Gaps, rings, and non-axisymmetric structures in protoplanetary disks

From simulations to ALMA observations.

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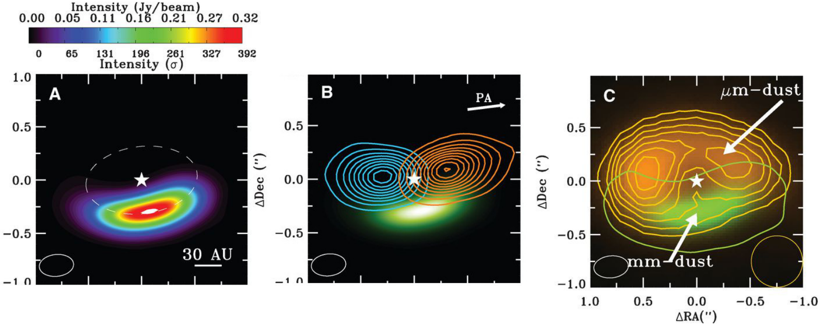
Signatures from observations

GAS turbulence by line broadening of molecule (CS or CO)
(todays talks by Jeremy Goodman and Jacob Simon)

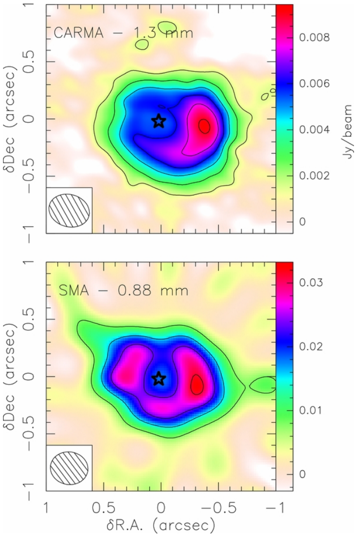
DUST structure by continuum emission
shows large scale structures in the disk

IRS 48 Van der Marel et al. (2013)



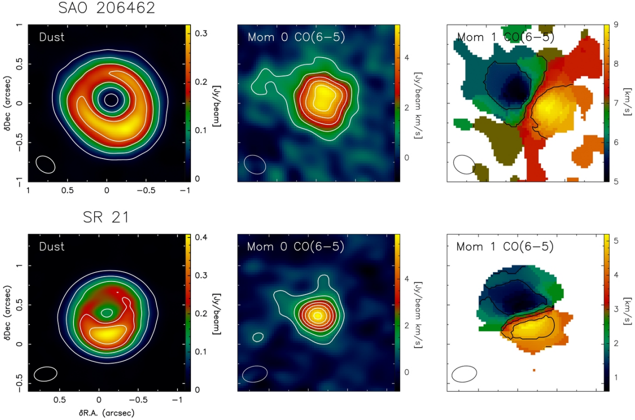
Left The 0.44-mm (685 GHz) continuum emission.
Middle The integrated CO 6-5 emission.
Right The VLT Imager and Spectrometer for the mid-infrared (VISIR) 18.7-m emission in orange contours.

LkHα 330 Isella et al. (2013)



Maps of the continuum emission at the wavelength of 1.3 mm (**top**) and 0.88 mm (**bottom**).

Sao 206462, SR 21 Pérez et al. (2014)



Left: dust continuum emission (color scale)
and dust brightness temperature (contours starting at 10 K, spaced by 5 K)
Middle and right panels: 12CO J = 65 moment 0 and 1 map.

Motivation

- How can we explain the observed asymmetries in protoplanetary disks ?

Most used theory

→ planet inside the disk → surface density bump at outer gap edge → vortex → concentration of particles → asymmetry

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magnetized disk + planet simulations by Zhu & Stone 2014 (see talk tomorrow)

- need of magnetic diffusion to allow vortex formation

Most used theory

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However

- planet size and position not always in agreement with planet population synthesis models

  (core accretion timescale $>$ disk lifetime (at R $>$ 30 AU), difficult also for metal poor systems, Benz et al. (2014)
- GI – Janson et al. 2012 $<$ 10 % of the stars can form and retain a planet at 5-500 AU ?

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$\longrightarrow$ magneto-rotational instability (Balbus & Hawley 1991,92,98)

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Motivation

I How can we explain the observed asymmetries in protoplanetary disks ?

II How can we distinguish between **A** turbulent and **B** laminar disks ?

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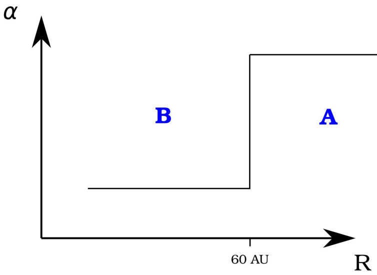

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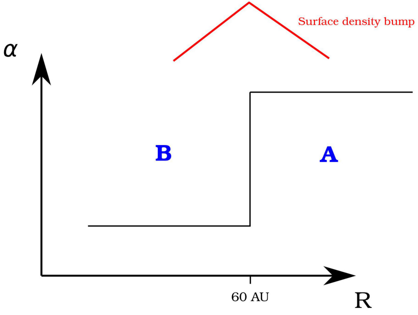

Varnière et al (2006)

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The transition is smooth (M. Wardle 2007, Dzyurkevich et al. 2013, Turner et al. 2014)

→ **no jump in surface density**

Let's try it ! Merge expertise !!

I Global 3D MHD simulations of accretion disks Flock et al. (2011,12)

II Parameterized disk model fitting high-angular resolution multi-wavelength observations of various circumstellar disks

Wolf et al. (2003)... Gräfe et al. (2013)

III Resistivity profile by dust chemistry Dzyurkevich et al. (2013)

Global model

PLUTO code	Godunov type code, 2nd order in space and time, CT MHD.
Riemann solver	HLLD (Miyoshi and Kusano 2005).
FARGO MHD	optimized for MHD in fast rotating flows (Mignone et al. 2012).
Domain	in spherical coordinates $\mathrm{r} = 20 - 100\mathrm{AU}$ $\Delta\theta = 0.72$ $\Delta\phi = 2\pi$ (256x128x512) (well resolved H/dx $>$ 20).
Magnetic field	Vertical net-flux field (talk by Takeru Suzuki) fields show $\sim 1/R$ Flock et al. 2011 and Suzuki et al. 2014 $\rightarrow$ set vertical field to $\sim 1/R$ (1 mGauss at 40 AU) close to upper limit see Okuzumi et al. (2014)

Merged expertise !

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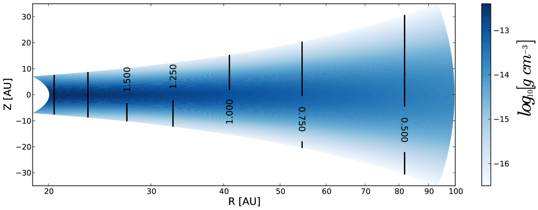
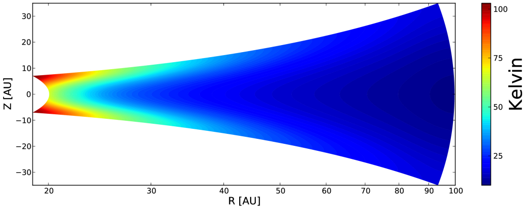
Disk model





$\Sigma = 5.94\ \mathrm{g\ cm^{-2}}\ \frac{R}{100AU}$

$T_* = 4000K$

$0.95\ L_{\odot}$

$M_* = 0.5 M_{\odot}$

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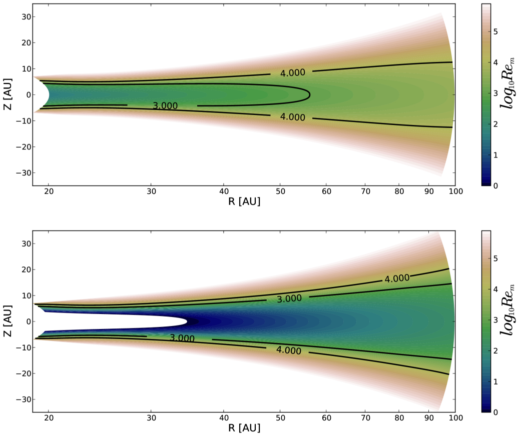
Resistivity



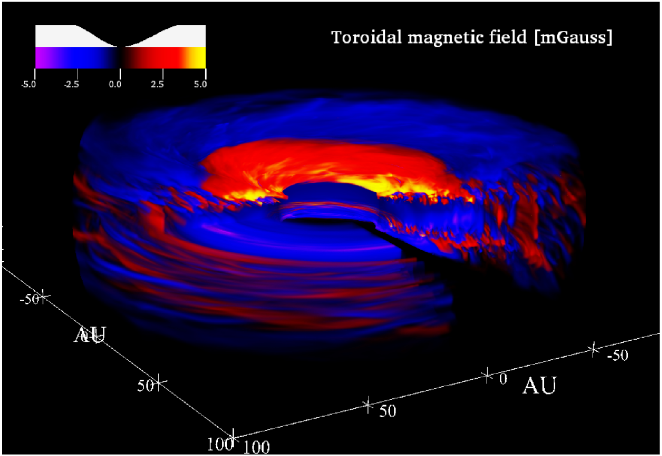
$\mathrm{Re_m} = \mathrm{c_s H}/\eta$
$\rho_d/\rho_g = 10^{-4}$ **(top)** and 10^{-2} **(bottom)**

- densities of charged species (I+, e-, Dust-) determined following Okuzumi 2009
- magnetic diffusivity calculation follows Wardle 2007
- method uses fractal dust aggregates with (2 μm) and 0.1 μm monomers.
- metals are frozen out, rep. ion $\mathrm{HCO^+}$
- X-ray ionization rate following Bai & Goodman 2009.
- Cosmic ray ionizaten rate $5{\cdot}10^{-18}$ erg/s
- radio-nuclide is $7 \cdot 10^{19}$ (d2g /0.01)

Turbulence and disk evolution

- Both models develop a turbulent state:
  - $\rho_d/\rho_g = 10^{-2}$ $\rightarrow$ includes the dead-zone edge $\rightarrow$ less turbulent in total ($\alpha = 0.003$)
  - $\rho_d/\rho_g = 10^{-4}$ $\rightarrow$ fully turbulent disk ($\alpha = 0.013$)

Turbulence and disk evolution



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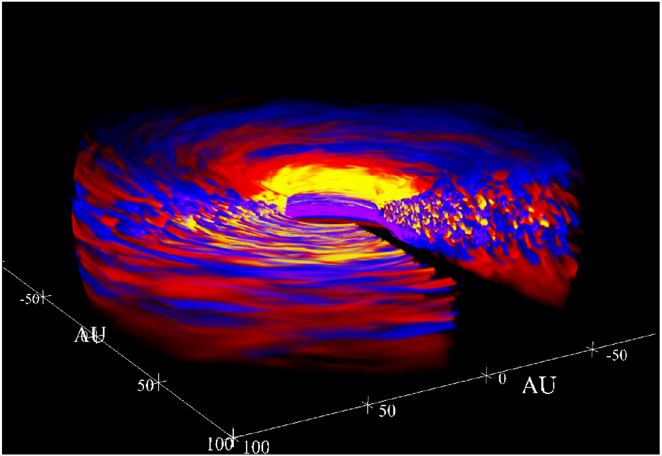

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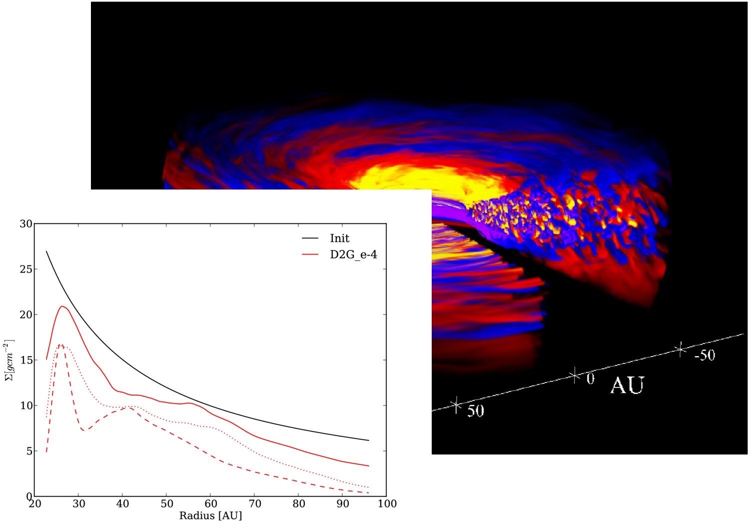

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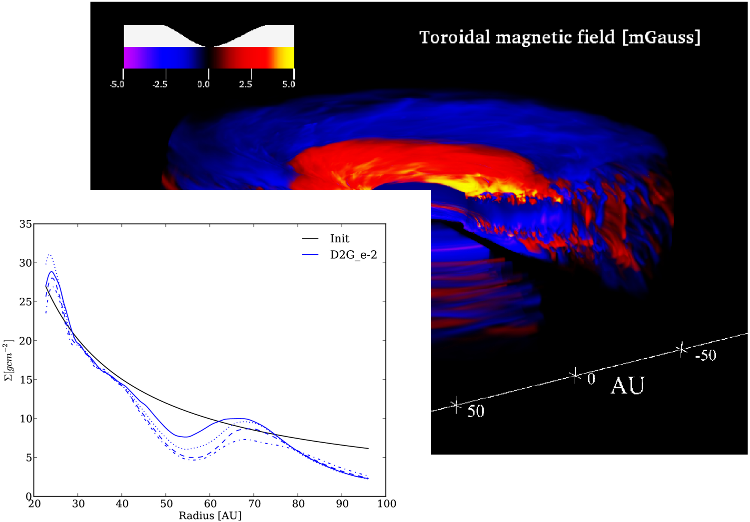
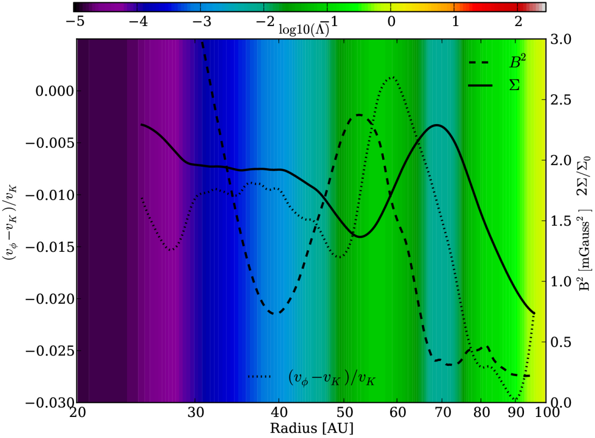
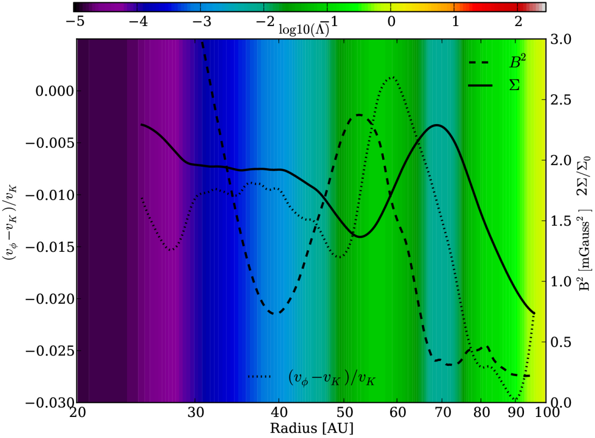


Zonal flow ?

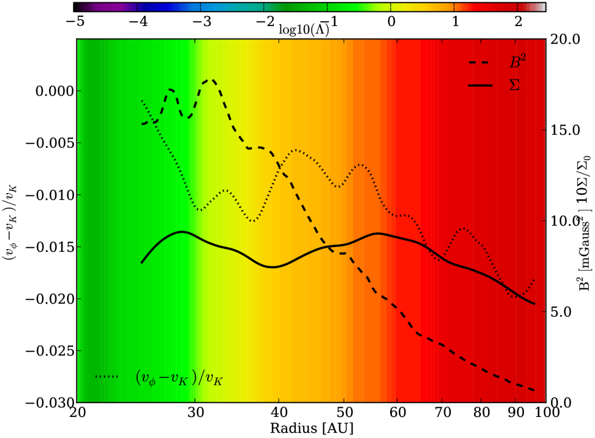

−5
−4
−3
−2
log10(Λ)
−1
0
1
2
B^2
Σ
0.000
−0.005
−0.010
−0.015
−0.020
−0.025
−0.030
$(v_\phi - v_K)/v_K$
3.0
2.5
2.0
1.5
1.0
0.5
0.0
B^2 [mGauss^2] $2\Sigma/\Sigma_0$
20
30
40
50
60
70
80
90
100
Radius [AU]

Zonal flow ?

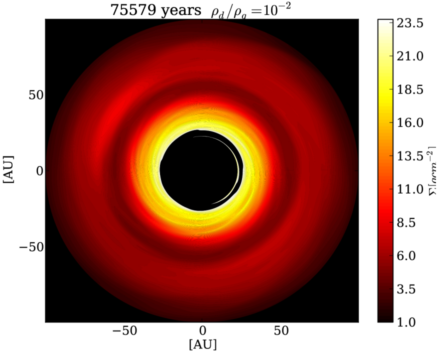


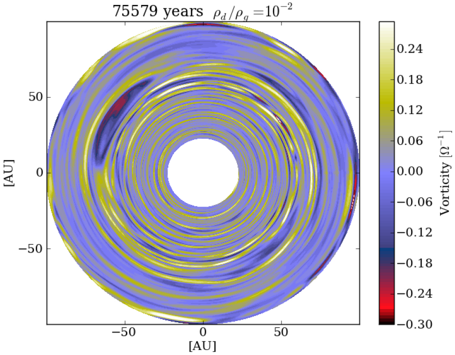
Zonal flow in Ambipolar dominated regions, see Simon & Armitage 2014

Zonal flow ?

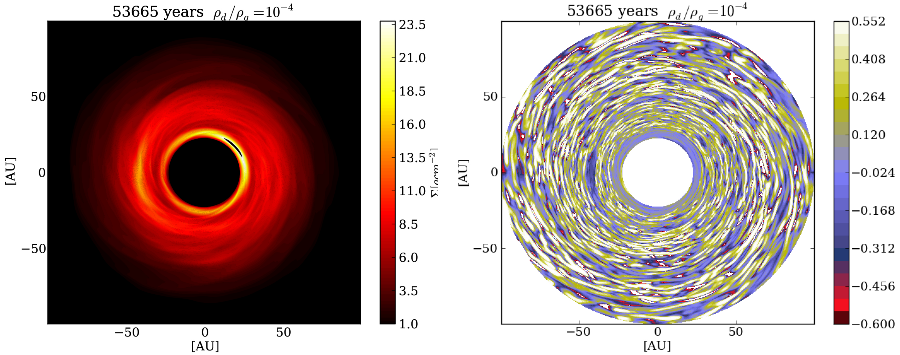

−5
−4
−3
−2
−1
0
1
2
log10(Λ)
B^2
Σ
0.000
−0.005
−0.010
−0.015
−0.020
−0.025
−0.030
$(v_\phi - v_K)/v_K$
20.0
15.0
10.0
5.0
0.0
B^2 [mGauss^2] 10Σ/Σ$_0$
20
30
40
50
60
70
80
90
100
Radius [AU]

Surface density and vorticity





Surface density and vorticity - Part II



What do we observe with ALMA ?

- Use dataset in MC3D Monte Carlo Radiative Transfer !
- Calculate dust emission
- CASA 4.2 simulator (consider influence of thermal noise by water vapor) (75pc)

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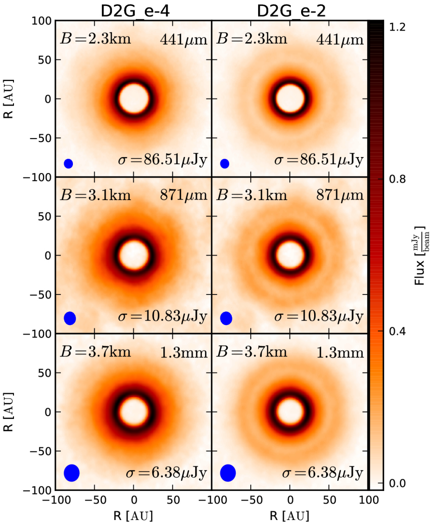

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Motivation

I How can we explain the observed asymmetries in protoplanetary disks ?

- **A combination of dead-zone edge and zonal flow could work !**
- **Analyse particle data !!**

II How can we distinguish between **A** turbulent and **B** laminar disks ?

- **Difficult: turbulent structures too small !**
- **Ring structure at the dead-zone outer edge !?**

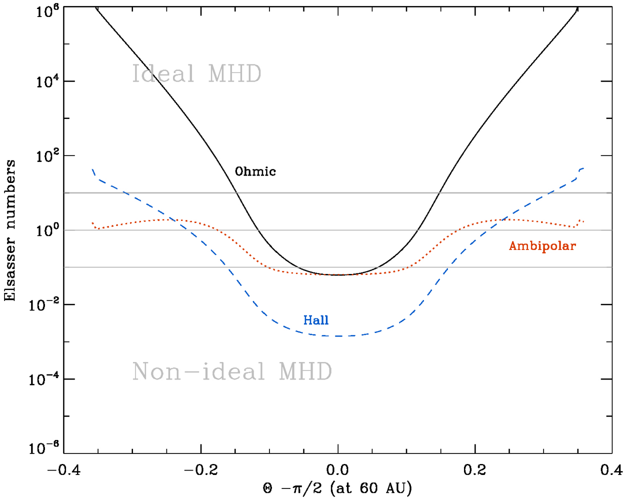
Summary

- Formation of a large gap and bump structure in the surface density close to the dead-zone edge.
- Vortices are formed inside the ring by the Rossby wave instability with a lifetime of around 40 local orbits at a location of 60 AU (19000 years lifetime).
- The gap and ring structure produced by the MRI at the dead zone outer edge can be traced by ALMA

Outlook

- Next: dust analysis !
  - Hall MHD (Geofroy Lesur...)
  - Radiation transfer– G.S.F (Richard Nelson...)
  - Non-linear Ohmic law (Satoshi Okuzumi)

Appendix


Ideal MHD
Non−ideal MHD
Ohmic
Ambipolar
Hall
Elsasser numbers
Θ −π/2 (at 60 AU)
10^6
10^4
10^2
10^0
10^{-2}
10^{-4}
10^{-6}
−0.4
−0.2
0.0
0.2
0.4