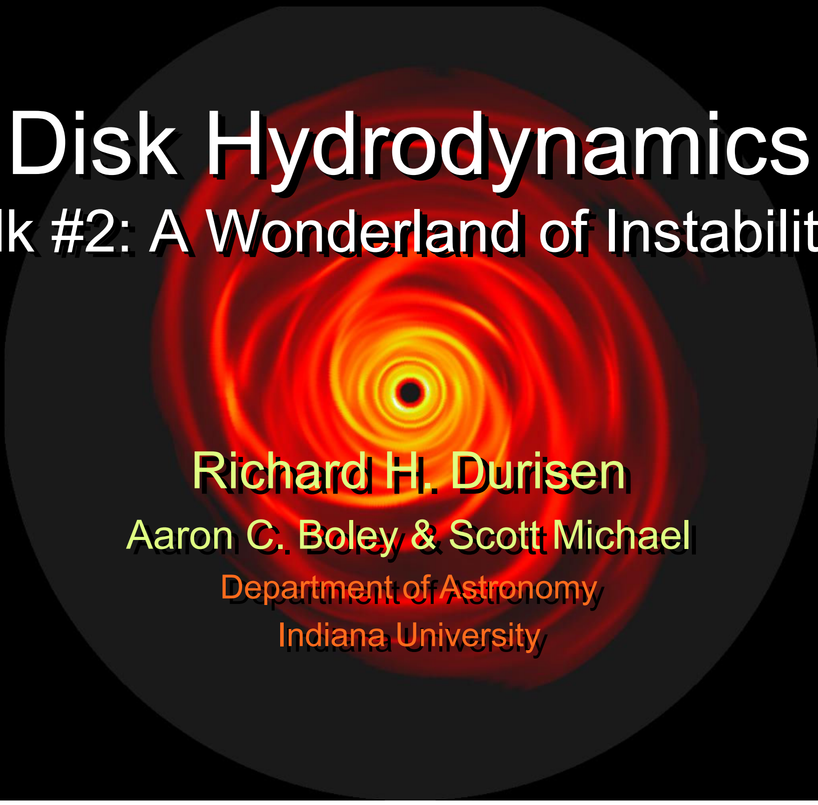
Vidago Workshop 2006

Physical Processes in Circumstellar Disks Around Young Stars



Disk Hydrodynamics

Talk #2: A Wonderland of Instabilities

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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?

Outline of Talk #2

A Wonderland of Instabilities

- Classic results
  - Hydrodynamic instability
  - Convective instability
  - Baroclinic instability
- Application to disks
  - Instabilities
    - hydrodynamic
    - convective
    - baroclinic and others
  - Large-scale structures
  - Tapping the energy in Keplerian shear
- Gravitational instabilities
- Conclusions

Classic Results

Classic Results

Tassoul 1978
Shu 1992
Paploizou &Lin 1995
Balbus & Hawley 1998
Balbus 2003
Gammie & Johnson 2005

Hydrodynamic Instability

- Why should shear flows be unstable?
  - Consider a simple linear planar shear
    - $dv_x/dz = v_x' =$ constant
  - There's energy to be had
    - redistribute momentum so v_x = constant over $z=z_0 \pm \varepsilon$
    - all else equal, the kinetic energy decreases by a fraction of order $(\varepsilon v_x'/v_x)^2$
    - this energy can feed full-blown turbulence
  - What can keep the shear flow stable?
    - high viscosity
    - stratification (s=entropy increases "upward")

Classic Results

Tassoul 1978
Shu 1992
Paploizou &Lin 1995
Balbus & Hawley 1998
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Gammie & Johnson 2005

Hydrodynamic Instability (cont'd)

- Conditions for instability of shear flow
  - Shear flows are *usually* unstable for
    - Re = Reynolds number = $vL/\nu > 10^3 - 10^4$
    - for low Re, viscosity can keep the flow laminar
    - at high Re, turbulence ensues
  - Stratified shears are stable when
    - Ri = Richardson number = $(g_z s'/c_P)/(v_x')^2 > 1/4$
    - Ri measures the relative importance of buoyancy and shear
  - Naïve application to astrophysical disks
    - molecular $\nu \sim v_{th} l \sim 10^4 - 10^5$ cm^2/s
    - Re ~ 10^{15} and Ri ~ $10^{-2} \Rightarrow$ unstable?

Classic Results

Tassoul 1978
Shu 1992
Paploizou &Lin 1995
Balbus & Hawley 1998
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Gammie & Johnson 2005

Convective Instability

- Condition for convective instability
  - Consider a plane parallel H.E. layer in R.E.
    - R.E. = radiative equilibrium = radiation carries all the energy flux
  - Convective instability
    - Schwarzschild criterion
    - $ds/dz_{R.E.} = s'(R.E.) < 0$
    - for high Re, convective flows are turbulent
  - Naïve application to disks
    - young stellar disks are convectively unstable in the z-direction for a wide range of conditions
    - a source of turbulent a.m. transport?

Classic Results

Tassoul 1978
Shu 1992
Paploizou &Lin 1995
Balbus & Hawley 1998
Balbus 2003
Gammie & Johnson 2005

Baroclinic Instability

- Condition for baroclinic instability
  - Consider an axisymmetric rotating flow in a gravitational field (e.g., planet atmosphere)
    - barocline: constant entropy surfaces not the same as constant effective potential surfaces
  - Baroclinic instability
    - Høiland criterion: instability occurs when
      - $j = r^2\Omega$ decreases outward on an s=const. surface
    - inertial waves and vortices can result
  - Naïve application to disks
    - such conditions can occur in disks
    - what happen then?

Applications to Disks

Application to Disks

Tassoul 1978
Shu 1992
Paploizou &Lin 1995
Balbus & Hawley 1998
Hawley et al. 1999
Balbus 2003
Gammie & Johnson 2005

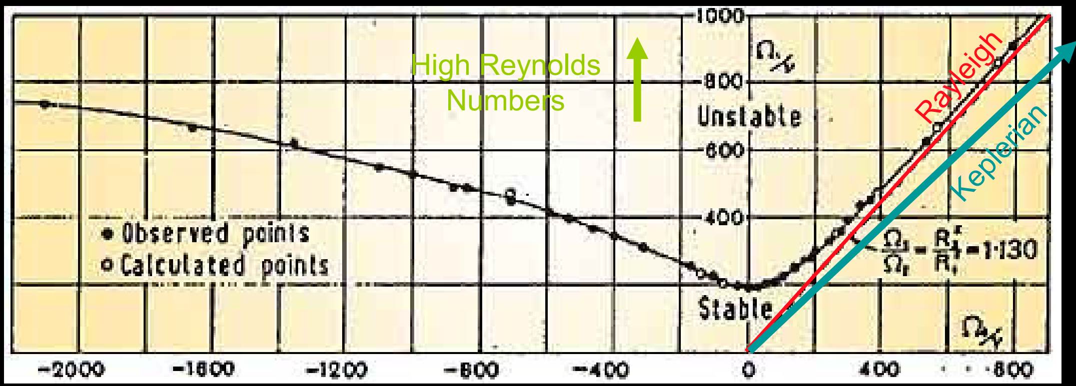
Instabilities

- What is unique here?
  - New dynamical elements
    - angular momentum
    - centrifugal and Coriolis forces
  - Axisymmetric stability
    - imagine exchanging rings of fluid between r_1 and $r_2 > r_1$ while conserving specific ang. mom.
    - if $j_1 > j_2$, the new state has less rotational K.E. and nonrestorative excess centrifugal forces
    - Rayleigh criterion: $\partial j/\partial r < 0 \Leftrightarrow$ instability!
    - $\partial j^2/\partial r = \partial(r^2\Omega)^2/\partial r = r^3\kappa^2$
  - Taylor-Couette flow between rotating cylinders

Application to Disks

Taylor-Couette Flow

Taylor 1923
Shu 1992
Brenner & Stone 2000
Barnes 2005



Keplerian disks are stable
by the Rayleigh criterion!
Taylor-Couette flow suggests
stability even though **Re >> 1**.
Caution: Incompressible & cylindrical

Application to Disks

Papaloizou & Pringle 1984, 1985
Goldreich et al 1986
Narayan & Goldreich 1989
Paploizou &Lin 1995
Hawley et al. 1999
Balbus 2003
Johnson & Gammie 2006

Instabilities (cont'd)

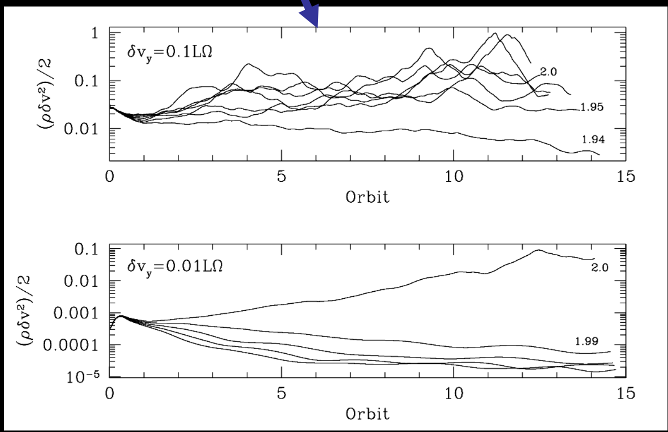
- Hydrodynamic
  - Precision local simulations
    - no linear or nonlinear instabilities detected for Keplerian shear
    - Re large does not cause local instability but
    - it is hard to exclude truly global effects
  - Interesting known global exception
    - Papaloizou & Pringle: narrow fluid annuli can be unstable due to interacting edge waves
    - instability for q > 1.732 with $\Omega \sim r^{-q}$ but
    - Keplerian annuli (q =1.5) are stable

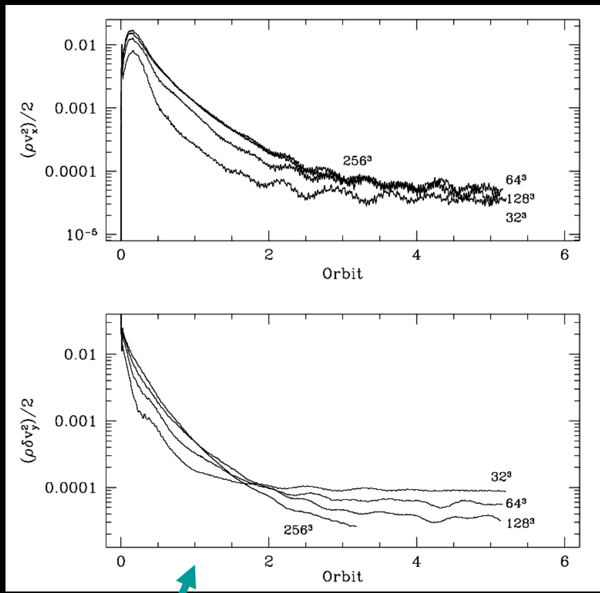
Application to Disks

Hawley et al. 1999: Local Simulations

Simulations for $\Omega \sim r^{-q}$ near the Rayleigh stability regime (q = 2). Shear acts like a planar shear because the epicyclic frequency $\kappa = 0$. No growth for q < 1.95.

3D Shearing Box, Isentropic Equilibrium





The Keplerian case (q = 1.5) is strongy damped and is stable regardless of code or resolution used.

Application to Disks

Lin & Papaloizou 1980
Stone & Balbus 1996
Cabot 1996
Balbus 2000
Klahr & Bodenheimer 2000, 2003
Johnson & Gammie 2006

Instabilities (cont'd)

- Convection (z-direction)
  - Precision local simulations and analytic work
    - convection in disks causes r,φ Reynolds stresses that have the wrong sign
    - convection transports a.m. inward
  - Some residual uncertainty from global 3D radiative hydro simulations but
    - effective $|\alpha|$'s probably not large in any case
    - no more than a few$\times 10^{-3}$ and probably much less

Application to Disks

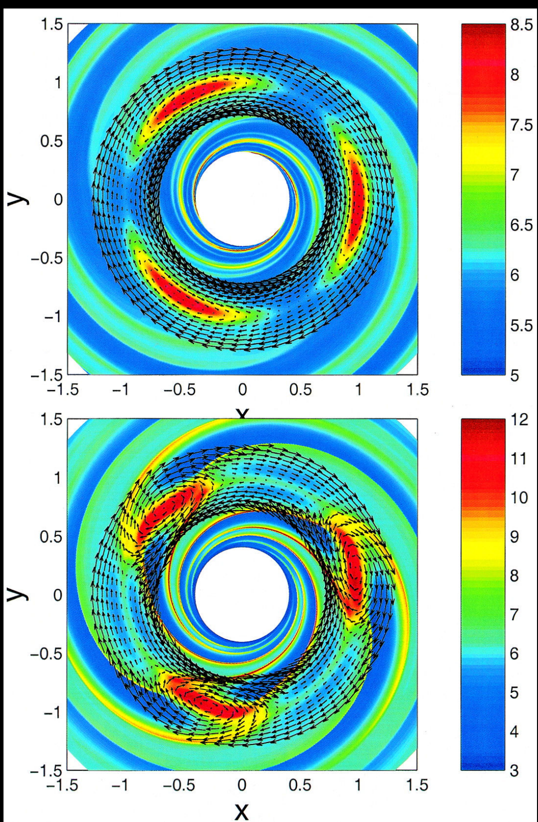
Lin & Papaloizou 1995
Lovelace et al. 1999
Li et al. 2000
Klahr & Bodenheimer 2003
Johnson & Gammie 2006
Klahr & Bodenheimer 2006

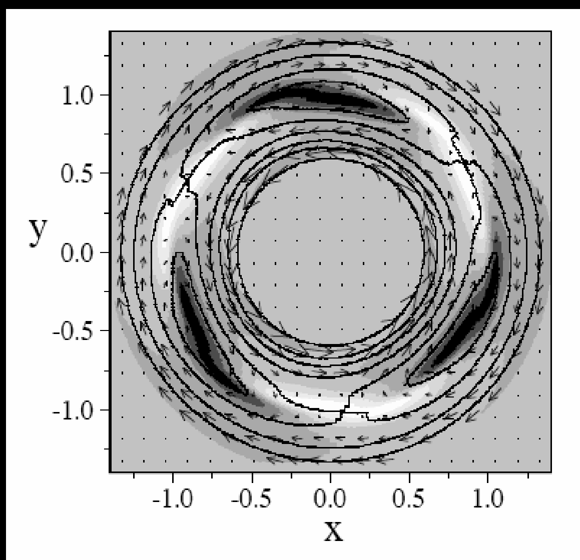
Instabilities (cont'd)

- Instabilities involving vorticity & entropy
  - Analogs of Papaloizou-Pringle and baroclinic instabilities
    - disks are broad, but they can have localized features which can act like edges
    - entropy gradients can also drive instabilities
  - Bumps, jumps, & extrema
    - vortensity $\nabla \times v/\Sigma$
    - "special" function $(\Sigma\Omega/\kappa^2)s^{2/\Gamma}$
    - extrema or sharp jumps in the r-distributions of these quantities can induce instability

Application to Disks

Li et al. 2000, 2001: Bumps and Jumps

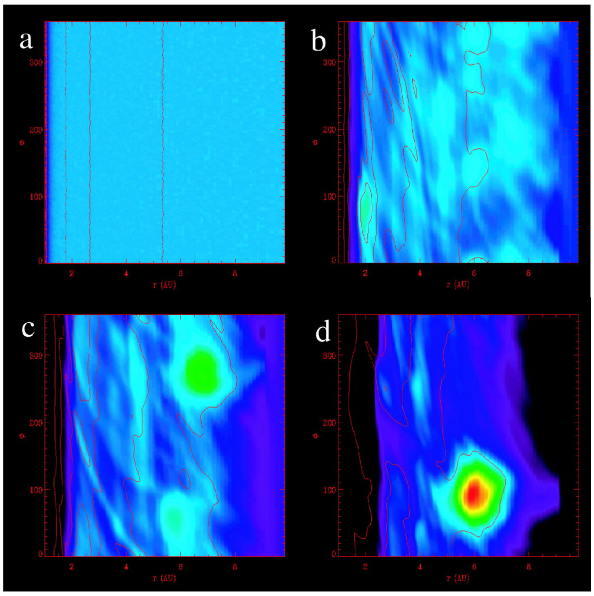


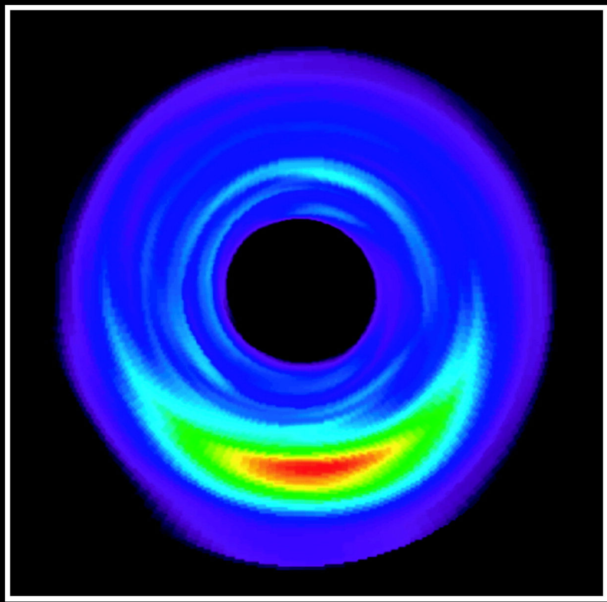


Instability results in anticyclonic vortices with large effective α but variable and global.
2D Nonlinear Simulation

Application to Disks

Klahr & Bodenheimer 2003: s´(r) < 0



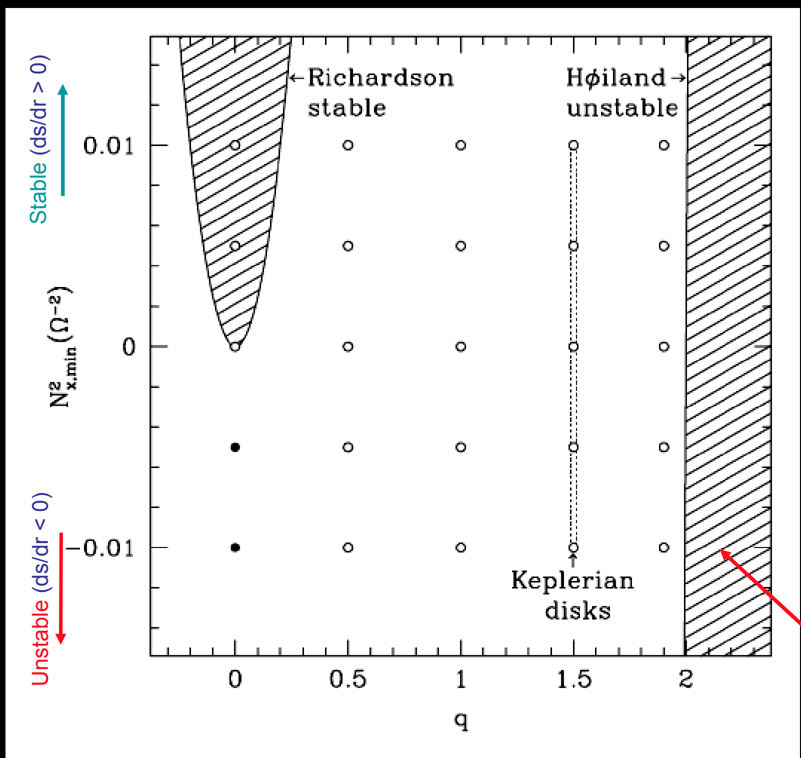


Large-scale dense anticyclonic vortex grows when s(r) < 0.
2D Annular Box, Radiative Hydro
No self-gravity

Same result in 3D.
3D Toroidal Grid, Radiative Hydro
No self-gravity

Application to Disks

Johnson & Gammie 2006: s(r)



Simulations for $\Omega \sim r^{-q}$ with radial entropy s gradients.
Only pure convective instability is detected.
Keplerian disks seem locally stable.
Cannot rule out global instability.
2D Shearing Box
Nonisentropic Equilibrium

dj/dr < 0

Application to Disks

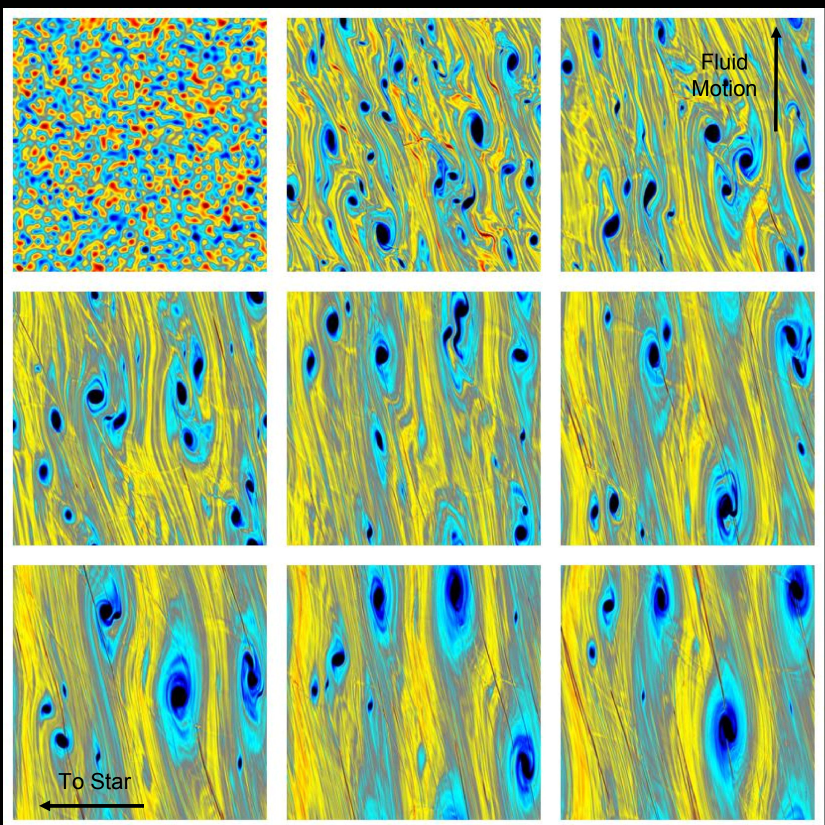
Admas & Watkins 1995
Li et al. 2001
Godon & Livio 1999, 2000
Klahr & Bodenheimer 2003
Umurhu & Regev 2004
Barranco & Marcus 2005
Johnson & Gammie 2005, 2006

Large-Scale Structures

- Vortices
  - Negative eddy viscosity
    - large-scale vortices in shallow flows preferentially absorb smaller eddies with the same vorticity
    - example: Jupiter’s Red Spot
    - thin disks might exhibit a similar phenomenon
  - Stresses
    - the preferential sign for large-scale vorticity (anticyclonic) causes net Reynolds stresses of the right sign
  - Various instabilities just discussed
    - could act as a source for vortical motions

Application to Disks

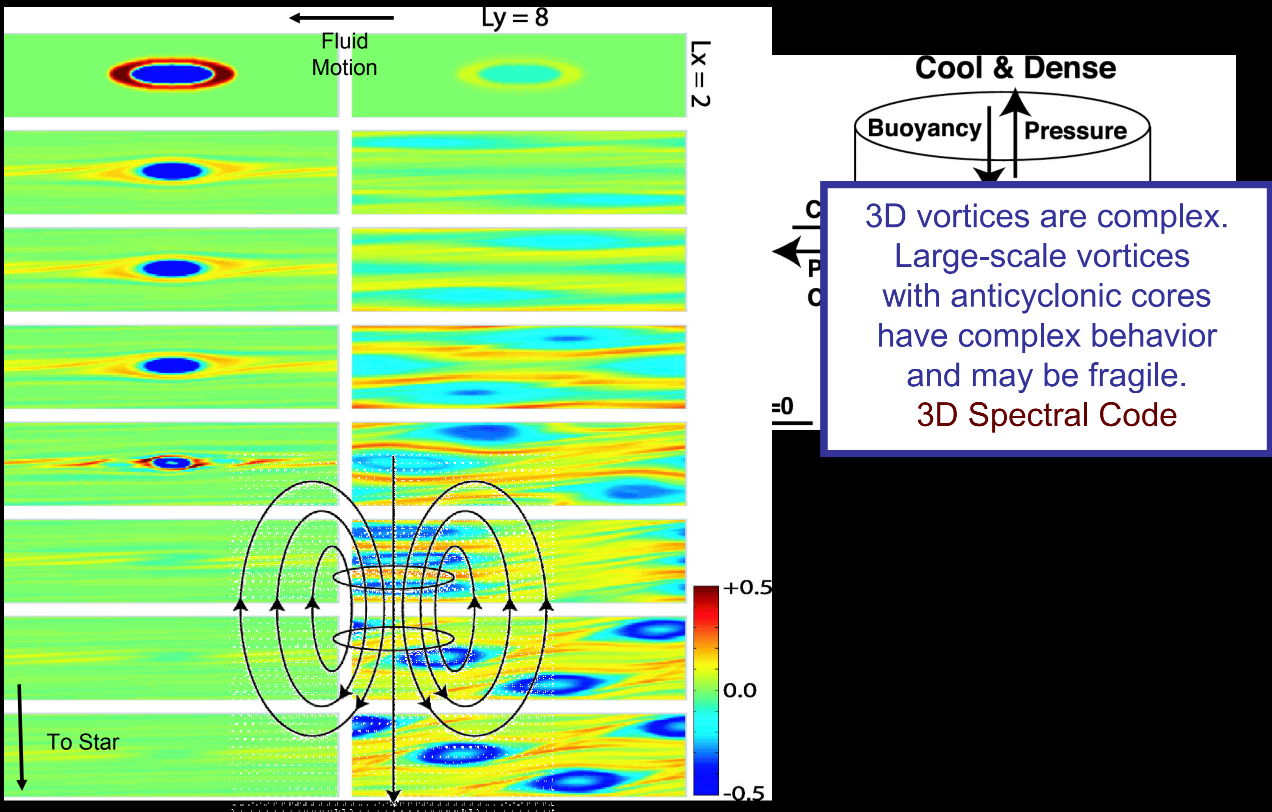
Johnson & Gammie 2005: 2D Vortex Growth



Large-scale anticyclonic vortices grow and are sustained in 2D Keplerian shear.
2D Shearing Box
Isothermal EOS
No self-gravity

Application to Disks

Barranco & Marcus 2005: 3D Vortices

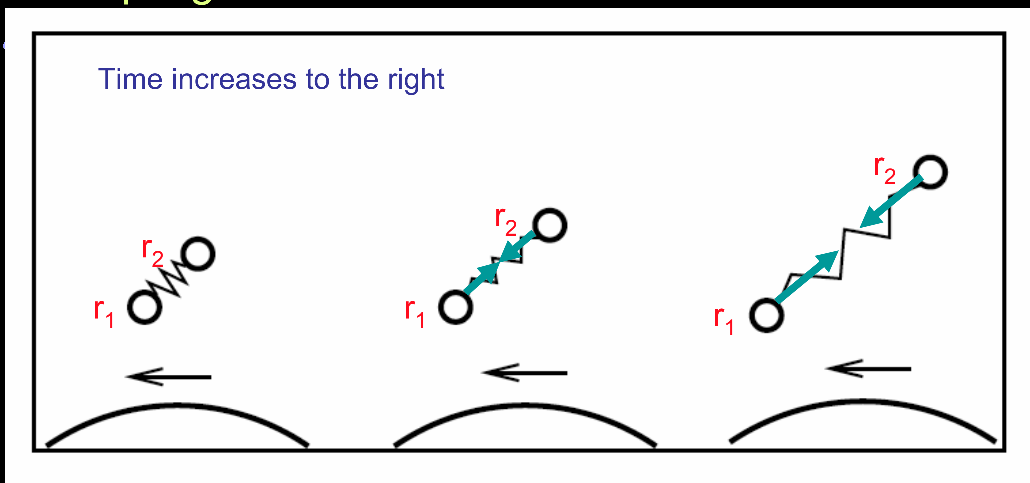


3D vortices are complex.
Large-scale vortices with anticyclonic cores have complex behavior and may be fragile.
3D Spectral Code

Application to Disks

Tapping the Energy of Keplerian shear

- Coupling the fluid elements



- What kind of "weak springs" are available?
  - B-fields ⇒ Magnetorotational Instability (MRI)
  - disk self-gravity ⇒ Gravitational Instability (GI)

Conclusions

Conclusions

Summary

- Instabilities that probably do not work
  - Hydrodynamic instability due to shear
    - Keplerian disks are locally stable
    - global stability difficult to establish
  - Convective instability in the z-direction
    - convection probably produces only weak inward a.m. transport
    - lingering uncertainty about the global regime

Conclusions

Summary (cont'd)

- Instabilities that probably do occur
  - Hydrodynamic instabilities due to edges
    - Keplerian shears are stable
    - but localized deviations from Keplerian could occur
  - Instabilities due to extrema
    - extrema of some properties in bumps or edges can induce waves to grow
    - transport can be substantial
  - Vortices
    - large-scale anticyclonic vortices grow from vorticity noise in 2D
    - their fate in 3D is uncertain

Conclusions

Summary (cont'd)

- Instabilities that definitely work
  - Magnetorotational instability
    - requires a sufficiently conducting fluid
    - weak magnetic field
    - others will discuss this at length
  - Gravitational instabilities
    - require a disk that is sufficently massive or cold
- Rest of my talks
  - The focus will be on GIs
  - But there is clearly room for further work on other instability mechanisms

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