Vertical structure of magnetized accretion disks

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Summary

I) Model of the magnetized accreting disk:

II) Vertical structure equilibrium:

III) Results for astronomical objects:
    - Lambda = 4 (strongly magnetized)
    - Lambda = 12 (weakly magnetized)

IV) Conclusion
The mass-to-magnetic flux ratio $\lambda$ determines the relevance of magnetic support in cloud cores. $\lambda = \frac{2\pi G^{1/2} M_*}{\Phi_d(\varpi)}$. After geometric corrections $\Rightarrow \lambda \sim 1-4$ (Falgarone et al. 2008).
Magnetic flux in protoplanetary disks

NGC 1333 IRS5

Figure 3
(a) NGC 1333 IRAS4A magnetic field with short Submillimeter Array (SMA) baselines (Girart, Rao & Marrone 2006). Dust emission flux is shown as white contours and color, whereas the red vectors show the magnetic field in the plane of the sky. (b) NGC 1333 IRAS4A magnetic field with only long SMA baselines (S-P Lai, unpublished), which is sensitive only to small-scale structure. White contours show dust emission flux, colors show polarized flux, and red vectors show the magnetic field in the plane of the sky. The negative flux contours are due to the missing flux that is filtered out by the interferometer. The separation of the two intensity peaks is \( \sim 400 \) AU.

Girart et al 2006
Magnetic field dissipation is needed to avoid catastrophic braking and form disks and normal stars. 

$\lambda \sim 4-12$ in protoplanetary disks (Shu et al, 2008)

Hourglass structure (Girart et al, 2006, Tang et al, 2009)
Effect of B on the radial dynamic

* The stellar gravity is diluted by magnetic tension

\[-\varpi \Omega^2 = \frac{B_z B_+}{2\pi \Sigma} - \frac{GM_*}{\varpi^2}\]

\[\Rightarrow \text{sub-Keplerian rotation}\]

\[\Omega = f \left(\frac{GM_*}{\varpi^3}\right)^{1/2}\]

with \(f\), a constant inferior to 1

\[\Rightarrow f \sim 0.7 \text{ in protoplanetary disks for } \lambda = 4 \text{ (Shu et al, 2008)}\]
**Effect of B on the vertical structure**

* The stellar gravity is enforced by the magnetic pressure

\[
\frac{dP}{d\Sigma} = -\frac{GM_\ast}{\varpi^3} \frac{z}{\left[1 + \left(\frac{z}{\varpi}\right)^2\right]^{3/2}} - \frac{dP_{rad}}{d\Sigma} - \frac{1}{8\pi} \frac{dB_\varpi^2}{d\Sigma},
\]

The magnetic pressure compresses the disk
B modifies the structure and dynamics of accretion disks

* Two diffusive processes:
  - Viscosity $\nu \rightarrow$ allows matter to accrete (MRI)
  - Resistivity $\eta \rightarrow$ allows matter to slip through the magnetic field

* Net emergent flux per unit area on the upper and lower surface due to viscous dissipation $\Psi$ and the resistive dissipation $Y$ rate per unit area:

\[
\Psi = \nu \Sigma \left( \frac{d\Omega}{d\varpi} \right)^2 = \frac{3}{2} f^2 \left( \frac{GM_* \dot{M}_*}{2\pi \varpi^3} \right),
\]

\[
Y \equiv J_\varphi E_\varphi = \left( \frac{cB^+}{2\pi} \right) \left( -\frac{u}{c} B_z \right) = (1 - f^2) \frac{GM_* \dot{M}_d}{2\pi \varpi^3}.
\]
How does it works?
Radial model of Shu et al 2007

* Disk in steady state:
  - constant and positive mass accretion rate
  - no disc evolution studied

Discs parameters for Lambda = 4 (Shu et al 2007)

<table>
<thead>
<tr>
<th>Object</th>
<th>$M_*$ ($M_\odot$)</th>
<th>$\dot{M}<em>d$ ($M</em>\odot$ yr$^{-1}$)</th>
<th>$t_{age}$ (yr)</th>
<th>$D$</th>
<th>$f$</th>
<th>$M_d(R_\Phi)$ ($M_\odot$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T Tauri star</td>
<td>0.5</td>
<td>$1 \times 10^{-8}$</td>
<td>$3 \times 10^6$</td>
<td>$10^{-2.5}$</td>
<td>0.658</td>
<td>0.0300</td>
</tr>
<tr>
<td>Low-mass protostar</td>
<td>0.5</td>
<td>$2 \times 10^{-6}$</td>
<td>$1 \times 10^5$</td>
<td>1</td>
<td>0.957</td>
<td>0.200</td>
</tr>
<tr>
<td>FU Ori</td>
<td>0.5</td>
<td>$2 \times 10^{-4}$</td>
<td>$1 \times 10^2$</td>
<td>1</td>
<td>0.386</td>
<td>0.0200</td>
</tr>
</tbody>
</table>

Some disks are very sub-keplerian
How does it works?
Radial model of Shu el 2007

From these parameters can be deduced:
- The Magnetic field
- The surface density
- The viscosity
- The resistivity

* Net emergent flux per unit area (viscous dissipation $\Psi$ and resistive dissipation $Y$)

All are expressed by a radial power law
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IV) Conclusion
Vertical structure

Some hypothesis

1) uniform dissipation in the disk:
   * Net emergent flux per unit area (viscous dissipation $\Psi$ and resistive dissipation $Y$)

2) opacity:
   - dust grains from 0.01 μm to 3 mm
   - composition: silicates, organics, and ice
   - no dust settling

3) no dead zones

4) Energy transport equation (only radiation, verified)
Vertical structure

Irradiation of the disk

Fig. 8.— Representation of a flared disk. The disk surface and midplane are shown as dashed lines. The stellar surface is plotted as a dot-dashed line and the red solid line indicates the surface visible from point P.
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3 different astronomical objects

Star parameter: \( M_* = 0.5 \, M_{\text{Sun}} \)

- Low mass protostar
- TTauri
- FU Orionis
3 different astronomical objects

Table 1. Model Parameters

<table>
<thead>
<tr>
<th>YSO</th>
<th>$\dot{M}<em>d$,(,M</em>\odot,yr^{-1})</th>
<th>$D$</th>
<th>$M_d$,(,M_\odot,)</th>
<th>$f$</th>
<th>$R_*$,(,R_\odot,)</th>
<th>$L_c$,(,L_\odot,)</th>
<th>$T_{eff}$,(K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LMP</td>
<td>$2 \times 10^{-6}$</td>
<td>1</td>
<td>0.2</td>
<td>0.957</td>
<td>3</td>
<td>7.1</td>
<td>5490</td>
</tr>
<tr>
<td>T Tauri</td>
<td>$1 \times 10^{-8}$</td>
<td>$10^{-2.5}$</td>
<td>0.03</td>
<td>0.658</td>
<td>2</td>
<td>0.93</td>
<td>4040</td>
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<tr>
<td>FU Ori</td>
<td>$2 \times 10^{-4}$</td>
<td>1</td>
<td>0.02</td>
<td>0.386</td>
<td>7</td>
<td>230</td>
<td>8570</td>
</tr>
</tbody>
</table>

Star parameters
Low-mass Protostar

Resistive dissipation \(\sim 6\%\) of the Viscous dissipation

Aspect ratio: \(0.15.(r/100)^{0.25}\)
Low-mass Protostar

Region dominated by direct Star irradiation

Region dominated by viscous and resistive dissipation

Region dominated by Reprocessed star irradiation
T Tauri

Resistive dissipation ~ viscous dissipation
Observation of Ttauri in Ophiucus:
Aspect ratio of 0.6-0.28
(Andrews et al, 2009)

Disk very thin!
Aspect ratio: $0.009 \cdot (r/100)^{0.25}$
Why so thin?

Effect of the magnetic pressure:

\[
\frac{dP}{d\Sigma} = -\frac{GM_*}{\mathcal{V}^3} \frac{z}{\left[1 + \left(\frac{z}{\mathcal{V}}\right)^2\right]^{3/2}} - \frac{dP_{\text{rad}}}{d\Sigma} - \frac{1}{8\pi} \frac{dB^2}{d\Sigma},
\]

The magnetic pressure compresses the disk.

It can be stronger than the gravitational force.
FU Orionis

Resistive flux ~ 3.8 times the viscous flux
TTauri are very active disks! Intern Flux >> Irradiation flux
Discussion

$\lambda = 4$

* It was the **standard** value of the mass-to-flux ratio in the model of Shu et al (2007)

* Rotation very sub-keplerian

* Disks strongly magnetized and compressed by both gravity and magnetic pressure.
  - T Tauri disk: magnetic pressure dominates the compression and the disk is very flat ($\sim 10$ less than in observations). Disk very cold.

* Probably Lambda is similar for the others disks

----------→ Lets try Lambda = 12 !
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Lambda = 12

Lambda = 4
Sub-keplerian factor \( f \)

<table>
<thead>
<tr>
<th></th>
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<th>T Tauri</th>
<th>FU Ori</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lambda = 4</td>
<td>0.957</td>
<td>0.658</td>
<td>0.386</td>
</tr>
<tr>
<td>Lambda = 12</td>
<td>0.995</td>
<td>0.968</td>
<td>0.952</td>
</tr>
</tbody>
</table>

* Disks are quasi Keplerian
* resistive dissipation becomes negligible (1\%, 5\% and 7\% of the viscous dissipation for the LMP, T Tauri, and FU Ori disk respectively)
Disks structure
Disks structure
Change in the disk structure with $\lambda$

<table>
<thead>
<tr>
<th>YSO</th>
<th>$f_4$</th>
<th>$A_{90,4}$</th>
<th>$\Sigma_4$ g/cm$^2$</th>
<th>$f_{12}$</th>
<th>$A_{90,12}$</th>
<th>$\Sigma_{12}$ g/cm$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LMP</td>
<td>0.957</td>
<td>0.16</td>
<td>30</td>
<td>0.995</td>
<td>0.21</td>
<td>209</td>
</tr>
<tr>
<td>T Tauri</td>
<td>0.658</td>
<td>0.01</td>
<td>85</td>
<td>0.968</td>
<td>0.08</td>
<td>127</td>
</tr>
<tr>
<td>FU Ori</td>
<td>0.386</td>
<td>0.09</td>
<td>201</td>
<td>0.952</td>
<td>0.47</td>
<td>891</td>
</tr>
</tbody>
</table>

Bigger and denser
With $\lambda = 12$
Conclusion

The resistive flux 'can' be very important, but only for $\lambda = 4$
- not in Low mass protostar where $F_{\text{res}} \sim 8\%$ of $F_{\text{vis}}$
- but in FU Orionis where it is the first source of heating

Weaker magnetized disks seem more coherent with observations.
- bigger aspect ratio
- warmer disks

Next steps:
- including dust settling, dead-zones, using a non-uniform viscosity
- having better measures of the magnetic flux in discs
Thank you!