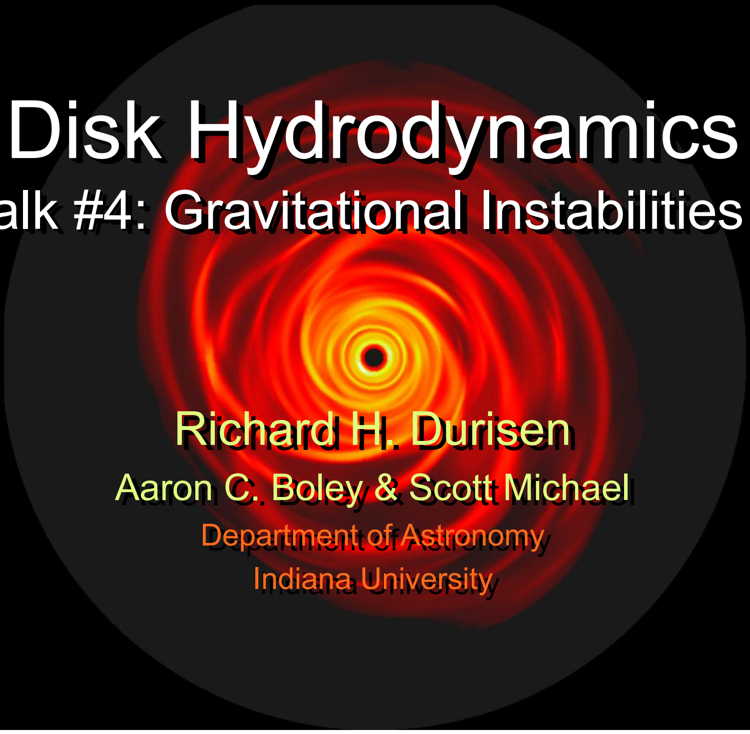


Vidago Workshop 2006

Physical Processes in Circumstellar Disks Around Young Stars

Disk Hydrodynamics

Talk #4: Gravitational Instabilities II

Richard H. Durisen
Aaron C. Boley & Scott Michael
Department of Astronomy
Indiana University

Questions

From the End of Talk #3

- What do REAL disks do?
  - Realistic radiative cooling
  - Realistic equation of state
  - Realistic conditions and environments
- How do REAL disks evolve under GIs?
  - Mass and angular momentum transport?
  - Fragmentation?
- Are GIs in REAL disks local or global?

Outline of Talk #4

Gravitational Instabilities II

- Simulations with radiative cooling
    - Introduction
    - 2D treatments
    - Boss
    - IU hydro group
    - UWash/Zurich group
- Discussion
    - Sources of disagreement?
    - Radiative tests
    - Analytic arguments
- Conclusions

Simulations with Radiative Cooling

Radiative Cooling

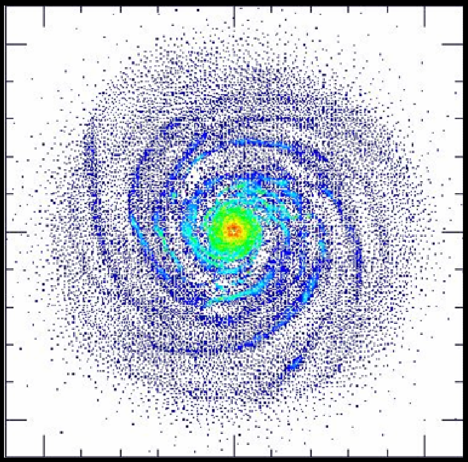
Treatments to Date

- 2D$^+$
  - Global: Nelson et al. 2000
  - Local: Johnson & Gammie 2003
- 3D
  - Grid-based
    - Boss 2001, 2002, 2004
    - IU Hydro Group 2004 to now
  - SPH
    - Mayer et al. 2006 (U Wash/Zurich)
    - Stamatellos & Whitworth (Cardiff) 2006
- Major disagreement
  - Boss & Mayer et al. ⇒ fast cooling due to “convection” independent of opacity
  - Nelson et al. & IU Group & Cardiff ⇒ slow cooling that depends on opacity

---

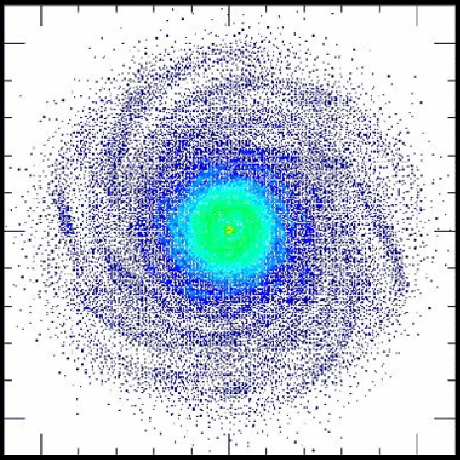
Radiative Cooling 2D$^+$

Isothermal



Nelson et al. 1998

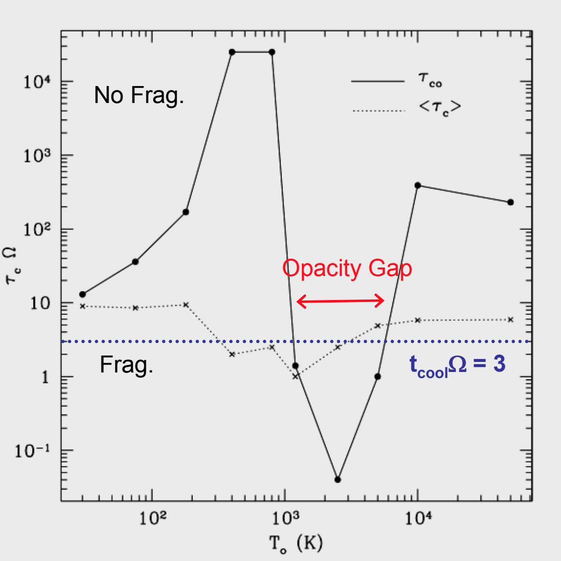
Radiative Cooling



Nelson et al. 2000

Radiative Cooling 2D

Johnson & Gammie 2003



Thin-disk shearing box simulations with one-zone radiative cooling ($\Gamma = 2$)

Conclusions:

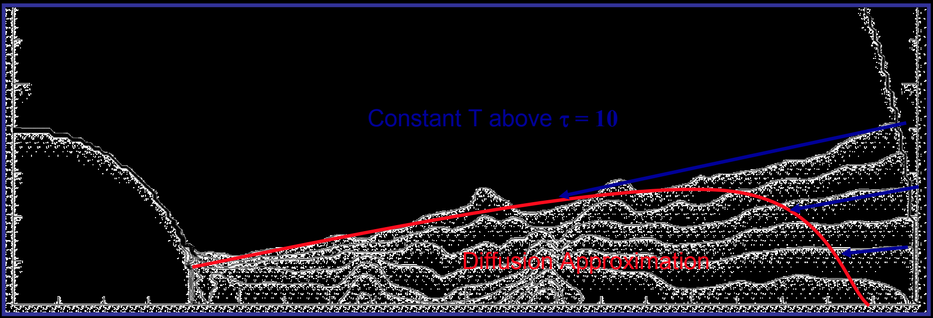
Opacity boundaries may be important.

You cannot predict fragmentation from the initial t_{cool}!!

Fragmentation occurs for $\langle t_{cool}\rangle\Omega < 1$ -10.

Radiative Cooling 3D

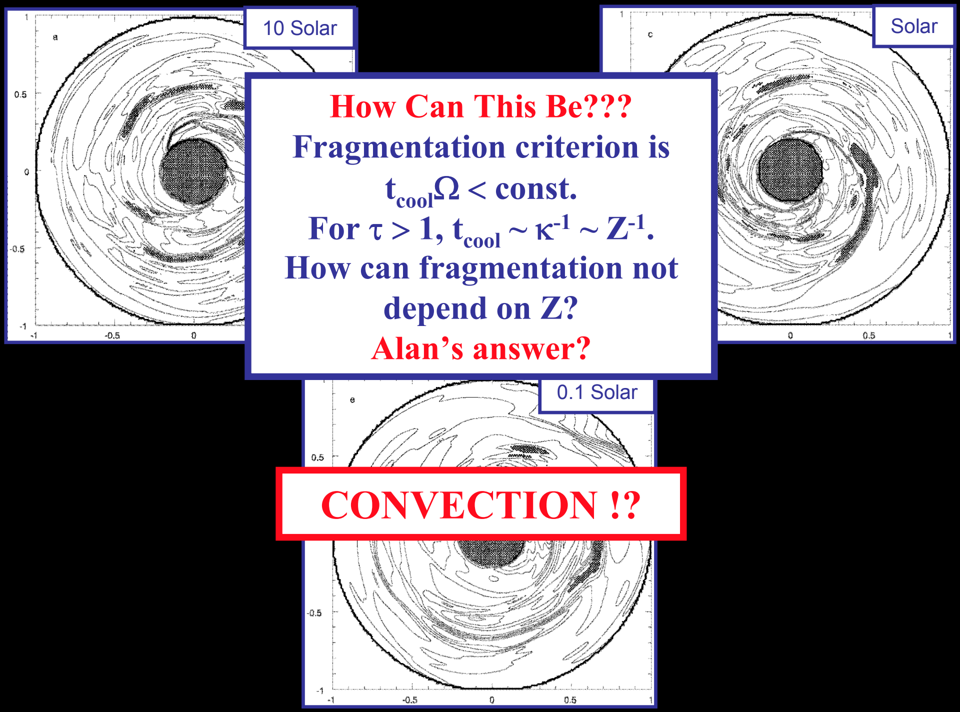
Boss 2001, 2002: Methods



3D radiative diffusion inside $\tau = 10$.
Constant temperature B.C. above $\tau =$ 10 represents envelope irradiation.
Optical depth τ is measured radially.
$M_d/M_s = 0.09$, $M_s = 1\ M_\odot$, 4 to 20 AU
Molecular hydrogen EOS
Pollack et al. 1994 opacities

Radiative Cooling 3D

Boss 2002: Metallicity



How Can This Be???

Fragmentation criterion is $t_{cool}\Omega < const.$

For $\tau > 1$, $t_{cool} \sim \kappa^{-1} \sim Z^{-1}$.

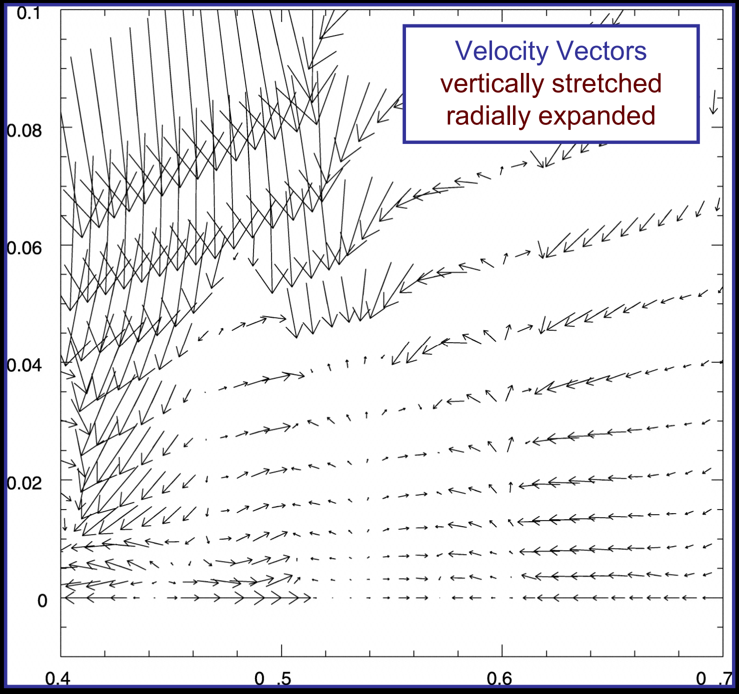
How can fragmentation not depend on Z?

Alan's answer?

CONVECTION !?

Radiative Cooling 3D

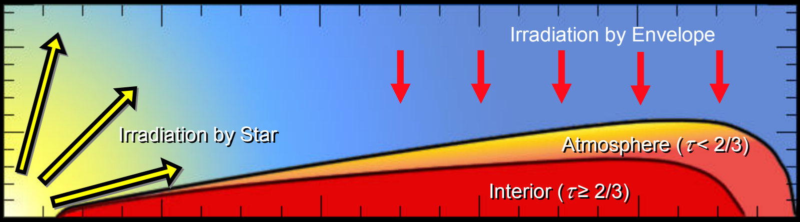
Boss 2004: Convection



Velocity Vectors
vertically stretched
radially expanded

Radiatve Cooling 3D

IU Hydro Group

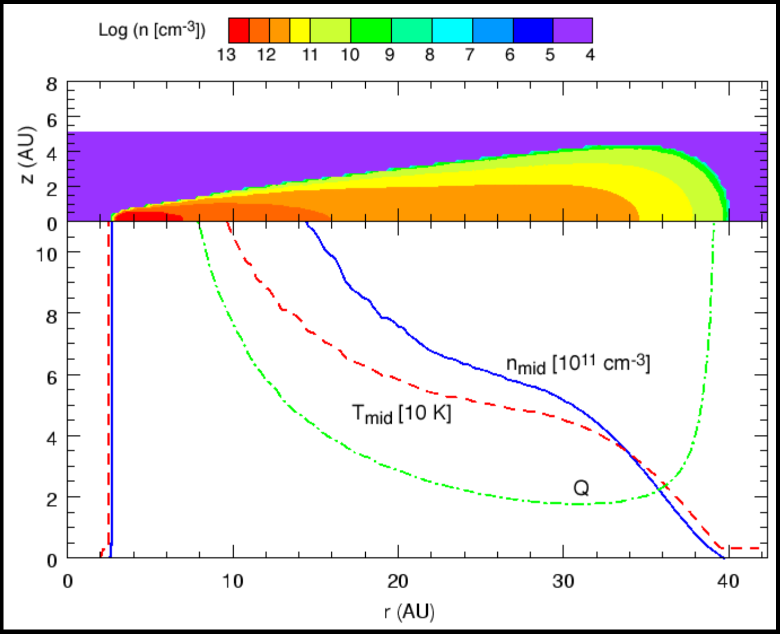


Irradiation, Flux-Limited Diffusion + Optically Thin Radiative Cooling:

- Irradiation by starlight (T_s = 4,000K) or envelope (T ~ 15 to 120K) can be on or off
- D'Alessio (2001) opacities, $a^{-3.5}$ with a_{min}= 0.005 μ and variable a_{max} (1 μ to 1 mm)
- Match optically thin and thick regions with an Eddington grey atmosphere at τ = 2/3

Radiative Cooling 3D

Mejía et al. 2005, Boley et al. 2006



Initial model

R = 40 AU

M_d = 0.07$M_\odot$

M_* = 0.5$M_\odot$

$\Sigma(r) \sim r^{-1/2}$

Q_{min}=1.8

ORP = outer rotation period = 250 years

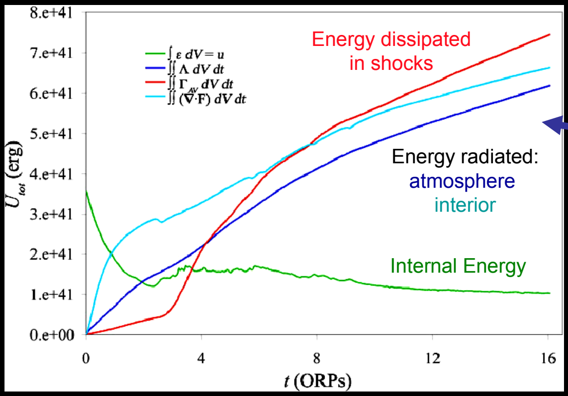
Radiative Cooling 3D

Mejía Disk with Realistic Cooling

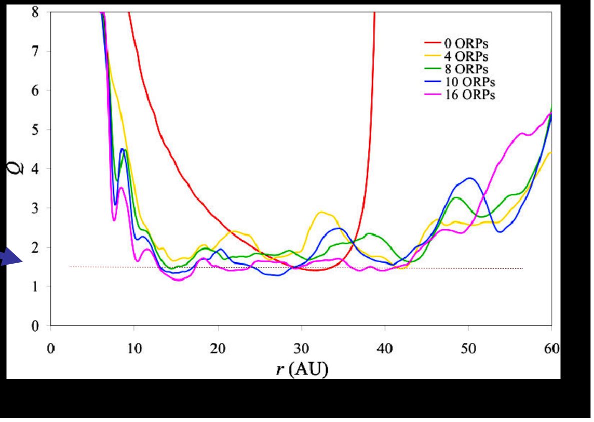
Mejía 2004, Cai et al. 2005, Boley et al. 2006

Radiative Cooling 3D

Boley et al. 2006



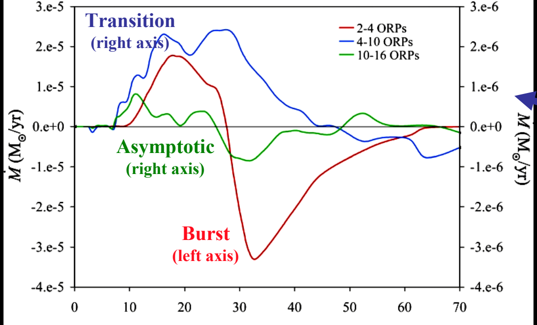
Energy Budget:
Large amounts of energy are processed through the internal energy (like a star). The disk asymptotes to a quasi-steady state.



Toomre Q asymptotes to an unstable value ≈ 1.5.

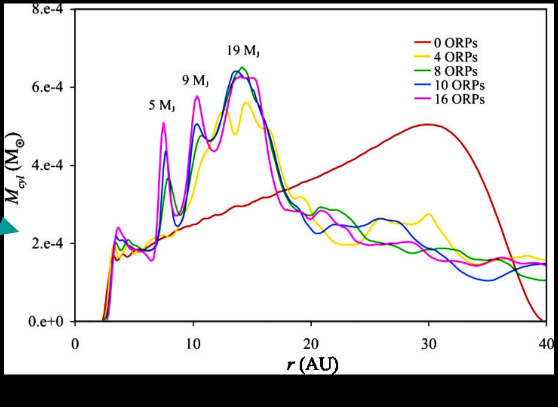
Radiative Cooling 3D

Boley et al. 2006



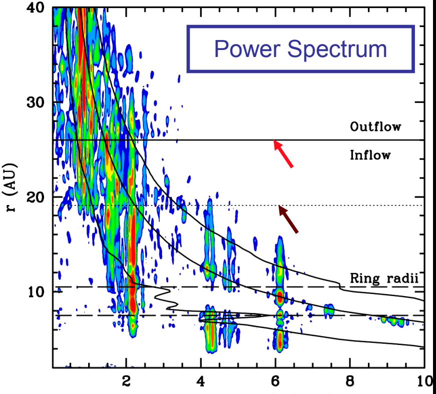
Mass inflow rates approach FU Orionis levels during the burst phase and level off to T Tauri star levels in the asymptotic phase.

Mass redistribution is strong but nonuniform. Rings and radial concentrations occur.



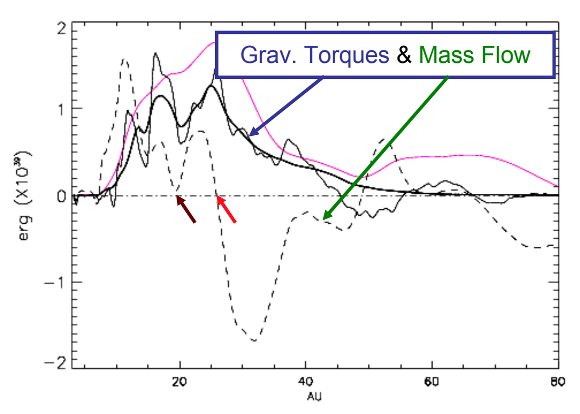
Radiative Cooling 3D

Boley et al. 2006



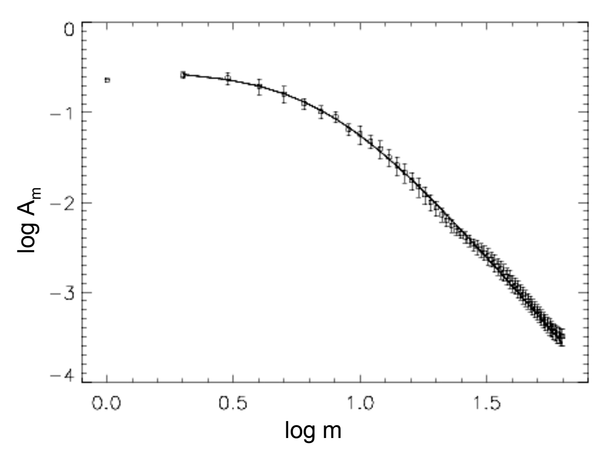
Corotation of global two-armed modes correlates with torque and mass flow features.

Transport by GIs is global!



Radiative Cooling 3D

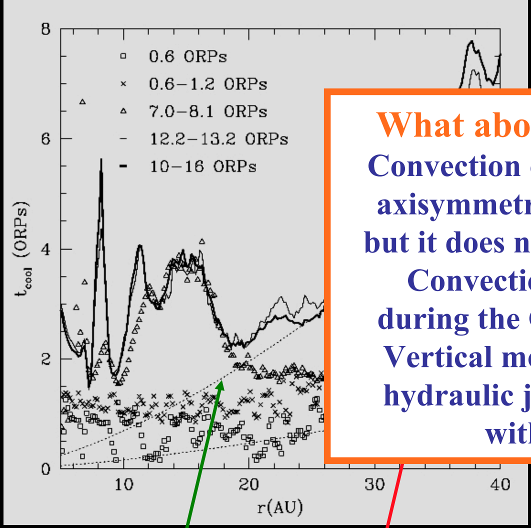
Boley et al. 2006



Globally integrated Fourier φ-components of δρ/ρ well fitted by $A_m \sim [m^2 + 7.5^2]^{-1.64}$ in the asymptotic phase. There is fully developed "gravitoturbulence"!

Radiative Cooling 3D

Boley et al. 2006

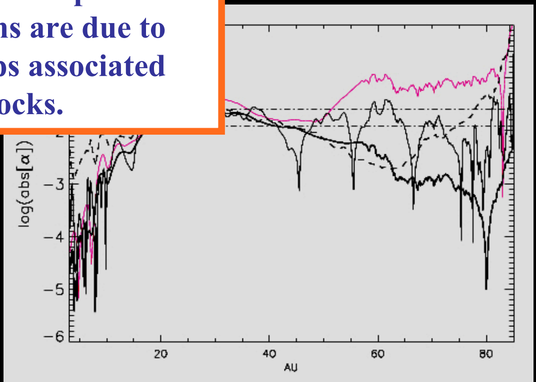


$t_{cool}\Omega = 25$

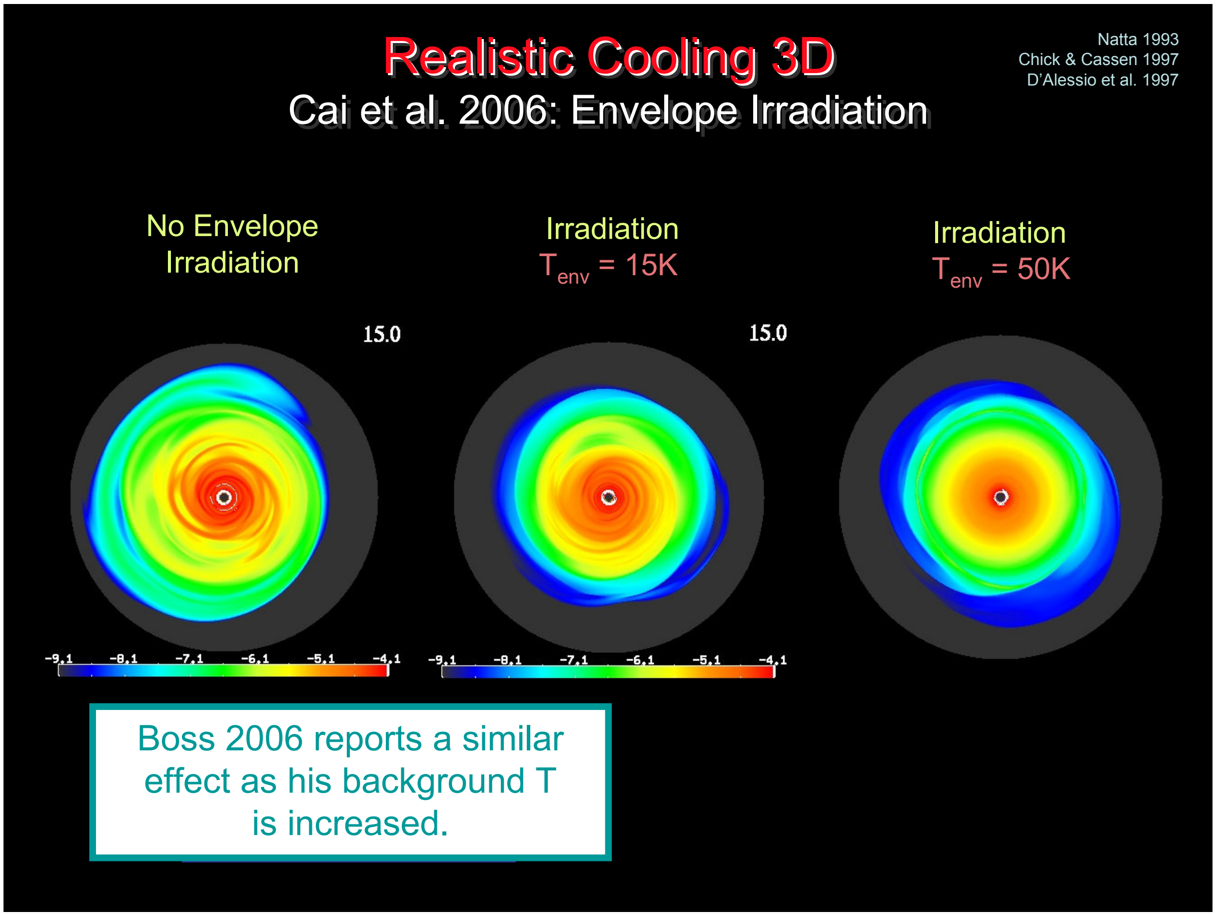
$t_{cool}\Omega = 6$

t_{cool} increases with time but is well above the naïve fragmentation ring GI-active phases.

nd α are roughly near the CR of the 2-armed mode.



What about convection?
Convection occurs during the axisymmetric cooling phase, but it does not keep t_{cool} short. Convection is disrupted during the GI active phases. Vertical motions are due to hydraulic jumps associated with shocks.



Realistic Cooling 3D

Cai et al. 2006: Envelope Irradiation

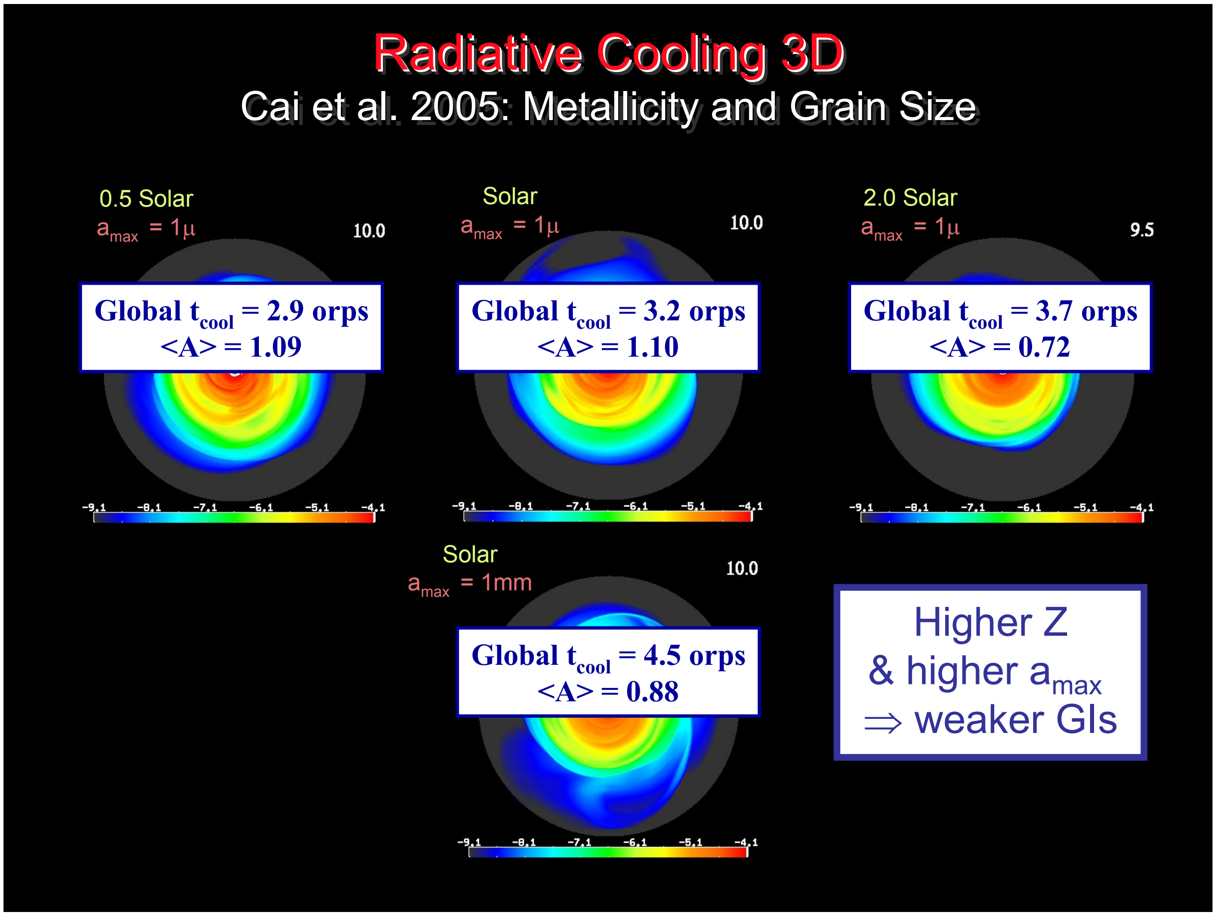
Natta 1993
Chick & Cassen 1997
D'Alessio et al. 1997

No Envelope Irradiation

Irradiation
T_{env} = 15K

Irradiation
T_{env} = 50K

Boss 2006 reports a similar effect as his background T is increased.



Radiative Cooling 3D

Cai et al. 2005: Metallicity and Grain Size

0.5 Solar
a_{max} = 1μ

Global t_{cool} = 2.9 orps
<A> = 1.09

Solar
a_{max} = 1μ

Global t_{cool} = 3.2 orps
<A> = 1.10

2.0 Solar
a_{max} = 1μ

Global t_{cool} = 3.7 orps
<A> = 0.72

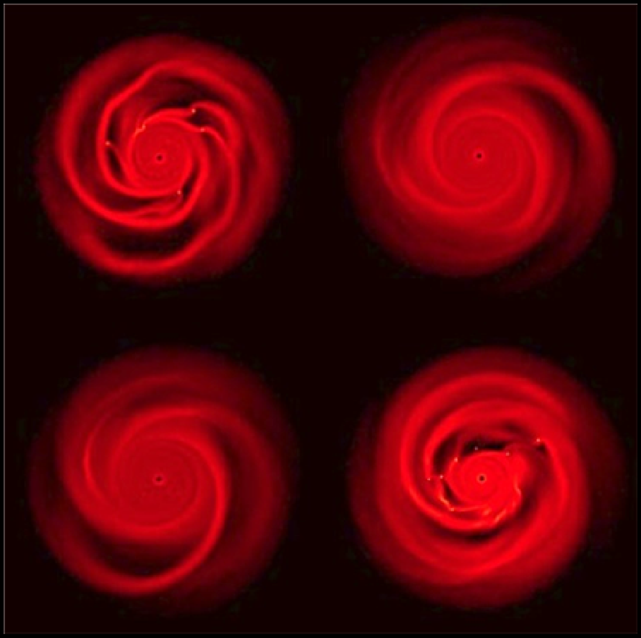
Solar
a_{max} = 1mm

Global t_{cool} = 4.5 orps
<A> = 0.88

Higher Z
& higher a_{max}
⇒ weaker GIs

Radiative Cooling 3D

Mayer et al. 2006



SPH Treatment:

3D diffusion approx. for interior particles.
"Edge" particles are those that see no particles in a vertically oriented cone.
Edge particles radiate like black body surfaces.
$M_d/M_s = 0.05$ to 0.2,
$M_s = 1\ M_{\odot}$, 20 AU
$\gamma = 7/5$
Fragmentation sensitive to mean molecular weight and cone opening angle!?

Radiative Cooling 3D & 2D$^+$

Summary of Global Results

- Boss & Mayer et al.
  - Convection ⇒ short t_{cool}'s & fragmentation
  - Insensitive to metallicity (Boss only)
- IU Group & Nelson et al. & Cardiff
  - No fast cooling due to convection
  - Longer t_{cool}'s & no fragmentation
  - Transport dominated by global modes (IU)
  - GI's weaken with increasing irradiation (IU & Cardiff… Boss agrees)
  - GI's on > few AU scale weaken as metallicity and grain size increase (IU)

Discussion

Discussion

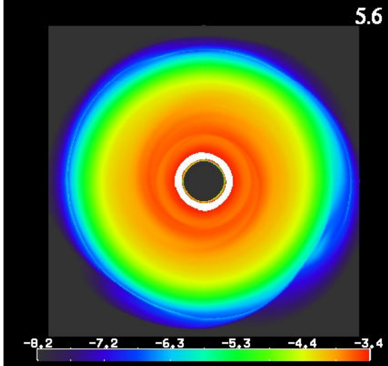
Problems/Solutions?

- Differences
  - Treatments of radiative physics, esp. B.C.'s
  - Initial models, EOS, opacities
  - Hydro codes
- Code comparisons
  - Boss/Cai , IU Group/Cardiff underway
  - IU Group/Mayer et al. planned
- Radiative routines
  - Rigorous testing of radiative routines
  - Better 3D techniques

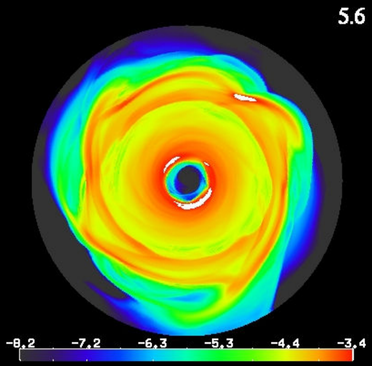
Discussion

Boss versus Mejía/Cai

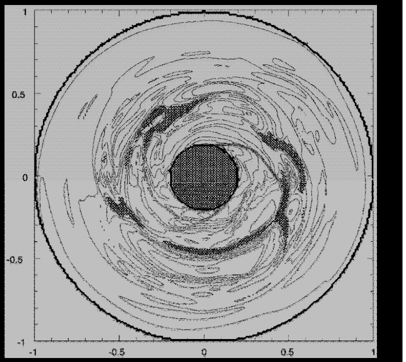
Boss Disk
Mejía/Cai Code
Mejía/Cai BC's



Boss Disk
Mejía/Cai Code
Boss BC's



Boss Disk
Boss Code

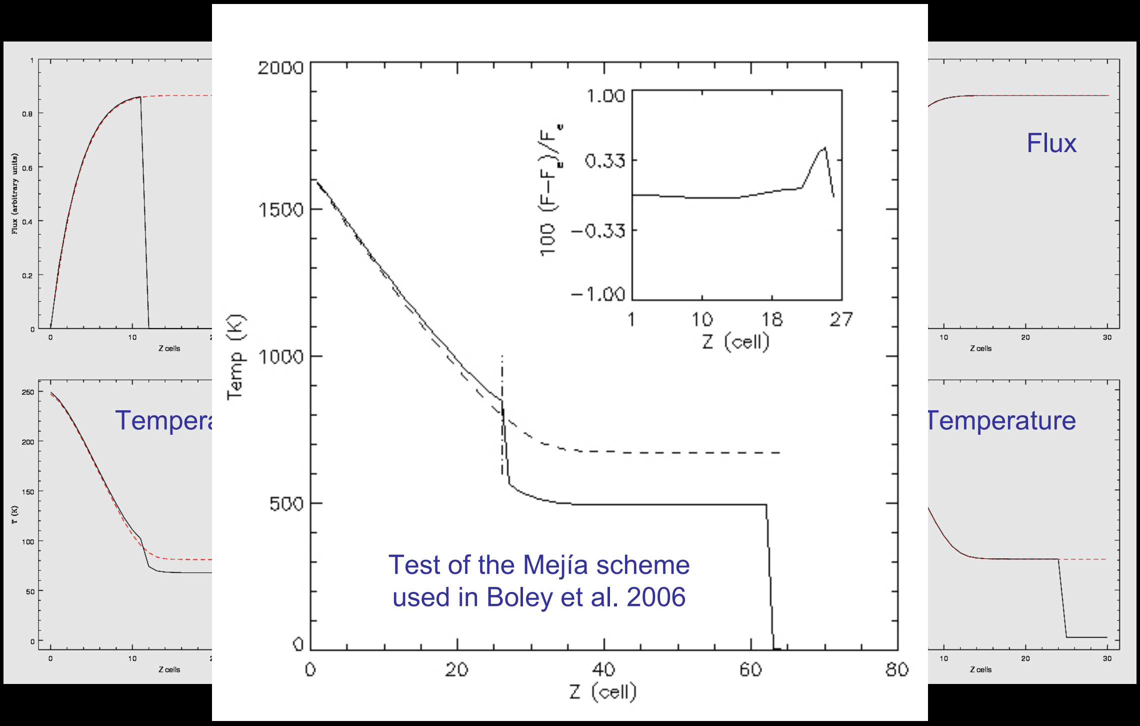


Cai et al. 2006

Boss 2001

Discussion

Plea for Radiative Tests



Test of the Mejía scheme
used in Boley et al. 2006

Discussion

Boley et al. Rerun with New Scheme

Animation courtesy of
Aaron C. Boley

Rafikov 2005
Boss 2005
Whitworth & Stamatellos 2006

Discussion

Analytic Arguments

- Fragmentation conditions
  - Fragmentation requires
    - cool disk ($Q < 1$ to 1.5)
    - fast cooling ($t_{cool} <$ 1 to a few P_{rot})
  - These conditions cannot easily both be met in the “planet forming” region (10’s AU) of disks
    - does not include convection explicitly
    - fragmentation possible beyond ~ 100 AU ?
      - $Q \sim c_s\Omega/\Sigma \sim r^{-0.75}$ for Keplerian disk with $T \sim r^{-1/2}$ and $\Sigma \sim 1/r$

Rafikov 2005
Durisen et al. 2006

Discussion

Analytic Arguments (cont’d)

- Behavior of t_{cool}
  - Consider a power-law mass absorption coefficient
    - $\kappa \sim T^{\beta}$ where $\beta \sim 1$ to 2 for $T < 150K$
  - In the absence of convection
    - Optically thin: $t_{cool} \sim \Sigma T/T_{eff}^4 \sim \tau/T^3 \sim \Sigma^2 Z T^{-3+\beta}$
    - Optically thick: $t_{cool} \sim T/\kappa T^4 \sim T^{-3-\beta}/Z$
  - As a disk cools for realistic β
    - t_{cool} ↑ in both thin and thick regions
  - As the metallicity Z increases
    - thin: t_{cool} ↓ but thick: t_{cool} ↑

Lin & Papaloizou 1980
Ruden & Pollack 1991
Boss 2004
Boley et al. 2006

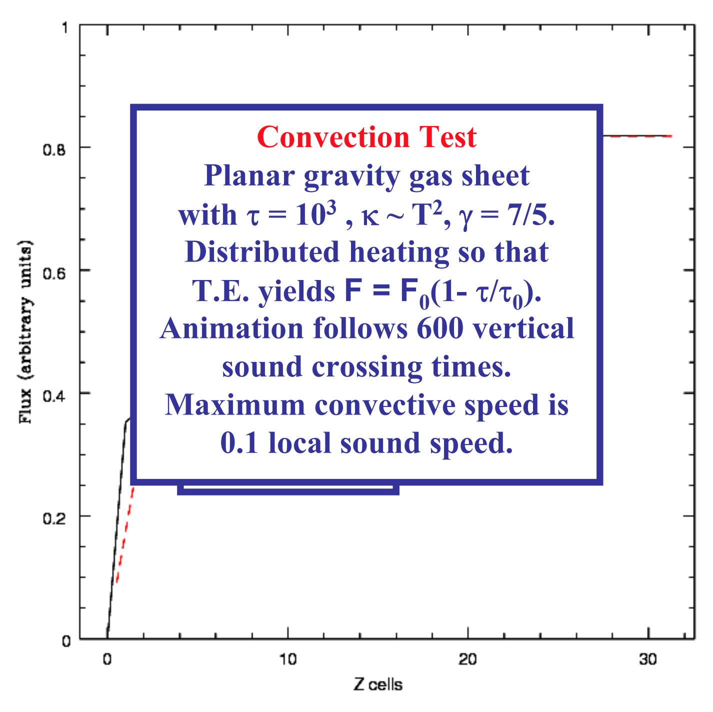
Discussion

Analytic Arguments (cont’d)

- Should convection occur?
  - Consider a disk contracting quasistatically due to the z-component of gravity
  - Optical depth condition
    - $\tau > 10$ or so
  - Condition for opacity law
    - $\beta > 1.5$ for $\gamma = 5/3$
    - $\beta > 0.5$ for $\gamma = 7/5$
  - Convection should probably occur in disks for realistic β’s and γ’s

Discussion

Convection Test



Convection Test

Planar gravity gas sheet with $\tau = 10^3$, $\kappa \sim T^2$, $\gamma = 7/5$. Distributed heating so that T.E. yields $F = F_0(1- \tau/\tau_0)$. Animation follows 600 vertical sound crossing times. Maximum convective speed is 0.1 local sound speed.

Animation courtesy of
Aaron C. Boley

Conclusions

Conclusions

My Personal Conclusions

- Thermal physics critical
  - Ra … y!
  - Hy … onvection, but do
  - W
- Real
  - Di
    -
  - G
    -
- Desp
  - Better & tested radiative routines
  - Code comparisons

This is a tough problem to get right!

Recall that $e_{int}/e_{grav} << 1$ and that all the energy lost by radiation must pass through e_{int}. This radiative bottleneck is what controls the evolution!

Proper treatment of both high and low τ parts of the disk and their interface is essential!

Conclusions

What About Our Questions?

- What do REAL disks do?
  - Realistic radiative cooling
  - Realistic equation of state
  - Realistic conditions and environments

Unclear: Simulations differ significantly

- How do REAL disks evolve under GIs?
  - Mass and angular momentum transport?
  - Fragmentation?

Transport strong; fragmentation hard

- Are GIs in REAL disks local or global?

Dominated by global modes but with full nonlinear gravitoturbulence

Vidago Workshop 2006

Physical Processes in Circumstellar Disks Around Young Stars

Disk Hydrodynamics

Talk #5: Special Effects and the Future

Richard H. Durisen
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Outline of Talk #5

Special Effects & the Future

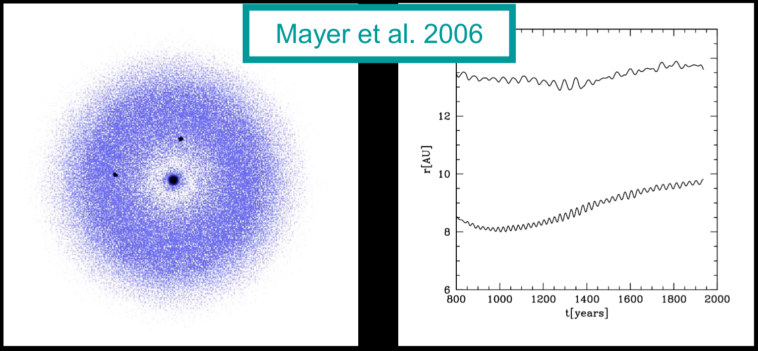
- Special effects & issues
  - Survival of dense clumps
  - Equation of State
  - Hydraulic jumps, mixing, & irradiation
  - Concentration of solids
  - Bursts & episodic behavior
  - GIs with MRIs
  - “Unified” theory
- Finale
  - Conclusions & controversies
  - Future prospects

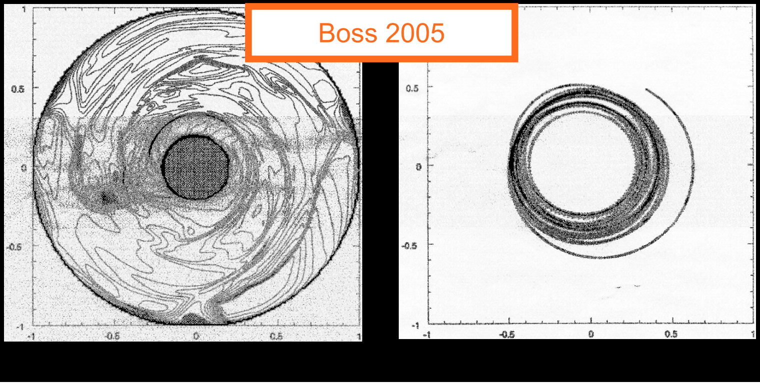
Special Effects

Clump Longevity

Migration in GI-Active Disks

Boss 2005
Mayer et al. 2002, 2004, 2006
Durisen et al. 2006


Mayer et al. 2006


Boss 2005

Mayer et al. & Boss: Clumps and/or virtual particles survive dozens of orbits (even migrate outwards) in GI-active disks.

Clump Survival

Mayer et al. 2004

Clump Survival

Numerical Effects

Isothermal Q = 1.35
Pickett & Durisen 2006

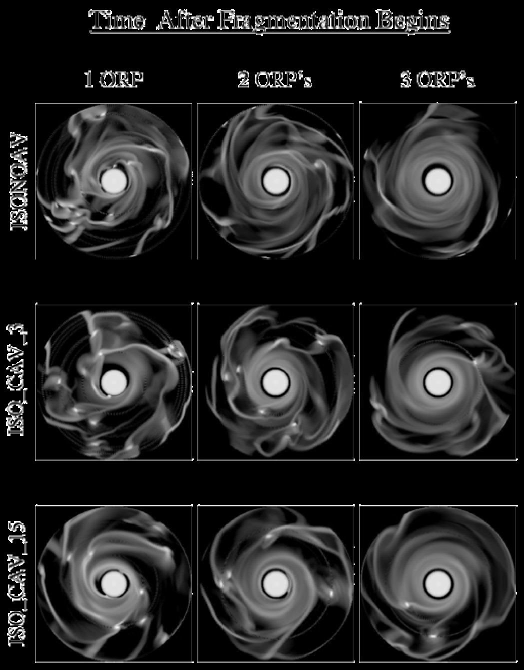
No Artificial Viscosity

C_Q =15 Artificial Bulk Viscosity

Clump Longevity

Pickett & Durisen 2006

Boss 2004, 2006
Mayer et al. 2004



No clumps form with higher artificial viscosity (CQ = 21).

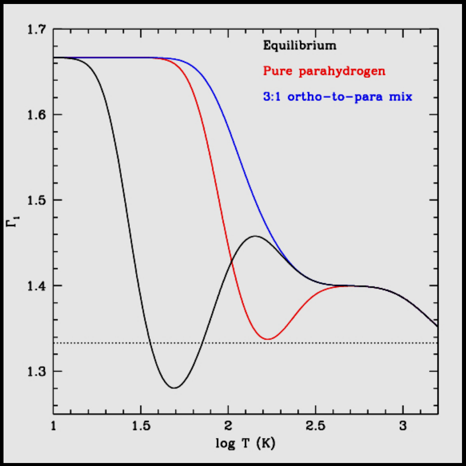
Mayer et al. see long-lived clump survival in isothermal SPH simulations with standard Monaghan SPH artificial viscosity. Clumps do not form with higher bulk viscosity.

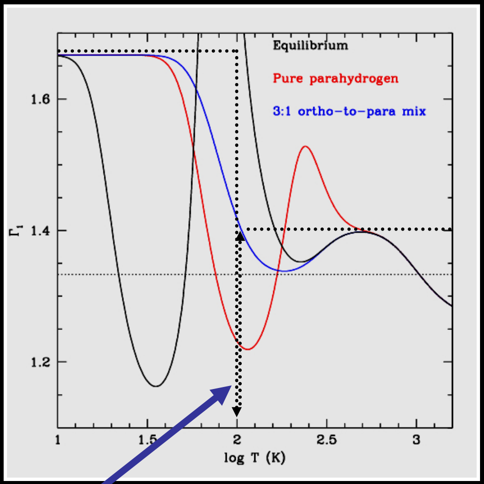
Boss finds no clumps with large artificial viscosity but his clumps survive without AV.

Equation of State

Molecular Hydrogen

Black & Bodenheimer 1975
DeCampli et al. 1978
Boss 1984
Boley et al. 2006





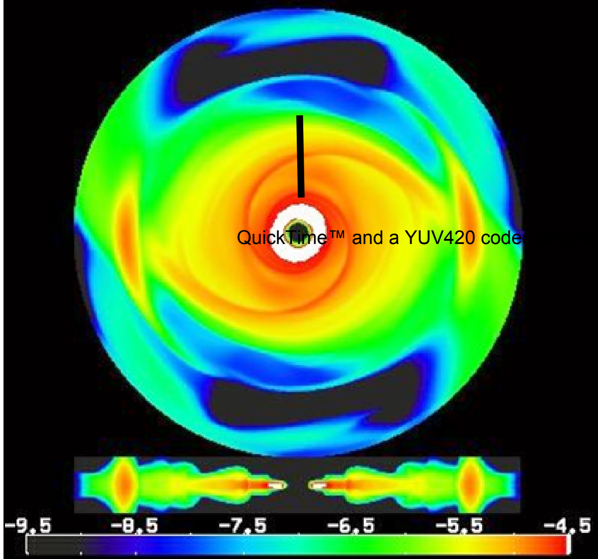
Correct $\Gamma_1 = \gamma$

Boss's "clumps" tend to show up near 100K

Dynamic consequences of using the wrong e(T)?
Solid: $e = C_V T$
Dotted: Boss e(T)

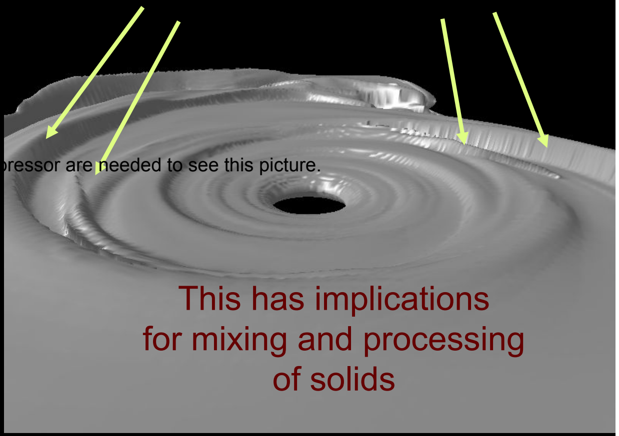
Jumps, Mixing, & Irradiation

Boley et al. 2005, Boley & Durisen 2006



QuickTime™ and a YUV420 code pressor are needed to see this picture.

Hydraulic jumps associated
with spiral shocks can lead
to breaking waves!

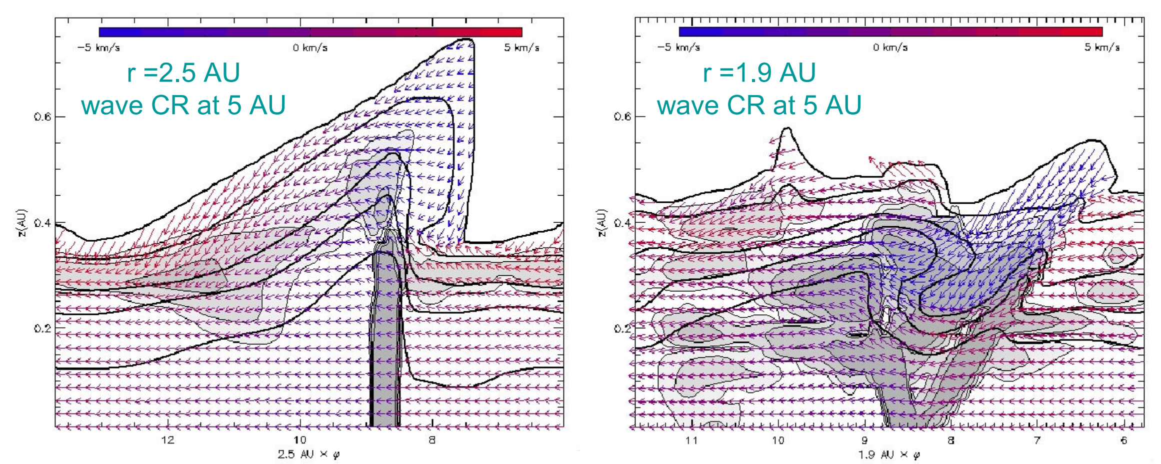


This has implications
for mixing and processing
of solids

Jumps, Mixing, & Irradiation

Boley & Durisen 2006

Martos & Cox 1998



“shocks”?

Froude # ≈ Mach #

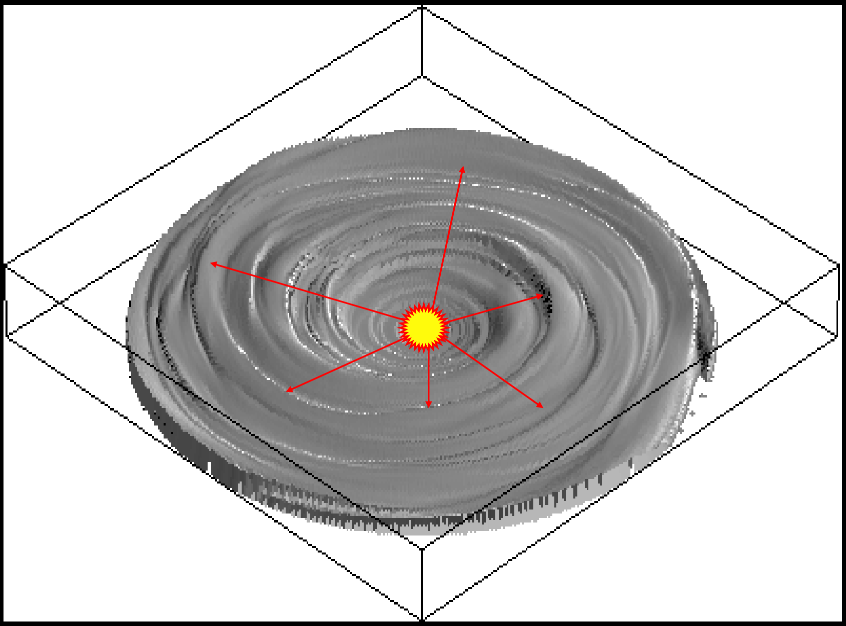
Adiabatic shocks do jump and are not simple “density” waves.

Isothermal shocks do not jump and are density waves.

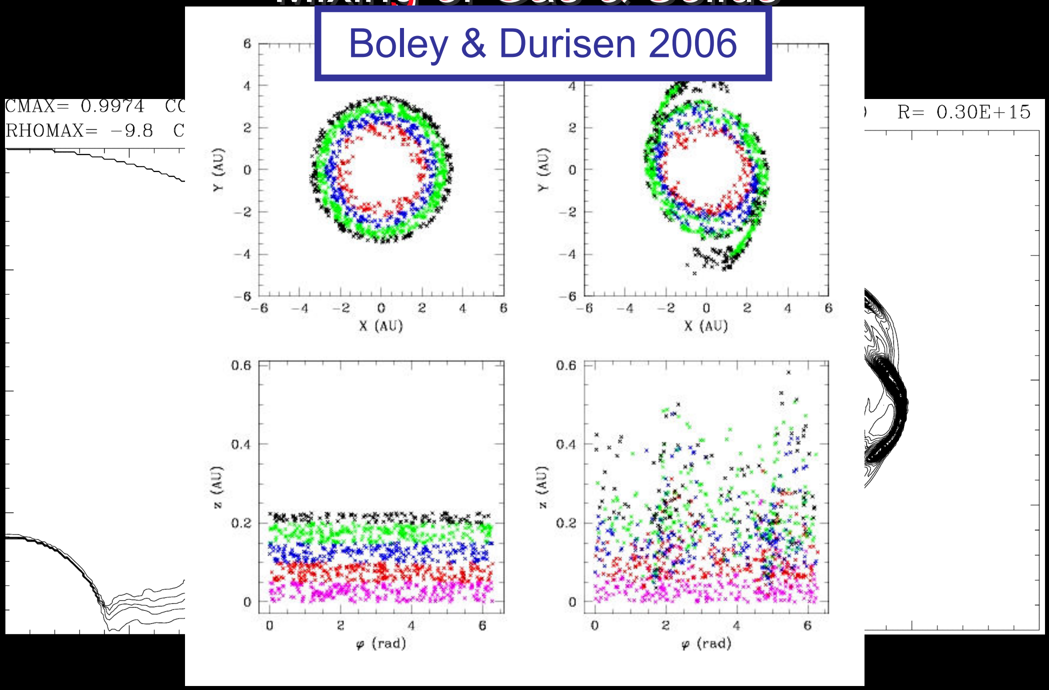
Jumps, Mixing, & Irradiation

Stellar Irradiation

Durisen et al. 2001
Mejia 2004
Dullemond et al. 2006



Mixing of Gas & Solids



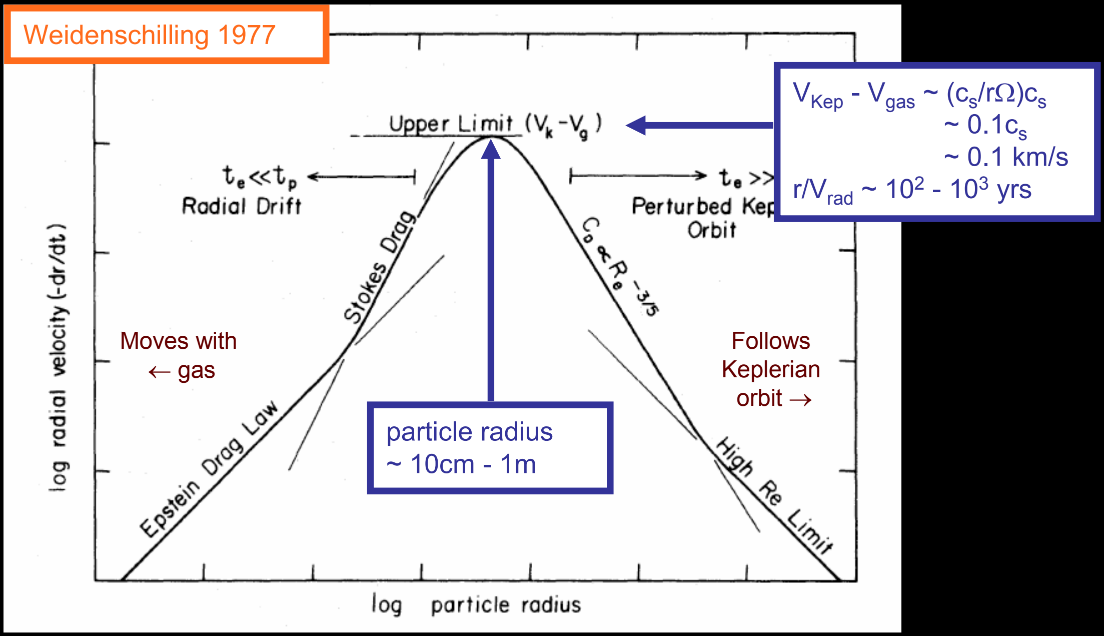
Boley & Durisen 2006

Dynamic time scale 3D mixing of gas and entrained particles by GI spiral waves

Concentration of Solids

Drift due to Gas Drag

Weidenschilling 1977
Haghighipour & Boss 2003
Haghighipour 2004
Rice et al. 2004, 2006
Durisen et al. 2005



Weidenschilling 1977

$V_{Kep} - V_{gas} \sim (c_s/r\Omega)c_s$
$\sim 0.1c_s$
~ 0.1 km/s
$r/V_{rad} \sim 10^2 - 10^3$ yrs

Moves with
← gas

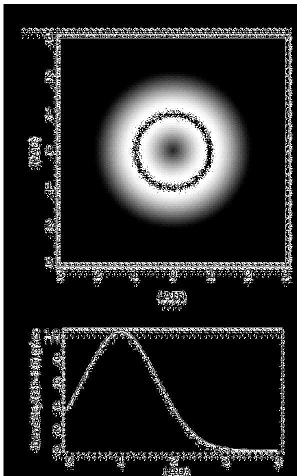
Follows
Keplerian
orbit →

particle radius
~ 10cm - 1m

Concentration of Solids

Drift due to Gas Drag

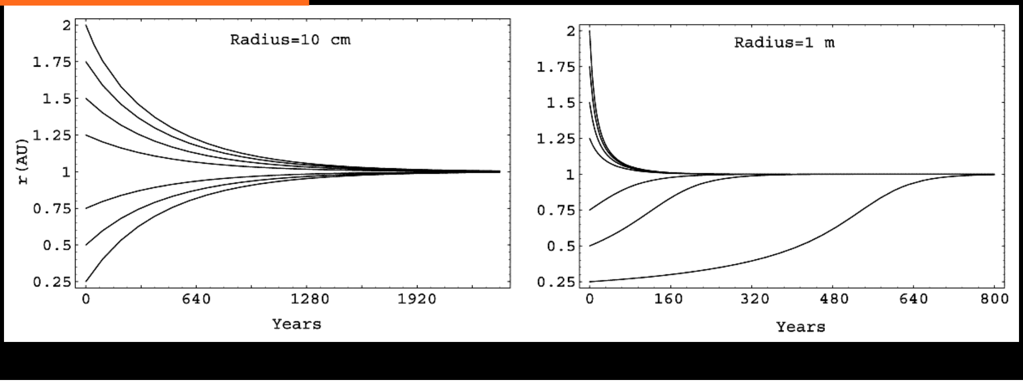
Klahr & Henning 1997
Haghighipour & Boss 2003
Haghighipour 2004
Klahr & Bodenheimer 2006



Haghighipour & Boss show that 10cm - 1m particles do indeed drift to the center of a gas pressure maximum in a matter of 10's to 100's of years.

Klahr & Bodenheimer suggest that gas giant cores can grow quickly in vortices.

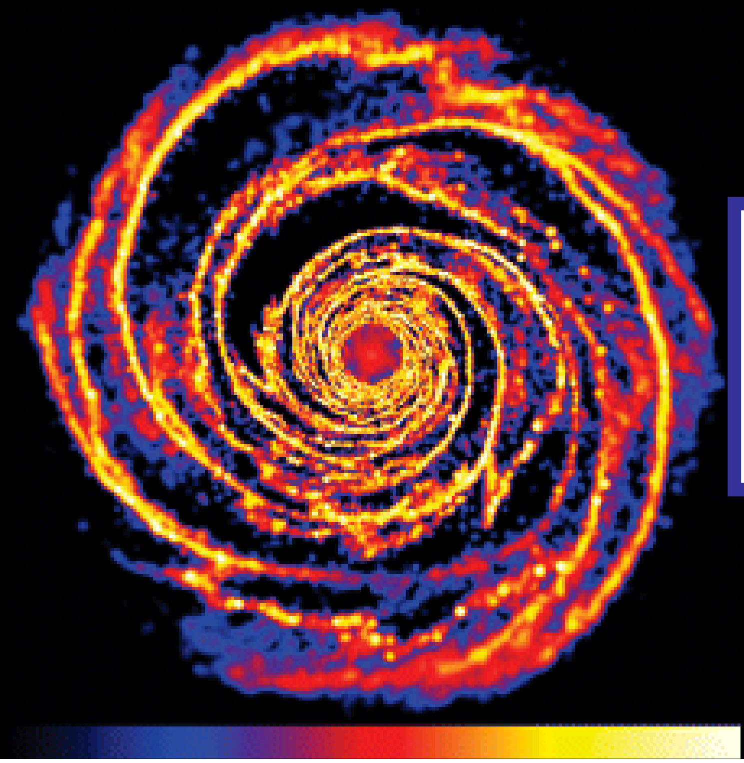
Haghighipour & Boss 2003



Concentration of Solids

10’s cm Particles Concentrate in GI Waves

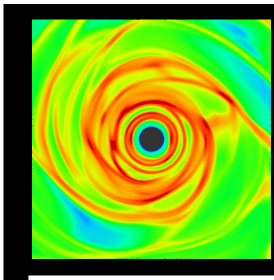
Youdin & Shu 2002
Rice et al. 2004, 2006
Johansen et al. 2006



Rice et al. 2006

SPH particle gravity

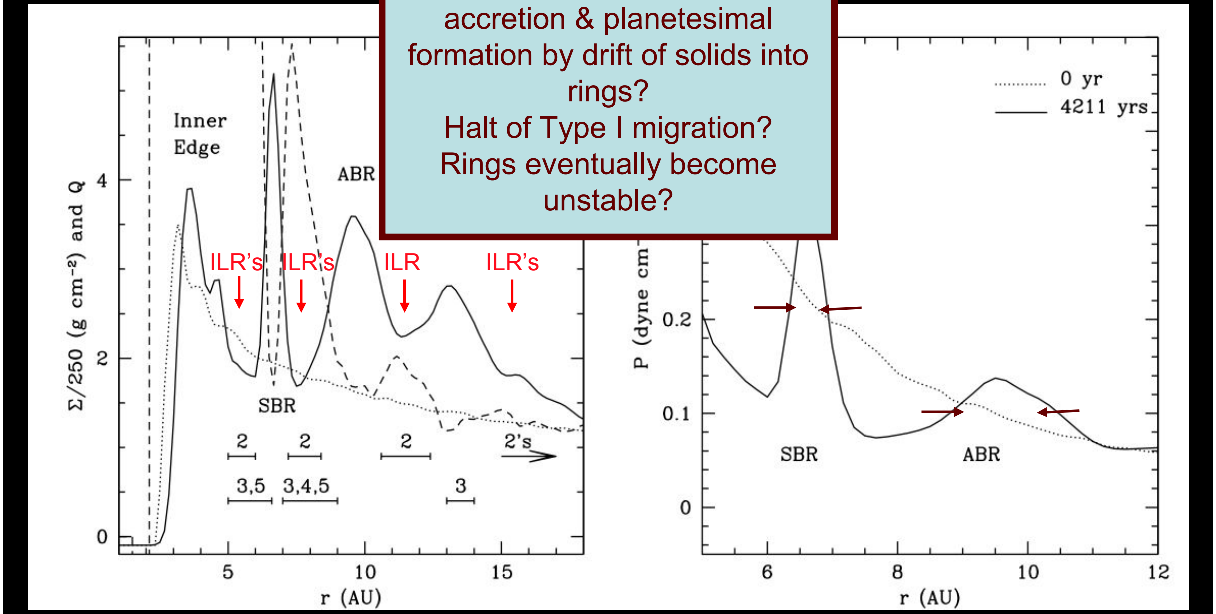
1.5 m particles not only concentrate in spiral arms but also fragment into self-gravitating bound clumps!



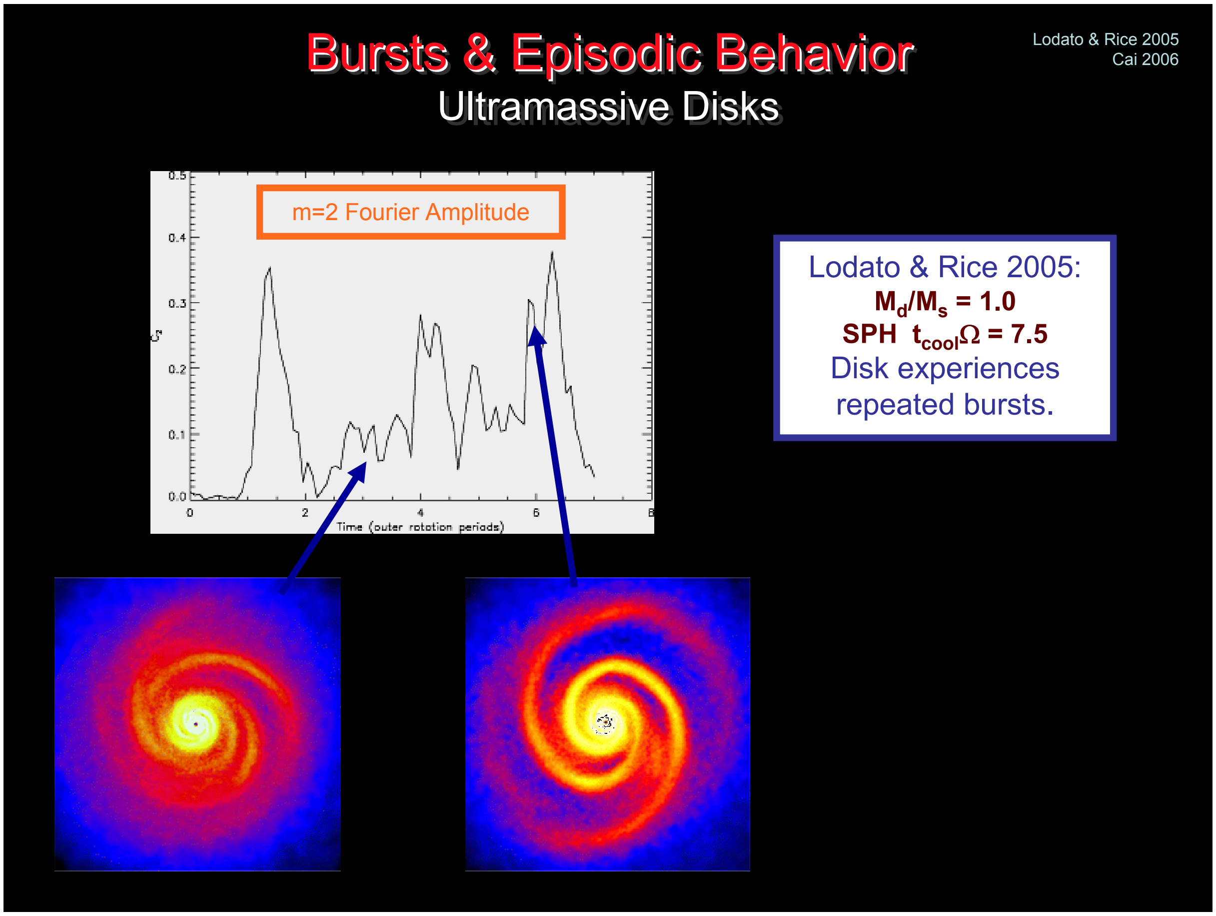
Concentration of Solids

Dense Rings, Resonances, & Planets

Durisen et al. 2005



Accelerated core accretion & planetesimal formation by drift of solids into rings?
Halt of Type I migration?
Rings eventually become unstable?

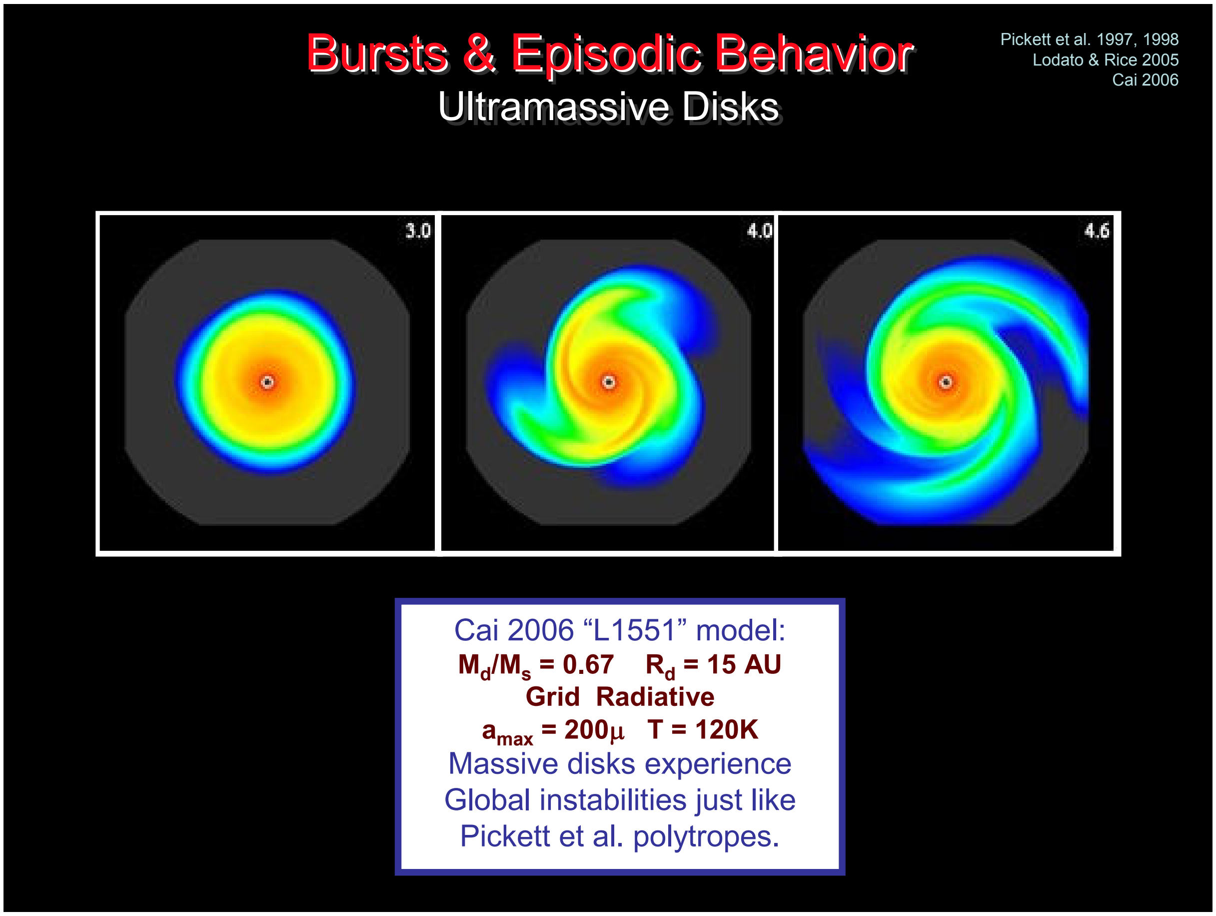


Bursts & Episodic Behavior

Ultramassive Disks

Lodato & Rice 2005
Cai 2006

Lodato & Rice 2005:
$M_d/M_s = 1.0$
SPH $t_{cool}\Omega = 7.5$
Disk experiences
repeated bursts.



Bursts & Episodic Behavior

Ultramassive Disks

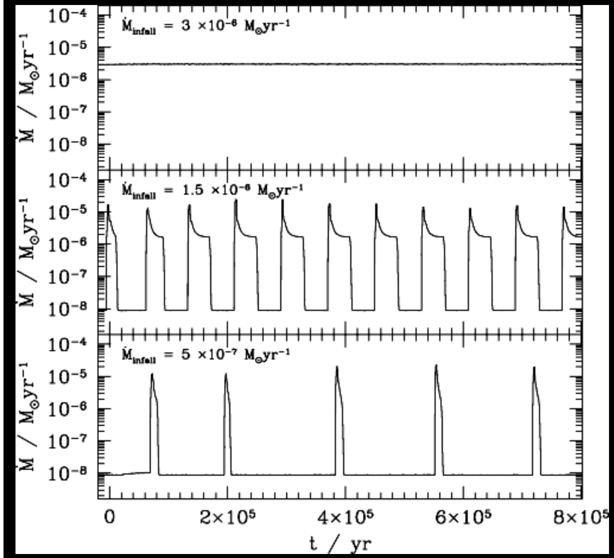
Pickett et al. 1997, 1998
Lodato & Rice 2005
Cai 2006

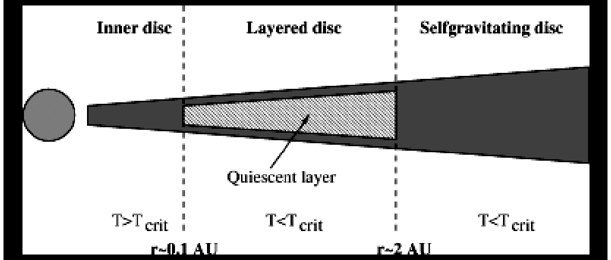
Cai 2006 “L1551” model:
$M_d/M_s = 0.67$ $R_d = 15$ AU
Grid Radiative
$a_{max} = 200\mu$ T = 120K
Massive disks experience
Global instabilities just like
Pickett et al. polytropes.

Bursts & Episodic Behavior

Layered Accretion & the "Dead Zone"

Gammie 1996, 1999
Armitage et al. 2001
Vorobyov & Basu 2005,2006
Wunsch et al. 2005
Hartmann et al. 2006





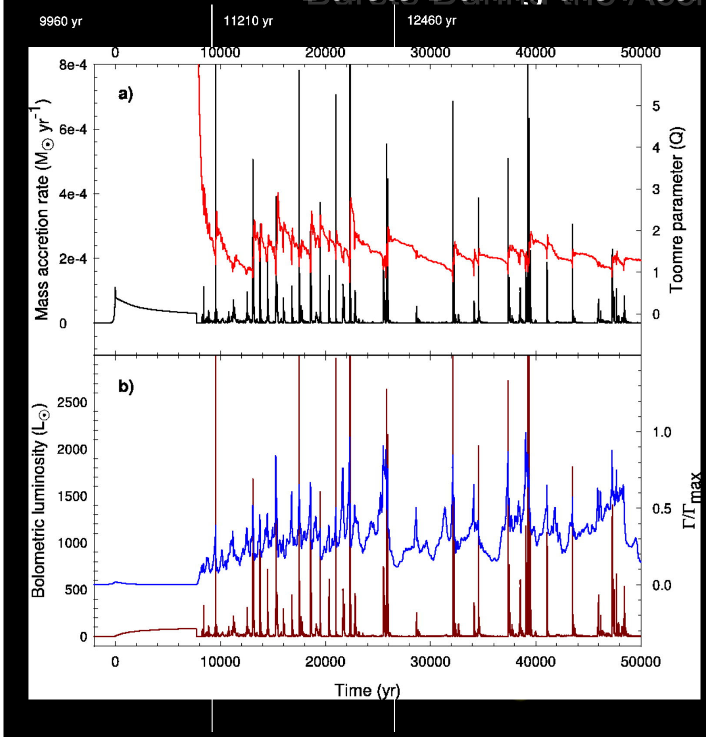
GIs can cause outbursts in Dead Zones

Armitage et al. 2001

Bursts & Episodic Behavior

Bursts During the Accretion Phase

Gammie 1996, 1999
Armitage et al. 2001
Vorobyov & Basu 2005,2006
Wunsch et al. 2005
Hartmann et al. 2006



Disk Formed by Accretion:
2D Grid Parametric EOS
Rather Coarse Resolution

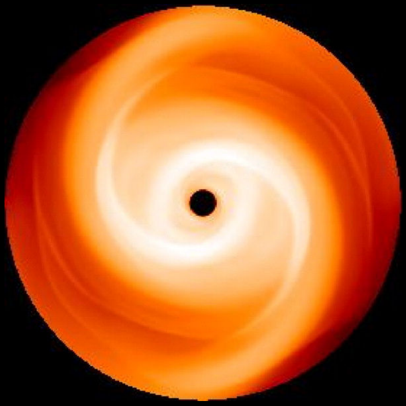
GIs can cause disk outbursts during the accretion phase

Vorobyov & Basu 2005, 2006

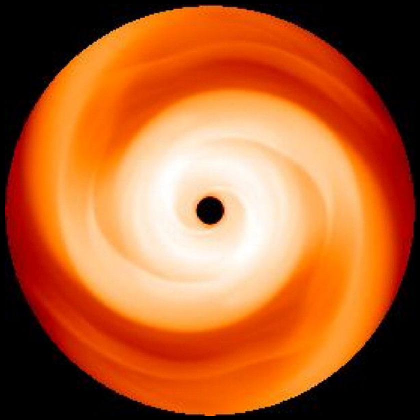
GI's with MRI

Fromang et al. 2004

High GI Stress Phase



Low GI Stress Phase



GI stresses weaken & oscillate due to MRI

GI's with MRI

Fromang 2005

Same Resolution

2x's φ Resolution

Add β **= 8** Magnetic Field to isothermal disk.

Results depend on Resolution.

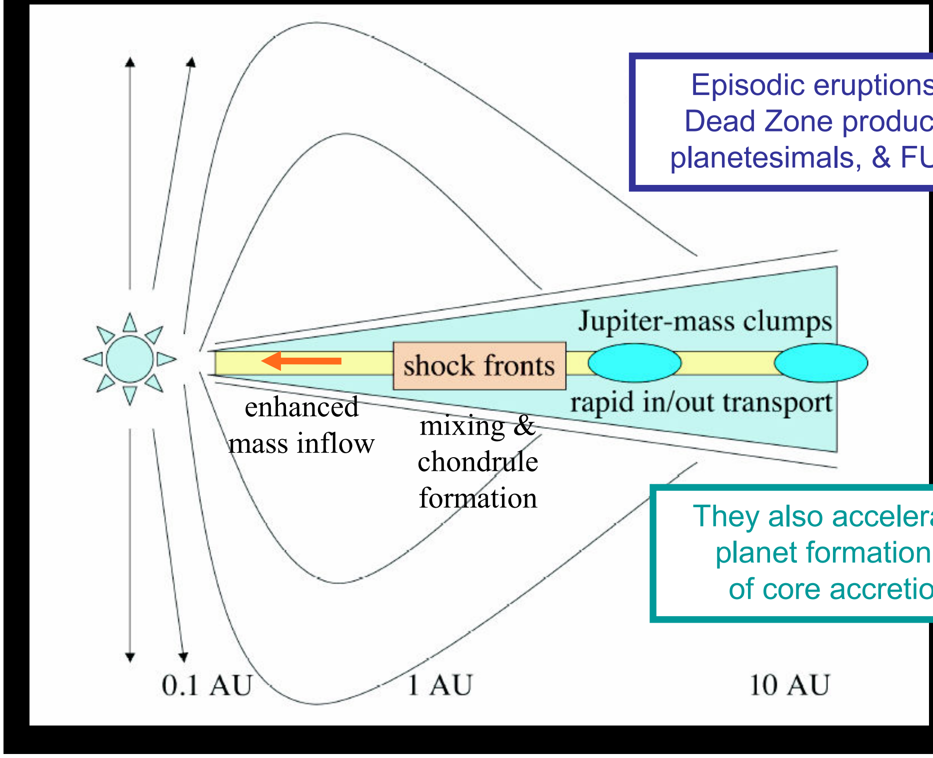
GI stresses tend to be weakened by the MRI turbulence.

Fragmentation depends on small-scale turbulent interactions.

Unified Theory?

Planets, Dead Zones, FU Ori, & Chondrules

Armitage et al. 2001
Boss & Durisen 2005
Boley et al. 2005, 2006
Vorobyov & Basu 2005



Episodic eruptions of GIs in the Dead Zone produce chondrules, planetesimals, & FU Ori outbursts.

They also accelerate gas giant planet formation by a hybrid of core accretion and GIs.

Finale

Finale

What Do We Agree About?

- Occurrence & manifestation
    - GI’s will occur in any sufficiently cold massive disk
    - Multiple spiral waves grow on a dynamic time scale through swing amplification
- Nonlinear amplitude
    - Regulated by disk thermal physics
        - Real disks are not well represented by idealized cooling laws or EOS’s
        - Radiative and convective cooling must be correctly modeled

Finale

What Do We Agree About? (cont’d)

- Ultimate behavior?
    - Asymptotic balance of heating & cooling
        - disk hovers near marginal Q stability
        - α_{eff} increases as t_{cool} decreases
        - large mass transport rates possible in bursts
        - moderate quasi-steady rates are sustainable
    - Fragmentation
        - $\gamma > 1$: for fast enough cooling ($t_{cool} < P_{rot}$ or so)
        - becomes easier as γ decreases but harder for realistic radiative cooling (if no convection)
        - isothermal: for $Q <$ about 1.4

Finale

What Else Seems Reasonably Likely?

- Local vs Global
  - You get what you pay for
    - treat t_{cool} as local (e.g., $t_{cool}\Omega$ = constant) & GIs behave locally
    - treat t_{cool} as global (e.g., t_{cool} = constant) & the GIs are global (dominated by low-order global modes)
      - except massive disks always act globally
    - GIs will act globally in real disks
  - Waves probably do transport energy when global modes dominate

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Finale

What Else Seems Reasonably Likely? (cont'd)

- The third spatial dimension
  - Dynamics
    - GIs corrugate the disk surface
    - spiral shock waves in nonisothermal disks are shock bores not density waves
    - strong vertical and radial mixing occurs
  - Energy transport
    - radiative and convective transport must be modeled
    - energy input from irradiation weakens and can suppress GIs

Finale

What Else Seems Reasonably Likely? (cont’d)

- Effect of additional physics
  - Magnetic fields
    - MRI turbulence interacts with GI turbulence and tends to weaken GI stresses
  - Irradiation
    - envelope ⇒ weaken and suppress GIs
    - stellar ⇒ not yet well studied (Mejía 2004)
  - Binary companion
    - shock heating can suppress fragmentation
    - tidal stresses can induce fragmentation
    - which wins or when depends on cooling

Finale

What Else Seems Reasonably Likely? (cont’d)

- Planet formation
  - GIs have something to do with gas giant planet formation
    - conditions exist in principle when disk fragmentation will occur
    - GIs rapidly concentrate particles with sizes of 10’s cm to a few meters
    - GIs can shock process solids
  - Hybrid scenarios?
    - GIs accelerate planetesimal, embryo, and core formation
    - GIs interfere with Type I migration

Finale

Where Is There Little or **NO** Agreement?

- Cooling in real disks
  - Radiative cooling
    - treatment of B.C.'s, esp. transitions from optically thin to thick
  - Convective transport
    - does it occur at all in a GI-active disk?
    - if it does, how effective can it be?
    - can it really make all disks fragment, regardless of metallicity?
  - Metallicity
    - are GIs sensitive to metallicity or not?

A. Nelson 2006

Finale

Where Is There Little or **NO** Agreement? (cont'd)

- Clump survival in fragmented disks
  - Sensitive to numerical effects
  - Resolution
    - if too low, causes numerical fragmentation but also suppresses real fragmentation
    - Examples of resolution issues
      - cell size in a grid-based code
      - gravitational softening in an SPH code
  - Artificial viscosity
    - suppresses clump formation if too high
    - but enhances longevity at moderate levels

Finale

What Is Required For Further Progress?

- Better radiative schemes
  - Fast 3D monochromatic radiative transport? Can we do it?
    - y?
    -
  - R
- AMR schemes for disks
- Code comparisons
  - The same calculation run by two or more groups using disparate numerical codes

THIS IS A TOUGH PROBLEM TO GET RIGHT!

Job Security!

Finale

What Is Required For Further Progress? (cont’d)

- More inclusive physics
  - Particle dynamics, growth, and mixing
    - affects the dust opacity
    - reacts back on the dynamics
  - External sources of irradiation & mass
  - Companions & embedded bodies
  - Inclusion of MRI
  - Chemistry, EOS, shock processing
  - More and better Dead Zone modeling
- Hybrid planet formation scenarios
  - The best of both worlds?

TAKE THESE POINTS WITH YOU

IF NO OTHERS

- Proper treatment of radiative effects is absolutely critical for modeling GIs and understanding their effects.
- Spiral waves in disks are intrinsically 3D with interesting consequences.
- GIs may assist planet formation by creating dense structures, marshalling solids into them, and halting Type I migration.