Particles in Viscously Accretion Disks with Planets

If the disk is actively accreting, dust particles will try to follow the gas flowing inwards across the gap. However, at the outer gap edge dust particles also try to drift outwards. The flow which manages to cross the gap is dust free. This dust filtration mechanism was thought to be efficient to stop micron sized dust particles (Rice et al. 2006). However, we find that including dust diffusion due to disk turbulence significantly makes dust filtration less efficient, especially for small particles. Micron sized particles can hardly be stopped by the gap edge induced by a Jupiter mass planet in an α=0.01 disk. However, mm-sized particles can still be efficiently trapped at the gap edges.

Right: The gas and dust surface densities in the X-Y plane with a planet at 20 AU. The upper panel shows the visous disks with α=0.01, while the lower panel shows the inviscid disks as in the previous section, and the vortex is elongated.



Our result that small dust can exist at the inner disk seems to be consistent with recent findings that a lot of transitional disk showing sub-mm cavities do not show cavities at near-IR scattered light images.

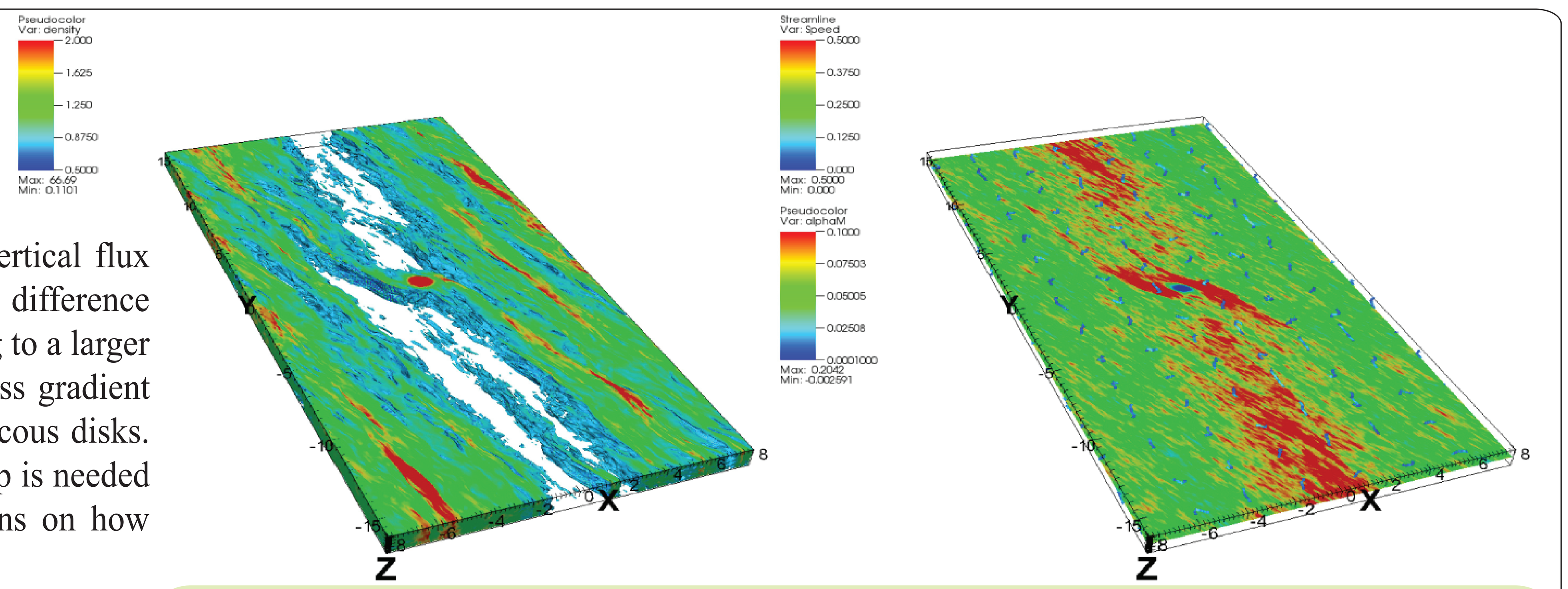


Left: Near IR polarized scattered light image of SR 21 from Follette et al. 2013 compared with the submm SMA interferometry from Andrews et al. 2011 at the same spatial scale. The disk is dramatically different at these two wavelengths.

Planet gap opening in MRI turbulent disks

We have carried out 3-D unstratified shearing box MHD simulations to study the planet gap opening process in MRI turbulent disks which are threaded by net vertical flux.

We find that the same mass planet opens a significantly deeper and wider gap in net vertical flux MHD disks than that in the viscous disks which have the same equivalent stress. This difference arises due to the efficient magnetic field transport into the gap region in MRI disks, leading to a larger effective α within the gap. The gap shape is determined by the balance between the stress gradient and the planetary torque density. The planetary torque density is similar in MHD and viscous disks. To balance this torque density, in net vertical flux MHD disks, a deeper/sharper density gap is needed to produce enough Maxwell stress gradient with a non-uniform α. Further investigations on how MHD turbulence affects dust particles are underway.



Left Panel: Volumetric rendering of the density during the interaction between the planet and the net vertical flux MRI turbulent disk. Regions with densities below 0.8 midplane density are removed. Right Panel: The time averaged α_{Max}= $-\langle B_x B_y \rangle/\Sigma$ at the z=0 slice for this case. The time averaged magnetic field streamlines are also plotted. The turbulent component of the magnetic fields is averaged out and the averaged fields show the net vertical field geometry. The net vertical magnetic fields diffuse freely into the gap, causing a higher α.

References:

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