Dusts in an eccentric protoplanetary disk with an embedded massive planet

Pin-Gao Gu (辜品高)
He-Feng Hsieh (謝何峰)

Institute of Astronomy & Astrophysics, Academia Sinica
Taipei, Taiwan

outline

- motive
- brief review on eccentric disks and dust aerodynamics
- works done by other groups
- our simple study
- summary

outline

- motive
- brief review on eccentric disks and dust aerodynamics
- works done by other groups
- our simple study
- summary

Gap in protoplanetary disks

observation

Andrews et al. 2011

cavity & asymmetry

signpost of a giant planet?

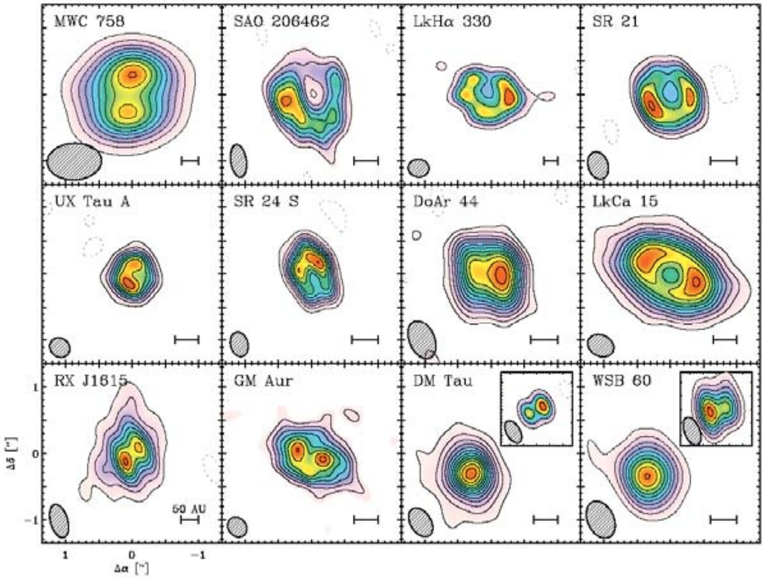
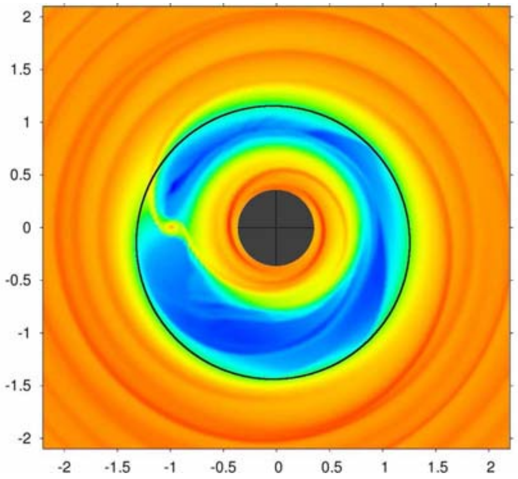


Figure 1. SMA aperture synthesis maps of the 880 μm continuum emission from this sample of transition disks. Each panel is $2''\!.7$ on a side (offsets are referenced to the disk centers listed in Table 1; see Section 2) and contains a 50 AU projected scale bar in the lower right for reference. Contours are drawn at 3σ intervals, and the synthesized beam dimensions are marked in the lower left corner (rms noise levels and beam dimensions are provided in Table 2). The inset images for the DM Tau and WSB 60 disks were synthesized with higher angular resolution and are shown to scale.

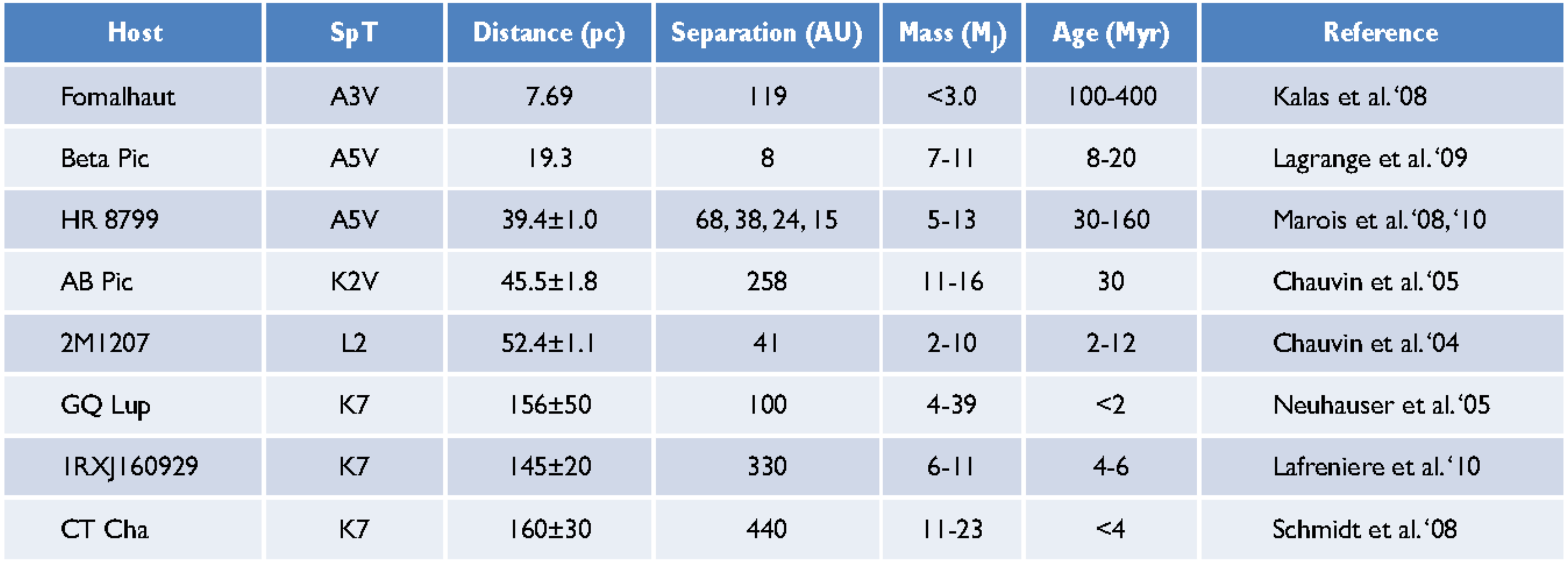
simulation

Kley & Dirksen 2006



Exoplanets on wide orbits!

Kalas 2011 direct imaging by coronagraph techniques



Host	SpT	Distance (pc)	Separation (AU)	Mass (M_J)	Age (Myr)	Reference
Fomalhaut	A3V	7.69	119	<3.0	100-400	Kalas et al.'08
Beta Pic	A5V	19.3	8	7-11	8-20	Lagrange et al.'09
HR 8799	A5V	39.4±1.0	68, 38, 24, 15	5-13	30-160	Marois et al.'08,'10
AB Pic	K2V	45.5±1.8	258	11-16	30	Chauvin et al.'05
2M1207	L2	52.4±1.1	41	2-10	2-12	Chauvin et al.'04
GQ Lup	K7	156±50	100	4-39	<2	Neuhauser et al.'05
1RXJ160929	K7	145±20	330	6-11	4-6	Lafreniere et al.'10
CT Cha	K7	160±30	440	11-23	<4	Schmidt et al.'08

Table 1. Properties of directly detected exoplanet candidates

Why on large orbits: Boss 2011, Crida et al. 2009

outline

- motive
- brief review on eccentric disks and dust aerodynamics
- works done by other groups
- our simple study
- summary

Eccentric instability

Lubow 1991

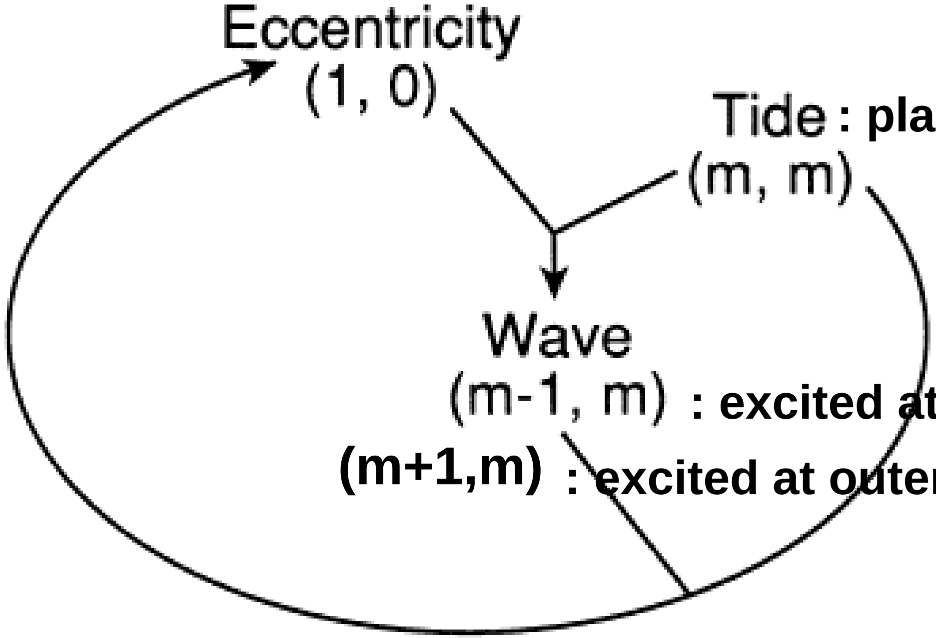
velocity departure from circular orbit:

$\mathbf{v} \propto \exp[i(k\phi - l\Omega_{planet}t)]$:

(k,l) mode with patter speed $= \frac{l}{k}\Omega_{planet}$

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v}\cdot\nabla)\mathbf{v} = -\frac{1}{\Sigma}\nabla p - \nabla\Phi_{grav}$$

nonlinear term leads to mode coupling



: planet on circular orbit

: excited at inner ELRs $\Omega=(m/m-2)\ \Omega_{planet}$

(m+1,m) : excited at outer ELRs $\Omega=(m/m+2)\ \Omega_{planet}$

Resonances in Keplerian disks

- **epicyclic oscillation as a result of angular momentum conservation gives the "natural freq" of the disk gas =** κ
- **pattern speed of density waves** $\Omega_{\mathrm{pattern}} = (l/k)\,\Omega_{\mathrm{planet}}$
- **locations of Lindblad resonances:** $k(\Omega_{\mathrm{pattern}} - \Omega) = \pm\,\kappa$
- **locations of corotation resonances:** $\Omega_{\mathrm{pattern}} = \Omega$
- **for circular orbits,** $l=k=m$ **→ Lindblad resonance (LR)**
- **for eccentric orbits, besides LR,** $l=k\pm 1$ **→ eccentric Lindblad (ELR) and corotation resonance (ECR)**

$$\kappa^2 = \frac{1}{r^3}\frac{\mathrm{d}(r^4\Omega^2)}{\mathrm{d}r}$$

Resonances in Keplerian disks

primary star
r=0

r≈0.48

r≈0.63

planet/ companion
r=1

r≈1.59

r≈0.2.08

eccentric orbit (1st order):

3:1 ELR

4:2 ELR
2:1 ECR

4:2 ELR
2:1 ECR

3:1 ELR

2:1 LR

2:1 LR

circular orbit:

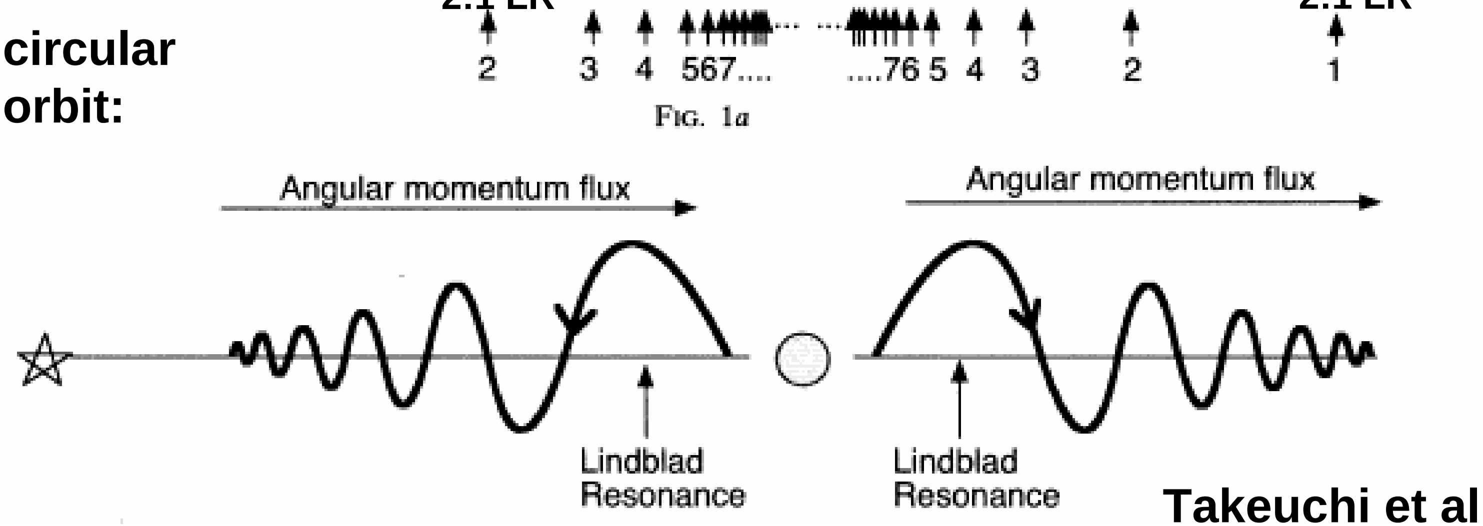
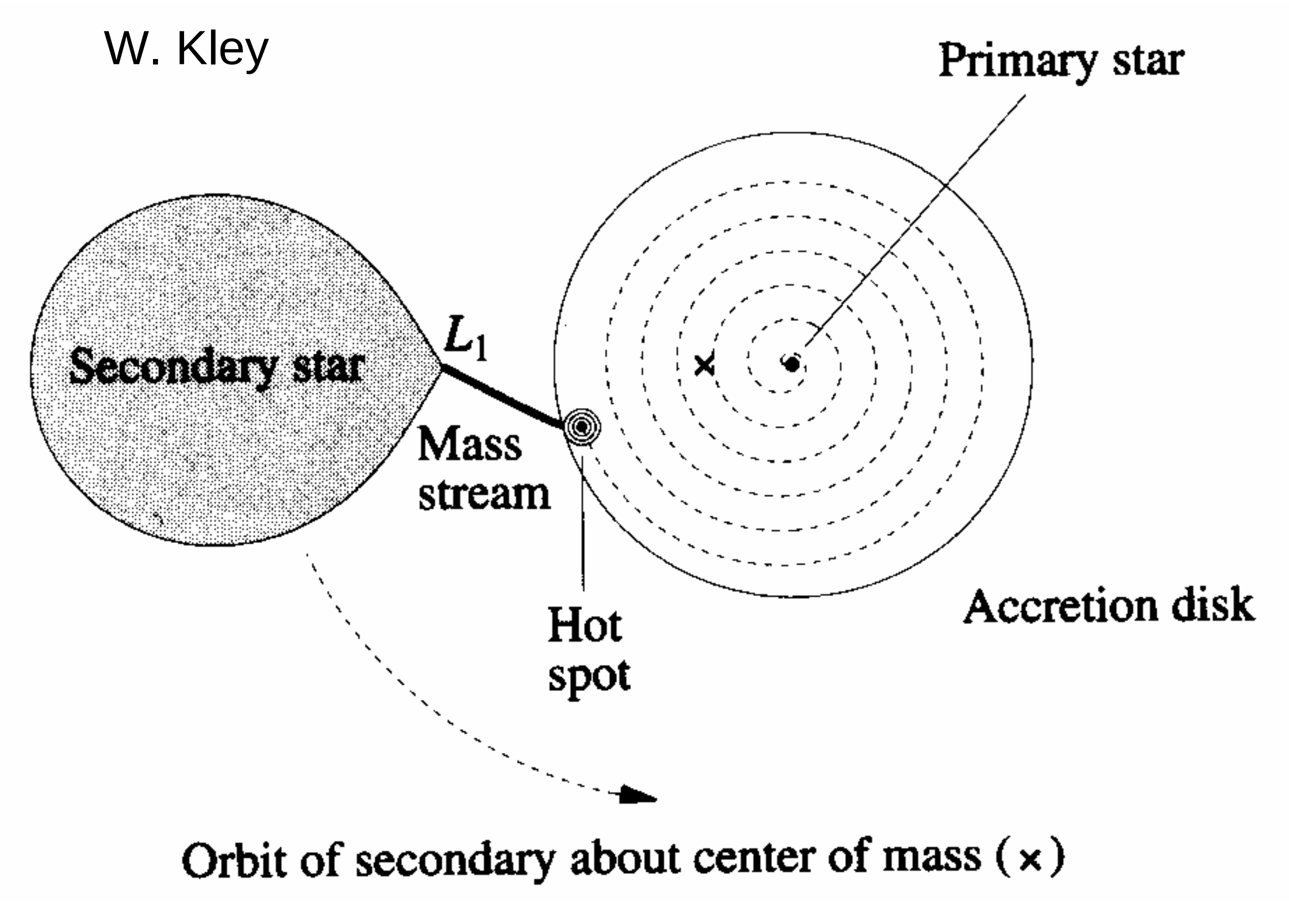


FIG. 1a

Takeuchi et al. 1996

Cataclysmic Variable

W. Kley

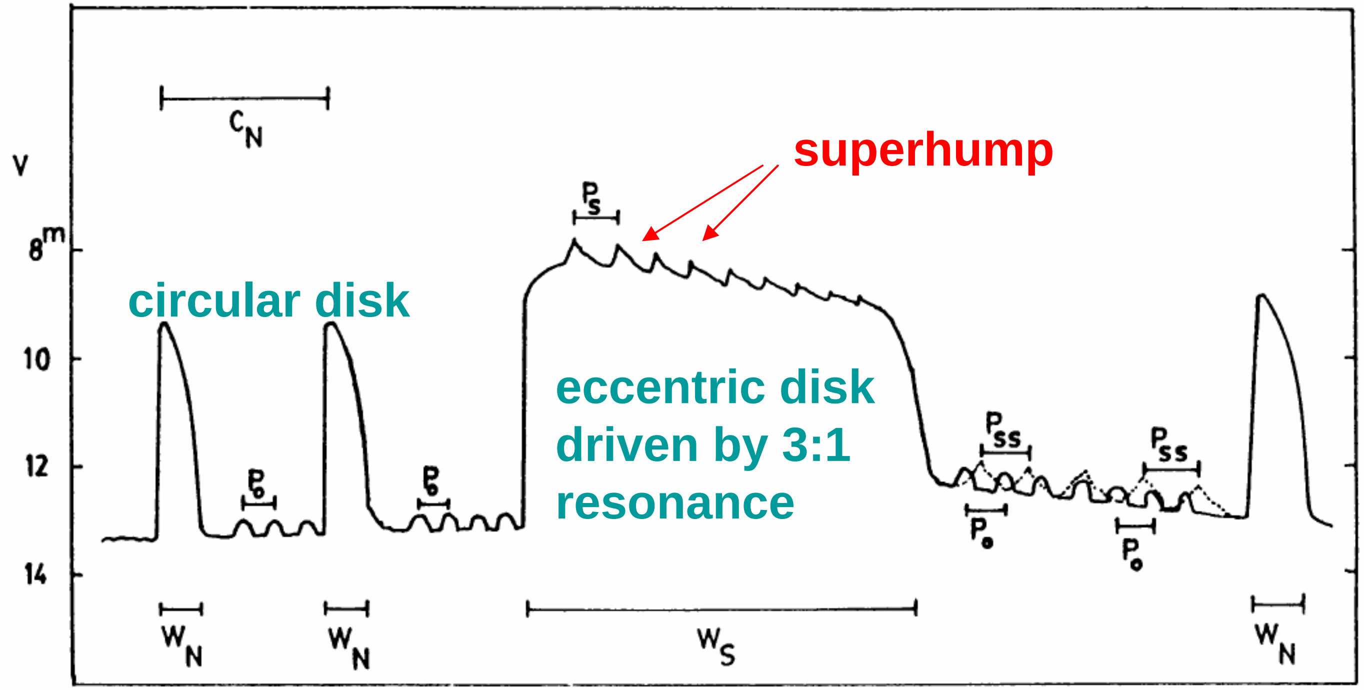


Orbit of secondary about center of mass (×)

Superhump light curve in SU UMa systems

- $m_2/m_1=q<0.35$

Vogt 1982



superhump

circular disk

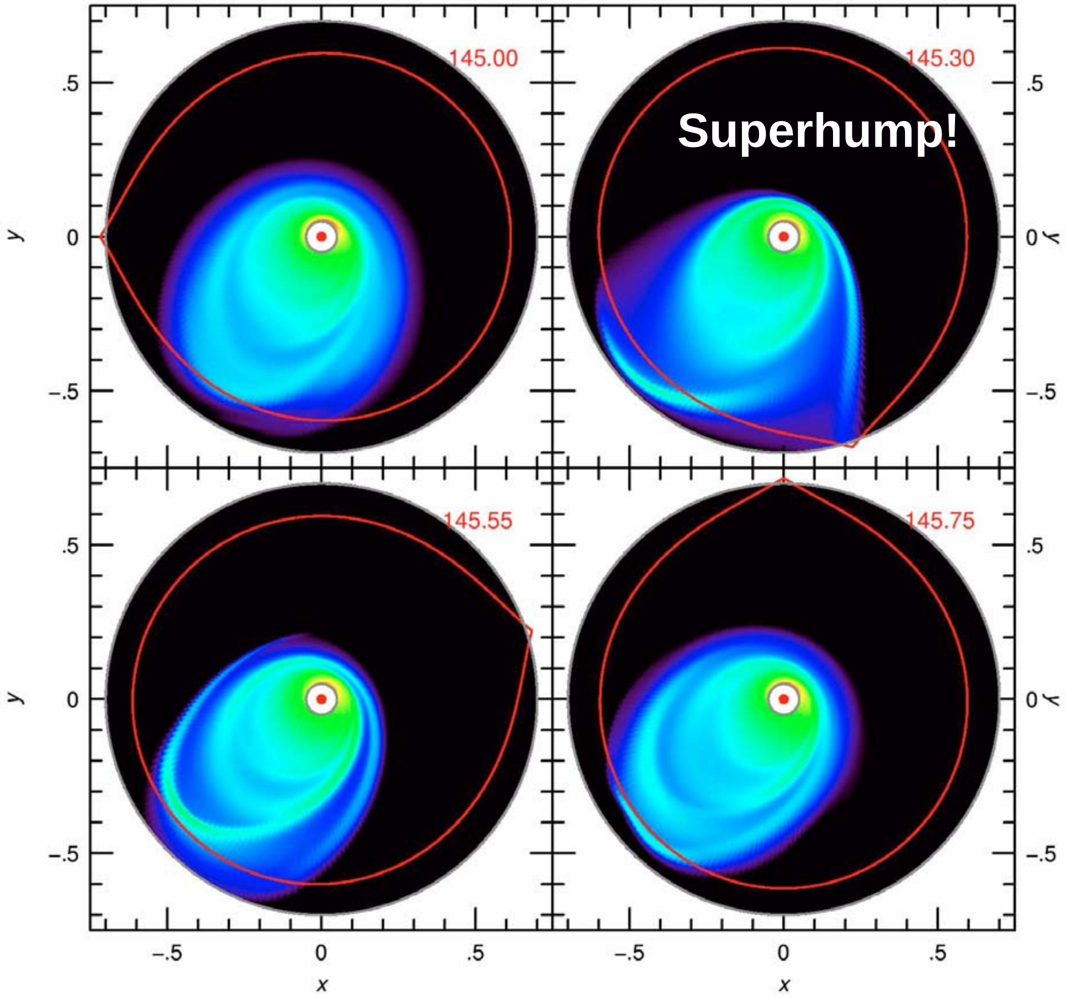
eccentric disk driven by 3:1 resonance

Abb. 1 Schematische Darstellung der Variationen mit verschiedenen Zeitskalen, die für einen SU-UMa-Stern beobachtet werden (Beispiel: VW Hyi). Symbole siehe Text.

Superhump light curve in SU UMa systems

Kley et al. 2008

$q=0.1$ ($r_{1:3}\approx0.496$)
$\nu = 10^{-4}$
$H/r=0.05$
Σ_{init} propto $1/r$



Superhump!

prograde/retrogarde precession depends on H/r (i.e. radial pressure gradient)

Particle aerodynamics

$$\mathbf{F}_{drag} = -\frac{\mathbf{v}_{dust} - \mathbf{v}_{gas}}{t_{stop}} \qquad \text{(Weidenschilling 1977)}$$

$$a_{dust} < \frac{9}{4}\lambda_{gas}\,\text{(Epstein regime)}: \quad t_{stop} = \frac{\rho_{dust} a_{dust}}{\rho_{gas} v_{th}}$$

$$\mathrm{Re} = \frac{2a_{dust}\rho_{gas}\Delta \mathrm{v}}{\mu} < 1\,\text{(Stokes regime)}: \quad t_{stop} = \frac{2a_{dust}\rho_{dust}}{9\mu}$$

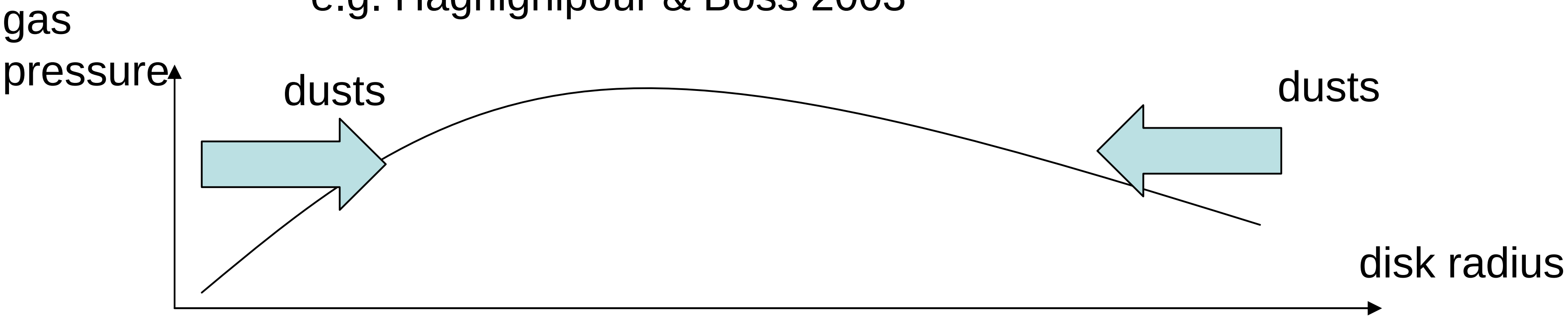
t_{stop} (stopping time): a timescale measureing how long dusts are coupled to the gas

N.B. t_{stop} depends on dust size and gas density

Particle aerodynamics

radial drift of dusts in a protoplanetary disk

e.g. Haghighipour & Boss 2003



Gas rotation velocity is super-Keplerian due to positive radial pressure gradient

Gas rotation velocity is sub-Keplerian due to negative radial pressure gradient

efficiency of radial drfit depends on $\tau_s \equiv t_{stop}\Omega_K$

Particle aerodynamics

efficiency of radial drfit depends on

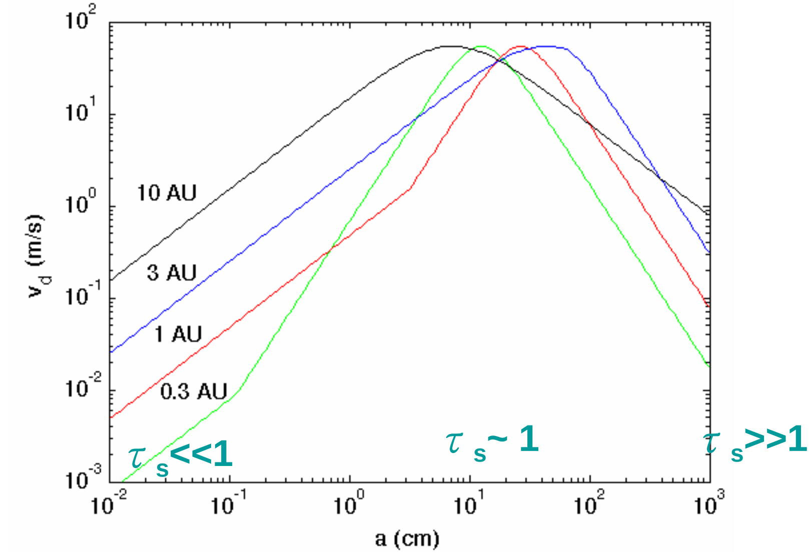
the dimensionless stopping time $\tau_{\mathrm{s}} \equiv t_{stop}\Omega_K$

$\tau_s << 1$: well coupled to the gas in one orbit, slow drift

$\tau_{\mathrm{s}} \approx 1$: weakly coupled in one orbit, fast drift

$\tau_{\mathrm{s}} >> 1$: decoupled in one orbit, slow drift

Nakagawa, Sekiya, & Hayashi 1986



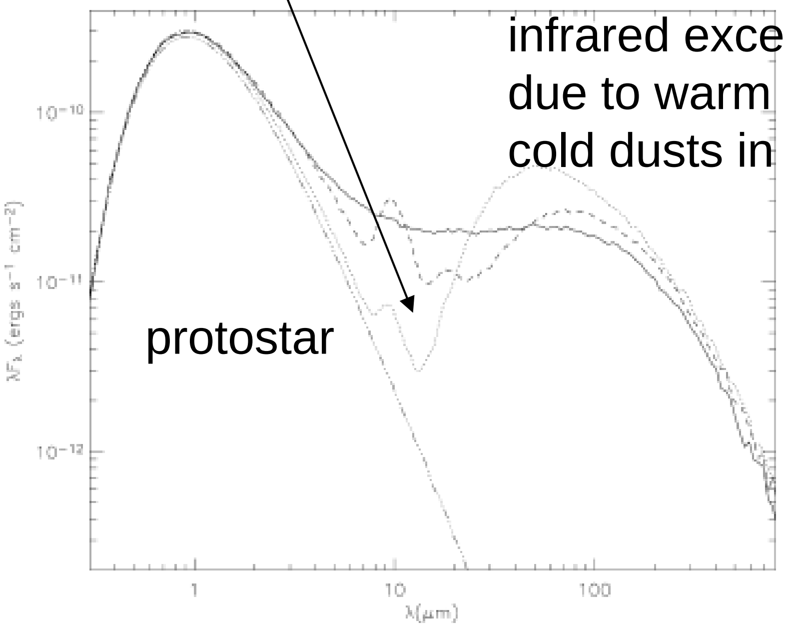
outline

- motive
- brief review on eccentric disks and dust aerodynamics
- **works done by other groups**
- our simple study
- summary

Dusts in a protoplanetary disk harboring a giant planet

Circular disk:

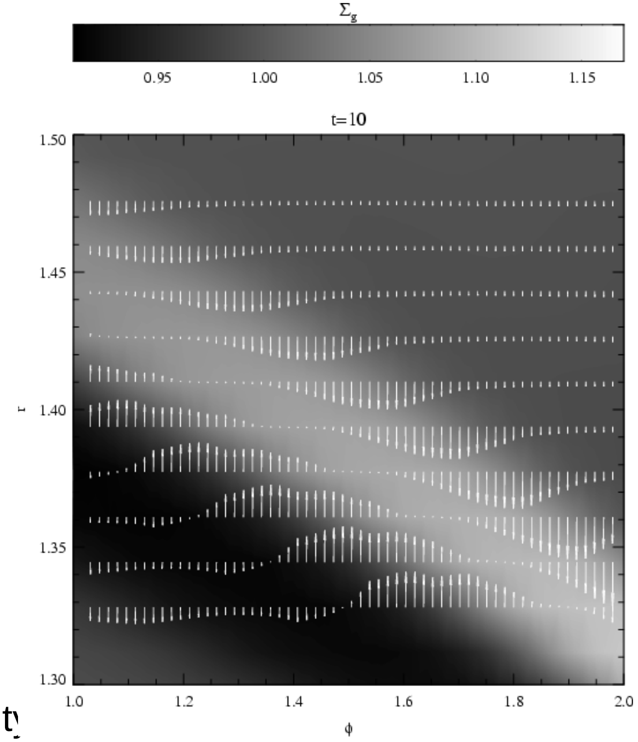
Rice et al. 2006: dust filtration affects SED. large dusts are stalled by the outer edge of the gap → lower dust abundance in the inner disk (warm dusts)



infrared excess due to warm & cold dusts in disk

protostar

Paadekooper & Mellema 2006: transient concentration of dust toward spiral density waves



Dusts in a protoplanetary disk harboring a giant planet

Eccentric disk: Fouchet et al. 2010

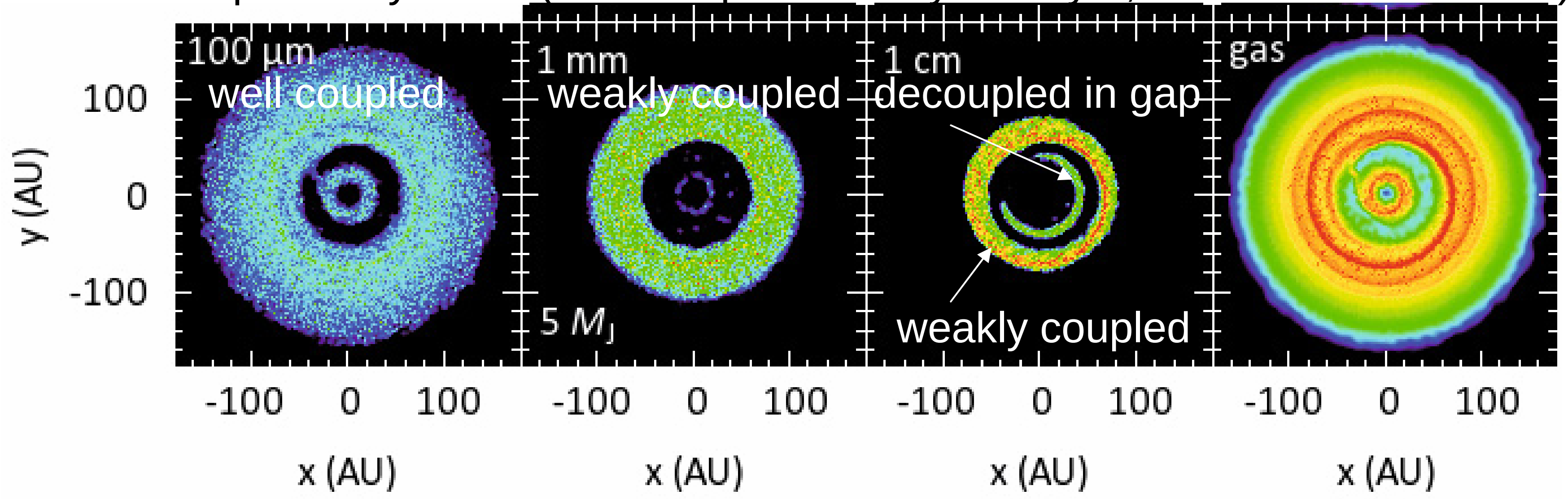
Fouchet et al. 2010 (SPH: gas+dust)

$M_{\star}=1M_{sun}$, $M_{disk}=0.02\ M_{sun}$, $M_{dust}=0.01M_{disk}$, $\alpha=0.01$

Initial conditions: Σ=const. from 4-120AU, $T(r)=T_0(1/r)$

Planet on a fixed circular orbit at 40 AU

t =104 planetary orbits (not in a quasi-steady state yet, thus no secular effect)



outline

- motive
- brief review on eccentric disks and dust aerodynamics
- works done by other groups
- our simple study
- summary

Our investigation for dusts in eccentric disks

- **aim: focus on secular (long-term) effect rather than short-period effect**
- **standard parameters (Kley & Dirksen 2006): $M_\odot$, $5M_{jup}$, $H/r=0.05$(locally isothermal), $a_p=5AU$ (protoplanetary disk) &100AU ("transition disk"), $\nu=10^{-5}a_p^2\Omega_p$, $\Sigma=10^{-4}M_\odot/a_p^2$, dust/gas in the basic state = 0.01**
- **gas info from 2D disk simulation in quasi-steady state: FARGO code (Masset 2000)**
- **time averaging → reveal secular features associated with eccentric disks**
- **secular gas info → secular perturbation theory for dusts with gas drag (depends on gas density and dust size) → dust surface density**

Eccentricity equation for a dust

Secular perturbation theory for dusts with gas drag

$$\text{linearized eqns with } k=1, \text{ and define } E(r,t)=e\exp(i\varpi)$$

$$\frac{\partial E_{dust}}{\partial t}=i\frac{E_{dust}}{t_{precession}}+i\frac{E_{planet}}{t_{forced}}-\frac{E_{dust}-E_{gas}}{t_{stop}}$$

Orbital evolution
due to the **axisymmetric**
part of the small
planet’s potential that is not
related to mean longitude
(e.g. Murray & Dermott 1999)

Orbital evolution
“forced” by **planetary**
eccentricity (e.g.
Murray & Dermott 1999)

Orbital evolution
due to **gas drag**
(Marzari & Scholl
2000; Paardekooper
et al. 2008)

Eccentricity equation for a dust

Consider the steady state (drag balanced by planet potential)
→ solve for E_{dust} in terms of E_{gas} and E_{planet}

define the "secular" dimensionless stopping time $\tau_{s,\mathrm{sec}}$

$$\tau_{s,\mathrm{sec}} \equiv \frac{t_{stop}}{t_{precession}}, \qquad E_{forced} \equiv \frac{t_{precession}}{t_{forced}} E_{planet}$$

If $\tau_{s,\mathrm{sec}} << 1$, $E_{dust} \approx E_{gas}$ (i.e. well coupled to gas on the secular timescale)

If $\tau_{s,\mathrm{sec}} \approx 1$, weakly coupled to gas on the secular timescale

when $E_{planet} = 0$, less eccentric orbit, precession with phase lag = acrtan($\tau_{s,\mathrm{sec}}$)

when $\tau_{\mathrm{s,sec}} |E_{forced}| > |E_{gas}|$, pericenter alignment & libration

Protoplanetary disk

a_p=5 AU Σ=900 g/cm^2

Eccentricity profiles: decrease with *r* outside the gap

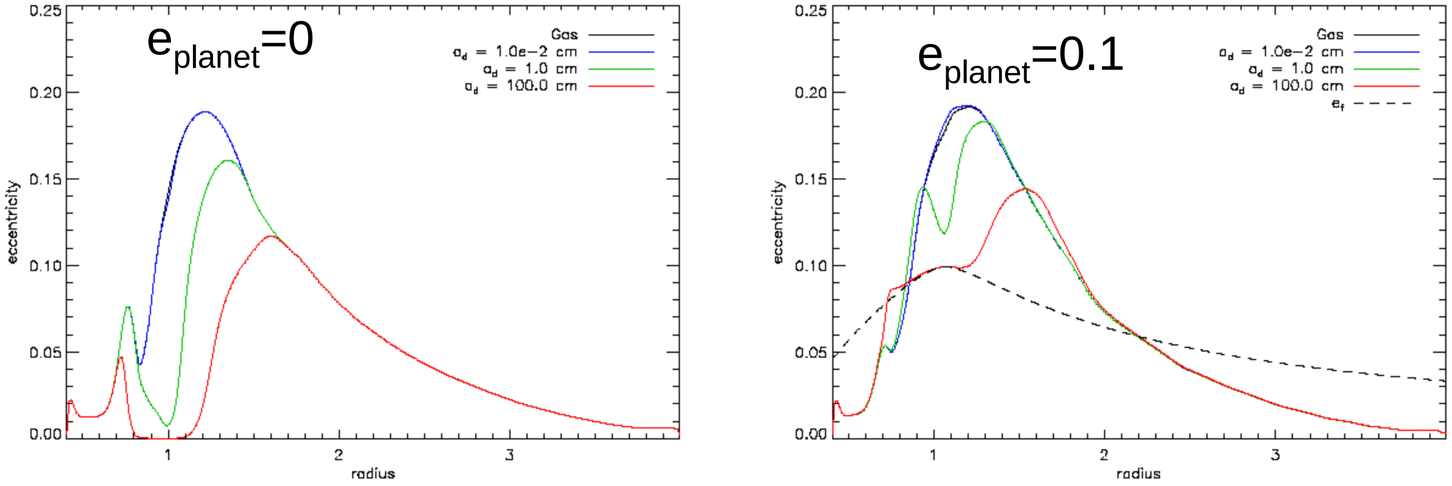


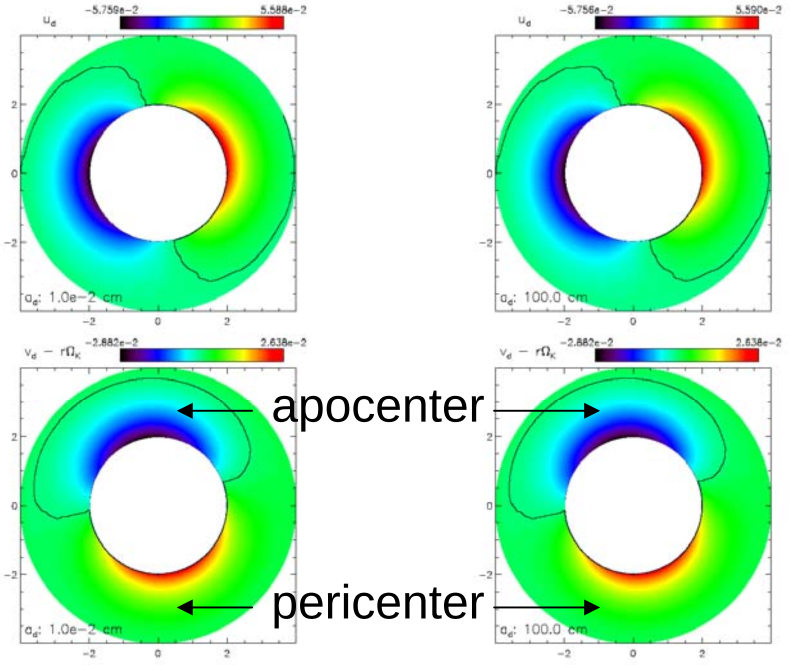
Fig. 5.— Azimuthally averaged eccentricities of gas and dusts of various sizes in the case of $e_p = 0$ (left panel) and $e_p = 0.1$ (right panel). The forced eccentricity $e_f = |E_f|$ is als plotted in the $e_p = 0.1$ case.

$\tau_{s,\mathrm{sec}} \ll 1$: well coupled to gas in disk exterior to the gap ($r \geq 2$)

Protoplanetary disk

focus only on the disk almost exterior to the gap

dust velocity map: exhibit *k*=1



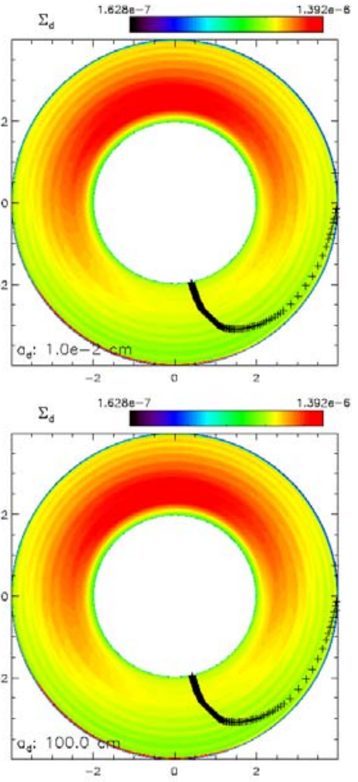
apocenter

pericenter

Fig. 6.— Radial (top panels) and azimuthal (bottom panels) dust velocities departure from the Keplerian circular velocity for the $e_p = 0$ case. The left panels show the results for size of 1×10^{-2} cm and the right panels show the results for 1 m. The black lines are the zero contours. The unit of the velocity is about 4.24×10^4 cm s^{-1}.

linear continuity equation

dust surface density map



k=1 dust distribution: density excess (~ 10%) around the apocenter!

$$\tau_{s,\mathrm{sec}} << 1: \text{ well coupled to gas} \qquad t_{drift} / t_{prec} = (r / \mathrm{v_d}) / t_{prec} > 1$$

Transition disk (low gas density)

a_p=100 AU Σ=2.5 g/cm^2

$$\tau_{s,\sec}(0.01\,\mathrm{cm}) \approx 10^{-(3-4)} << 1:\ \text{well coupled}$$

$$\tau_{s,\sec}(1\,\mathrm{cm}) \approx 10^{-(1-2)} << 1:\ \text{well coupled}$$

$$\tau_{s,\sec}(100\,\mathrm{cm}) \approx 1 \sim 10:\ \text{weakly coupled}$$

Eccentricity profile:

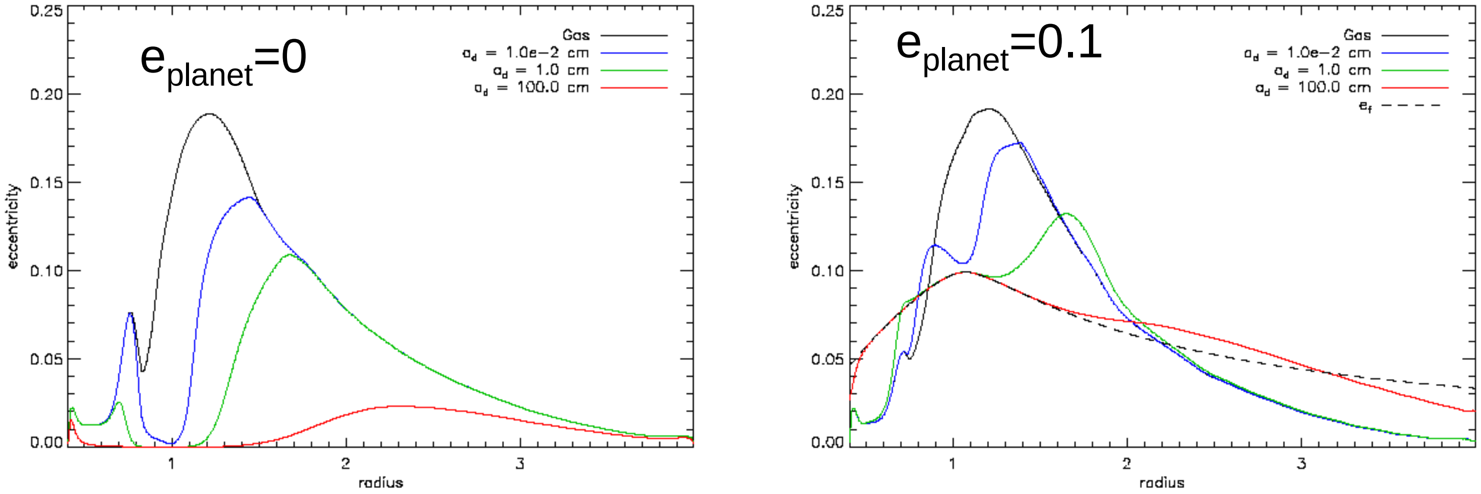


Fig. 12.— The azimuthal average of dust and gas eccentricities for the transition disk. Th
left panel shows the case for $e_p = 0$ and the right panel shows the cases for $e_p = 0.1$. Th
forced eccentricity $e_f = |E_f|$ is also plotted in the $e_p = 0.1$ case.

Transition disk
(low gas density)

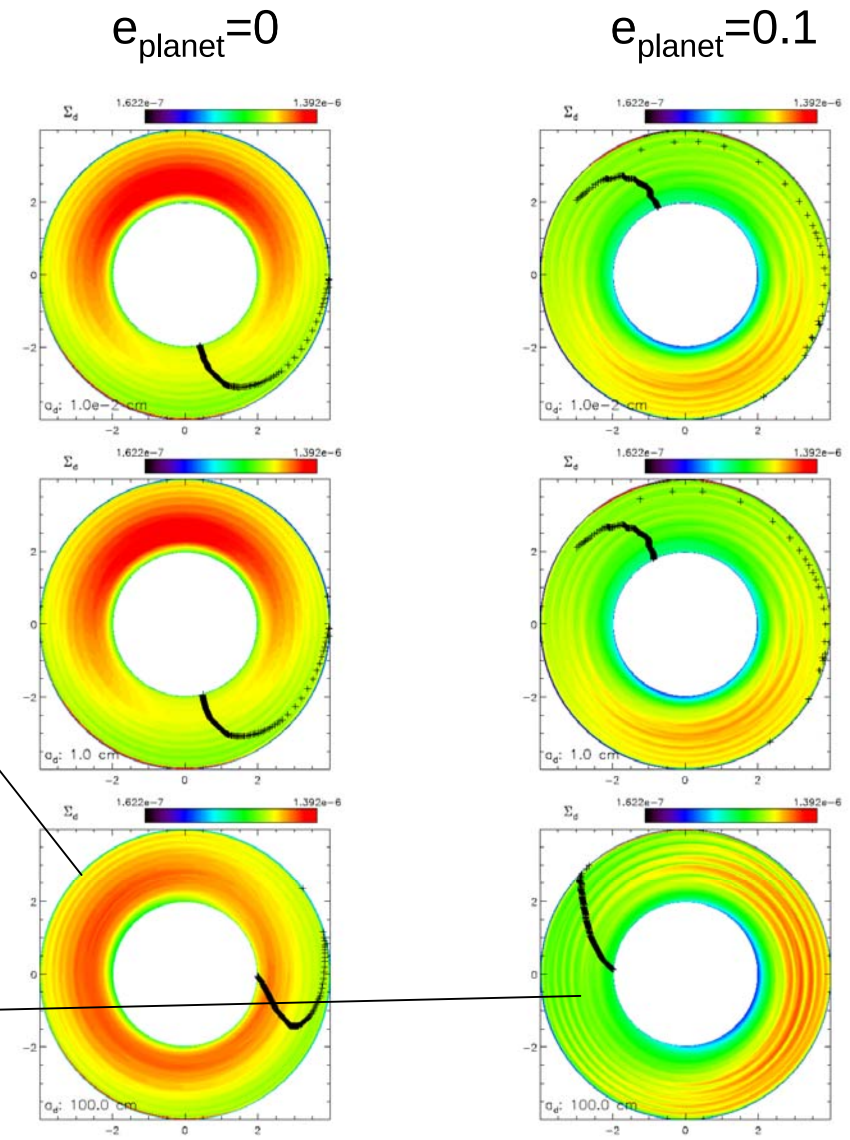


Fig. 11.— The dust surface density of various sizes for the $e_p = 0$ (left panels) and $e_p = 0$ (right panels) cases. The length unit is $a_p = 100$ AU. The unit of the surface density 2.5×10^4 g cm^{-2}.

e_{planet}=0:
weakly coupled ($\tau_{s.sec} \approx$1-10)
→ less eccentric,
precess but with phase lag ≈ arctan($\tau_{s.sec}$)=80°

e_{planet}=0.1:
weakly coupled ($\tau_{s.sec} \approx$1-10)
→ eccentricity excited by e_{planet},
pericenter libration around planet's pericenter

what I didn’t tell you

- dust coagulation/fragmentation
- laminar vs. turbulence (diffusion)
- secular vs. wave & resonance trapping
- isothermal vs. realistic radiative
- 2D vs. 3D (settling, streaming instability)
- fixed planetary orbit vs. orbit free to evolve
- gap shape & disk eccentricity
- etc….

Summary

- **secular dimensionless stopping time** $\tau_{\mathrm{s.sec}}$
- $\tau_{\mathrm{s.sec}} \ll 1$: dust moves with gas on eccentric orbits
- $\tau_{\mathrm{s.sec}} \sim 1$: dusts precess with a phase lag. Pericenter libration may occur in the presence of planetary eccentricity.
- max. dust density (10% contrast) lies around the apocenter, within ALMA detectability.