Vidago Workshop 2006

Physical Processes in Circumstellar Disks Around Young Stars

Disk Hydrodynamics

Talk #1: Introduction

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PERSONAL INTRODUCTION:

What Kind of Fool Am I?

What Kind of Astrophysicist Am I?

- Numerical simulator
- Using mostly grid-based 3D hydro

How Did I End Up Studying Disks?

- I came to disk dynamics by extrapolation from global studies of rotating stars & now I have to think about local disk physics
- Relevant T-shirt slogan? "Think globally, drink locally!"

Notice: **3D, Global, Rotating, Self-Gravitating**

BIG QUESTIONS

What Purely Hydrodynamical (B=0) Processes Affect Disk Evolution?

- Which can and do alter the structure of disks?
- Which, if any, can and do affect planet formation?

Which Can Transport Mass & Ang. Mom.?

- How efficient are they?
- Is the transport local or global?

STRONG PERSONAL BIAS

What Purely Hydrodynamical (B=0) Processes Affect Disk Evolution?

- Which can and do alter the structure of disks? Gravitational Instabilities
- Which, if any, can and do affect planet formation? GIs

Which Can Transport Mass & Ang. Mom.? GIs

- How efficient are they? Very
- Is the transport local or global?

Outline of Talks

- Talk #1: Introduction
- Talk #2: A Wonderland of Instabilities
- Talk #3: Gravitational Instabilities I
- Talk #4: Gravitational Instabilities II
- Talk #5: Special Effects and the Future

Outline of Talk #1

- What is a disk?
  - Thin sheet vs a flat star
- Important processes
  - Internal
  - External
- Origins of disks
  - Rotating Cloud Collapse
  - Turbulent Cloud Collapse
- Evolution due to stresses
  - Turbulent accretion disks
  - The big three stressors
  - Overstressed?

What is a Disk?

Hartmann 1998

What is a Disk?

Disks as Thin

- Zero-order axisymmetric equilibrium
  - Gas orbiting a star in circular coplanar orbits
- Radially smooth and dominated by
  - Centrifugal balance in the r-direction
    - $\partial P/\partial r \sim \partial \rho c_s^2/\partial r << \rho r \Omega^2 \Rightarrow c_s << r\Omega$
    - $M_d << M_s \Rightarrow$ nearly Keplerian $\Omega = (GM_s/r^3)^{1/2}$
    - $M_d < M_s \Rightarrow \Omega \approx (GM_r/r^3)^{1/2}$
  - Pressure balance in the z-direction
    - $\partial P/\partial z = \rho g_z \Rightarrow c_s \sim \Omega H$ where $\Sigma \sim 2\rho H$
    - and so $c_s^2/(r\Omega)^2 \sim (H/r)^2 << 1$
    - $H/r < 0.1 \Rightarrow e_{therm}/e_{rot} < 0.01$

What is a Disk?

Shakura & Sunyaev 1973
Lynden-Bell & Pringle 1974
Hartmann 1998
Gammie 2001
Balbus 2003
Gammie & Johnson 2005

Disks as Thin (cont'd)

- Vertically integrated equations
  - Time-dependent Keplerian viscous accretion disk theory for ν (= $\alpha c_s H$) << $r^2\Omega$

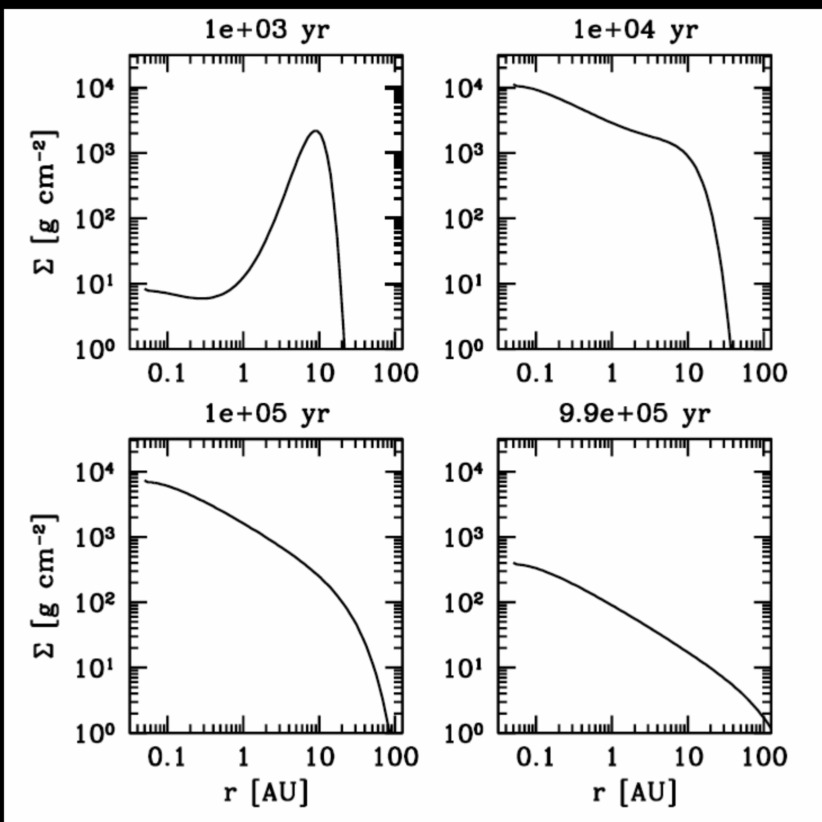
$$\frac{\partial \Sigma}{\partial t} = \frac{3}{R}\frac{\partial}{\partial R}\left[R^{1/2}\frac{\partial}{\partial R}(\nu R^{1/2}\Sigma)\right]$$

  - Equation of state (low frequency)
    - $U = \int u dz$ and $\mathbf{P} = \int P dz$
    - $P = (\gamma-1)u \Rightarrow \mathbf{P} = (\Gamma-1)U$
    - g_z dominated by star: $\Gamma = (3\gamma-1)/(\gamma+1)$
    - g_z dominated by disk: $\Gamma = 3 - 2/\gamma$
  - Instantaneous adjustment of equilibrium in the z-direction assumed

What is a Disk

Gammie & Johnson 2005

Simple α-Disk Evolution



Simple "Solar Nebula"
$M_d/M_s = 0.1$
$M_s = 1.0\ M_\odot$
$\alpha = 10^{-2}$
fixed $T \sim r^{-3/4}$
The point here is that even this simplistic evolution is not well described as a "steady state".

Hartmann 1998

What is a Disk?

Disks as Thick

- Zero-order axisymmetric equilibrium
  - Centrifugal balance in the r-direction
    - P_{rot} = rotation period = $2\pi/\Omega$
    - sets the “dynamic” time scale
  - Pressure balance in the z-direction
    - c_s/H = the vertical sound crossing time = t_z
    - $c_s/H \sim \Omega \Rightarrow t_z \sim P_{rot}/2\pi$
- Dynamic time scales are comparable in r and z regardless of H/r!
  - r and z dynamics are coupled
    - 3D disks have richer dynamics than 2D disks

Lin & Paploizou 1980
Hartmann 1998
Pickett et al. 1996, 2000
Lubow & Ogilvie 1998
Dullemond et al. 2006
Boley & Durisen 2006

What is a Disk?

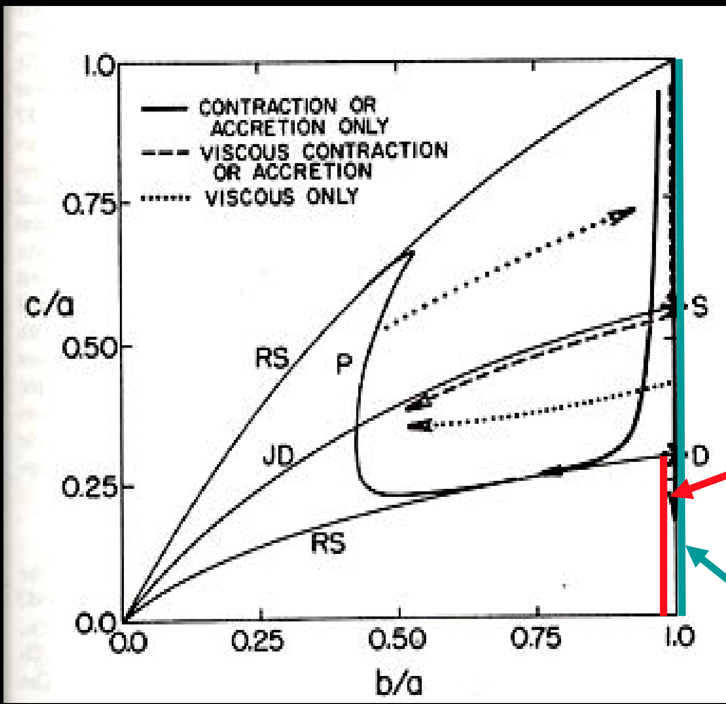
Disks as Thick (cont’d)

- Critical physics
  - Energy transport couples in 3D
    - radiation flows in both r and z
    - convection cells & vortices $\Delta r \sim 2H$
  - External effects often set a vertical B.C.
    - accretion
    - irradiation
- Global dynamics resembles flattened star
  - “Density” waves are also surface distortions
- Vertical dynamics
  - Hydraulic jumps (“shock bores”)

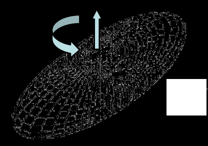
What is a Disk?

Disks as Thick

Chandrasekhar 1969
Tassoul 1978
Hachisu & Eriguchi 1984
Durisen & Tohline 1985, 2001



Ellipsoidal Equilibrium States:
Uniformly Rotating
Uniform Density
Incompressible Fluids
Semiaxes $c \leq b \leq a$

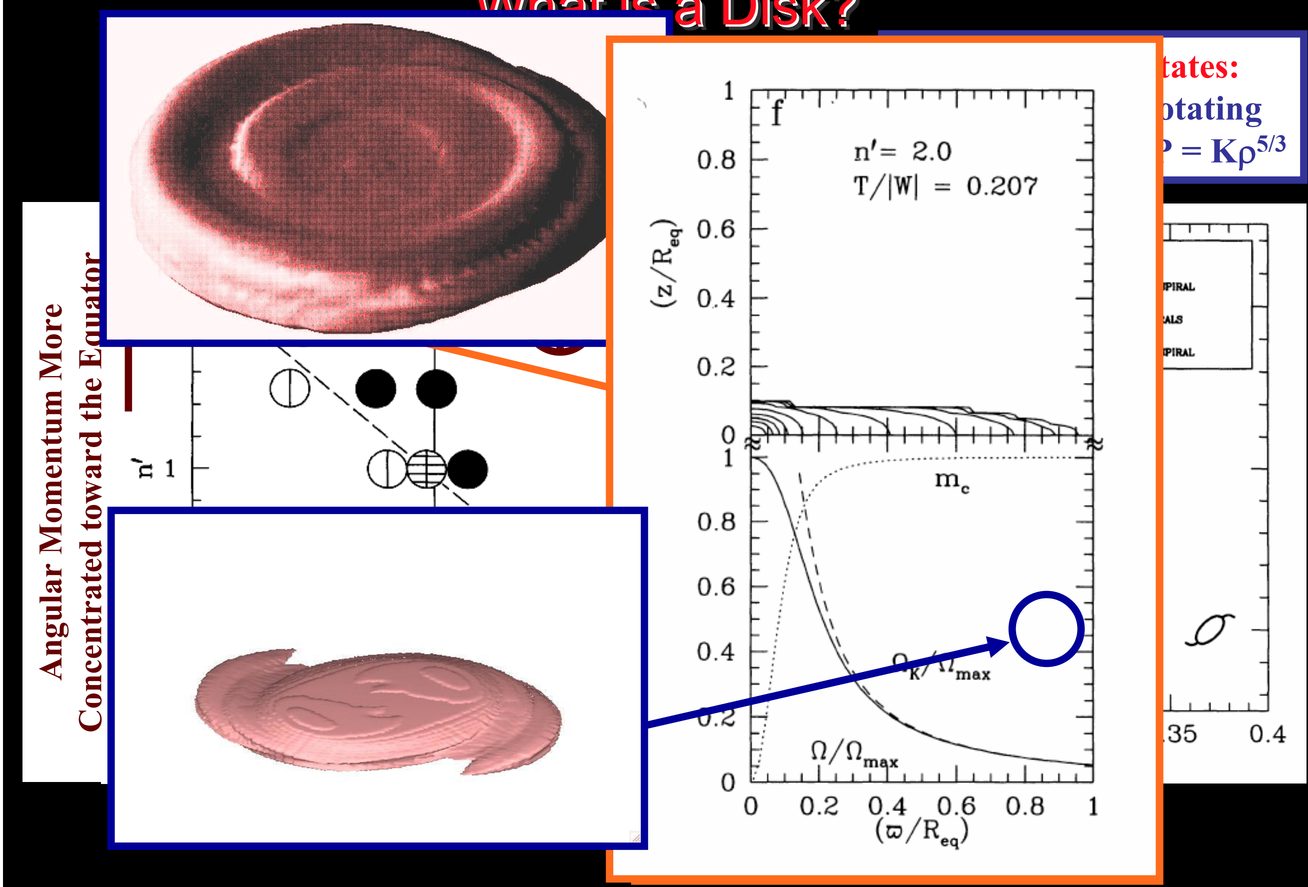


Dynamic Bar Instability
(Kelvin or f-mode)
$T/|W| \geq 0.27$

Maclaurin Spheroids
(axisymmetric ⇒ "thick" disks)

What is a Disk?

Pickett et al. 1996



What is a Disk?

Shock Bore

Boley & Durisen 2006

Driven Spiral Shock in a High Mass Solar Nebula Model

Meridional Slice

Shock Heating
by artificial viscosity

Animation courtesy of
Aaron C. Boley

Important Processes

Important Processes

Internal Processes

- Gravitational
  - Disk self-gravity
  - Gravity of embedded objects
    - planets & planetesimals
    - gravitationally bound protoplanets
    - transient clumps & other structures
- Material
  - Growth and settling of solids
  - Chemistry
    - gas phase & on grains
  - Dust
    - major opacity source

Important Processes

Internal Processes (cont'd)

- Radiation (& radioactivity)
  - Energy
    - deposition
    - transport
  - Nonlocal effects
    - irradiation
    - shadowing
  - Ionization equilibrium
    - thermal & nonthermal
- Thermodynamics
  - Equation of state
    - molecular hydrogen
    - effective Γ_1

Important Processes

Internal Processes (cont'd)

- Hydrodynamics & MHD
  - Instabilities
    - hydrodynamical
    - gravitational
    - magnetohydrodynamical
    - turbulence due to instabilities
  - Gas/solid interactions
    - gas drag
    - gravity
    - differential drift & mixing of solids
  - Shocks & shock bores
  - Magnetic fields

Important Processes

External Processes

- Gravitational
  - Binary or multiple components
  - Tidal encounters
- Material
  - Accretion or wind outflow
  - Disk collisions
- Radiation & energetic particles
  - Cosmic rays
  - Central or nearby star(s)
  - Warm envelope around the star & disk
- Global magnetic fields

Formation

Formation

Cassen 1994
Hartmann 1998

Rotating Cloud Collapse

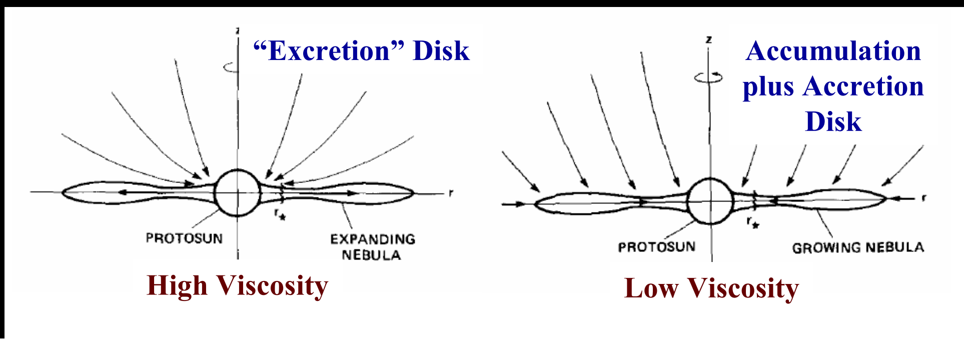
- Initial cloud state
  - No universal agreement
    - Probably: centrally concentrated clumps in a turbulent MHD environment
- General
  - Collapse time scale
    - $t_{ff} = (3\pi/32G\rho_{cl})^{1/2} \sim 10^5$ yrs
  - Disk evolution time due to transport
    - $t_{ev} \approx r^2/\nu = r^2/\alpha c_s H = (r/H)^2 P_{rot}/2\pi\alpha$
    - $t_{ev} \approx 10^4 P_{rot}$ for $H/r = 0.1$ & $\alpha = 10^{-2}$
  - Accumulation disk where or when $t_{ff} < t_{ev}$
  - Transition to accretion disk after a few t_{ff}

Formation

Shu 1977
Cassen & Moosman 1981
Cassen & Summers 1983
Tereby et al. 1984

Rotating Cloud Collapse (cont'd)

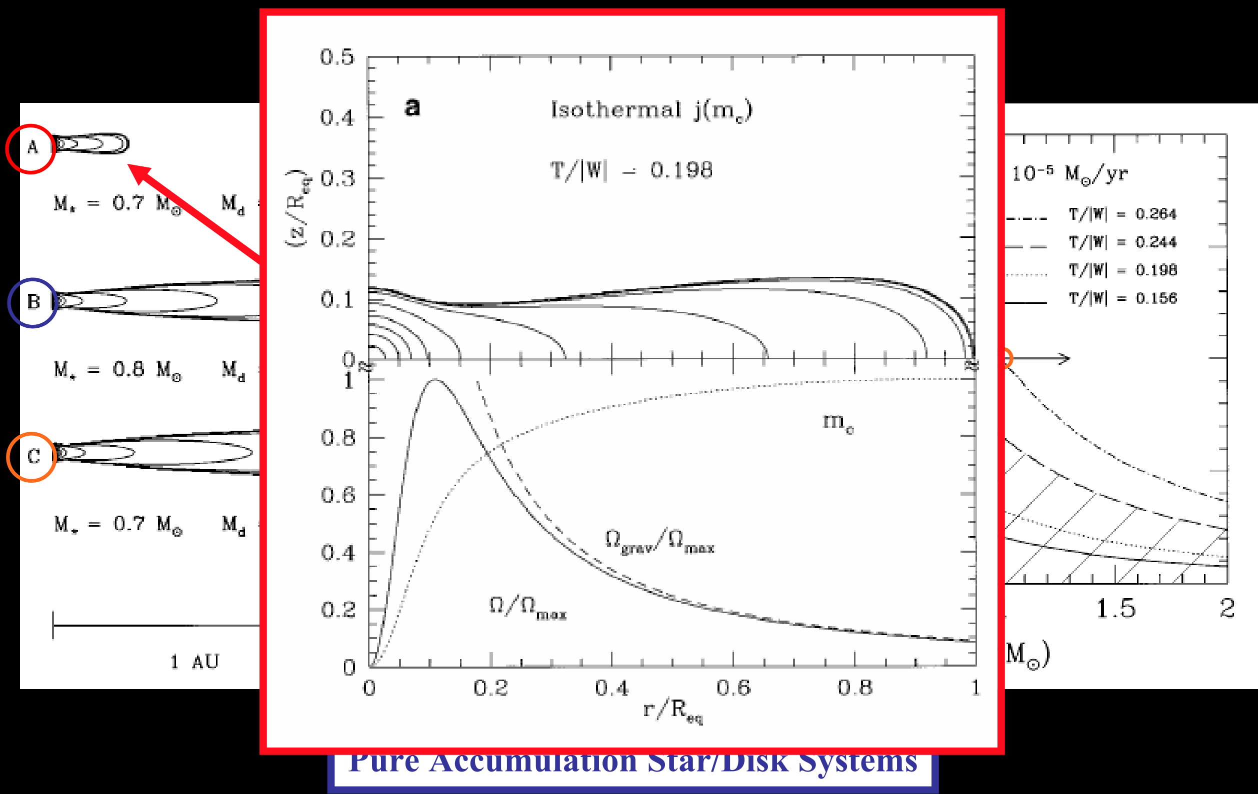
- Singular isothermal cloud in slow UR
  - Analytic solutions
    - dM/dt(r,t), M ~ t, and specific a.m. $j_d \sim t^2$
    - once $r_d > r_s \Rightarrow r_d \sim j_d^2/M \sim t^3$
    - the disk grows rapidly in radius
  - High vs low viscosity
    - disk radius grows even faster when $t_{ev}(r_d) < t$



Formation

Rotating Cloud Collapse

Stahler et al. 1984
Yang et al. 1991
Pickett et al. 1997



Formation

Cassen 1994
Laughlin & Bodenheimer 1994
Bate 1998
Yorke & Bodenheimer 1999
Matzner & Levin 2005
Vorobyov & Basu 2006

Rotating Cloud Collapse (cont'd)

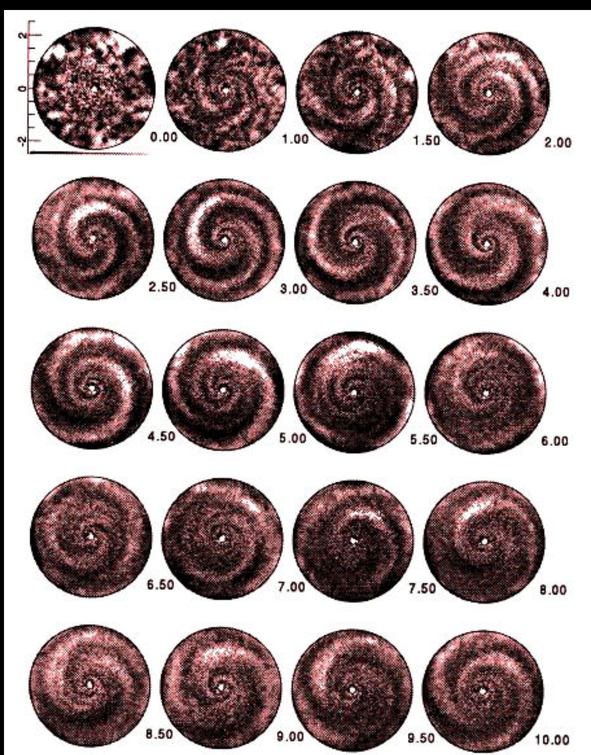
- More general collapses
  - Quasi-analytic
    - evolutions differ depending on dM/dt(r,t), J(r,t), and t_{ev}(r,t)
    - depend critically on assumed physics of t_{ev} if and when a disk forms
  - Numerical solutions in 3D
    - sensitive to initial conditions
    - sensitive to assumed physics of t_{ev}
    - eruption of GIs in disk may control t_{ev} in early stages of evolution
    - physics is "calculated" in some recent cases

Formation

Laughlin & Bodenheimer 1994

Rotating Cloud Collapse

400 AU



Unstable Accumulated Disk: Collapse from Small UR Singular Isothermal Cloud

SPH 25,000 particles

One time unit = 477 yrs

Formation

Rotating Cloud Collapse

Bate 1998

100 AU

Formation

Turbulent Cloud Collapse

Bate & Bonnell 2005

$50\ M_{\odot}$ Cloud
$R = 0.6$ pc
$T = 10$ K
$M_J = M_{\odot}$
$P(k) \sim k^{-4}$

SPH 3.5×10^6 particles

Disk Evolution

Disk Evolution

General

- External processes
  - Already mentioned
- Internal processes
  - Evolution of disk constituents
    - particle growth and settling
    - planet formation and migration
    - chemistry
  - Internal stresses that create torques
    - molecular viscosity too small
      - $t_{ev} \sim r_d^2/\nu$ > Hubble time
    - turbulent stresses due to instabilities

Disk Evolution

Shakura & Sunyaev 1973
Lynden-Bell & Pringle 1974
Hartmann 1998
Gammie 2001
Balbus 2003

Turbulent Evolution

- Axisymmetric equilibrium
  - Simple φ-independent forces
    - gravity, rotation, isotropic pressure
    - specific ang. mom. ⇒ orbit radius
- Angular momentum transport
  - Energy release by mass↓ & ang mom↑
  - Consider transport as a perturbation
    - deviations from equilibrium small
    - ang. mom. changes lead to orbit changes
  - Net z-components of the torque
    - requires off-diagonal stress tensor terms
    - generally requires nonaxisymmetry

Disk Evolution

Shakura & Sunyaev 1973
Lynden-Bell & Pringle 1974
Hartmann 1998
Gammie 2001
Balbus 2003

Turbulent Evolution (cont'd)

- Turbulent accretion disk
  - Consider physical quantities fluctuating about the axisymmetric equilibrium
    - < f > = "local" average in space and time
  - Thin-disk evolution equation

$$\frac{\partial \Sigma}{\partial t} = \frac{1}{R}\frac{\partial}{\partial R}\left[\frac{1}{(R^2\Omega)'}\frac{\partial}{\partial R}(\Sigma R^2 W_{R\phi})\right]$$

  - Keplerian viscous evol. eq. recovered by
    - $W_{r\varphi} = \alpha c_s^2$ ⇒ α compares rφ stresses to gas pressure
    - $\nu = \alpha c_s^2/\Omega = \alpha c_s H$ with Keplerian Ω

Disk Evolution

Lynden-Bell & Kalnajs 1972
Balbus & Papaloizou 1999
Gammie 2001
Balbus 2003

Turbulent Evolution (cont'd)

- Evolution equation

$$\frac{\partial \Sigma}{\partial t} = \frac{1}{R}\frac{\partial}{\partial R}\left[\frac{1}{(R^2\Omega)'}\frac{\partial}{\partial R}(\Sigma R^2 W_{R\phi})\right]$$

- The Big Three Stressors
  - What stresses change z-comp of ang mom?
  - Reynolds (or Hydrodynamic) stress
    - $W^R_{r\varphi} = < \int dz\, v_r \delta v_\varphi >$
  - Gravitational (or Newtonian) stress
    - $W^G_{r\varphi} = < \int dz\, g_r g_\varphi / 4\pi G\rho >$
  - Maxwell (or Magnetic) stress
    - $W^M_{r\varphi} = - < \int dz\, B_r B_\varphi / 4\pi\rho >$

Disk Evolution

Balbus & Papaloizou 1999
Gammie 2001
Balbus 2003

Turbulent Evolution (cont'd)

- Local vs Global
  - Two ways to be intrinsically global
    - #1: local treatment cannot determine $W_{r\varphi}$
    - #2: energy dissipation is not local
  - Thin disk, local transport, in thermal equil.
    - $\alpha = 4/[9\Gamma(\Gamma-1)t_{cool}\Omega]$
    - t_{cool} = U/F = cooling time
    - note that $t_{cool}\Omega$ = constant is necessary for a steady state (i.e., constant accretion rate)
  - Global
    - for either #1 or #2, alpha-disk breaks down
    - in case #2, waves transport energy

Rice et al. 2005
Michael et al. 2006

Disk Evolution

Turbulent Evolution (cont'd)

- Is there a maximum stress?
  - Can $W_{r\varphi}$ (or α) get too large?
  - What then?
    - disk fragmentation?
  - For gravitational stresses
    - $\alpha > 0.06$ in $t_{cool}\Omega$ = constant simulations of self-gravitating disks
    - stress levels $\alpha > 0.1$ are sustained without fragmentation for t_{cool} = constant (& are also large in global bursts)
    - cooling controls gravitational fragmentation
  - "She can't take no more, Captain!"

Michael et al. 2006

Disk Evolution

Fragmenting Disk

One time unit is an orp or Outer Rotation Period = 180 years

80 AU

$M_s = 1.0 M_\odot$
$M_d/M_s = 0.14$
$\gamma = 7/5$ gas
$t_{cool} = 1$ orp

Animation courtesy of Scott Michael

Big Questions Revisited

BIG QUESTIONS

What Hydrodynamical (**B**=0) Processes Really Affect Disk Evolution?

- Which can and do alter the structure of disks?
- Which, if any, can and do affect planet formation?

Which Can Transport Mass & Ang. Mom.?

- How efficient are they?
- Is the transport local or global?