Hydrodynamical Processes in Protoplanetary Disks

• Why do we ask for turbulence?
• Where does it come from?
• Does it help Planet Formation, or not?

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Outline:

1. Motivation for a non-laminar flow
2. Sources for Turbulence
3. Effects on Particle Distribution
4. Effects on Disk Appearance
5. Conclusions

... and many many movies! ;}

03.06.2004
Part I: Why do we ask for turbulence in disks anyway?
Observation:

No direct evidence for turbulence!

* No observation of turbulent velocity fields.
* No observation of magnetic fields in disks.
Properties of T Tauri Disks: What is Known?

- 50% of the objects have disks
- $M_{\text{disk}} << M_\ast$ in case of T Tauri stars
  (typically: $M_{\text{disk}} \approx 10^{-2} M_{\odot}$)
- Disk diameters: $\approx 50$-200 AU
- Disk lifetime: $\approx 10^6$ yr
- Accretion rates: $10^{-9} ... 10^{-7} M_{\odot} \text{ yr}^{-1}$
Only indirect detection of accretion via some UV-excess in SED of some protoplanetary disks.

Intensity of UV-excess depends on the mass flux onto the star.

Steady state only if: accretion onto the star = accretion within the disks.
Age versus accretion rate

Hartmann et al. 1998

\[ \log \frac{dM}{dt} \text{ (M}_\odot \text{ yr}^{-1}) \]

\[ \log \text{ age (yr)} \]

- Tau
- Cha I 150
A Jet must be fed by accretion!
Accretion in a rotating system is only possible if matter loses its angular momentum.

Viscosity could do this, but molecular viscosity is far too low.
Accretion in a rotating system is only possible if matter looses its angular momentum.

Idea by Weizsäcker: turbulence provides “viscous” transport of angular momentum.

Thus one always mixes the terms viscosity and turbulence.
Turbulence can provide the so called Reynolds stress:

\[ T_{r \phi} = \overline{u' r u' \phi} \]

But Disks are Rayleigh stable! (Angular momentum increases radially outward)

\[ \Rightarrow \text{No linear Shear Instability.} \]
Disk geometries proposed for Herbig Ae/Be stars: Are they stable?

Group I
with FIR excess

Group II
no FIR excess

flaring disk

self-shadowing disk

The special feature of these models is the puffed-up hot inner rim of the disk

Dullemond, Dominik & Natta 2001
Dominik, Dullemond, Waters & Walch 2003

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Part II:
Where does it come from?
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Where does turbulence come from?
Where does angular momentum transport come from?
Possibilities:

1. Non-Linear Shear Instability
2. Self Gravity
3. Thermal Convection
4. Magneto (Rotational) Instability
5. Baroclinic Instability
6. Midplane Shear Instability
1. Non-Linear Instability because of high Reynolds Numbers produces Turbulence.

Richard A&A 2003

Extrapolation of Laboratory Experiments.
Unproven!
Pure speculation!
2. Self Gravitational Instabilities:

Toomre 1964

Ang. Mom. Transport by Gravitational Torques!

Only for young massive disks!

Toomre Parameter:

\[ Q \sim \left( \frac{H}{R} \right) \left( \frac{M_{\text{star}}}{M_{\text{disk}}} \right) \]
Disk Instability (Boss 2001)

Self Gravity plus isothermal gas!

Mayer et al. 2002
Simulation by Picket et al. 2003

0.46

Adiabatic: AV On
3.) Thermal Convection

Klahr, Henning & Kley 1999
Vertical Thermal Convection:
Ryu & Goodman 1992
Generates a turbulent flow!
But no correct Angular Momentum Transport:
Reynolds Stresses NEGATIVE!
4. MHD Instabilities: Balbus & Hawley 1991 etc. see talk by Steven

Ang. Mom. Transport by Maxwell Stresses!
A.k.A: Rockets in an earth orbit accelerate when they break!
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3D Simulation by John Hawley
MHD-Turbulence provides the so-called Maxwell stress:

\[ T r \phi = \overline{B'} r B' \phi \]

Ang. Mom. Transport by both Maxwell and Reynolds Stresses!

But: Disk must have the proper Ionisation!
Part of the disk may not be ionized enough for MRI to work!

Sano, Miyama, Umebayashi & Nakano 2000
Fromang, Terquem, & Balbus 2002
Semenov, Wiebe, & Henning 2004

Dead Zone

Gas-grain chemistry,
$\ t = 10^6 \text{ yrs}$
2D axisymmetric simulation of active/dead zone interaction.

A toy model for layered accretion: e.g. Gammie

\[ \alpha(T > 1000 \text{K}) = 0.01 \]
\[ \alpha(T < 1000 \text{K}) = 0 \]
\[ \alpha(\Sigma < 100) = 0.01 \]
\[ \alpha(\Sigma > 100) = 0 \]

Wünsch, Rozyczka & Klahr, in prep.
2D axissymmetric simulation of active/dead zone interaction.

Wünsch, Rozyczka & Klahr
5. Baroclinic Instability:
Klahr & Bodenheimer 2003
Generates moderate turbulence vorticity!
Correct Angular Momentum Transport:
Reynolds Stresses POSITIVE!
Rossby Wave Instability of Thin Accretion Disks. III. Nonlinear Simulations Li, Colgate, Wendroff & Liska 2001

Vortex Formation via the Global Baroclinic Instability in Protoplanetary Accretion Disks
Klahr & Bodenheimer 2003


Formation of Giant Planets by Concurrent Accretion of Solids and Gas inside an Anti-Cyclonic Vortex
How turbulent is the dead zone of a protoplanetary accretion disks?

Answer:
A radial entropy gradient can create waves and angular momentum transport. Vorticity is also generated.

We learn: Dead zones are not completely dead.

Entropy Transport

Are Vortices stable? some can be… numerical simulations will have to tell… or direct Observation!
Simulated Observation: 900 GHz

6. Shear Turbulence at midplane prevents gravitational formation of planetesimals!

Part III: Does turbulence help Planet Formation, or not?
Accretion and Strong Turbulence is generally bad for Planet Formation!

* Limits Lifetime of Gas Disk
* Grinds Boulders to Dust
* Helps Planets Migrate
* Prevents solids from settling
Weak Turbulence is good for Planet Formation!

* May trap Dust in vortices!
* May help migration stop?
  - No loss of boulders into the star
  - Soft accumulation of Planetesimals in vortices
  - Shortens formation time of planets
  - Reduces the min. Mass of the Disk
Diffusion of Molecules & Grains and Concentration of Boulders!

*Sedimentation vs. Diffusion
=>grav. Instability of dust Sub-disk
*transient concentration between turbulent eddies (e.g. Jeff Cuzzi et al.) \( a = 1\text{mm} \)
*concentration in vertical vortices e.g. convective cells (Klahr & Henning 1997) \( a = 1\text{mm} \)
*concentration in anti-cyclonic vortices (Barge & Sommeria 1995) \( a = 1\text{m} \)
The biggest Problem in Planet Formation:

Experiments by Blum & Wurm show: No sticking if $dV > 10\text{m/s}$ (~1m boulders)

sedimentation & radial drift: Growth by sweep up of tiny dust grains.

$\Rightarrow$ 1m boulders get lost to the star.
The biggest Problem in Planet Formation:

How to grow boulders from 1m to 100m?

The Gas can help!

- dust
- surface tension
- gravity

\[ \text{dV} > 10 \text{m/s} \]

The Gas can help!
Prorous Solid: mass flow
Wurm & Klahr, in prep.

mass flux in and around a porous body
A possible Solution:

Capture of boulders in hydrodynamical traps.

=> 0.1m boulders get trapped in vortices.
Anti Cyclonic Vortices are Dust Traps!

Balance between Centrifugal Forces, Gravity and Friction.

Inner side: Gas faster than Kepler!
Surplus of Centrifugal Acceleration:
\[ \Rightarrow \text{Drift of dust outward towards the vortex center} \]
Analog: Outer side Drift inwards
Will boulders be concentrated in these vortices?

c.f. Barge & Sommeria 1995
1000 years disk evolution:
1000 years dust drift: 1m objects
What happens to the boulders inside the Vortex?

1. they accumulate to one large core.

2. they enrich the gas until they undergo Gravitational Collaps. (Gurevich & Lebedinskii 1950, Safronov 1969, Goldreich & Ward 1973, etc.)

3. they accumulate to planetesimals and scatter (in part / at all) out of the vortex.
Core Accretion in Vortices
(Bodenheimer & Klahr submitted)

2.2E-4 \( M_{\text{earth}}/\text{yr} \); 3g/cm\(^2\); minimum Nebula!

\[ t = 300,000 \text{ yrs} \]
3D Cylindrical MHD simulation of Planet Disk Interaction.

Nelson & Papaloizou

Warning: Disk is vertically infinite and planet is actually a rod.
Detecting Planets in Protoplanetary Disks
Wolf et al. (2002), Steinacker & Henning (2003)

Radial density profile in the midplane (M = 1 Mj at 5.2 AU)

Normalized visibilities at $\lambda = 10\mu$m, $d = 140$ pc
($0^\circ$ - face on, $60^\circ$)
Temperature in r-θ:

3D – Radiation Hydro of Gap Opening: Klahr and Kley, in prep.

800 K
Core Accretion plus Vortices:

- Collision velocities for boulders: $dV < 10 \text{ m/s} \Rightarrow$ no fragmentation
- No loss of 1m boulders into central object
- Fast buildup of cores from 0.1-1m boulders
- Minimum mass nebula and solar metallicity
- Accretion time for 12 Earth mass core $< 10^5 \text{ yrs}$
- Formation time for Jupiter $< 10^6 \text{ yrs}$
Jets are launched from disks

Jets from Young Stars

PRC95-24a · ST ScI OPO · June 6, 1995
C. Burrows (ST ScI), J. Hester (AZ State U.), J. Morse (ST ScI), NASA
Outlook 1:
Is a self consistent Simulation of Disk and Jet possible?
2.5D Simulation by Christian Fendt: disk only boundary condition.
2.5D Simulation by Casse & Keppens: Including the Disk

see also:
Ghosh & Lamb 1978
Uchida & Shibata 1985
Goodson, Winglee & Böhm 1997
Miller & Stone 1997
Küker, Henning & Rüdiger 2003
Outlook 2: Interaction between different instabilities?
e.g. Sebastian Fromang
3D Simulation by Sebastien Fromang
MRI + Selfgravity
Conclusions:

• Angular Momentum Transport is not equal to Turbulent Diffusion
• Turbulent State of Disks still unclear
• Strong (Weak) Turbulence would be bad (beneficial) for Planet Formation
• Future: More Consistent Models (magneto, radiation, self-gravity, dust, chemistry, …)