Accretion and Mixing in Protostellar Disks: Probing the Underlying Processes with ALMA

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Outline

• **Current Picture:**
  1. Gravitational Instability.

• **Prospects with ALMA.**
1. Gravitational Instability
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Small disturbances grow if

\[ \frac{r^2 \Sigma}{M_*} \geq \frac{H}{r} \]
If cooling time < orbital period, instability leads to collapse.
With slower cooling, instability leads to sustained accretion.
2. Magneto-Centrifugal Winds

Conditions for operation?  

Wardle & Koenigl 1993
3. Magneto-Rotational Turbulence
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\[ \lambda_c = \frac{2\pi v_A}{\Omega} \]

Balbus & Hawley 1991
MRI turbulence requires

\[
\frac{v_{\text{Az}}^2}{\eta \Omega} > 1
\]

Fig. 14.—Saturation level of the magnetic energy as a function of the magnetic Reynolds number $Re_{M0}$ for zero net flux $B_z$ models ($\beta_0 = 3200$). Open circles denote the models with only the ohmic dissipation ($X_0 = 0$), and the other symbols are including also the Hall effect ($X_0 = 2, 4, 100$, and 1000).
0.1\mu m grains with the interstellar geometric cross-section per unit gas mass.
Dead Zone

1um grains conserving mass
Dead Zone

10um grains conserving mass
Dead Zone

100um grains conserving mass
Dead Zone

No grains
Magnetic Stresses Can Occur in the Dead Zone

Ideal MHD

Resistive MHD with Ionization Chemistry

Turner et al. 2007
Do multiple A.M. transfer mechanisms coexist?

Fromang et al. 2004
Mass Transport

Crystalline forsterite grain from Comet Wild 2

Zolensky et al. 2006
• **G.I.** – little direct mixing, but shock heating $\Rightarrow$ convection $\Rightarrow$ mixing.
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• **Disk winds** – little mixing. Solids exchanged between disk & wind?
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• **Disk winds** – little mixing. Solids exchanged between disk & wind?

• **MRI turbulence** – mixing and A.M. transfer coefficients roughly equal.
Global Circulation

Urpin 1984
Kley & Lin 1992
Takeuchi & Lin 2002
Prospects for ALMA

Two basic questions:

1. How is angular momentum removed?
2. What mixing processes are at work?
Prospects for ALMA

• **Directly detect gas flows.** Expect spiral shocks, helical outflow, or surface layer turbulence.
CO Overtone Bandhead in SVS13

Carr et al. 2004
Prospects for ALMA

- Directly detect gas flows.
- Is gravitational instability active? Map the surface density and midplane temperature.
Prospects for ALMA

- Directly detect gas flows.
- Is gravitational instability active?
- Is the gas tied to magnetic field lines?
  Measure charged particle fraction.
Model H$_2$D$^+$ 372.4 GHz Maps

Model 1 Edge–on

Model 1 (30°)

Intensity units $10^{-6}$ erg cm$^{-2}$ s$^{-1}$ sr$^{-1}$

Asensio Ramos et al. 2007
Prospects for ALMA

- Directly detect gas flows.
- Is gravitational instability active?
- Is the gas tied to magnetic field lines?
- Are the fields straight or tangled? Are the strength and orientation consistent with a wind? With MRI?
850\,\mu m continuum polarization vectors from JCMT

Tamura et al. 1999
Prospects for ALMA

• Directly detect gas flows.
• Is gravitational instability active?
• Is the gas tied to magnetic field lines?
• Are the fields straight or tangled?

• What are the mixing rates? Match abundances against chemical models including mixing.
Abundances can be increased or reduced by vertical mixing.

Ilgner et al. 2004
Prospects for ALMA

• Directly detect gas flows.
• Is gravitational instability active?
• Is the gas tied to magnetic field lines?
• Are the fields straight or tangled?
• What are the mixing rates?