Turbulence-Assisted Planetary Growth

Wladimir Lyra

Uppsala University - Sweden

UPPSALA UNIVERSITET

UPPSALA UNIVERSITET

Collaborators:

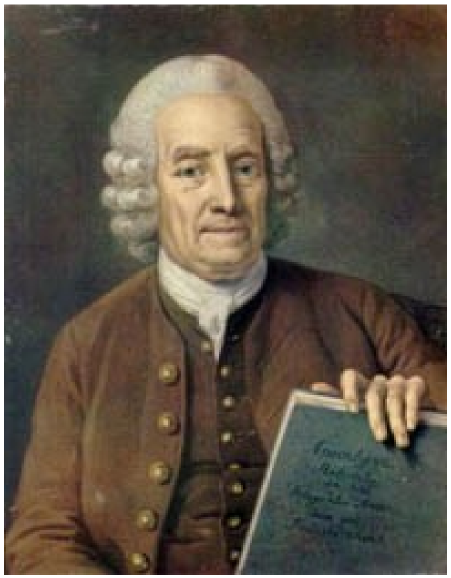
Anders Johansen (Leiden)

Hubert Klahr (Heildeberg)

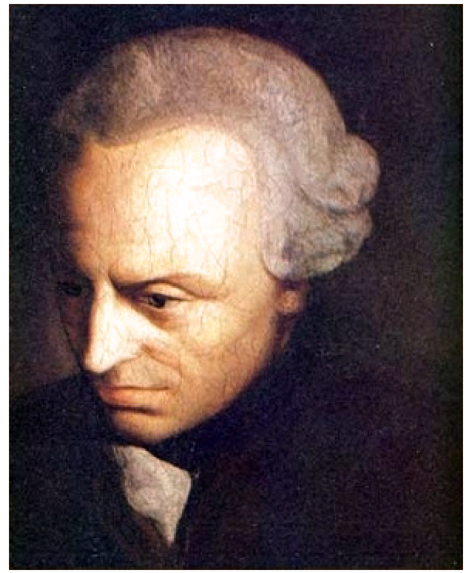
Nik Piskunov (Uppsala)

Planet Formation

"Planets form in disks of gas and dust"

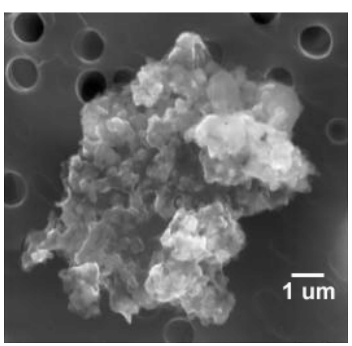


Swedenborg 1735



Kant 1755

Laplace 1796



HOW????

14 orders of magnitude in size

Planet Formation

Planetesimal Hypothesis (Safronov 1969)

From dust to boulders

μm -> m: Electrostatic forces cause sticking

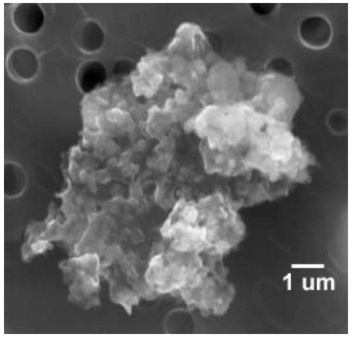
From planetesimals to protoplanets

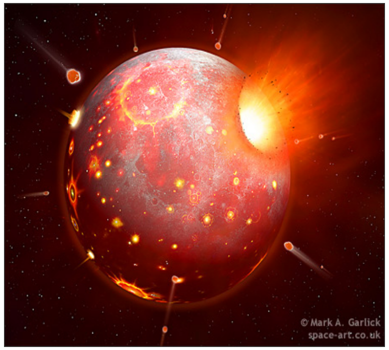
km -> 1000 km: Gravity

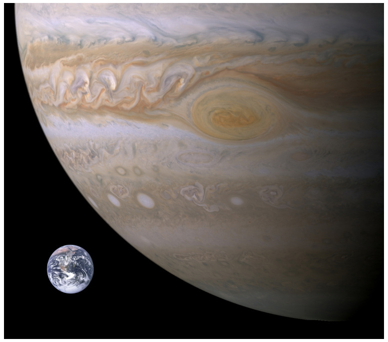
From protoplanets to planets

Rocky Planets: Protoplanets collide

Gas Giants: Attract gaseous envelope



Planet Formation

Planetesimal Hypothesis (Safronov 1969)

From dust to boulders

μm -> m: Electrostatic forces cause sticking

m -> km: ***HOW????***

From planetesimals to protoplanets

km -> 1000 km: Gravity

From protoplanets to planets

Rocky Planets: Protoplanets collide

Gas Giants: Attract gaseous envelope

From meter to kilometer

Growth barrier

- through EM?

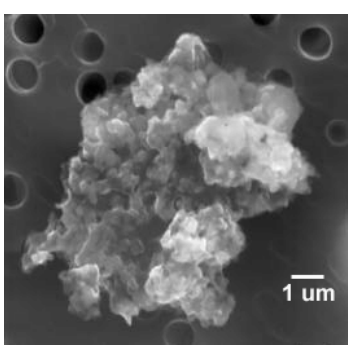
They don't stick, they break

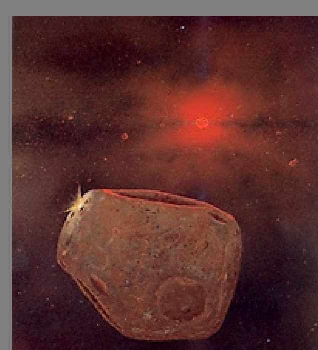
- through Gravity?

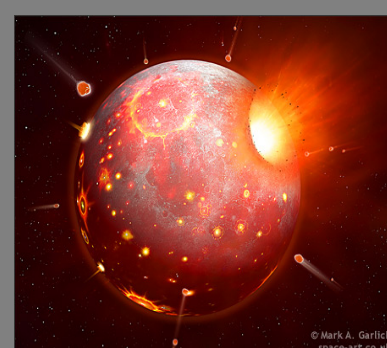
They aren't massive enough

Timescale barrier

They migrate quite fast







Planet Formation

Planetesimal Hypothesis (Safronov 1969)

From dust to boulders

μm -> m: Electrostatic forces cause sticking

m -> km: ***HOW????***

From planetesimals to protoplanets

km -> 1000 km: Gravity

From protoplanets to planets

Rocky Planets: Protoplanets collide

Gas Giants: Attract gaseous envelope

From meter to kilometer

Growth barrier

- through EM?

They don't stick, they break

Gentle Collisions

- through Gravity?

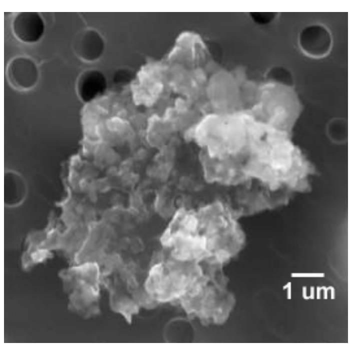
They aren't massive enough

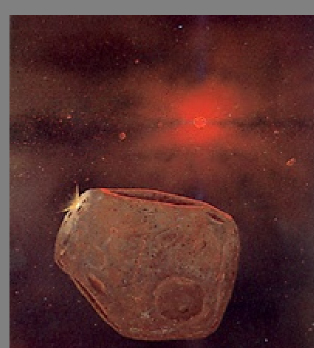
High number density

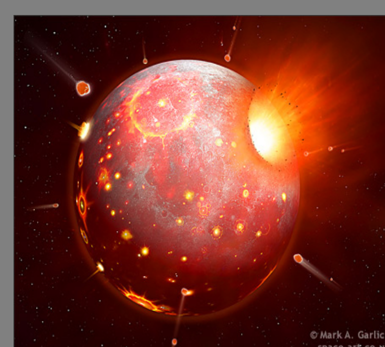
Timescale barrier

They migrate quite fast

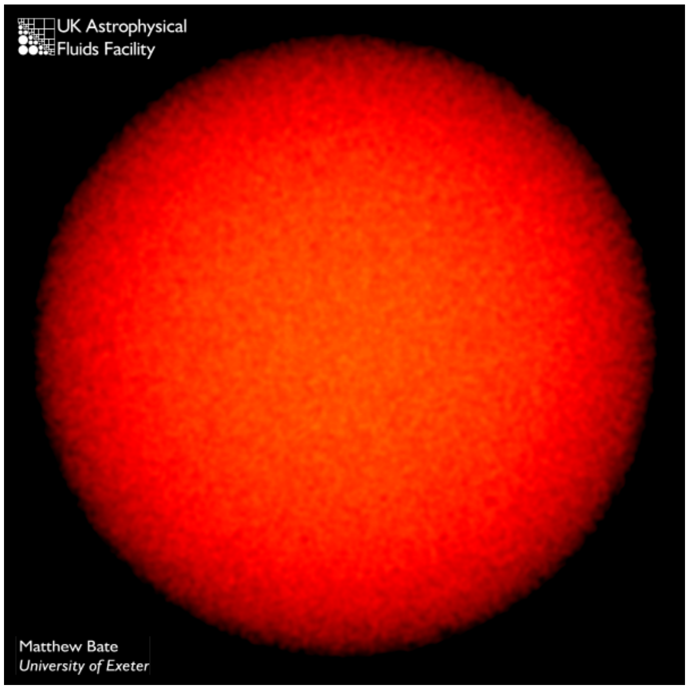
Stopping Mechanism



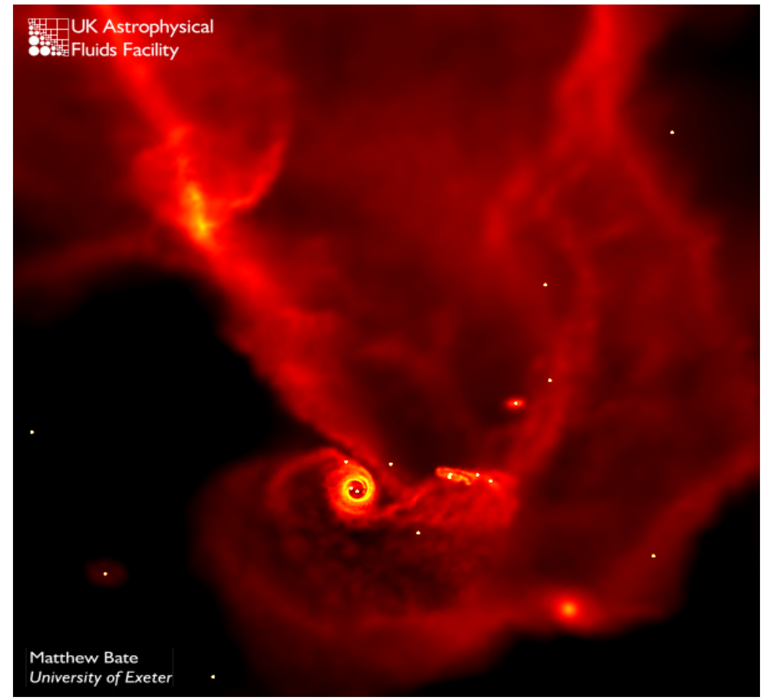




Star Formation - *[The B3 Simulation]* ***(Bate, Bonnell, Bromm 2003)***



t=0



t=266 000 yr

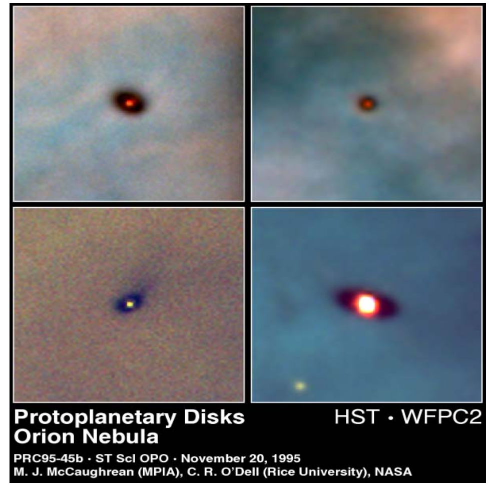
Some stars are seen to be born with lots of surrounding gas.

This gas is bound to the star and referred to as

circumstellar disk* or *protoplanetary disk.

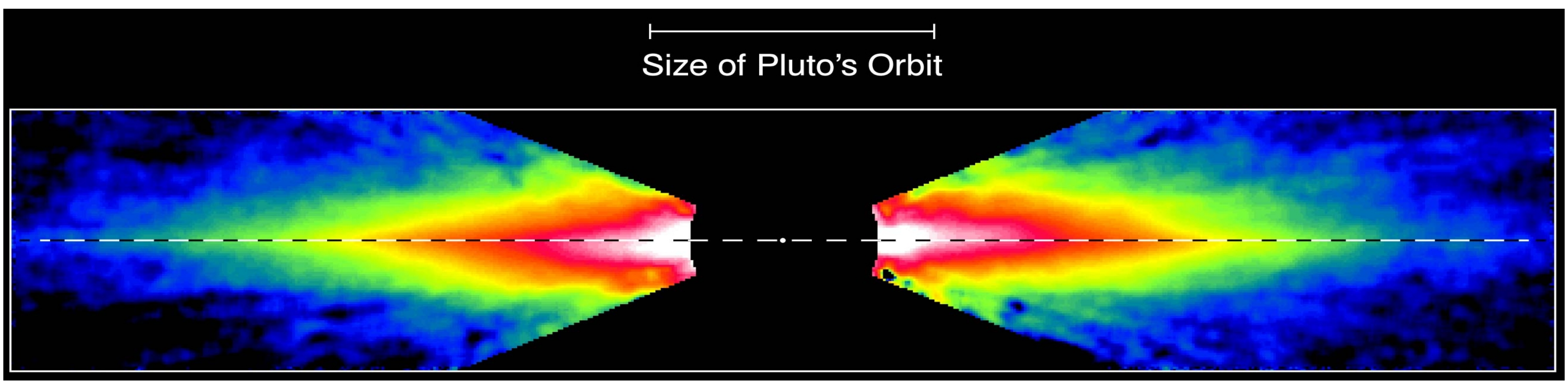
“Extra-Solar Nebulae” - Circumstellar Disks

Dust lane
blocks view



A light background
reveals the disks

Warm dust shines
in infrared



The disk of the star *Beta Pictoris*

Paper I – Testing the Code

Planet opening a gap in the gaseous disk

Pencil agrees well with the results of other 17 codes

Mon. Not. R. Astron. Soc. 370, 529–558 (2006) doi:10.1111/j.1365-2966.2006.10488.x

A comparative study of disc–planet interaction

M. de Val-Borro,[1*] R. G. Edgar,[1,2] P. Artymowicz,[1,3] P. Ciecielag,[4,5] P. Cresswell,[6] G. D'Angelo,[7] E. J. Delgado-Donate,[1] G. Dirksen,[8] S. Fromang,[6,9] A. Gawryszczak,[5] H. Klahr,[10] W. Kley,[8] W. Lyra,[11] F. Masset,[12,13] G. Mellema,[14] R. P. Nelson,[6] S.-J. Paardekooper,[14] A. Peplinski,[1] A. Pierens,[6,15] T. Plewa,[16] K. Rice,[17] C. Schäfer[8] and R. Speith[8]

[1]Stockholm University, AlbaNova University Centre, SE-106 91, Stockholm, Sweden
[2]Department of Physics and Astronomy, University of Rochester, NY 14627, USA
[3]University of Toronto at Scarborough, 1265 Military Trail, Toronto, Ontario M1C 1A4, Canada
[4]University Observatory Munich, Scheinerstr. 1, D-81679 Munich, Germany
[5]Nicolaus Copernicus Astronomical Centre, Bartycka 18, Warsaw, PL-00-716, Poland
[6]Astronomy Unit, Queen Mary, University of London, Mile End Road, London E1 4NS
[7]School of Physics, University of Exeter, Stocker Road, Exeter EX4 4QL
[8]Institute of Astronomy and Astrophysics Tübingen, Auf der Morgenstelle 10, D-72076 Tübingen, Germany
[9]DAMTP, University of Cambridge, Centre for Mathematical Sciences, Wilberforce Road, Cambridge CB3 0WA
[10]Max-Planck-Institut für Astronomie, Königstuhl 17, D-69117 Heidelberg, Germany
[11]Department of Astronomy & Space Physics, Uppsala Astronomical Observatory, Box 515, 751 20, Sweden
[12]AIM, UMR 7158 CEA/CNRS/Univ. Paris VII, Service d'Astrophysique, Saclay, 91191 Gif-sur-Yvette Cedex, France
[13]IA-UNAM, Ciudad Universitaria, Apartado Postal 70-264, Mexico DF 04510, Mexico
[14]Leiden Observatory, PO Box 9513, NL-2300 RA Leiden, the Netherlands
[15]Luth, Observatoire de Paris-Meudon, 92 195 Meudon Cedex, France
[16]ASC FLASH Center, University of Chicago, 5640 South Ellis, Chicago, IL 60637, USA
[17]Scottish Universities Physics Alliance, Institute for Astronomy, University of Edinburgh, Blackford Hill, Edinburgh EH9 3HJ

Accepted 2006 April 11. Received 2006 March 8; in original form 2005 October 24

ABSTRACT

We perform numerical simulations of a disc–planet system using various grid-based and smoothed particle hydrodynamics (SPH) codes. The tests are run for a simple setup where Jupiter and Neptune mass planets on a circular orbit open a gap in a protoplanetary disc during a few hundred orbital periods. We compare the surface density contours, potential vorticity and smoothed radial profiles at several times. The disc mass and gravitational torque time evolution are analysed with high temporal resolution. There is overall consistency between the codes. The density profiles agree within about 5 per cent for the Eulerian simulations. The SPH results predict the correct shape of the gap although have less resolution in the low-density regions and weaker planetary wakes. The disc masses after 200 orbital periods agree within 10 per cent. The spread is larger in the tidal torques acting on the planet which agree within a factor of 2 at the end of the simulation. In the Neptune case, the dispersion in the torques is greater than for Jupiter, possibly owing to the contribution from the not completely cleared region close to the planet.

Key words: accretion, accretion discs – hydrodynamics – planets and satellites: general.

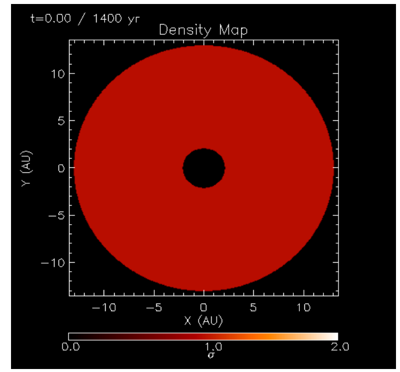
1 INTRODUCTION

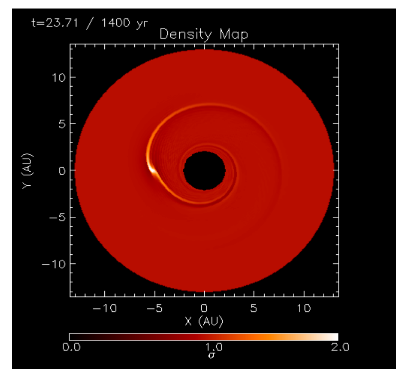
Hydrodynamics is a difficult subject, which has caused many problems for many distinguished physicists. However, it is not a topic which can be avoided due to the central part that gas plays in the cosmos.

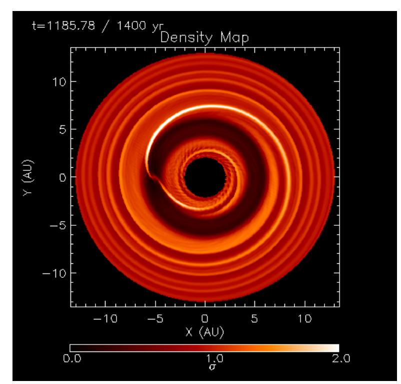
The basic equations of hydrodynamics are the Navier–Stokes equations, and have been known for almost two centuries:

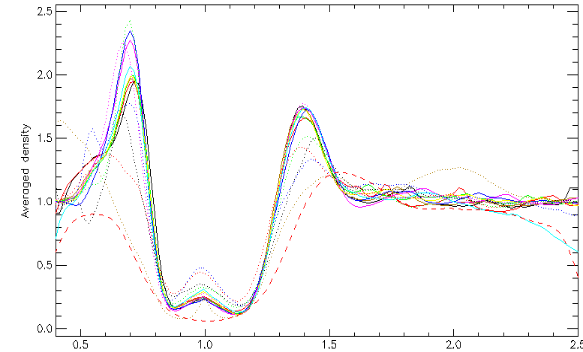
$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho v) = 0, \quad (1)$$

*E-mail: miguel@astro.su.se

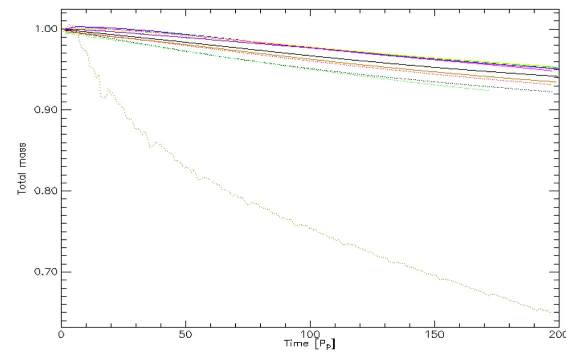




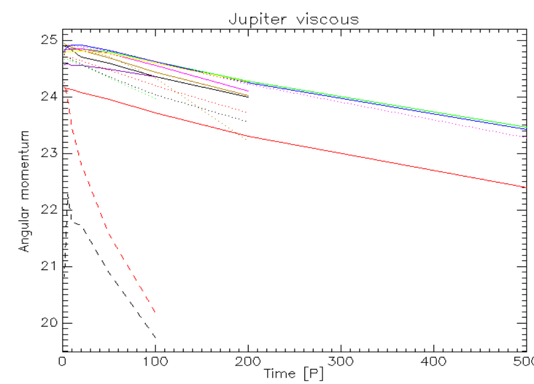




Surface Density



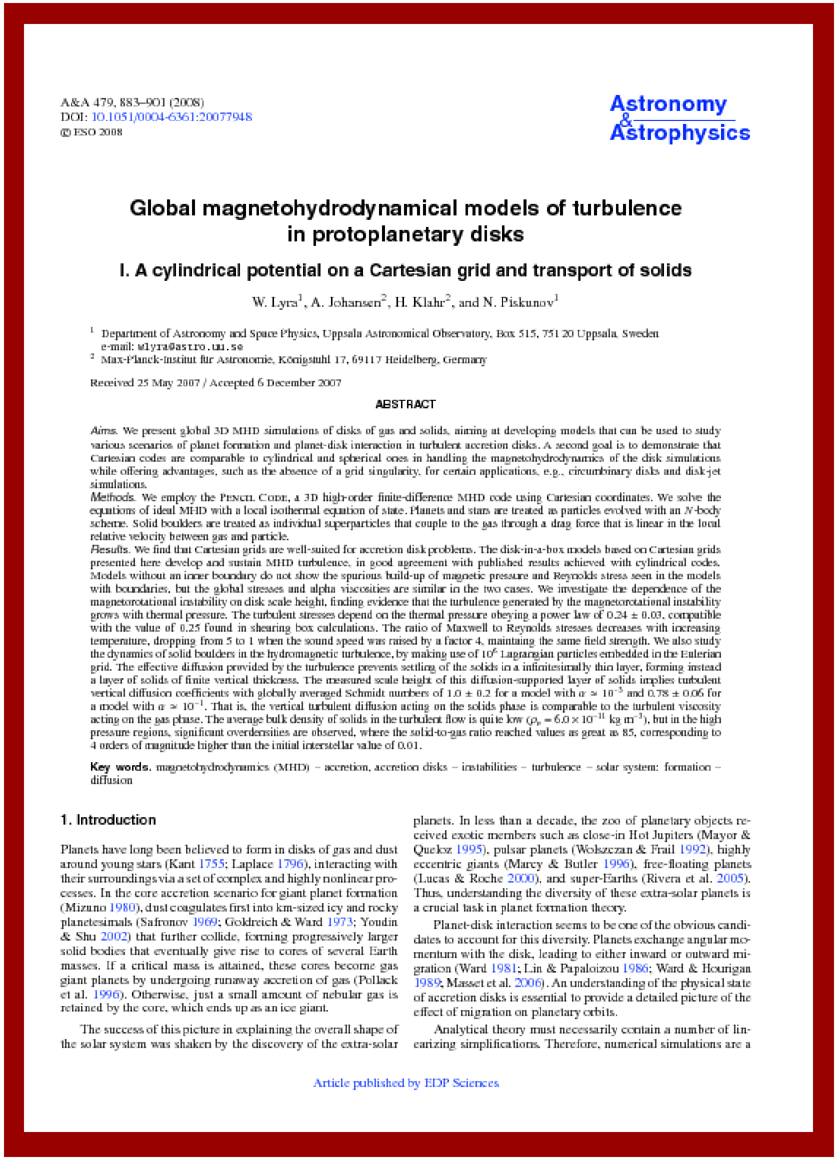
Total Mass



Angular Momentum

Paper II – Turbulent Disk Models

Accretion disks are unstable to the Magneto-Rotational Instability (MRI)
The turbulence that ensues is the best candidate to explain accretion
(Balbus and Hawley 1991)


A&A 479, 883–901 (2008)
DOI: 10.1051/0004-6361:20077948

Astronomy & Astrophysics

Global magnetohydrodynamical models of turbulence in protoplanetary disks

I. A cylindrical potential on a Cartesian grid and transport of solids

W. Lyra[1], A. Johansen[2], H. Klahr[2], and N. Piskunov[1]

[1] Department of Astronomy and Space Physics, Uppsala Astronomical Observatory, Box 515, 751 20 Uppsala, Sweden
e-mail: wlyra@astro.uu.se
[2] Max-Planck-Institut für Astronomie, Königstuhl 17, 69117 Heidelberg, Germany

Received 25 May 2007 / Accepted 6 December 2007

ABSTRACT

Aims. We present global 3D MHD simulations of disks of gas and solids, aiming at developing models that can be used to study various scenarios of planet formation and planet-disk interaction in turbulent accretion disks. A second goal is to demonstrate that Cartesian codes are comparable to cylindrical and spherical ones in handling the magnetohydrodynamics of the disk simulations while offering advantages, such as the absence of a grid singularity, for certain applications, e.g., circumbinary disks and disk-jet simulations.
Methods. We employ the Pencil Code, a 3D high-order finite-difference MHD code using Cartesian coordinates. We solve the equations of ideal MHD with a local isothermal equation of state. Planets and stars are treated as particles evolved with an N-body scheme. Solid boulders are treated as individual superparticles that couple to the gas through a drag force that is linear in the local relative velocity between gas and particle.
Results. We find that Cartesian grids are well-suited for accretion disk problems. The disk-in-a-box models based on Cartesian grids presented here develop and sustain MHD turbulence, in good agreement with published results achieved with cylindrical codes. Models without an inner boundary do not show the spurious build-up of magnetic pressure and Reynolds stress seen in the models with boundaries, but the global stresses and alpha viscosities are similar in the two cases. We investigate the dependence of the magnetorotational instability on disk scale height, finding evidence that the turbulence generated by the magnetorotational instability grows with thermal pressure. The turbulent stresses depend on the thermal pressure obeying a power law of 0.24 ± 0.03, compatible with the value of 0.25 found in shearing box calculations. The ratio of Maxwell to Reynolds stresses decreases with increasing temperature, dropping from 5 to 1 when the sound speed was raised by a factor 4, maintaining the same field strength. We also study the dynamics of solid boulders in the hydromagnetic turbulence, by making use of 10^6 Lagrangian particles embedded in the Eulerian grid. The effective diffusion provided by the turbulence prevents settling of the solids in a infinitesimally thin layer, forming instead a layer of solids of finite vertical thickness. The measured scale height of this diffusion-supported layer of solids implies turbulent vertical diffusion coefficients with globally averaged Schmidt numbers of 1.0 ± 0.2 for a model with $\alpha \approx 10^{-3}$ and 0.78 ± 0.06 for a model with $\alpha \approx 10^{-1}$. That is, the vertical turbulent diffusion acting on the solids phase is comparable to the turbulent viscosity acting on the gas phase. The average bulk density of solids in the turbulent flow is quite low ($\rho_p = 6.0 \times 10^{-11}$ kg m^{-3}), but in the high pressure regions, significant overdensities are observed, where the solid-to-gas ratio reached values as great as 85, corresponding to 4 orders of magnitude higher than the initial interstellar value of 0.01.

Key words. magnetohydrodynamics (MHD) – accretion, accretion disks – instabilities – turbulence – solar system: formation – diffusion

1. Introduction

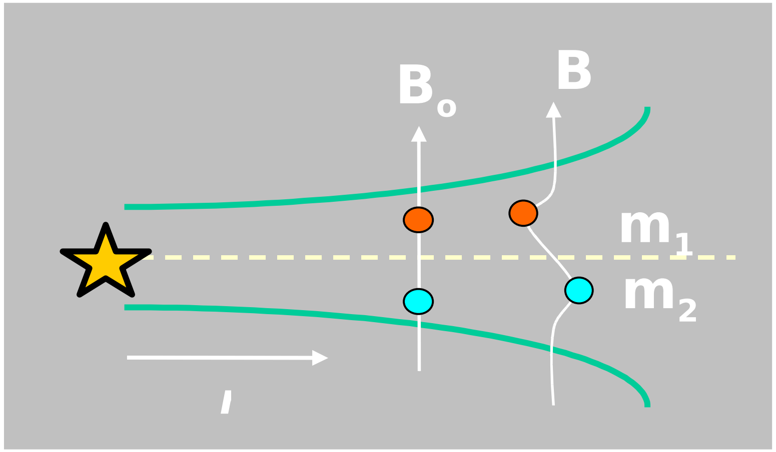
Planets have long been believed to form in disks of gas and dust around young stars (Kant 1755; Laplace 1796), interacting with their surroundings via a set of complex and highly nonlinear processes. In the core accretion scenario for giant planet formation (Mizuno 1980), dust coagulates first into km-sized icy and rocky planetesimals (Safronov 1969; Goldreich & Ward 1973; Youdin & Shu 2002) that further collide, forming progressively larger solid bodies that eventually give rise to cores of several Earth masses. If a critical mass is attained, these cores become gas giant planets by undergoing runaway accretion of gas (Pollack et al. 1996). Otherwise, just a small amount of nebular gas is retained by the core, which ends up as an ice giant.

The success of this picture in explaining the overall shape of the solar system was shaken by the discovery of the extra-solar planets. In less than a decade, the zoo of planetary objects received exotic members such as close-in Hot Jupiters (Mayor & Queloz 1995), pulsar planets (Wolszczan & Frail 1992), highly eccentric giants (Marcy & Butler 1996), free-floating planets (Lucas & Roche 2000), and super-Earths (Rivera et al. 2005). Thus, understanding the diversity of these extra-solar planets is a crucial task in planet formation theory.

Planet-disk interaction seems to be one of the obvious candidates to account for this diversity. Planets exchange angular momentum with the disk, leading to either inward or outward migration (Ward 1981; Lin & Papaloizou 1986; Ward & Hourigan 1989; Masset et al. 2006). An understanding of the physical state of accretion disks is essential to provide a detailed picture of the effect of migration on planetary orbits.

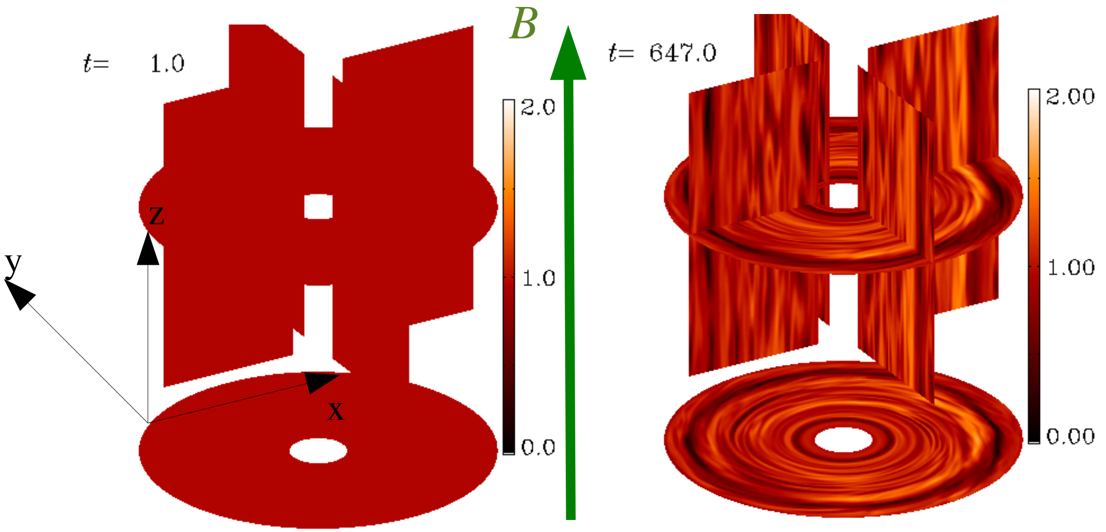
Analytical theory must necessarily contain a number of linearizing simplifications. Therefore, numerical simulations are a

Article published by EDP Sciences



Build-up of magnetic tension:
- tries to restore equilibirum (*resists streching*)
- tries to enforce rigid rotation (*resists shear*)

Density Evolution



Color code: **Density**

Time unit = (2pi/T_{Jup}) = **1.6 yr**

Density unit = **2x10^{-11} g/cm^3**

Turbulence stresses transport angular momentum

Closure model of Shakura & Sunyaev (1973)

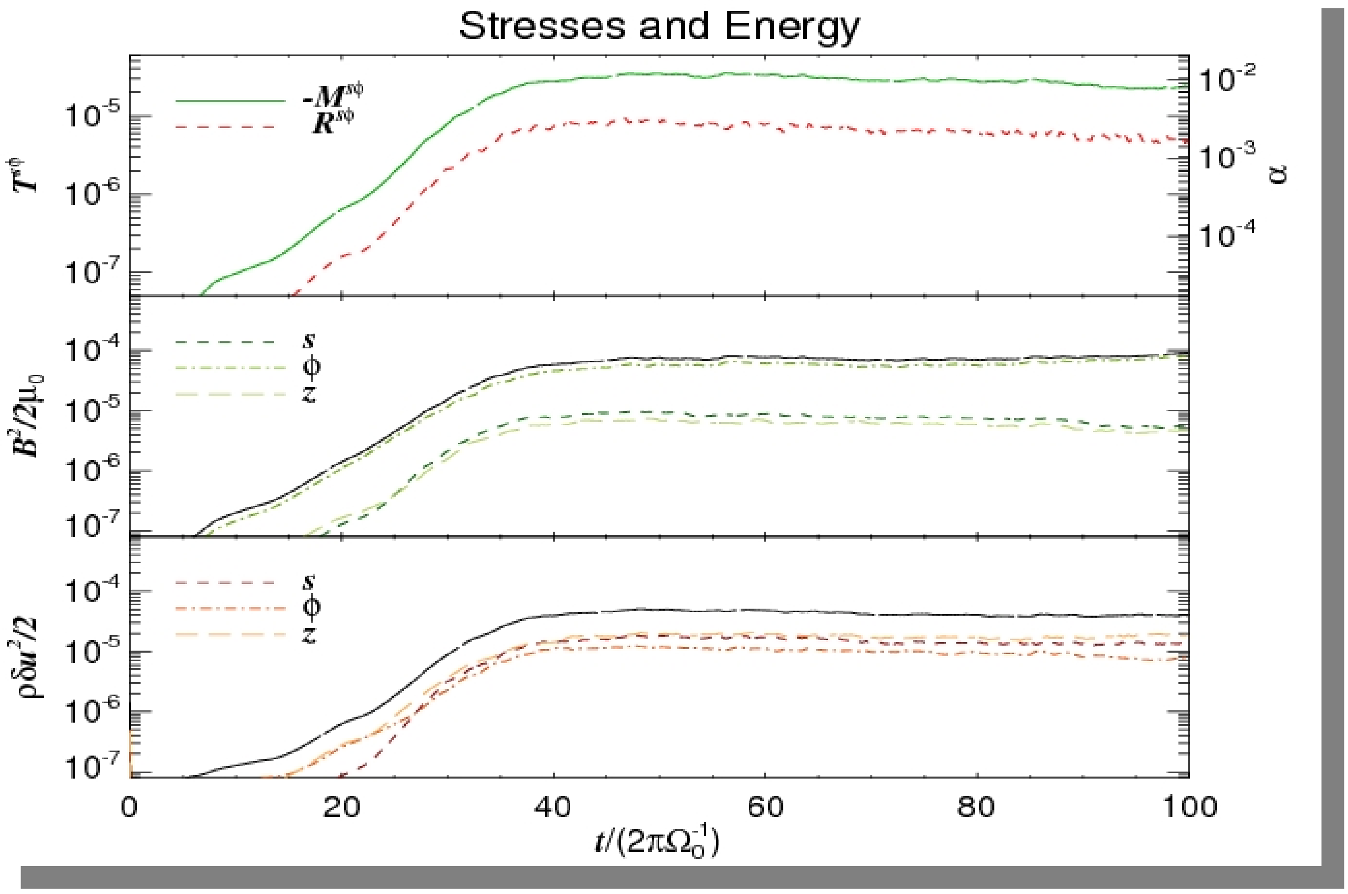
$$\partial_t \overline{L_\phi} + \nabla\cdot(\overline{L_\phi}\,\overline{\boldsymbol{u}}) = -\nabla\cdot(r\,T^{r\phi})$$ Reynolds Equation

$$\partial_t L_\phi + \nabla\cdot(L_\phi\,\boldsymbol{u}) = -\nabla\cdot(r^{-1}\,q\,\nu\,L_\phi)$$ Navier-Stokes Equation

$$L_\phi = \rho\,\Omega\,r^2$$

$$q = -\frac{d\ln\Omega}{d\ln r}$$

$$T^{r\phi} = q\,\alpha\,P \longrightarrow \nu = \alpha\,c_s^2\,\Omega^{-1}$$



α viscosity = 10^{-2}

Large scale B_ϕ field

Isotropic E_{kin}

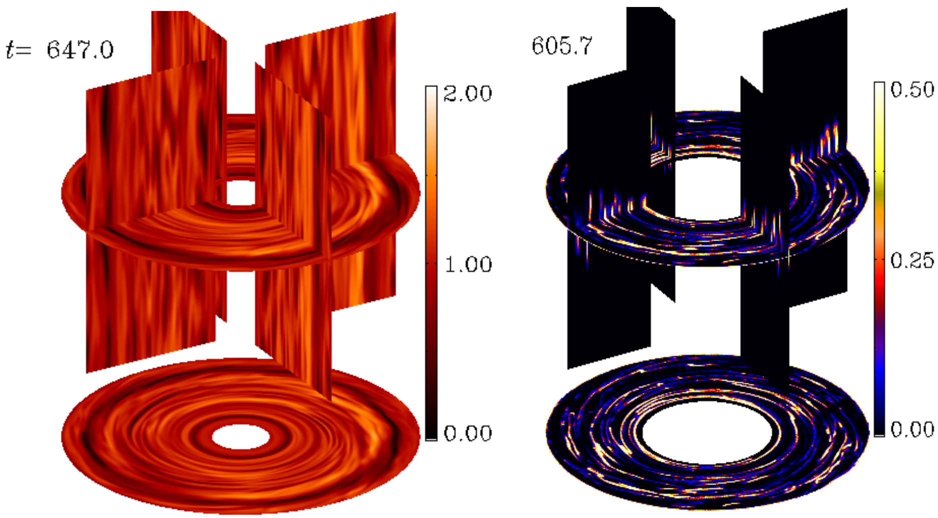
Solids in a turbulent disk

Gas $\frac{D\boldsymbol{u}}{Dt} = -\nabla\Phi - \rho^{-1}\nabla p$

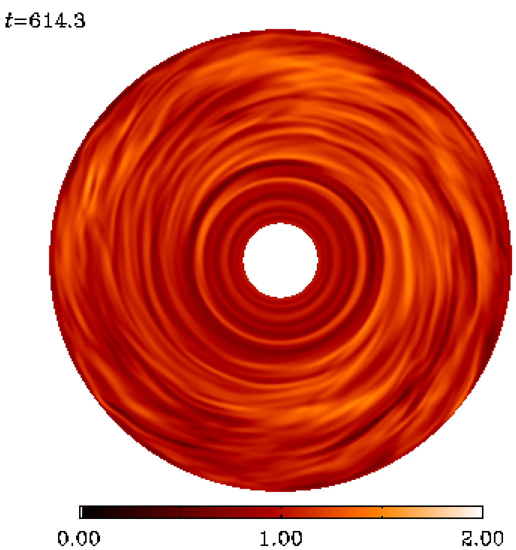
Solids $\frac{d\boldsymbol{w}}{dt} = -\nabla\Phi - \frac{(\boldsymbol{w}-\boldsymbol{u})}{\tau}$

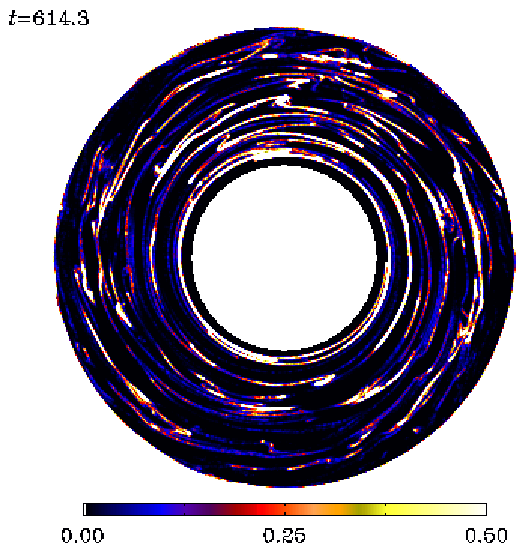
$$\boldsymbol{V} = \boldsymbol{u} - \boldsymbol{w}$$
$$\frac{D\boldsymbol{V}}{Dt} \approx \rho^{-1}\nabla p + \frac{\boldsymbol{V}}{\tau}$$

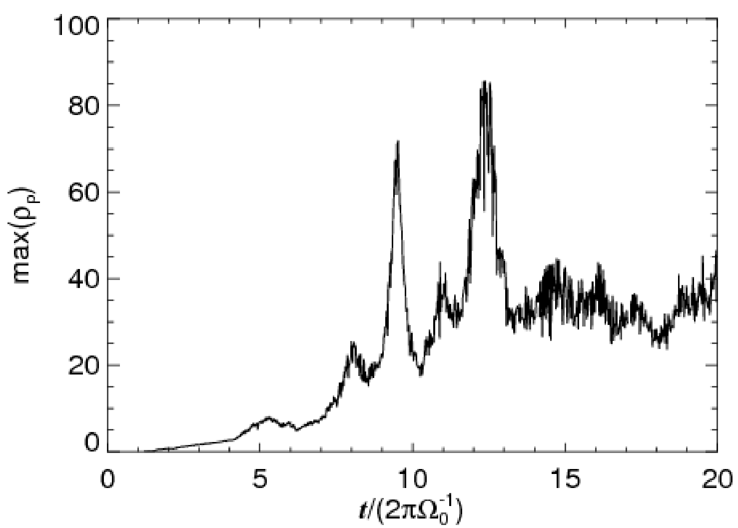
Instantaneously, the drag force pushes the solids *towards* the pressure gradient



Intense Clumping!!







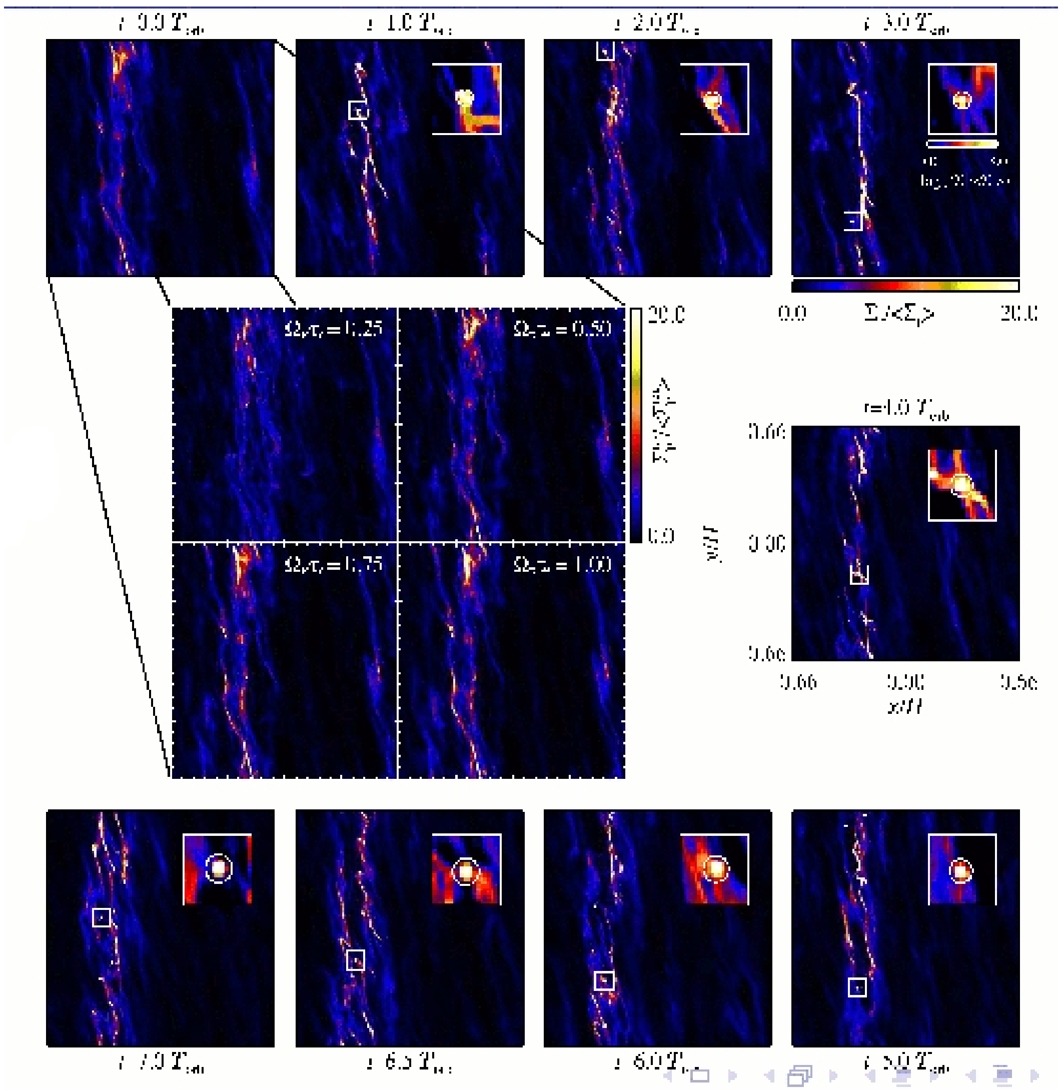
-Turbulent eddies are very efficient particle traps

-Correlation between gas and solids density maxima

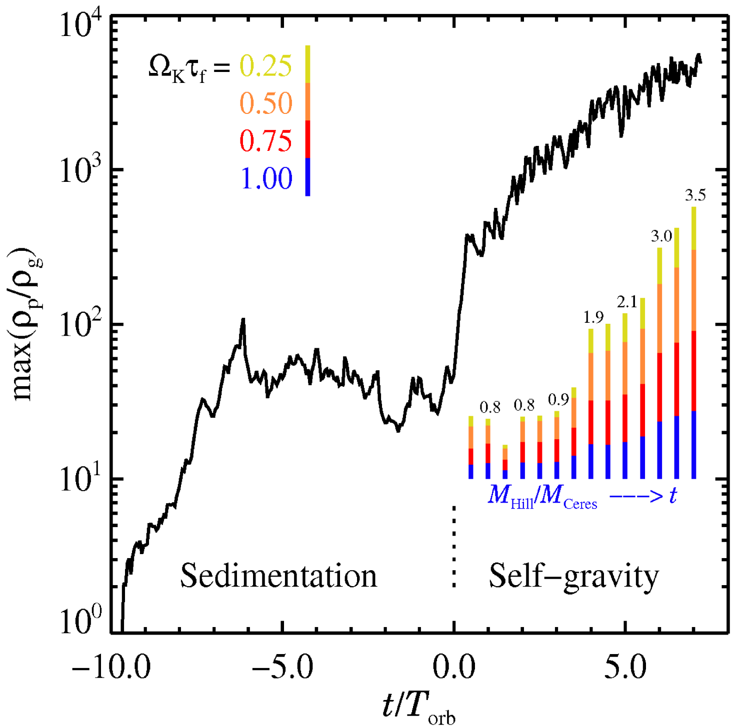
>3 orders of magnitude increase in the solids-to-gas ratio.

Including Self-Gravity: Gravitational Collapse into Dwarf Planets

Local model: MRI plus self-gravity



Source: Johansen et al. (2007)



Breaching the meter size barrier by a giant leap

Planet Formation

Planetesimal Hypothesis (Safronov 1969)

From dust to boulders

μm -> m: Electrostatic forces cause sticking

m -> km: ***HOW????***

From planetesimals to protoplanets

km -> 1000 km: Gravity

From protoplanets to planets

Rocky Planets: Protoplanets collide

Gas Giants: Attract gaseous envelope

From meter to kilometer

Growth barrier

- through EM?

They don't stick, they break

Gentle Collisions

- through Gravity?

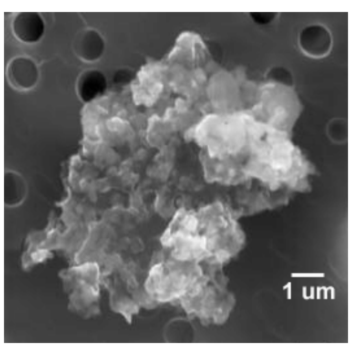
They aren't massive enough

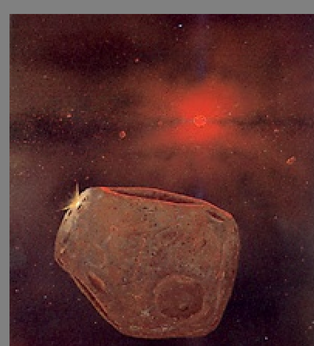
High number density

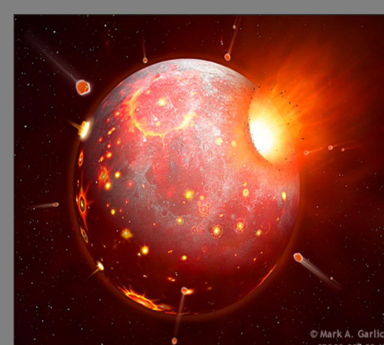
Timescale barrier

They migrate quite fast

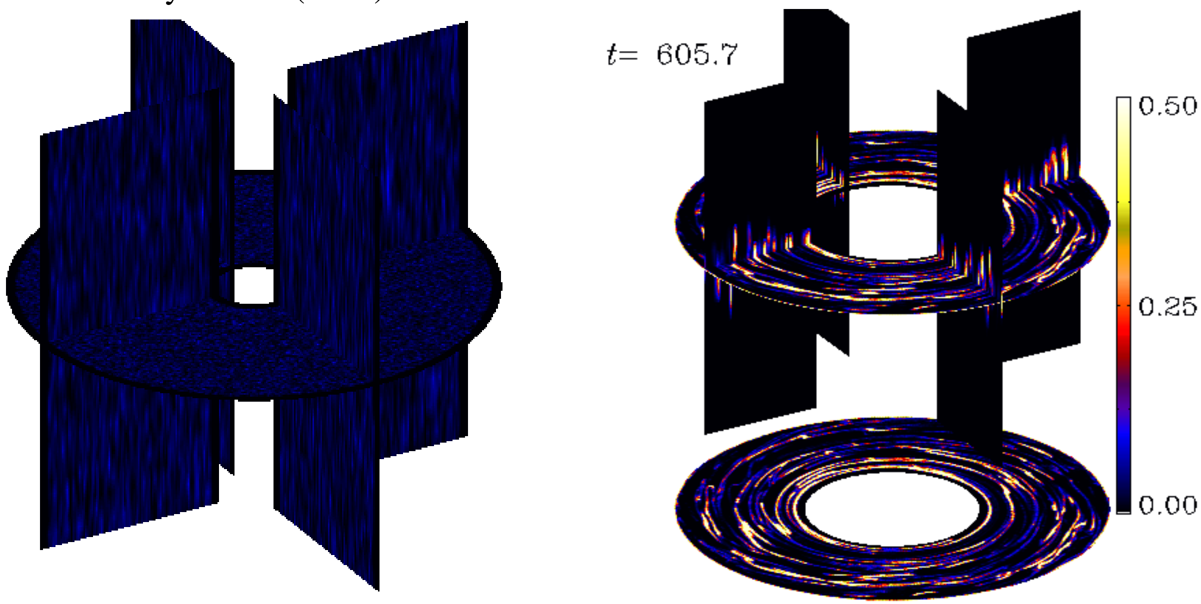
Stopping Mechanism







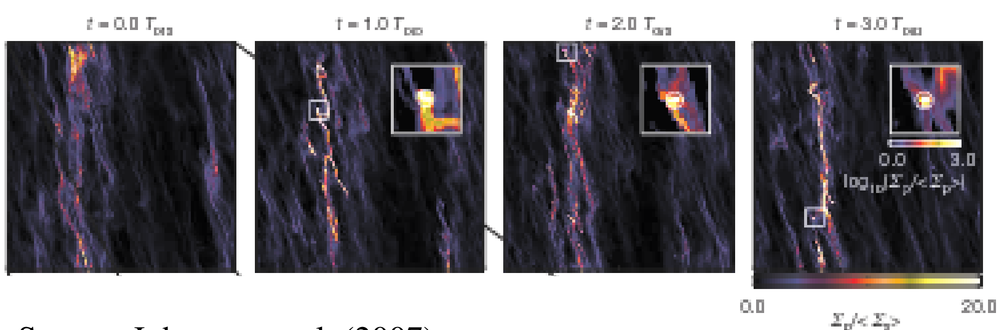
Source: Lyra et al. (2008)



Gentle Collisions

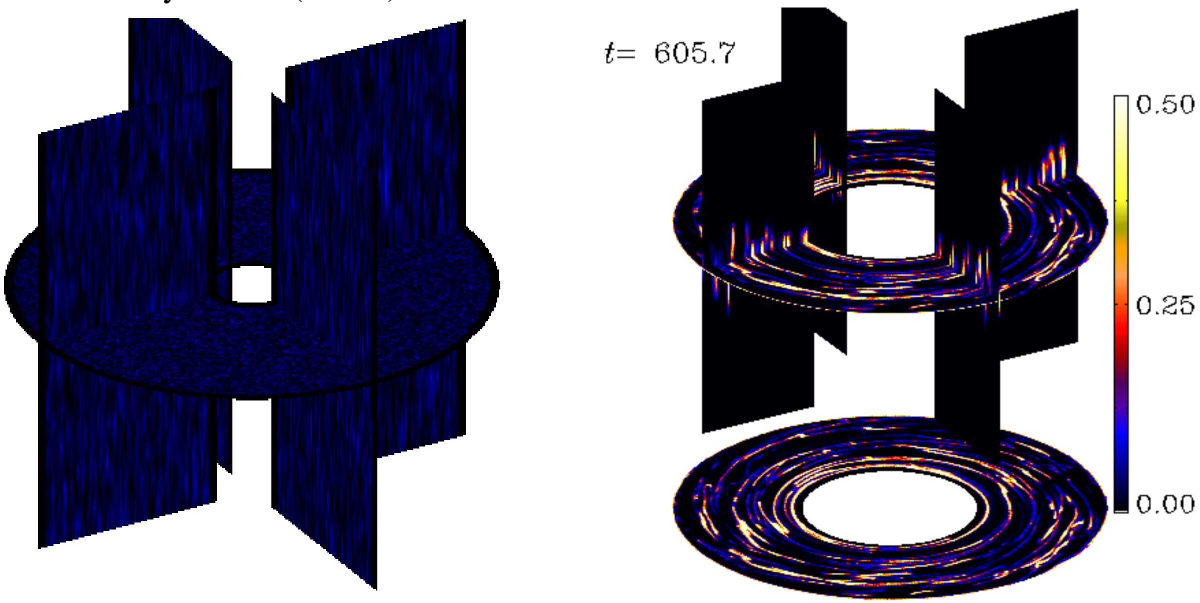
Turbulence provides → High number density

→ Stopping Mechanism



Source: Johansen et al. (2007)

Source: Lyra et al. (2008a)

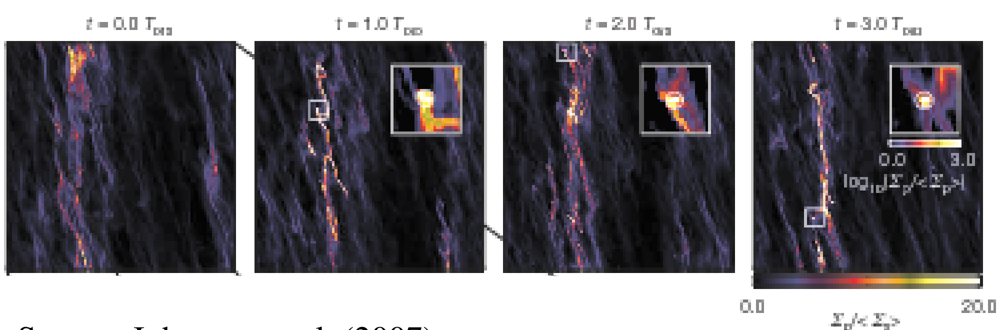


Gentle Collisions *NOT OK*

Turbulence provides

High number density OK

Stopping Mechanism OK



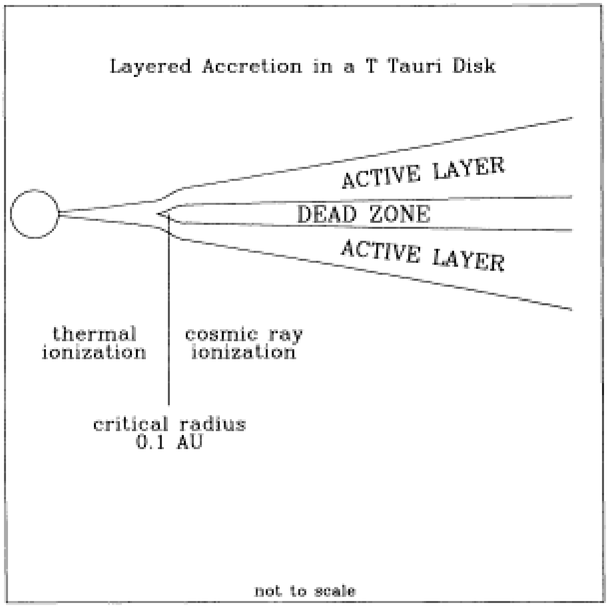
Source: Johansen et al. (2007)

The Dead Zone

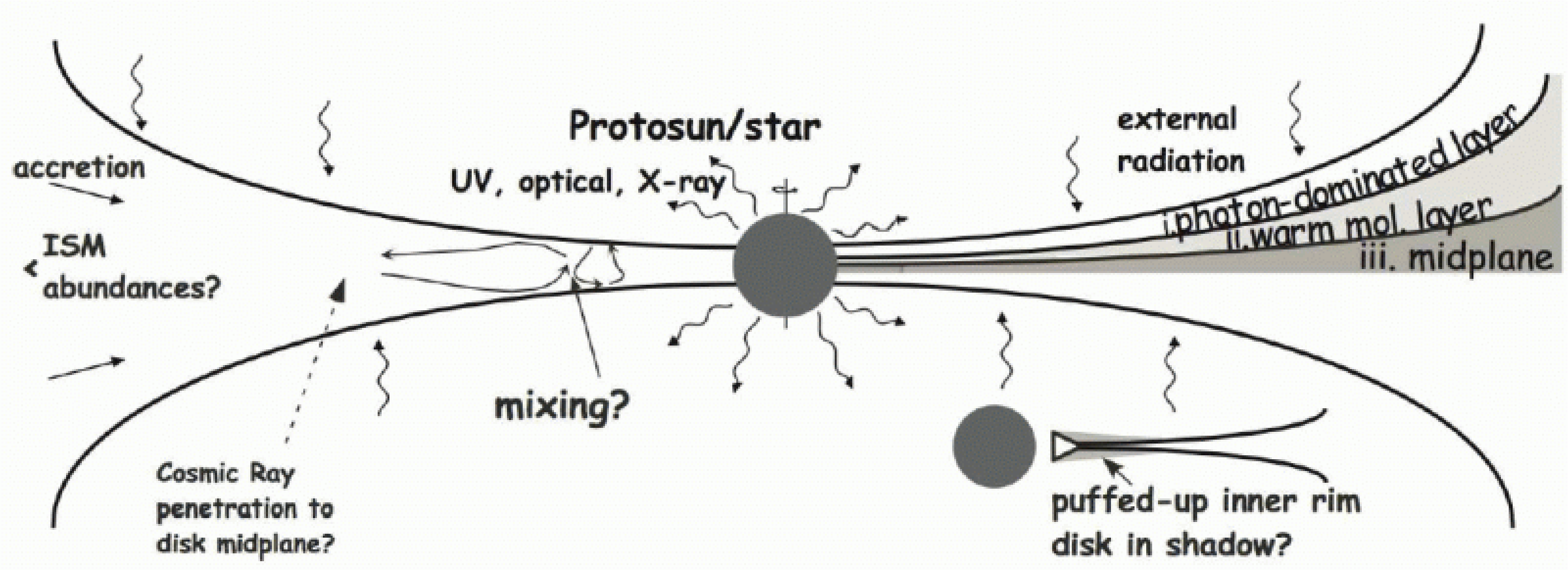
Midplane is

- too dense (no cosmic ray ionization)
- too cold (no thermal ionization)

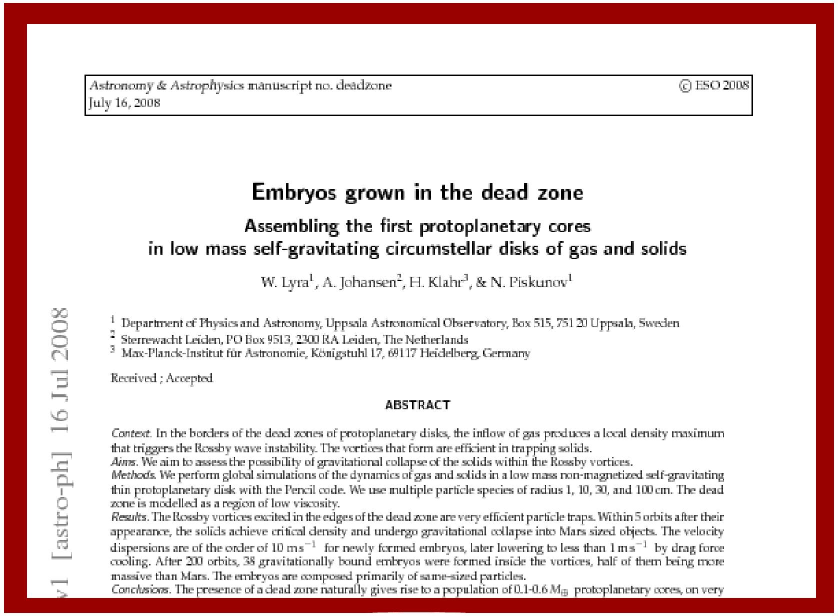
No ionization, no MRI turbulence...



Source: Gammie et al. (1996)



Paper III – A simple Dead Zone model



Astronomy & Astrophysics manuscript no. deadzone
July 16, 2008

Embryos grown in the dead zone

Assembling the first protoplanetary cores in low mass self-gravitating circumstellar disks of gas and solids

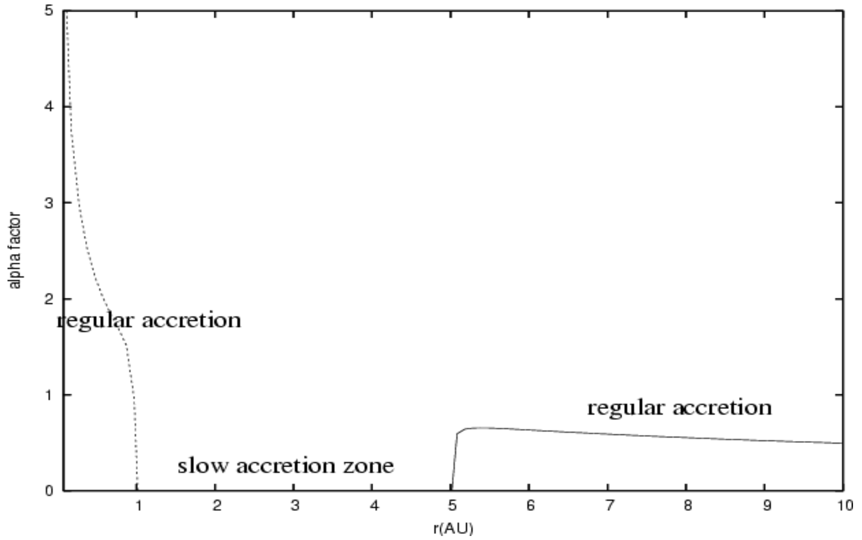
W. Lyra[1], A. Johansen[2], H. Klahr[3], & N. Piskunov[1]

[1] Department of Physics and Astronomy, Uppsala Astronomical Observatory, Box 515, 751 20 Uppsala, Sweden
[2] Sterrewacht Leiden, PO Box 9513, 2300 RA Leiden, The Netherlands
[3] Max-Planck-Institut für Astronomie, Königstuhl 17, 69117 Heidelberg, Germany

Received ; Accepted

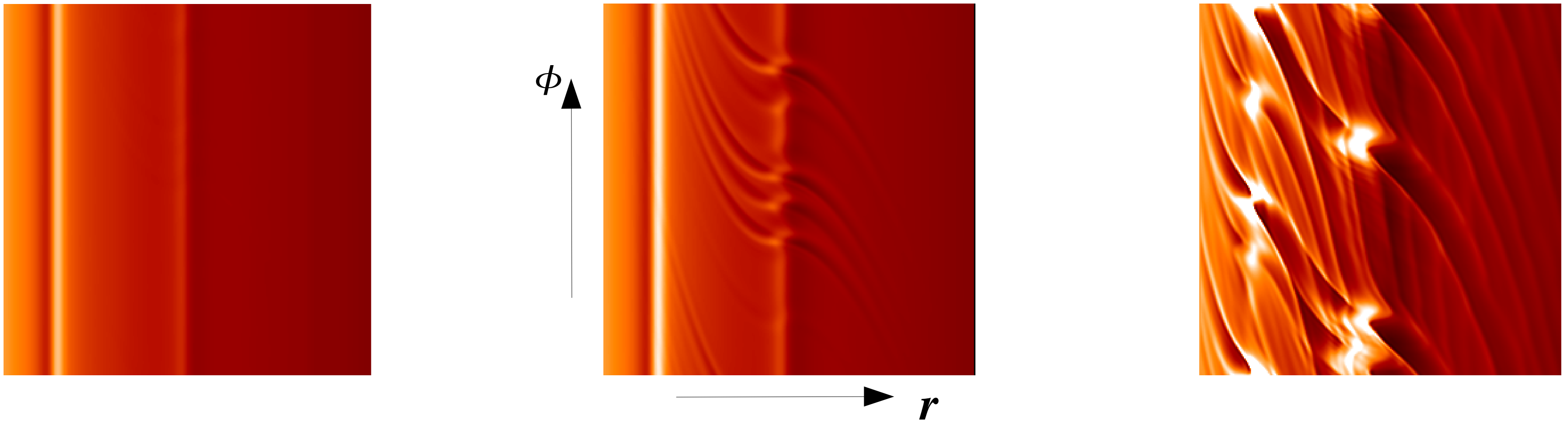
ABSTRACT

Context. In the borders of the dead zones of protoplanetary disks, the inflow of gas produces a local density maximum that triggers the Rossby wave instability. The vortices that form are efficient in trapping solids.
Aims. We aim to assess the possibility of gravitational collapse of the solids within the Rossby vortices.
Methods. We perform global simulations of the dynamics of gas and solids in a low mass non-magnetized self-gravitating thin protoplanetary disk with the Pencil code. We use multiple particle species of radius 1, 10, 30, and 100 cm. The dead zone is modelled as a region of low viscosity.
Results. The Rossby vortices excited in the edges of the dead zone are very efficient particle traps. Within 5 orbits after their appearance, the solids achieve critical density and undergo gravitational collapse into Mars sized objects. The velocity dispersions are of the order of 10 m s^{-1} for newly formed embryos, later lowering to less than 1 m s^{-1} by drag force cooling. After 200 orbits, 38 gravitationally bound embryos were formed inside the vortices, half of them being more massive than Mars. The embryos are composed primarily of same-sized particles.
Conclusions. The presence of a dead zone naturally gives rise to a population of 0.1-0.6 $M_\oplus$ protoplanetary cores, on very



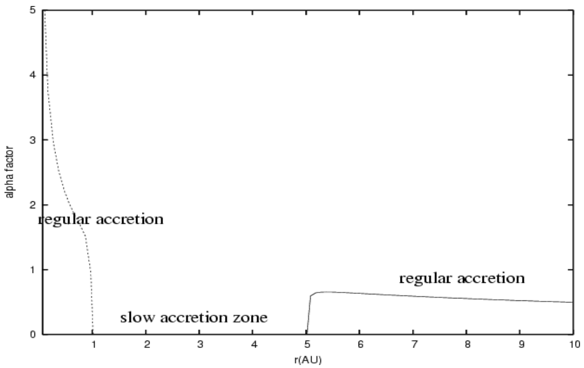
Alpha-disk with viscosity jumps

Source: Varniere & Tagger (2006)



Inflow discontinuity triggers the **Rossby wave instability** (RWI)... ...that saturates into vortices

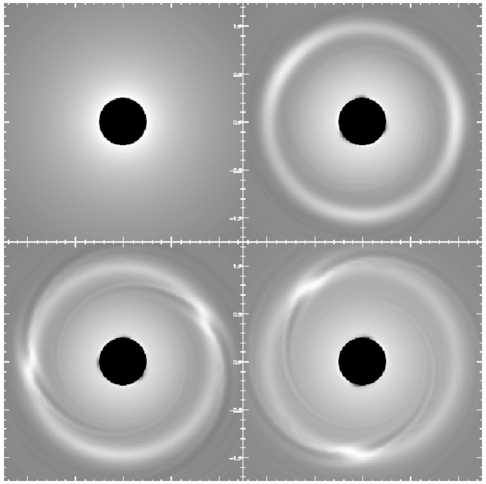
A simple Dead Zone model with particles



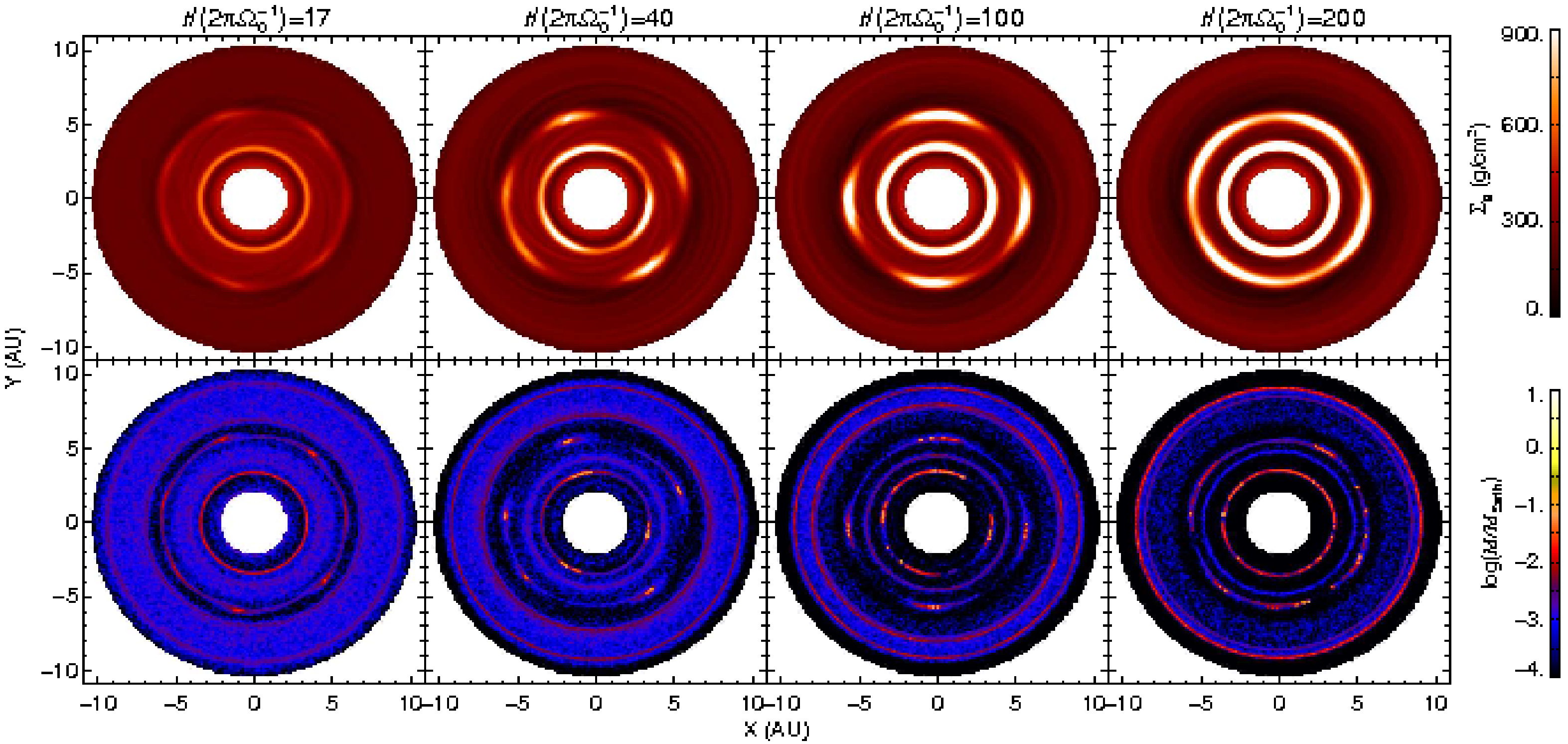
Alpha-disk with viscosity jumps

Inflow discontinuity triggers the RWI

When including particles and solving for their potential...

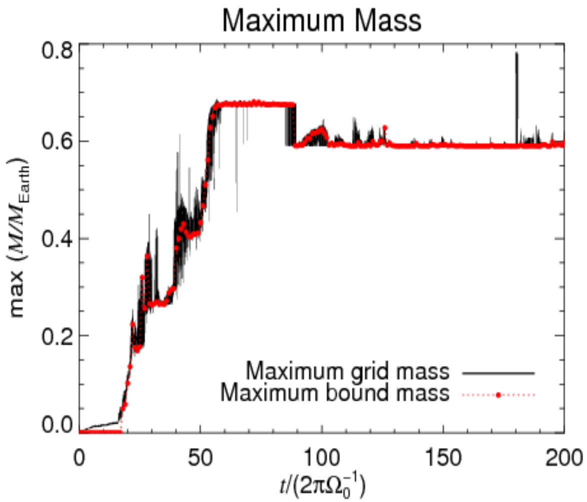


Source: Varniere & Tagger (2006)



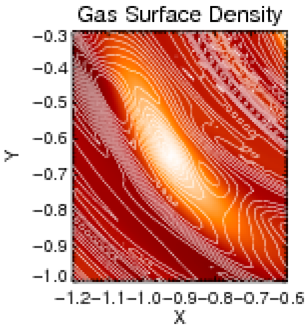
Source: Lyra et al. (2008b)

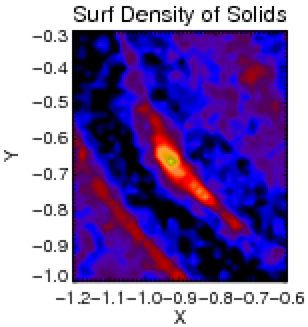
Result: A planet formation burst!

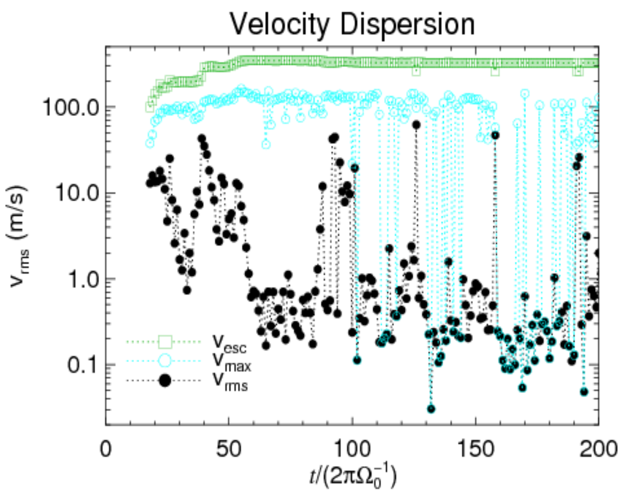


• Maximum mass: 0.6 Earth Masses

• Time between apperance of the vortices and collapse into a Mars sized embryo: 5 orbits





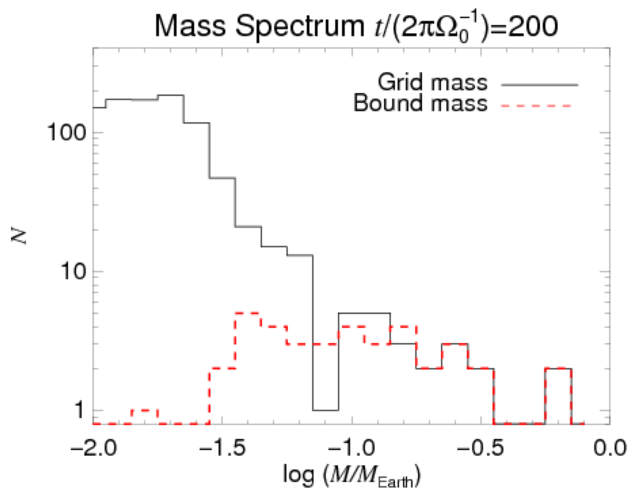


•Internal velocity dispersion is far below escape velocity

•Even the *maximum* velocity is below escape velocity

•Internal velocities of the order of **1-10 m/s**.

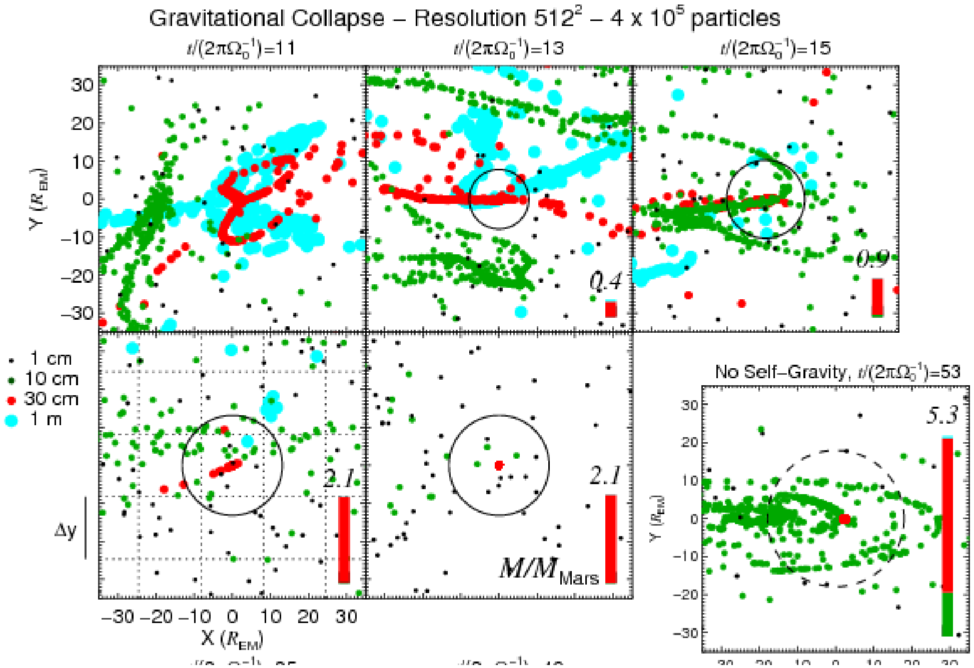
Gentle enough to prevent catastrophic collisions



•Mass spectrum by the end of the simulation

•38 bound clumps were formed, half of them above Mars mass

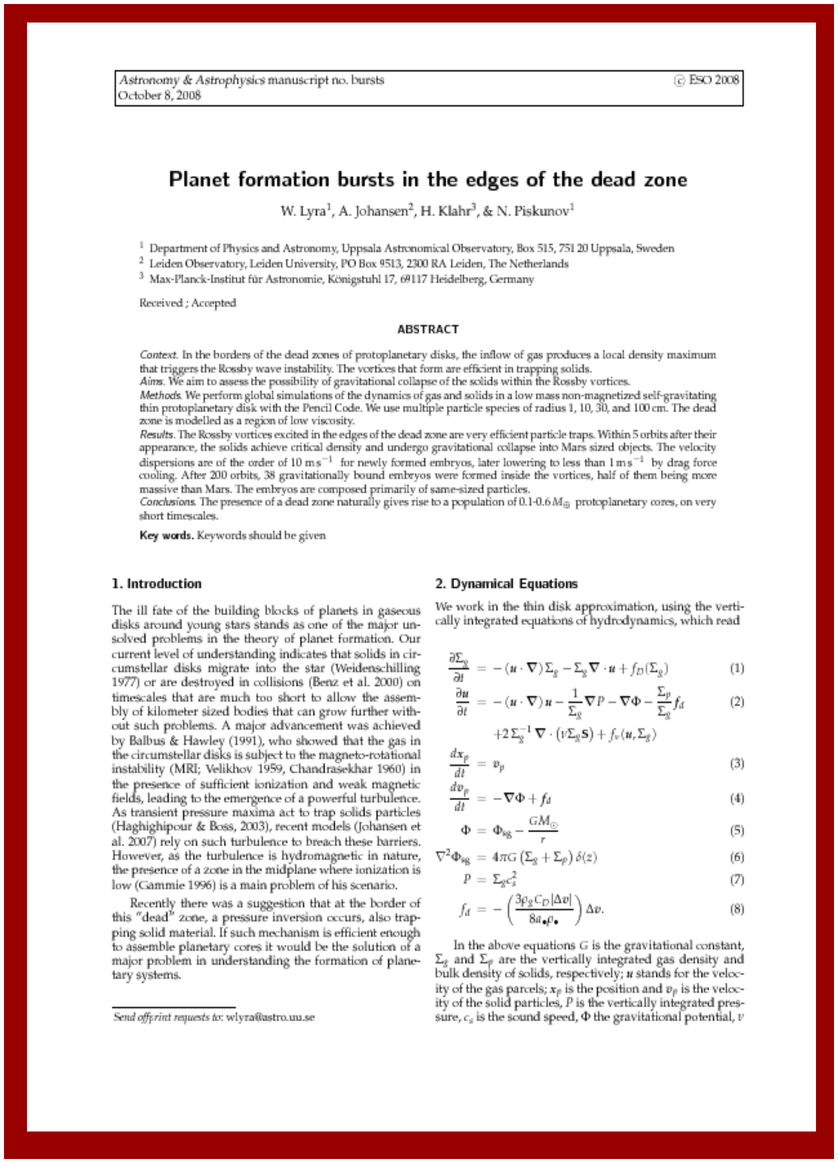
The counter-intuitive role of Self-Gravity...



Mass is far greater without selfgravity

WHY??

Paper IV – Enter the Dead Zone...



Astronomy & Astrophysics manuscript no. bursts
October 8, 2008
© ESO 2008

Planet formation bursts in the edges of the dead zone

W. Lyra[1], A. Johansen[2], H. Klahr[3], & N. Piskunov[1]

[1] Department of Physics and Astronomy, Uppsala Astronomical Observatory, Box 515, 751 20 Uppsala, Sweden
[2] Leiden Observatory, Leiden University, PO Box 9513, 2300 RA Leiden, The Netherlands
[3] Max-Planck-Institut für Astronomie, Königstuhl 17, 69117 Heidelberg, Germany

Received ; Accepted

ABSTRACT

Context. In the borders of the dead zones of protoplanetary disks, the inflow of gas produces a local density maximum that triggers the Rossby wave instability. The vortices that form are efficient in trapping solids.
Aims. We aim to assess the possibility of gravitational collapse of the solids within the Rossby vortices.
Methods. We perform global simulations of the dynamics of gas and solids in a low mass non-magnetized self-gravitating thin protoplanetary disk with the Pencil Code. We use multiple particle species of radius 1, 10, 30, and 100 cm. The dead zone is modelled as a region of low viscosity.
Results. The Rossby vortices excited in the edges of the dead zone are very efficient particle traps. Within 5 orbits after their appearance, the solids achieve critical density and undergo gravitational collapse into Mars sized objects. The velocity dispersions are of the order of $10\,\mathrm{m\,s^{-1}}$ for newly formed embryos, later lowering to less than $1\,\mathrm{m\,s^{-1}}$ by drag force cooling. After 200 orbits, 38 gravitationally bound embryos were formed inside the vortices, half of them being more massive than Mars. The embryos are composed primarily of same-sized particles.
Conclusions. The presence of a dead zone naturally gives rise to a population of 0.1-0.6 $M_\oplus$ protoplanetary cores, on very short timescales.

Key words. Keywords should be given

1. Introduction

The ill fate of the building blocks of planets in gaseous disks around young stars stands as one of the major unsolved problems in the theory of planet formation. Our current level of understanding indicates that solids in circumstellar disks migrate into the star (Weidenschilling 1977) or are destroyed in collisions (Benz et al. 2000) on timescales that are much too short to allow the assembly of kilometer sized bodies that can grow further without such problems. A major advancement was achieved by Balbus & Hawley (1991), who showed that the gas in the circumstellar disks is subject to the magneto-rotational instability (MRI; Velikhov 1959, Chandrasekhar 1960) in the presence of sufficient ionization and weak magnetic fields, leading to the emergence of a powerful turbulence. As transient pressure maxima act to trap solids particles (Haghighipour & Boss, 2003), recent models (Johansen et al. 2007) rely on such turbulence to breach these barriers. However, as the turbulence is hydromagnetic in nature, the presence of a zone in the midplane where ionization is low (Gammie 1996) is a main problem of his scenario.

Recently there was a suggestion that at the border of this "dead" zone, a pressure inversion occurs, also trapping solid material. If such mechanism is efficient enough to assemble planetary cores it would be the solution of a major problem in understanding the formation of planetary systems.

Send offprint requests to: wlyra@astro.uu.se

2. Dynamical Equations

We work in the thin disk approximation, using the vertically integrated equations of hydrodynamics, which read

$$\frac{\partial \Sigma_g}{\partial t} = -(\boldsymbol{u}\cdot\boldsymbol{\nabla})\Sigma_g - \Sigma_g\boldsymbol{\nabla}\cdot\boldsymbol{u} + f_D(\Sigma_g) \quad (1)$$

$$\frac{\partial \boldsymbol{u}}{\partial t} = -(\boldsymbol{u}\cdot\boldsymbol{\nabla})\boldsymbol{u} - \frac{1}{\Sigma_g}\boldsymbol{\nabla}P - \boldsymbol{\nabla}\Phi - \frac{\Sigma_p}{\Sigma_g}f_d + 2\Sigma_g^{-1}\boldsymbol{\nabla}\cdot(\nu\Sigma_g\mathbf{S}) + f_\nu(\boldsymbol{u},\Sigma_g) \quad (2)$$

$$\frac{d\boldsymbol{x}_p}{dt} = \boldsymbol{v}_p \quad (3)$$

$$\frac{d\boldsymbol{v}_p}{dt} = -\boldsymbol{\nabla}\Phi + f_d \quad (4)$$

$$\Phi = \Phi_{sg} - \frac{GM_\odot}{r} \quad (5)$$

$$\nabla^2\Phi_{sg} = 4\pi G\left(\Sigma_g + \Sigma_p\right)\delta(z) \quad (6)$$

$$P = \Sigma_g c_s^2 \quad (7)$$

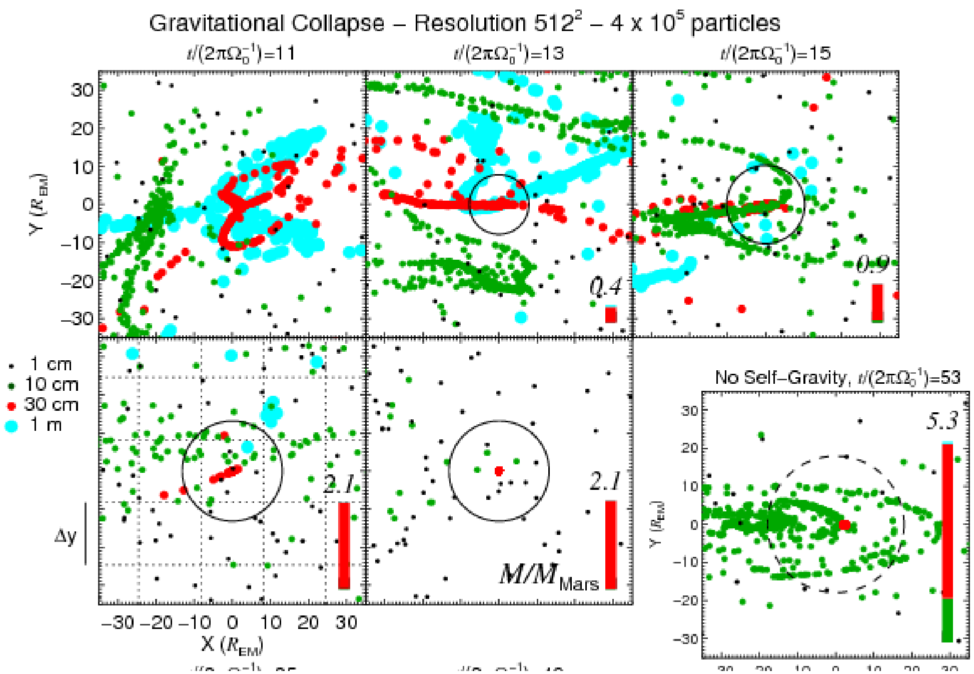
$$f_d = -\left(\frac{3\rho_g C_D|\Delta\boldsymbol{v}|}{8a_\bullet\rho_\bullet}\right)\Delta\boldsymbol{v}. \quad (8)$$

In the above equations G is the gravitational constant, Σ_g and Σ_p are the vertically integrated gas density and bulk density of solids, respectively; $\boldsymbol{u}$ stands for the velocity of the gas parcels; $\boldsymbol{x}_p$ is the position and $\boldsymbol{v}_p$ is the velocity of the solid particles, P is the vertically integrated pressure, c_s is the sound speed, Φ the gravitational potential, ν

Gory details not touched on in the letter

- Width of the viscosity jump
- Survival of vortices
- Drag force cooling
- Mass loss
  - Tidal disruption
  - Erosion
- Aerodynamical sorting
- Response of the RWI to
  - Drag force backreaction
  - Self-gravity
- Accretion through the dead zone

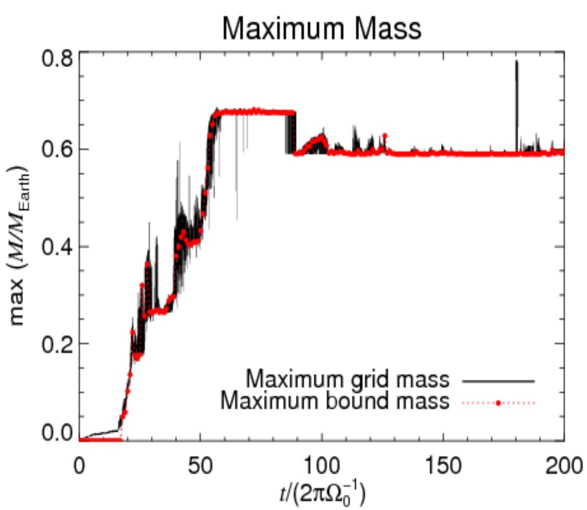
The counter-intuitive role of Self-Gravity...

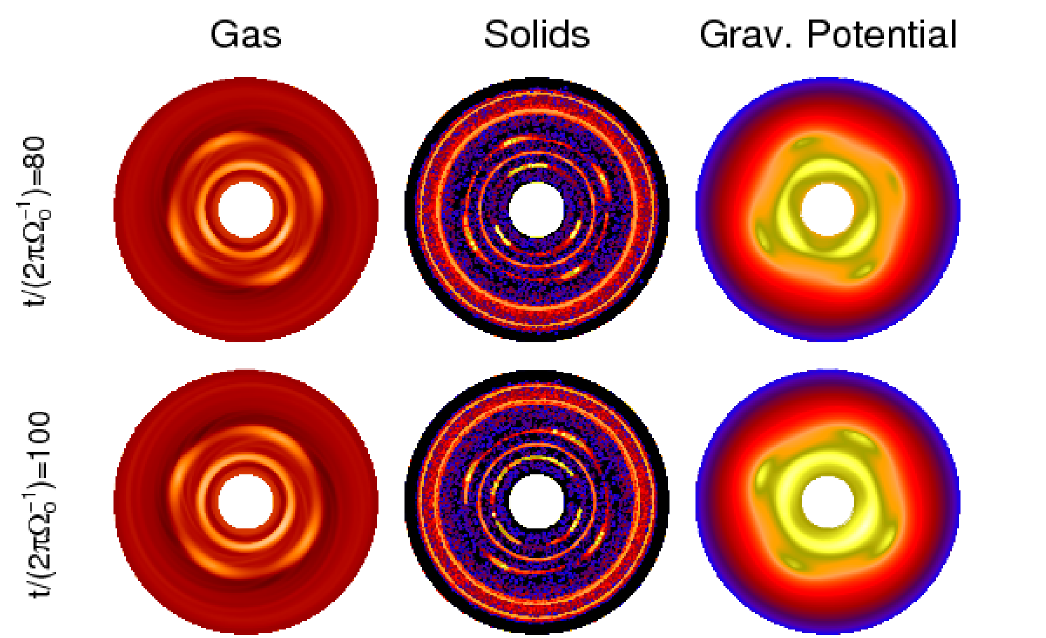


Mass is far greater without selfgravity

WHY??

TIDAL INTERACTION WITH THE FIELD OF MASSIVE VORTICES AFFECTS THE EMBRYOS!





A (very) simple tidal model

Tidal force

$$F_T \propto R \nabla a$$

$$\nabla a = -\nabla^2 \Phi$$

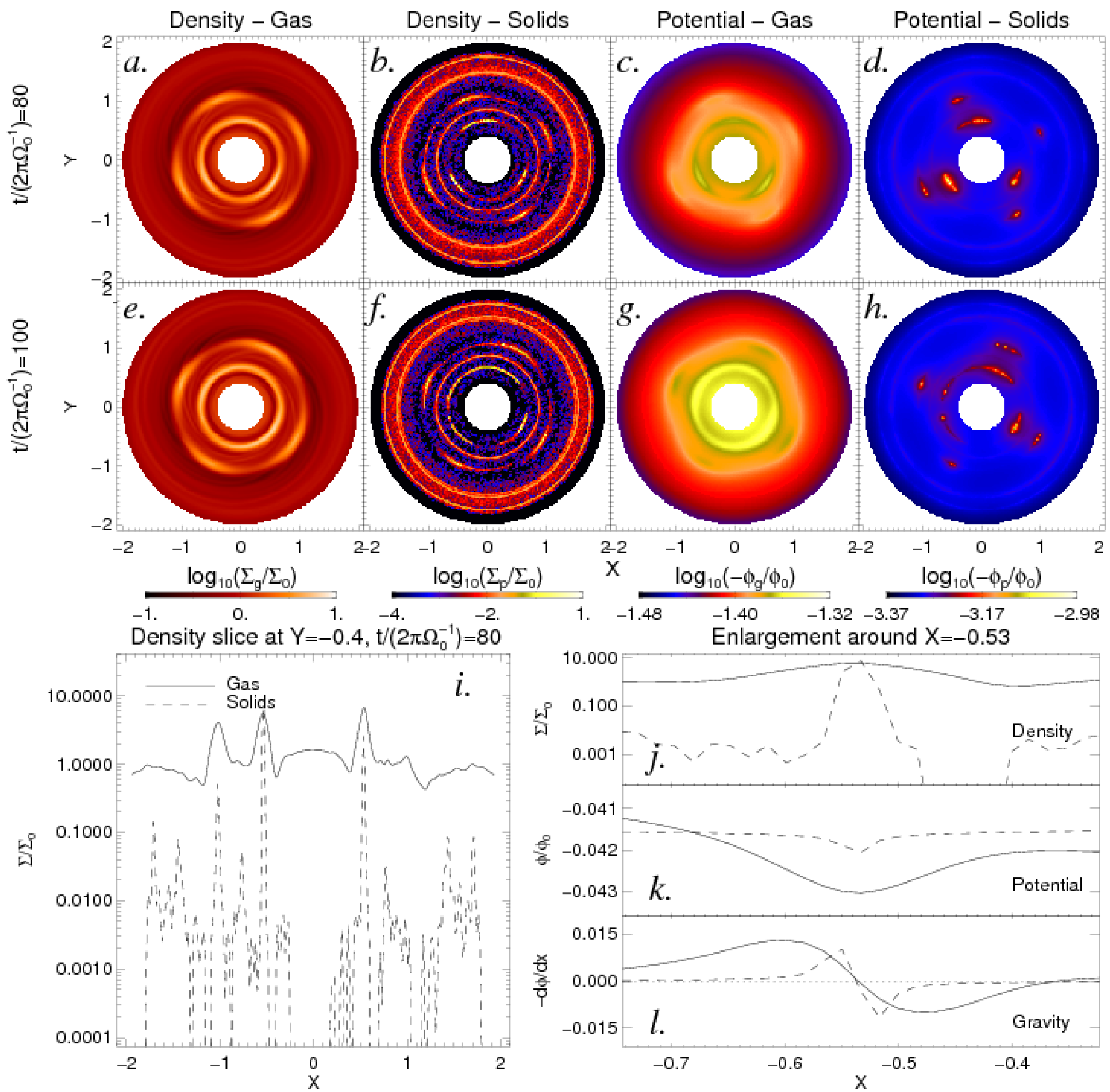
$$F_T \propto R \rho_g$$

Gravitational force

$$F_g = -\frac{GM}{R^2}$$

$$M = 4/3 \pi R^3 \rho_p$$

$$F_g \propto R \rho_p$$

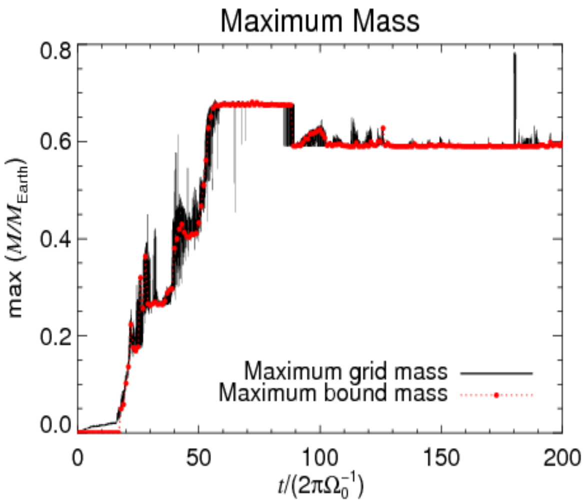


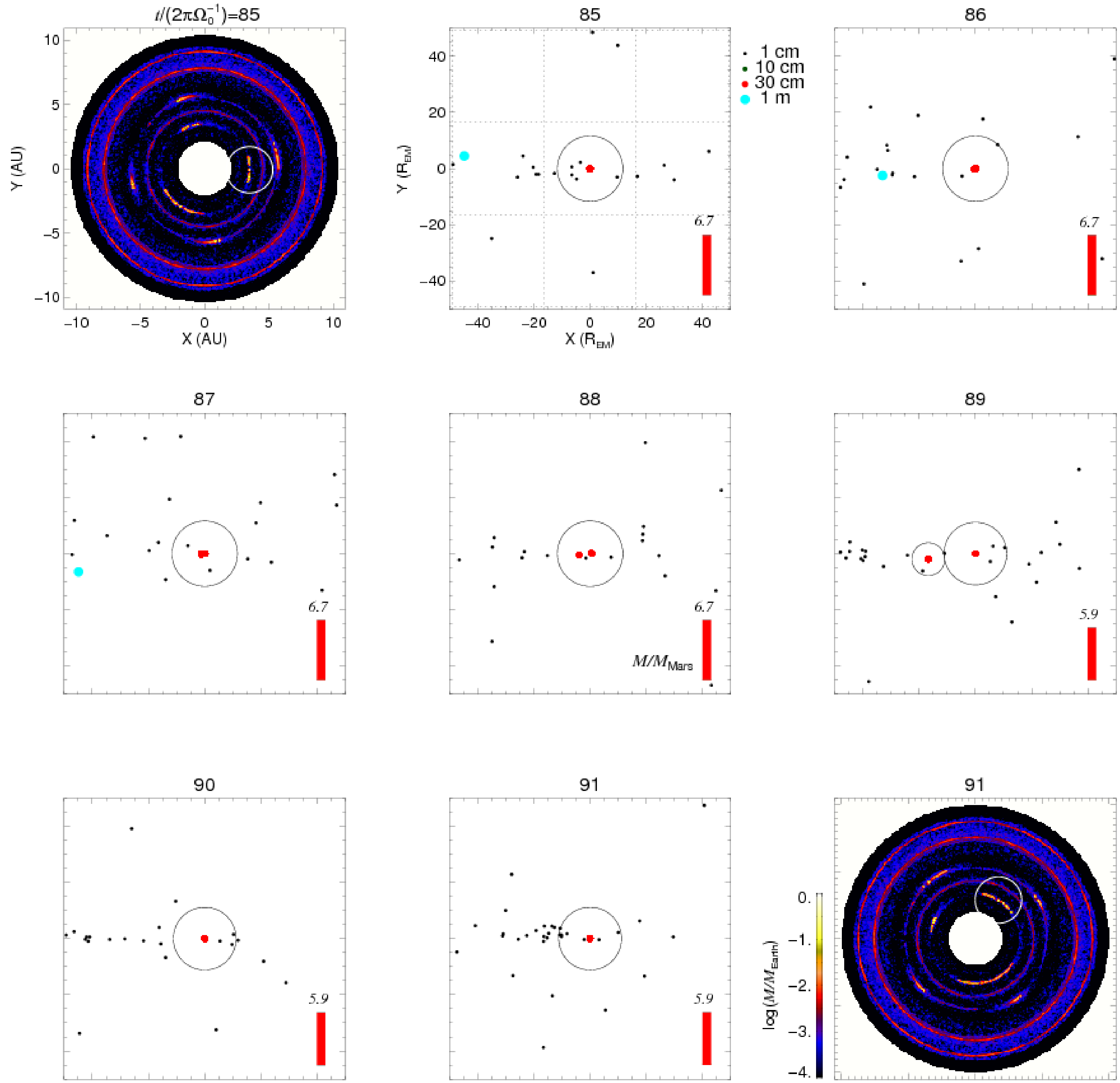
The relative strength of the tides is

$$\zeta = \frac{F_T}{F_g} \propto \frac{\rho_g}{\rho_p}$$

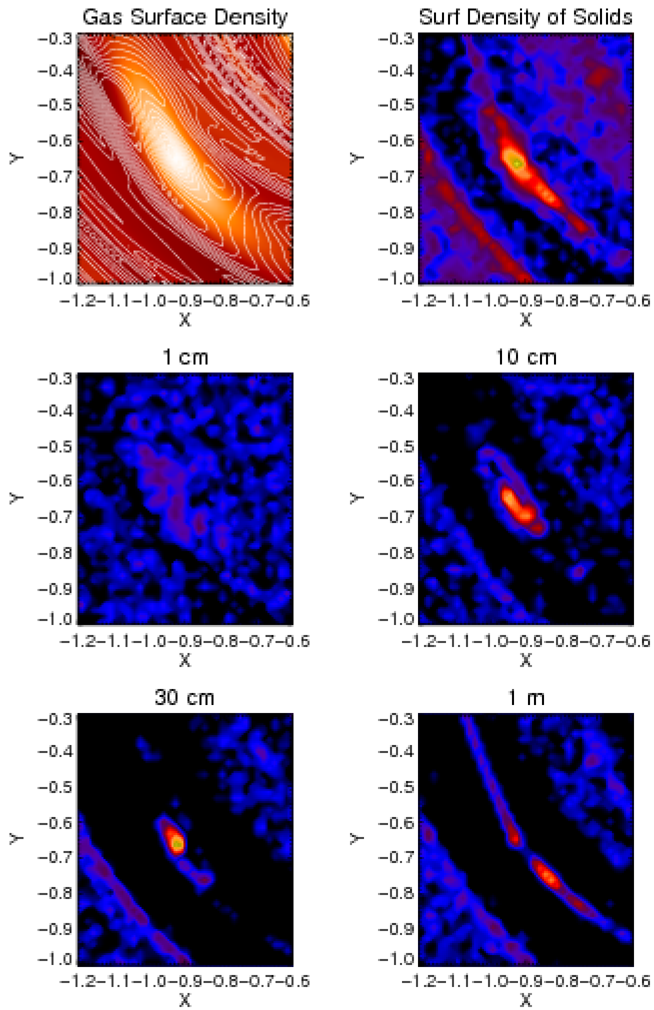
... proportional to the gas-to-solids ratio

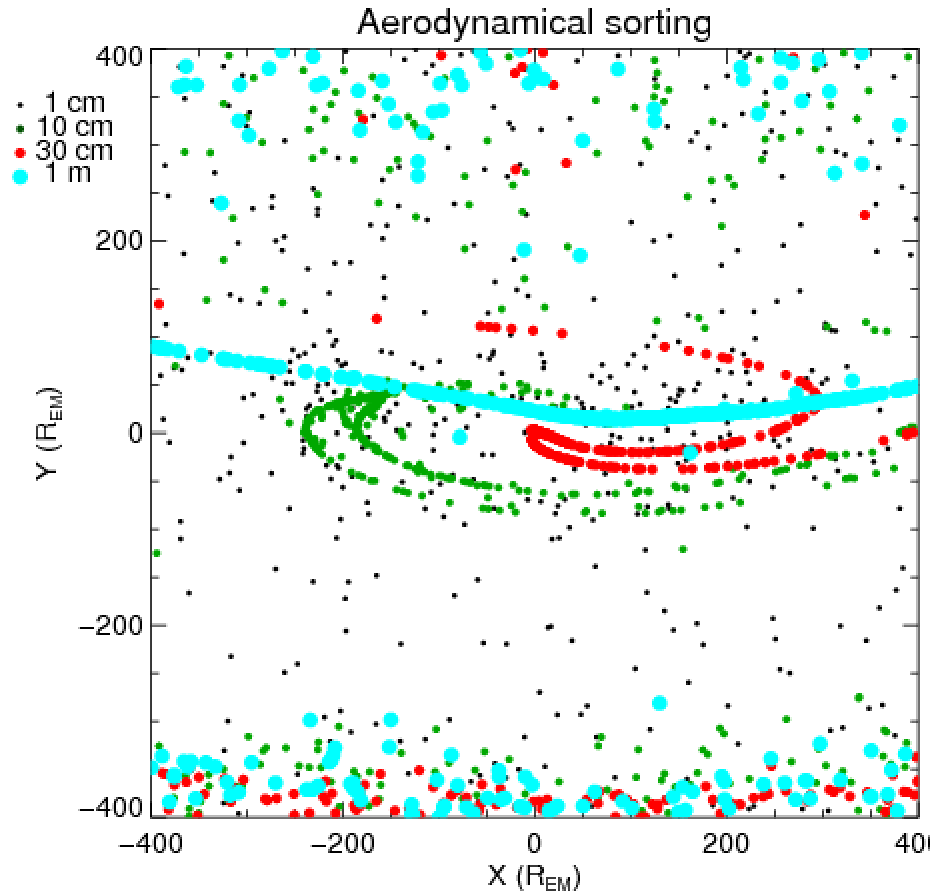
Tidal disruption





Size sorting





Preferential trapping for particles of 10 and 30 cm radii

Differential drag – aerodynamical sorting

First bound structures are formed of same-sized particles

Erosion

The liquid drop analogy of Cuzzi et al. (2008)

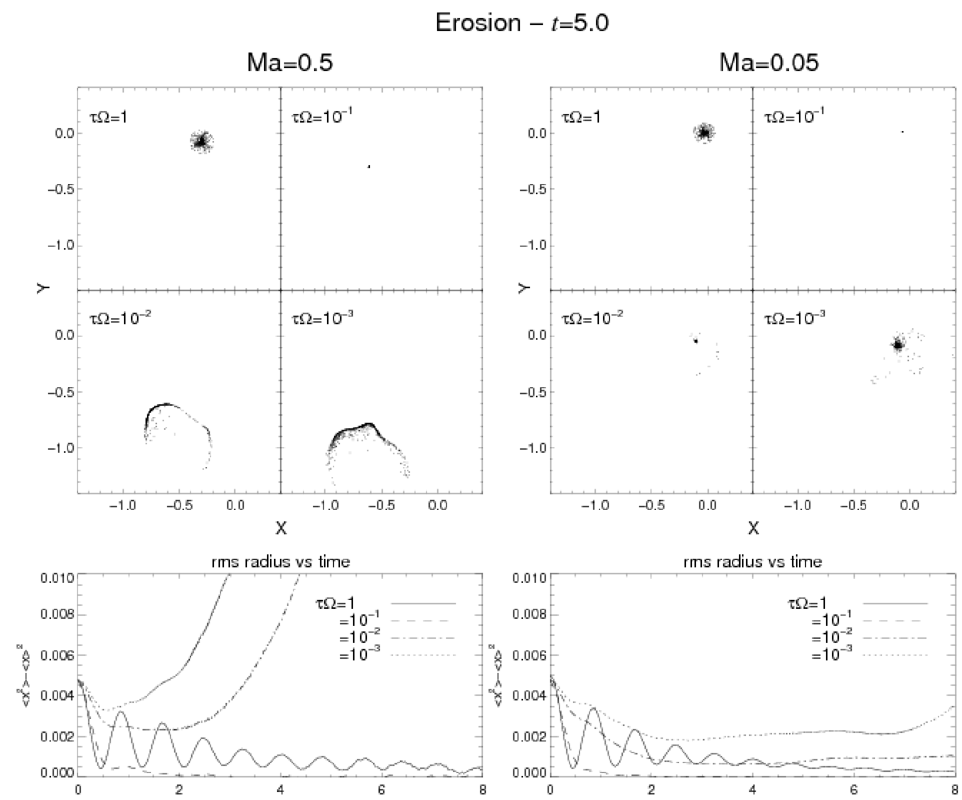
Stability: ***ram pressure*** vs ***surface tension***

Weber number

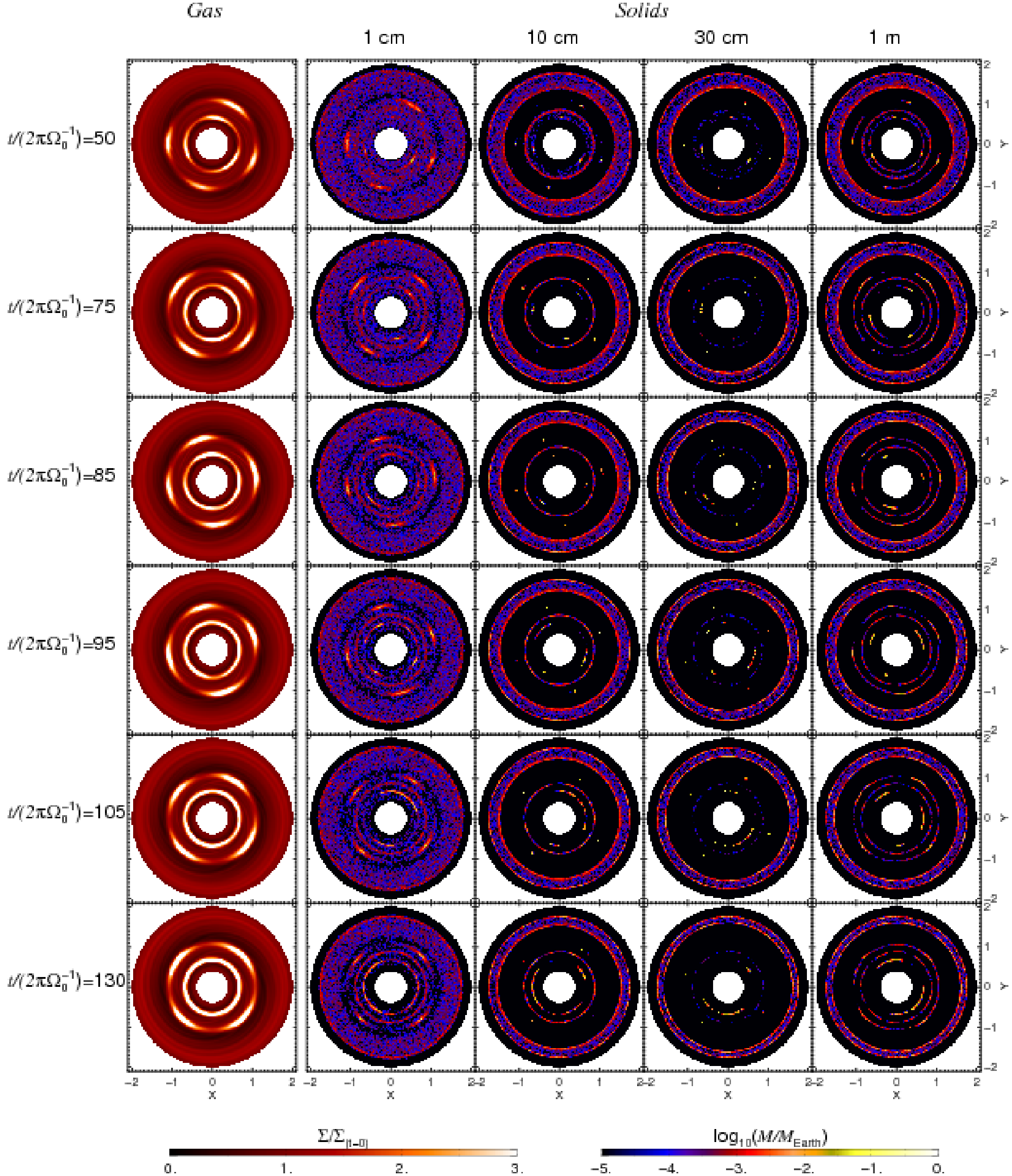
We = drag / tension

For a forming planet, selfgravity provides the tension

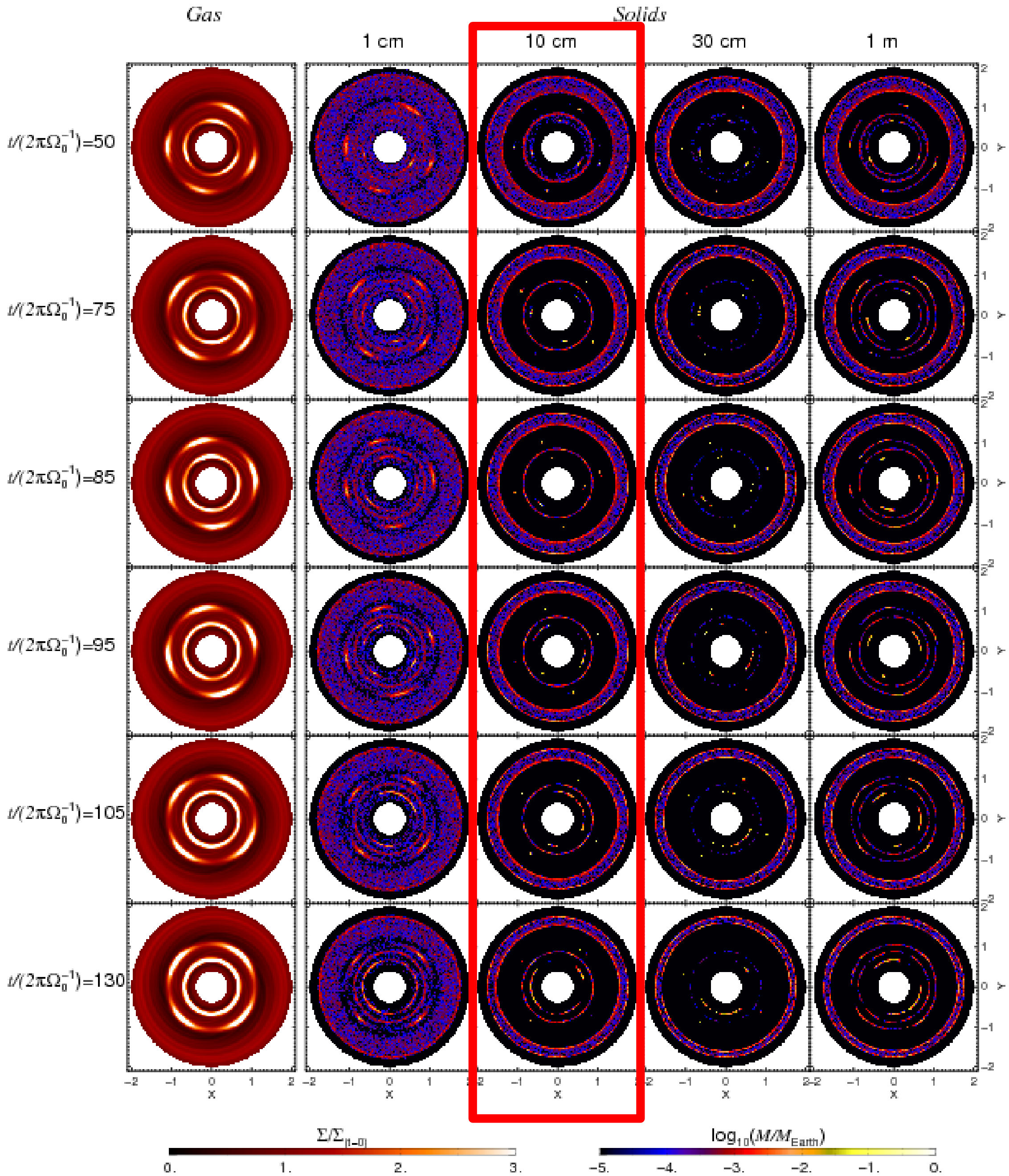
$$We_G = \frac{|f_D|}{|\nabla \Phi|} = \frac{Ma\, c_s}{\tau \pi G \Sigma_p}$$



Tidal Disruption + Size sorting + Erosion = Hell in the inner disk



Tidal Disruption + Size sorting + Erosion = Hell in the inner disk



What triggers the vortices?

Rossby Wave Instability

(Lovelace et al 1999, Li et al 2000, Li et al 2001)

-Non-Axisymetric

-Triggered by an extremum of $L = \frac{\Sigma \Omega}{\kappa^2} (P \Sigma^{-\gamma})^{2/\gamma}$ (=pressure bumps)

HYDRO INSTABILITY IN DISKS:

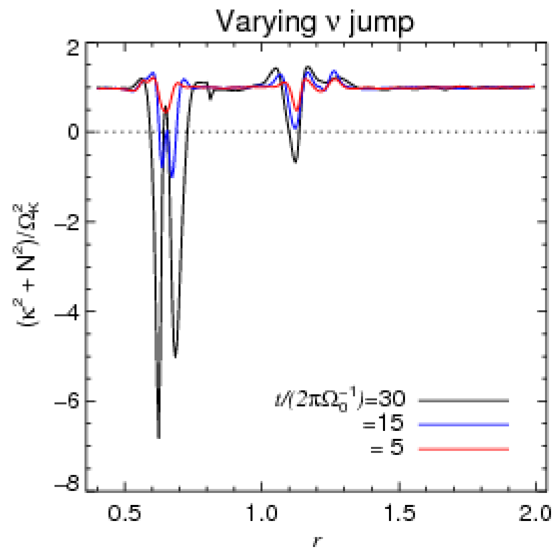
radial perturbations

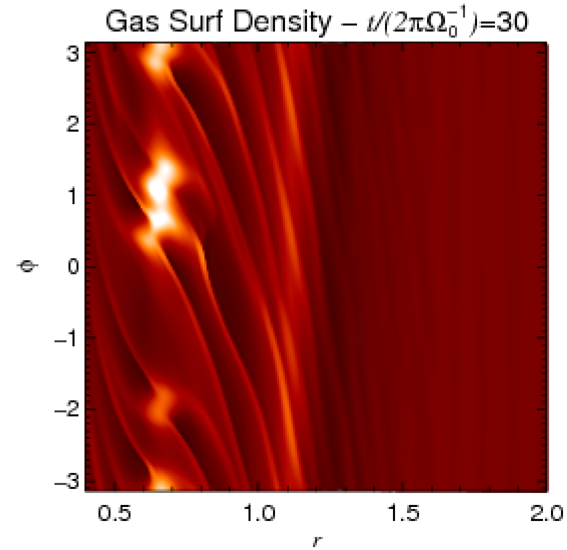
$$\kappa^2 + N^2 < 0$$

epicyclic frequency Brunt-Väisälä frequency

azimuthal perturbations

$$\frac{dL}{dr} = 0 \qquad \left| \frac{d^2 L}{dr^2} \right| > A_{trsh}$$





-Perturbed enthalpy obeys $\eta'' + C(r)\eta = 0$ (i.e., **Trapped!** Modes experience growth)

- Dispersion relation similar to that of Rossby waves in planetary atmospheres
- Saturated state: Vortices when RWs break and coalesce

Sharpness of the viscosity jump

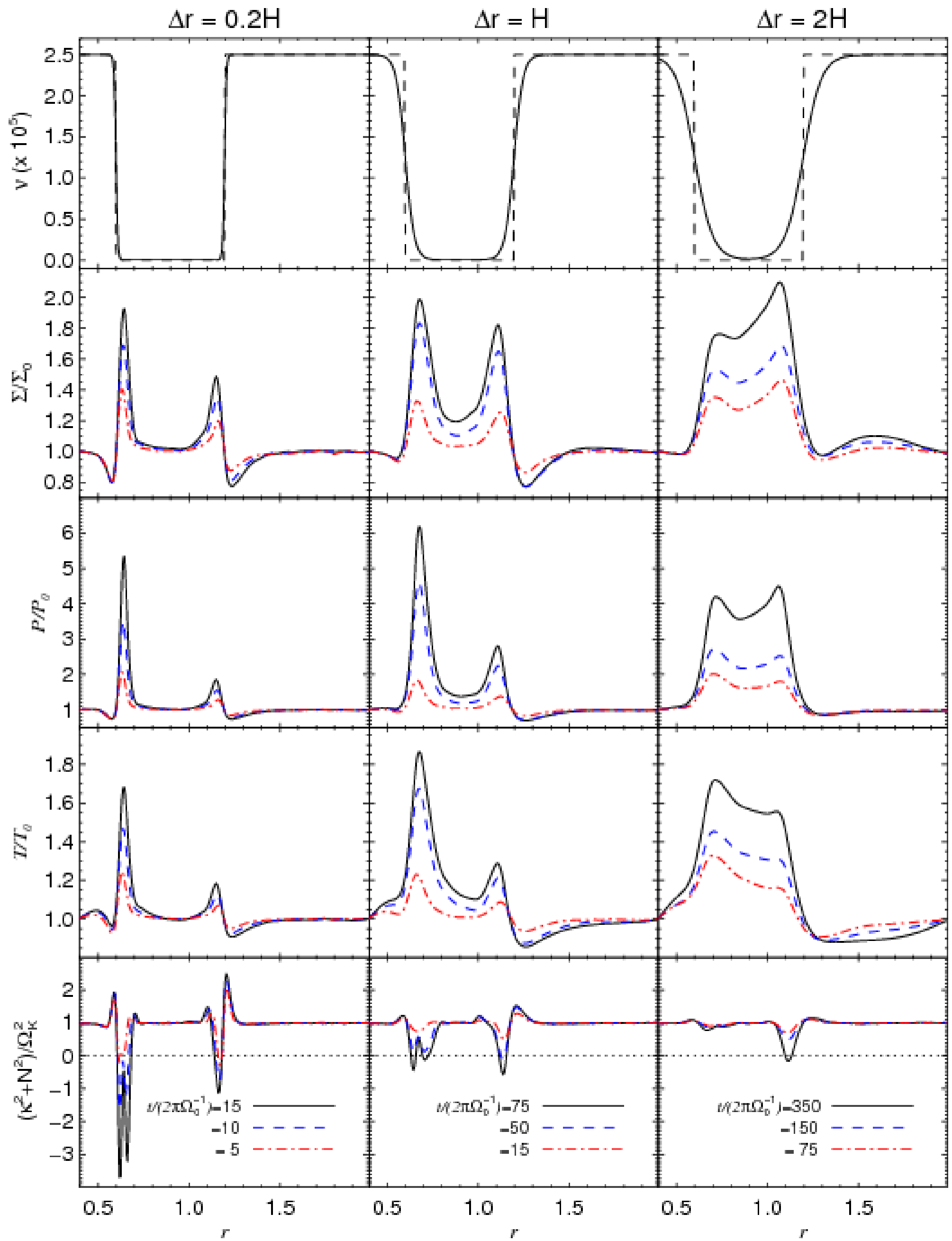
viscosity

density

pressure

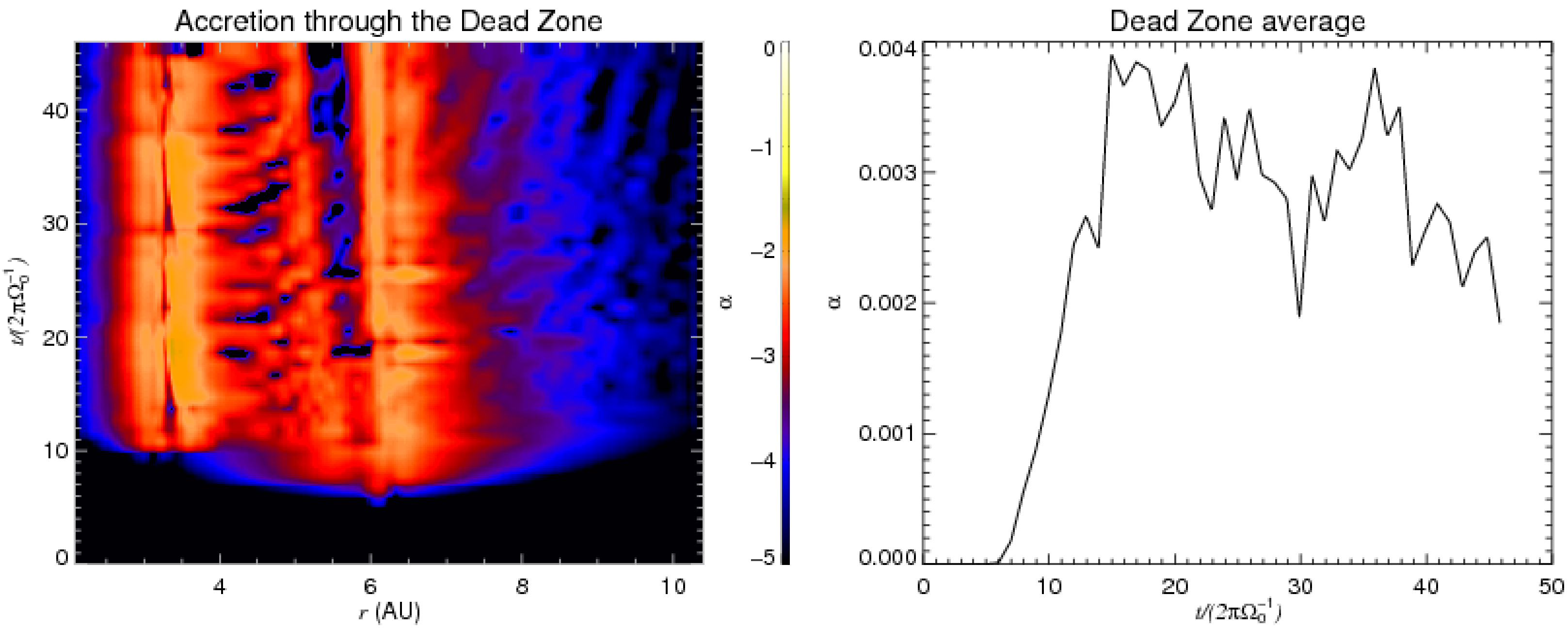
temperature

Solberg-Hoiland criterion



Accretion through the dead zone

The Rossby waves carry angular momentum...



... and accrete through the Dead Zone with alpha ~ 3e-3

Similar to the MRI itself!! (1e-2)

Does the RWI revive the Dead Zone?

Shall we speak of an "***Undead Zone***" instead?

Paper V – Home on Lagrange

Assess the possibility of a giant planet triggering a second round of planet formation

Astronomy & Astrophysics manuscript no. selfgrav
October 7, 2008

Standing on the shoulders of giants

Trojan Earths and vortex trapping in low mass self-gravitating protoplanetary disks of gas and solids

W. Lyra[1], A. Johansen[2], H. Klahr[3], & N. Piskunov[1]

[1] Department of Physics and Astronomy, Uppsala Astronomical Observatory, Box 515, 751 20 Uppsala, Sweden
[2] Leiden Observatory, Leiden University, PO Box 9513, 2300 RA Leiden, The Netherlands
[3] Max-Planck-Institut für Astronomie, Königstuhl 17, 69117 Heidelberg, Germany

Received ; Accepted

ABSTRACT

Context. Centimeter and meter sized solid particles in protoplanetary disks are trapped within long lived high pressure regions, creating opportunities for collapse into planetesimals and planetary embryos.
Aims. We aim to study the effect of the high pressure regions generated in the gaseous disks by a giant planet perturber. These regions consist of gas retained in tadpole orbits around the stable Lagrangian points as a gap is carved, and the Rossby vortices launched at the edges of the gap.
Methods. We perform global simulations of the dynamics of gas and solids in a low mass non-magnetized self-gravitating thin protoplanetary disk. We employ the Pencil code to solve the Eulerian hydro equations, tracing the solids with a large number of Lagrangian particles, usually 100000. To compute the gravitational potential of the swarm of solids, we solve the Poisson equation using Particle-Mesh methods with multiple fast Fourier transforms.
Results. Huge particle concentrations are seen in the Lagrangian points of the giant planet, as well as in the vortices they induce in the edges of the carved gaps. For 1 cm to 10cm radii, gravitational collapse occurs in the Lagrangian points in less than 200 orbits. For 5cm, a 2 $M_\oplus$ planet is formed. For 10 cm, the final maximum collapsed mass is around 3 $M_\oplus$. The collapse of the 1 cm particles is indirect, following the timescale of depletion of gas from the tadpole orbits. In the edges of the gap vortices are excited, trapping preferentially particles of 30cm radii. The rocky planet that is formed is as massive as 17 $M_\oplus$, constituting a Super-Earth. For 40 cm onwards, collapse does not occur. By using multiple particle species, we find that gas drag modifies the streamlines in the tadpole region around the classical L4 and L5 points. As a result, particles of different radii have their stable points shifted to different locations. Collapse therefore takes longer and produces planets of lower mass. 5 Earth mass planets are formed in the vortices, the most massive having 4.4 $M_\oplus$.
Conclusions. A Jupiter mass planet can induce the formation of other planetary embryos in the outer edge of its gas gap, explaining, perhaps, the formation of Saturn. Trojan Earth mass planets are easily formed, and although not existing in the solar system, might be common in the exoplanetary zoo.

Key words. Keywords should be given

1. Introduction

Losing angular momentum by friction with the ambient gaseous headwind, meter sized bodies in protoplanetary disks spiral into the star in timescales as short as a hundred years (Weidenschilling 1977). Avoiding this fate is a major unsolved problem in modern astrophysics. The question of the formation of rocky planets is intimately connected with this problem, since the kilometer sized bodies (planetesimals) whence they are believed to form from (Safronov, 1969) must be formed faster than the already rapid timescale of radial drift of the rocks (0.1-1 meter size) and boulders (1-10 meter size).

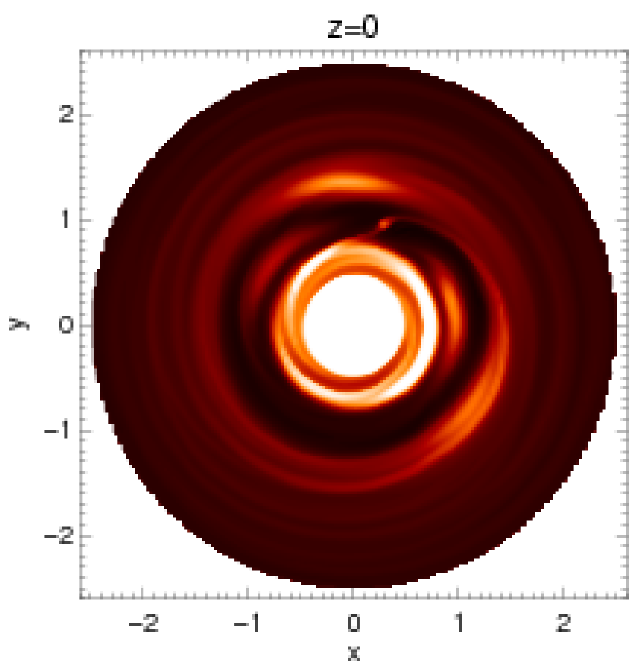
As colliding boulders have very poor sticking properties (Benz 2000), a possible scenario for the formation of planetesimals is direct gravitational collapse of the layer of boulders (Goldreich & Ward 1973). This hypothesis was met with criticism because no route for achieving critical densities could be found (Weidenschilling & Cuzzi 1993), but it has recently gained momentum due to a series of major progresses in modeling the coupled dynamics of gas and solids through both analytical calculations and numerical simulations. Youdin & Goodman

Send offprint requests to: wlyra@astro.uu.se

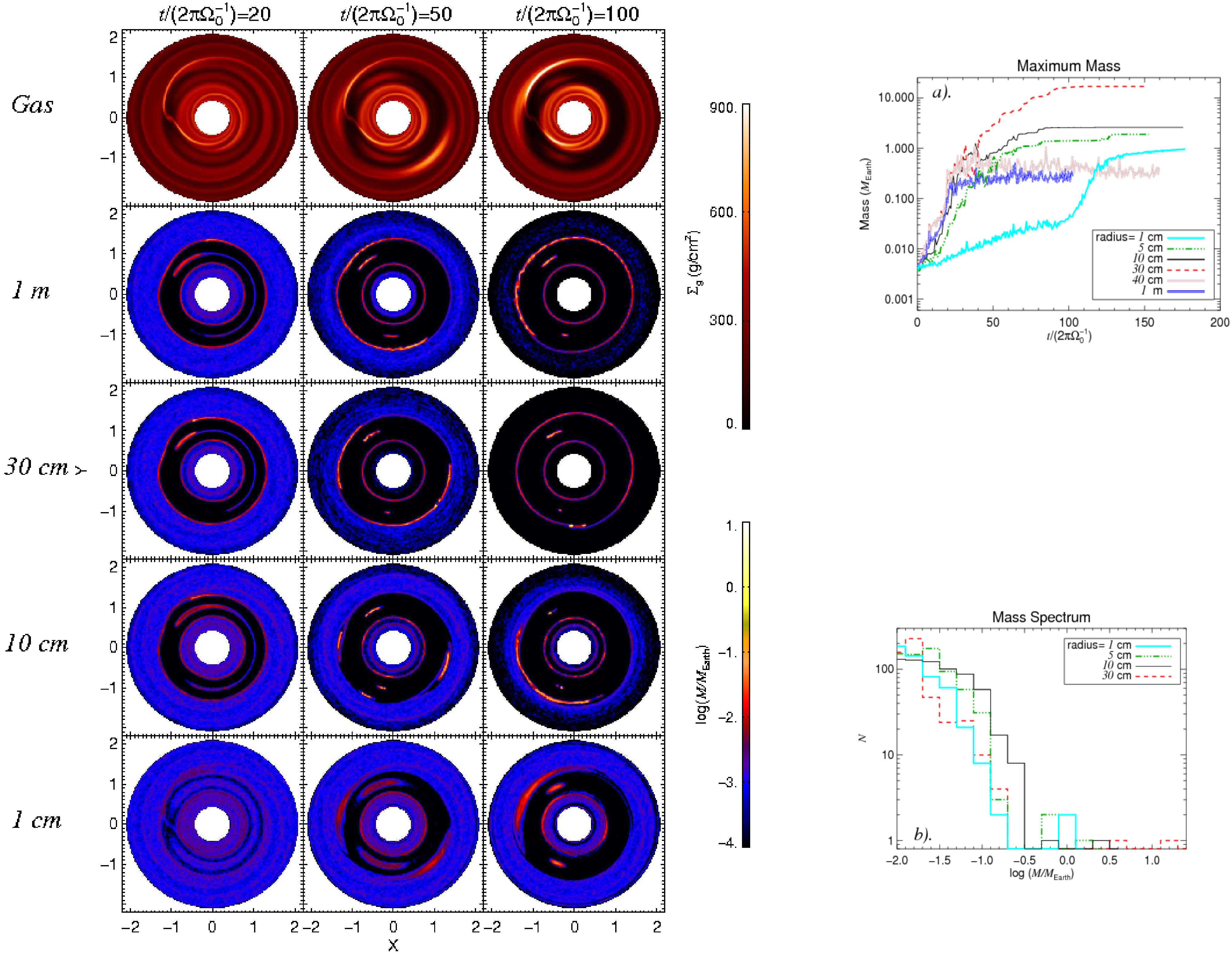
Interesting locations:

Lagrangian points

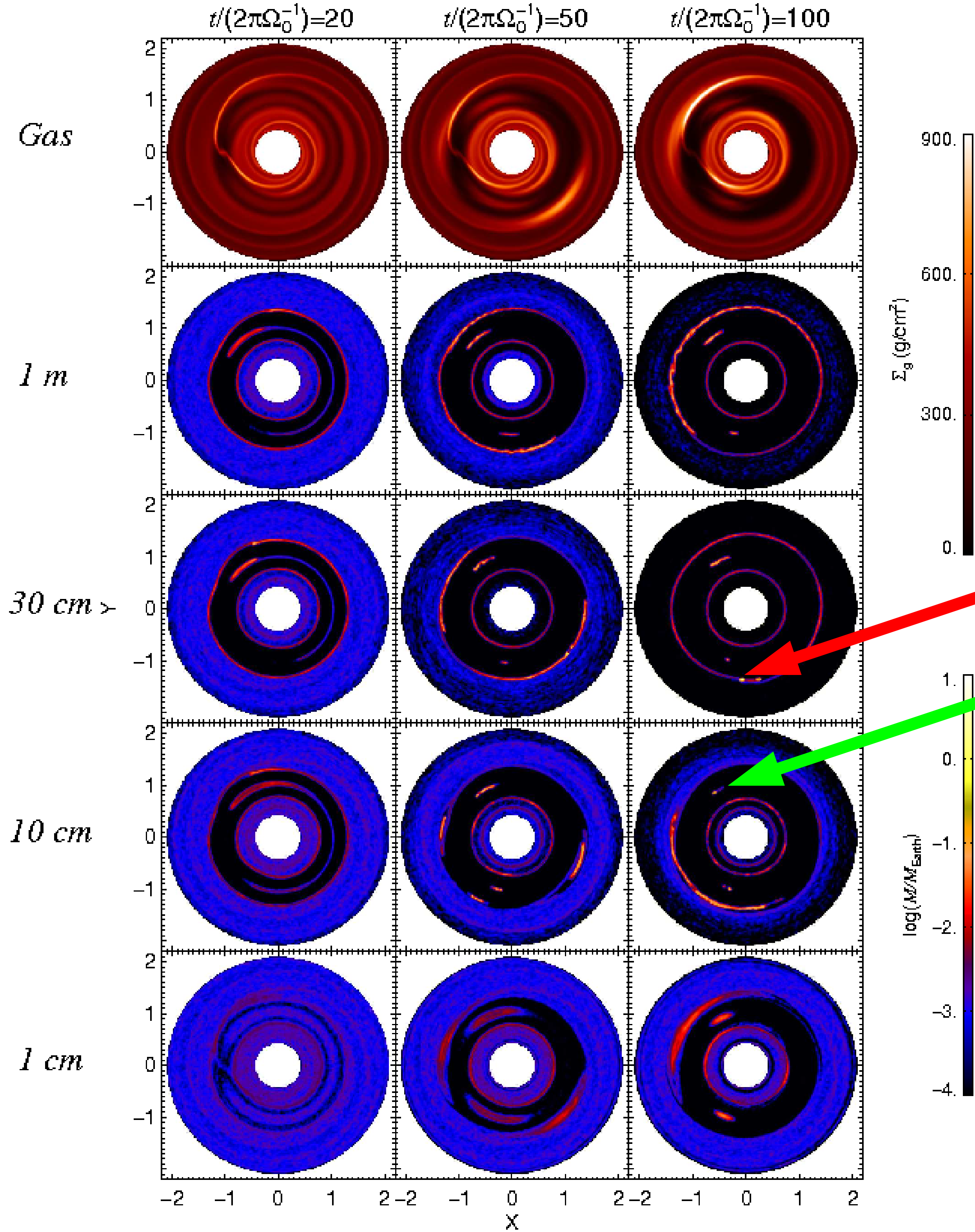
Gap edge vortices



Care for some particles?

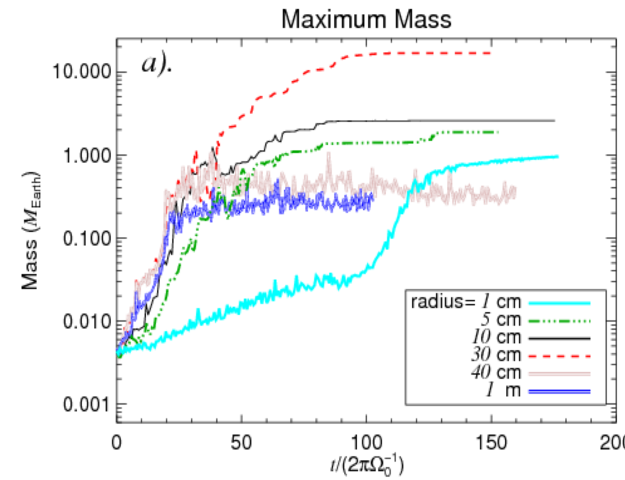


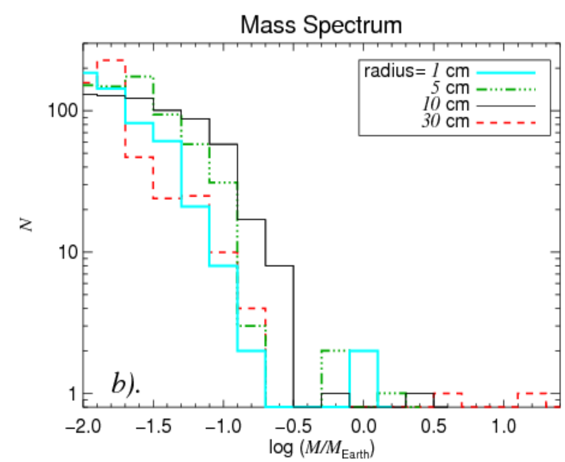
t/(2πΩ0^-1)=20
t/(2πΩ0^-1)=50
t/(2πΩ0^-1)=100
Gas
1 m
30 cm
10 cm
1 cm
X
Σg (g/cm²)
900.
600.
300.
0.
log(M/MEarth)
1.
0.
−1.
−2.
−3.
−4.
Maximum Mass
a).
Mass (MEarth)
t/(2πΩ0^-1)
radius= 1 cm
5 cm
10 cm
30 cm
40 cm
1 m
Mass Spectrum
b).
N
log (M/MEarth)
radius= 1 cm
5 cm
10 cm
30 cm



17 Earth masses!

A Trojan planet of 2.6 Earth masses





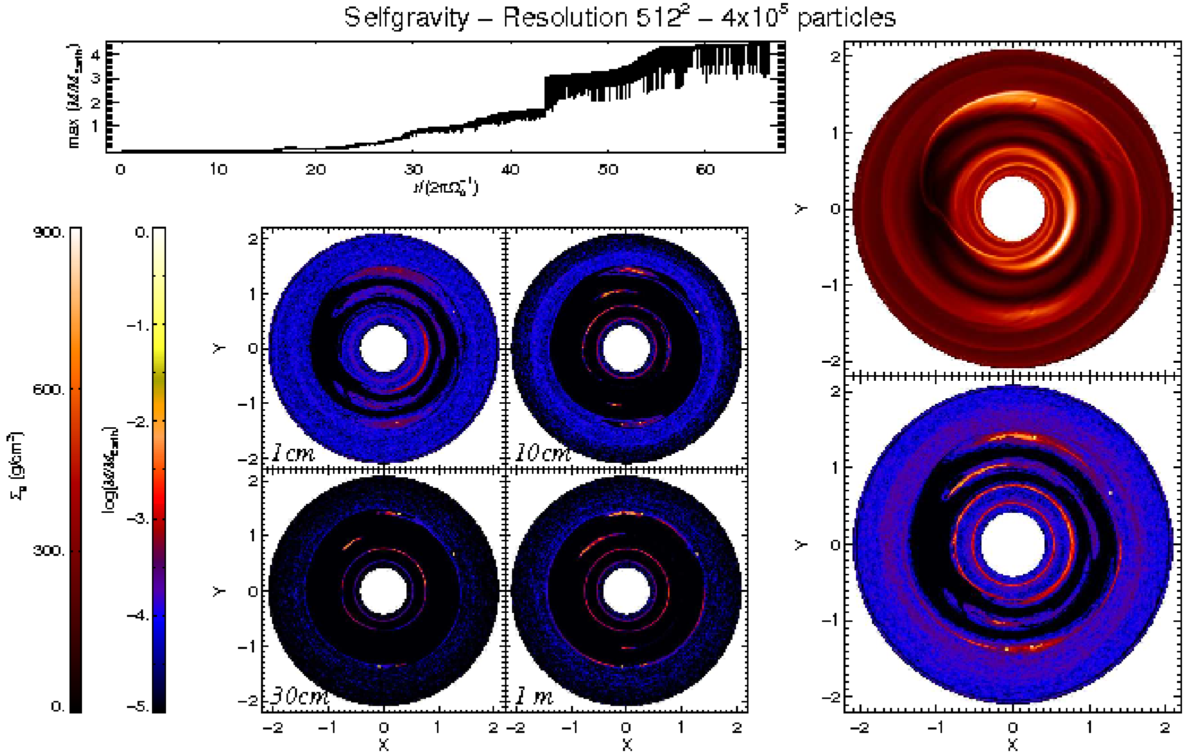
A spectrum of particle sizes

Lagrangian points are points of balance between

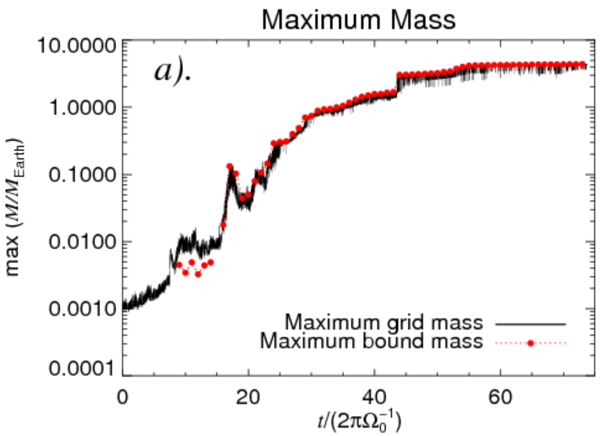
- Centrifugal force,
- Gravity from the 2 bodies,
- and **DRAG FORCE**

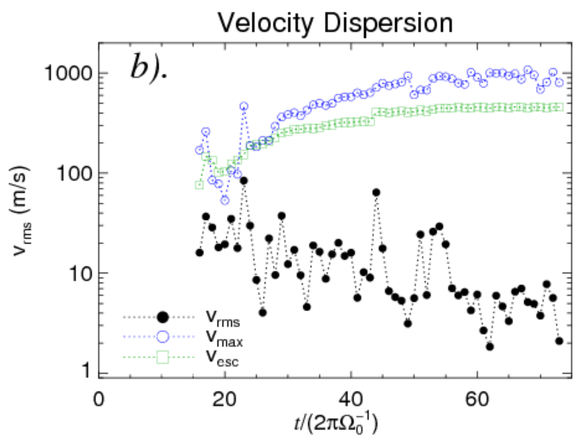
Asymmetry between L4 and L5

(Peale 1993, Murray 1994)



5 super Earths formed + Earth mass Trojans





***V*max ~ 1 km/s > *V*esc**

Although most particles survive (*V*rms < 10 m/s), **fragmentation** is anticipated to play a relevant role

Neptune mass perturber

1.6 Mars mass Trojan

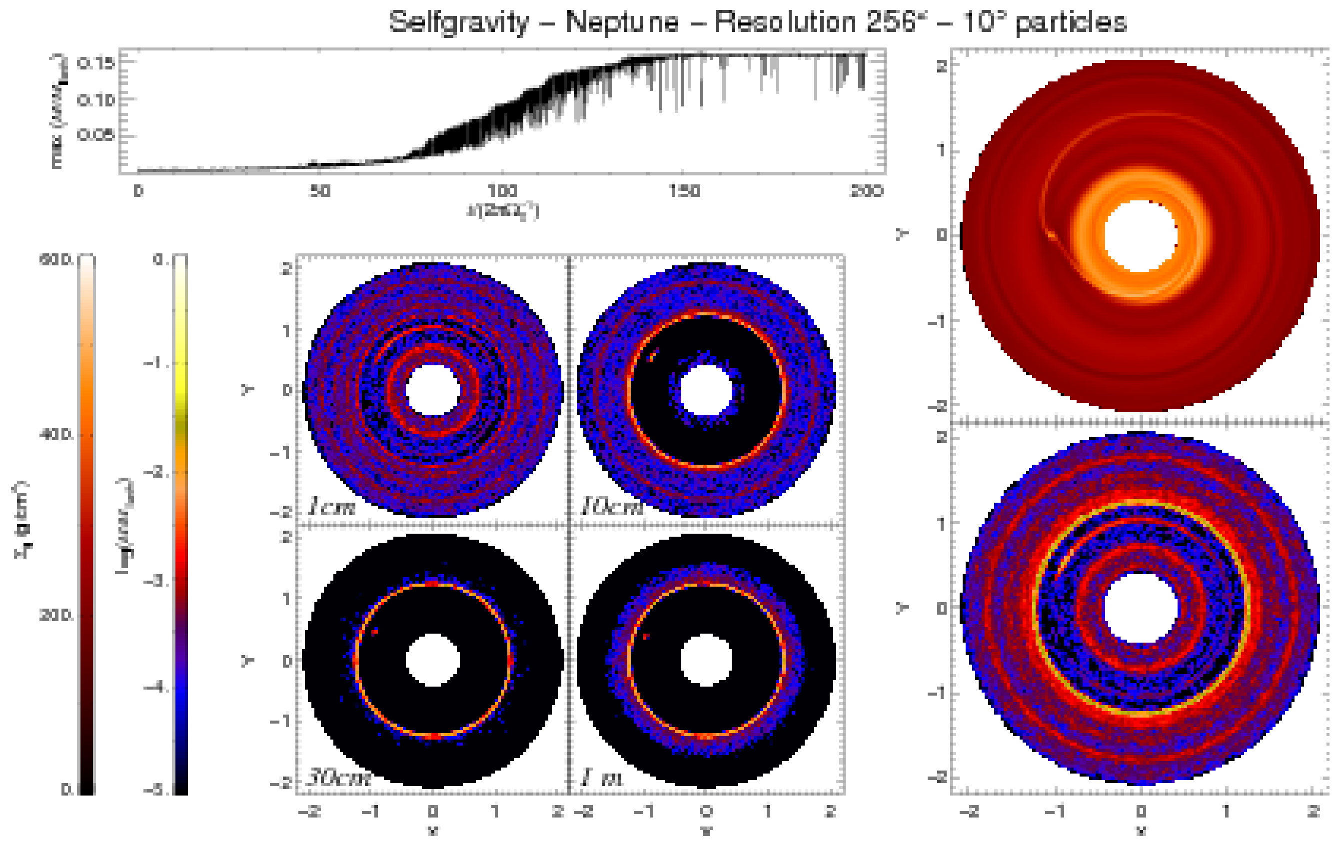
Stronger L4-L5 asymmetry

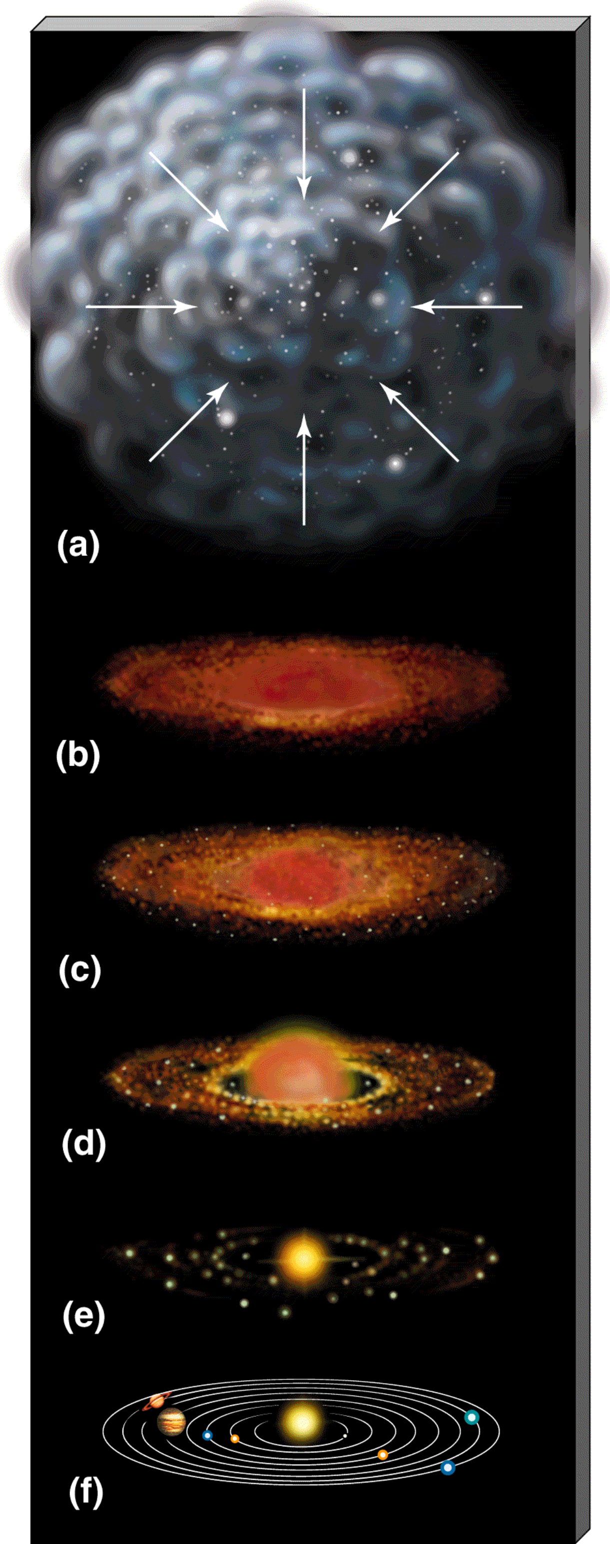
Shallower gap (20% depletion)

- no vortices

Longer timescales

- favors coagulation





Summarizing...

Gravitational collapse of an interstellar cloud

Outward transport of angular momentum through turbulence generated by the MRI. Dust coagulates into pebbles and boulders, sedimenting towards the midplane.

Rocks in the turbulent medium are trapped in transient pressure maxima and undergo collapse into planetesimals and dwarf planets.

The presence of a dead zone excites the RWI. Inside vortices, the first dozens of Mars-mass embryos are formed.

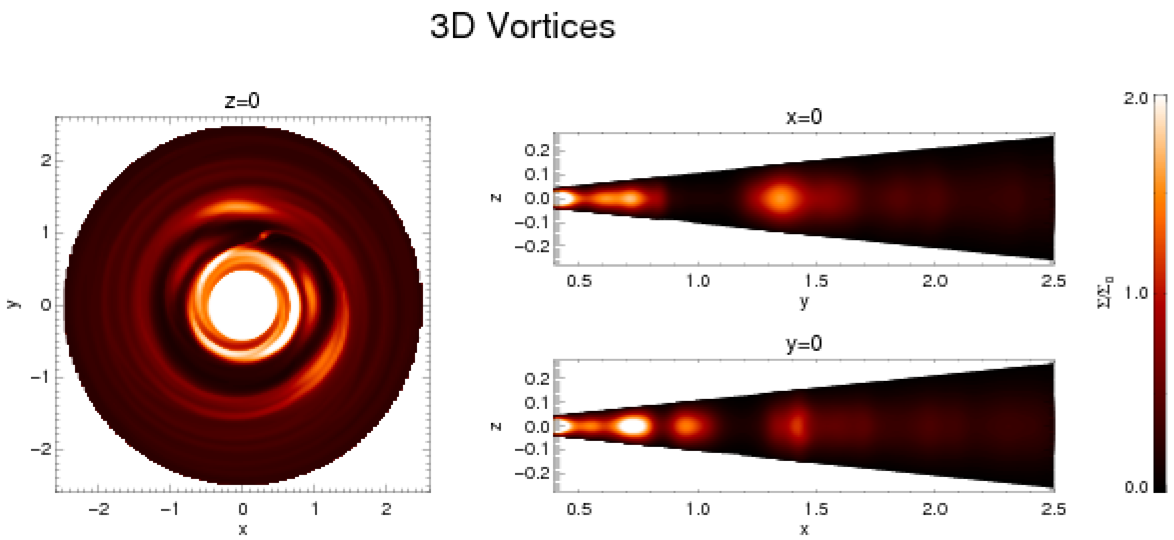
Embryos collide and give rise to the oligarchs (?)

When Jupiter is formed, a second round of planet formation is triggered (Trojan planets, Saturn?)

Nice model: Jupiter and Saturn cross 2:1 MMR and define the architecture of the Solar System

Work in progress

•Extend the simplistic model to a 3D configuration, modeling the dead zone with the MRI and ambipolar diffusion, to study how the RWI reacts to these more realistic conditions.



Expected date of disputation – March 2009

Future Work

- Inclusion of a coagulation/fragmentation model (?)
(with Frithjof Brauer, Kees Dullemond, and Andras Zsom, MPIA-Heidelberg)

Theoretical Modelling

$$\frac{\partial \rho_g}{\partial t} = -(\boldsymbol{u}\cdot\nabla)\rho_g - \rho_g \nabla\cdot\boldsymbol{u}$$

$$\frac{\partial s}{\partial t} = -(\boldsymbol{u}\cdot\nabla)s + \frac{1}{\rho T}\left(\nabla\cdot(K\nabla T) + \eta\mu_0 \boldsymbol{J}^2 + 2\rho\nu \boldsymbol{S}^2\right)$$

$$p = \rho_g c_s^2 / \gamma$$

$$\frac{\partial \boldsymbol{A}}{\partial t} = \boldsymbol{u}\times\boldsymbol{B} - \eta\mu_0 \boldsymbol{J}$$

$$\frac{\partial \boldsymbol{u}}{\partial t} = -(\boldsymbol{u}\cdot\nabla)\boldsymbol{u} - \nabla\Phi - \rho_g^{-1}\left(\nabla p + \boldsymbol{J}\times\boldsymbol{B} + \rho_p f_d\right) + 2\rho_g^{-1}(\nu\rho_g \boldsymbol{S})$$

$$\Phi = \Phi_{sg} - \sum_i^N \frac{GM_i}{\left|\boldsymbol{r}-\boldsymbol{x}_i\right|}$$

$$\nabla^2 \Phi_{sg} = 4\pi G(\rho_g + \rho_p)$$

$$f_d = -\left(\frac{3\rho_g C_D \left|\boldsymbol{w}-\boldsymbol{u}\right|}{8 a_\bullet \rho_\bullet}\right)(\boldsymbol{w}-\boldsymbol{u})$$

$$\frac{d\boldsymbol{w}}{dt} = -\nabla\Phi - f_d$$

$$\frac{d\boldsymbol{x}}{dt} = \boldsymbol{w}$$