The Role of Turbulence in Protoplanetary Disks

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Is turbulence driven by magnetic effects or purely hydrodynamic mechanisms?

Subcritical Baroclinic Instability (SBI)

Vertical Shear Instability (VSI)

Zombie Vortex Instability (ZVI)

Hubert Klahr

Nelson et al. (2013)

Marcus et al. (2013)
Magnetic fields are likely to be present.
The classic picture

Layered Accretion in a T Tauri Disk

ACTIVE LAYER

DEAD ZONE

ACTIVE LAYER

thermal ionization

cosmic ray ionization

critical radius
0.1 AU

not to scale

Gammie (1996)
Protoplanetary disks have low ionization fractions but are not devoid of magnetic effects.
Low ionization levels enhance non-ideal magnetohydrodynamic (MHD) effects

Three effects

1. Ohmic resistivity

\( e^- \) ions collide with neutrals
The classic picture

Fleming, Stone, & Hawley (2000)
Layered Accretion in a T Tauri Disk

not to scale

Gammie (1996)
The classic picture

Layered Accretion in a T Tauri Disk

The Hall Effect!

thermal ionization

not to scale

Dead Zone

ACTIVE LAYER

critical radius
0.1 AU

Gammie (1996)
Low ionization levels enhance non-ideal magnetohydrodynamic (MHD) effects

Three effects

1. Ohmic resistivity
   - $e^-$ ion $^+$ collide with neutrals

2. Hall effect
   - $e^-$ tied to mag. field
   - $e^-$ ion $^+$ collide with neutrals
Low ionization levels enhance non-ideal magnetohydrodynamic (MHD) effects

**Three effects**

1. Ohmic resistivity
   - $e^-$ collide with neutrals
   - $\text{ion}^+$

2. Hall effect
   - $e^-$ tied to mag. field
   - $\text{ion}^+$ collide with neutrals

3. Ambipolar diffusion
   - $e^-$ tied to mag. field
   - $\text{ion}^+$
The importance of each non-ideal effect depends on density and magnetic field strength.
Local simulations: examine small co-rotating disk patch

- Assume Cartesian geometry
- Add appropriate source terms
- Solve equations of MHD
- Shearing periodic boundaries
- Valid if $H/R \ll 1$
- Assume gas is isothermal
Local simulations: examine small co-rotating disk patch

- Assume Cartesian geometry
- Add appropriate source terms
- Solve equations of MHD
- Shearing periodic boundaries
- Valid if $H/R << 1$
- Assume gas is isothermal
Focus on individual localized regions where each effect is dominant.
Start in the inner disk
Start in the inner disk

- Ohmic diffusion
- Ambipolar diffusion
- Hall effect
Start in the inner disk

- Ohmic diffusion
- Ambipolar diffusion
- Hall effect
Start in the inner disk

- Ohmic diffusion
- Ambipolar diffusion
- Hall effect
We use an ionization model based on a chemical network and ionizing particles/photons at $z = 0$. 
We use an ionization model based on a chemical network and ionizing particles/photons

X-rays

\[ z = 0 \]
We use an ionization model based on a chemical network and ionizing particles/photons.

\[ X\text{-rays} \]

\[ \cdots \]

\[ z = 0 \]

\[ \text{cosmic rays} \]
We use an ionization model based on a chemical network and ionizing particles/photons.

- X-rays
- Far ultraviolet
- Cosmic rays

At $z = 0$: 

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We use an ionization model based on a chemical network and ionizing particles/photons

$z = 0$

X-rays  \[\rightarrow\]  Far ultraviolet  \[\rightarrow\]  cosmic rays

See Bai (2011) and Perez-Becker & Chiang (2011) for details
Inner disk (1-10 AU)
Dramatic differences!

Simon et al. (2015b), MNRAS
Inner disk (1-10 AU)
Dramatic differences!

Simon et al. (2015b), MNRAS

B\(_z\) < 0

B\(_z\) > 0

Bai (2015)
Inner disk (1-10 AU)

\( B_z > 0 \)

Strong, large-scale toroidal field

\( B_z < 0 \)

Non-axisymmetric bursts

Simon et al. (2015b), MNRAS
Inner disk (1-10 AU)

- $B_z > 0$
  - Strong, large-scale toroidal field
- $B_z < 0$
  - Non-axisymmetric bursts

Hall-shear instability (HSI) (Kunz 2008)

Simon et al. (2015b), MNRAS
Let’s get a little more technical

\[ B_z > 0 \]

\[ B_z < 0 \]

Lesur (unpublished), Armitage (Saas-Fee lectures)
$B_z > 0$
$B_z > 0$
$B_z < 0$
$B_z < 0$
$B_z < 0$
$B_z < 0$
$B_z < 0$

Amplification of field due to shear leads to HSI unstable regime
$B_z < 0$

Amplification of field due to shear leads to HSI unstable regime

Toby Heinemann
Let’s look at the outer disk ~100 AU
Outer disk (10-100 AU)
The field orientation does not matter

Simon et al. (2015b), MNRAS
A new emerging paradigm

Simon et al. (2015b), MNRAS
What about those hydrodynamic mechanisms?

• They could still very well be at play

• The regions of parameter space in which there is no magnetic activity (e.g., radial regions of classic dead zones, Hall effect with Bz < 0 and higher diffusivities/lower ionizations) may exhibit these hydrodynamic behaviors

• They could co-exist with magnetic processes

• More studies needed
Switch gears: Test this with observations (only the outer disk for now)
Strong gradient in turbulent velocity towards disk mid-plane

Simon et al. (2015a), ApJ
Construct turbulence model by interpolating simulation results.
Construct turbulence model by interpolating simulation results.
Observational signatures: Line profile

CO (3-2)

Probes upper layers

Normalized Flux

Velocity (km/s)

\[ \beta_0 = 10^4, \Sigma_{\text{FUV}} = 0.1 \]

\[ \beta_0 = 10^5, \Sigma_{\text{FUV}} = 0.1 \]

\[ \beta_0 = 10^5, \Sigma_{\text{FUV}} = 0.01, \text{With Dust} \]

\[ \beta_0 = 10^5, \Sigma_{\text{FUV}} = 0.01, \text{No Dust} \]

\[ \beta_0 = 10^4, \Sigma_{\text{FUV}} = 0.01 \]

No turbulence

Simon et al. (2015a), ApJ
Observational signatures: Line profile

CO (3-2)

Increasing turbulence leads to line broadening

Probes upper layers

Simon et al. (2015a), ApJ
Observational signatures: Line profile

Increasing turbulence leads to line broadening

CO (3-2)
Probes upper layers

Simon et al. (2015a), ApJ
So, what do ALMA observations tell us?
Weak turbulence in HD 163296!

Flaherty ... Simon et al. (2015), ApJ
What does this mean?
Other accretion mechanisms
Other accretion mechanisms

Some other form of turbulence? Hydro?
Other accretion mechanisms

Some other form of turbulence? Hydro?

Would expect non-negligible turbulence at large disk heights
Other accretion mechanisms

Some other form of turbulence? Hydro?

Would expect non-negligible turbulence at large disk heights

Simon et al. (2011)
Maybe the outer disk just isn’t accreting...

Need larger sample size!
Strong turbulence in TW Hya

Teague et al. (2016)
Next

1. Improve our understanding of the ionization environment - will be key to the cause of transport!

2. Observe more sources - are disks really turbulent?

3. Determine ways to probe the inner disk and the bimodal nature of the Hall effect
Take away points

1. Protoplanetary disks may still very well be turbulent due to magnetic effects

2. Inner regions of protoplanetary disks have either a strong, laminar Maxwell stress or an intermittent turbulent stress (or maybe no stress), depending on the orientation of the vertical magnetic field

3. Outer regions of protoplanetary disks are predicted to have turbulent velocities ~10% of the local sound speed in the upper layers, which is detectable by ALMA

4. However, observations of HD163296 show that turbulence at high altitudes is very weak - inconsistent with the MRI (and likely other hydrodynamic processes as well)

5. But do not fear! The disk in TW Hya may not be so quiescent. More disks need to be observed to determine whether or not turbulence is present in protoplanetary disks