Transport and Accretion in Planet-Forming Disks

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Outline

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  - Magneto-rotational instability
  - Disk-driven winds
- Gravitational instability
- Hydrodynamical processes
  - Vortex production mechanisms
  - Other hydrodynamical instabilities
- Observational signatures
- Conclusions and perspectives
An accretion problem...

- Gas can fall on the central object only if it loses angular momentum.
- One needs a way to transport angular momentum outward to have accretion: «angular momentum transport problem»

First idea: molecular viscosity
- Theoretical accretion rate due to viscous transport is very small compared to observational constrains

Other ways to extract angular momentum in discs?

Credit: C. Burrows and J. Krist (STScI), K. Stapelfeldt (JPL) and NASA
Angular momentum transport processes

I- turbulent transport

- Transport angular momentum in the bulk of the disc
- Turbulence leads to enhanced transport («mixing length theory»)
- One defines a turbulent viscosity

\[ \nu_t = \alpha c_s H \]

«turbulent transport» \hspace{1cm} «sound speed» \hspace{1cm} «1/2 disc thickness»

\[ 10^{-3} < \alpha < 10^{-2} \]
Angular momentum transport processes

II- disc wind

Angular momentum extracted from the disc by a magnetic wind

Magnetic field exerts a torque on the disc surface which generates accretion (not described by $\alpha$-disc!)
MHD processes
The magnetorotational instability (MRI)


Field line

Ideal MHD instability, modified (possibly suppressed) by nonideal effects
Ideal MRI: main properties

Global simulations are consistent with box simulations *in the same conditions*

\[ \alpha \sim 10^{-3} \text{--} 10^{-2} \]


Nonideal MHD effects (1)

- Protoplanetary discs are far from being in the ideal MHD regime: very low ionisation fraction $\sim 10^{-13}$

- 3 nonideal effects enters the scene
  - Ohmic resistivity (electrons-neutrals collisions)
  - Hall effect (electrons-ions drift)
  - Ambipolar diffusion (electrons-neutral drift)
Nonideal MHD effects (2)

Determining the absolute importance of the nonideal terms (i.e., their ratios to the inductive term) requires solving for the ionization state of the disk. As we have already observed, this is difficult everywhere except in the very innermost regions, interior to about 0.1 AU, where thermal ionization dominates. It is much easier to assess the relative magnitude of the nonideal terms, which depend only upon the temperature, \( T \), and total number density, \( n \).

Balbus & Terquem (2001) estimate these ratios by assuming that electrons and singly-ionized ions are the charge carriers, that the typical fluid velocities are \( \sim v_A \), the Alfvén speed, and that typical gradients are \( \sim h^{-1} \).

They obtain,

\[
\frac{O}{H} = \left( \frac{n}{10^{17} \text{ cm}^{-3}} \right)^{1/2} \left( \frac{v_A c_s}{10^3} \right)^{-1},
\]

(26)

\[
\frac{A}{H} = \left( \frac{n}{10^{12} \text{ cm}^{-3}} \right)^{-1/2} \left( \frac{T}{10^3 \text{ K}} \right)^{1/2} \left( \frac{v_A c_s}{10^3} \right).
\]

(27)

Using these expressions, we show in Figure 5 the relative importance of the three nonideal effects as a function of density and temperature (after Kunz & Balbus 2004). Over-plotted on the figure are very approximate tracks showing the radial variation of physical conditions at the midplane, and near the surface, of protoplanetary disks. The midplane conditions are estimated for a disk around a solar-mass star with \( \Sigma_1 = 10^3 \frac{r}{1 \text{ AU}}^{-1} \) g cm\(^{-2}\) and \( \frac{h}{r} = 0.04 \). The surface conditions are estimated from the density at \( z = \pm 4 h \) (using a Gaussian density profile), assuming that the temperature is the effective temperature for a steady-state disk accreting at \( \dot{M} = 10^{-7} \) M\(_{\odot}\) year\(^{-1}\).

The magnetic Prandtl number crisis

- \( \text{Pm} \) compares Ohmic diffusion to viscous diffusion
- \( \text{Pm} < 1 \) in protoplanetary discs (Ohmic diffusion more important)

\[ \alpha \]

\[ \alpha \sim \frac{1}{P_m} \]


\( \alpha(P_m \ll 1) ? \)
Dead Zones

Ohmic diffusion picture

Sources of ionisation in discs include
- Thermal ionisation
- X-rays+FUV from the central star
- Cosmic rays

- FUV+X-rays

Dead zone (MRI quenched by Ohmic diffusion)

~1AU

~10AU

ions and neutrals, respectively (for a derivation see, e.g., Balbus 2011). The terms on the right-hand-side describe magnetic induction (the frozen-in field behavior of ideal MHD) and the three nonideal effects, Ohmic diffusion (denoted as $O$), the Hall effect ($H$), and ambipolar diffusion ($A$). Physically, ambipolar diffusion is dominant when the field is well-coupled to the ions and electrons, such that the field drifts with the charged species relative to the neutral component. Ohmic diffusion dominates when the conductivity is so low that the field is imperfectly coupled to both the electrons and the ions. Finally, the Hall effect is most important in an intermediate regime where the field is well coupled to the electrons but not to the ions.

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$$\frac{O}{H} = \left(\frac{n}{10^8} \times 10^{17} \text{ cm}^{-3}\right)^{1/2} \left(\frac{v_A}{c_s}\right)^{-1}$$

(26)

$$\frac{A}{H} = \left(\frac{n}{10^9} \times 10^{12} \text{ cm}^{-3}\right)^{-1/2} \left(\frac{T}{10^3 \text{ K}}\right)^{1/2} \left(\frac{v_A}{c_s}\right)^{-1}$$

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Dead zones
Ambipolar diffusion makes it worse

- Turbulent layers are dominated by ambipolar diffusion & Hall effect
- If the disc is not threaded by a mean vertical field, ambipolar diffusion kills the MRI in the turbulent layer: $\alpha < 10^{-4}$ [Bai's poster 2S049; Bai & Stone (2013), ApJ, 769, 76]

Results depend strongly on FUV ionisation, PAHs, chemistry, grains...

Dead zones are definitely dead
Hall effect might not save the MRI

- Hall effect could revive dead zones

- Despite being strongly unstable to the MRI, Hall dominated discs do not produce turbulence but zonal fields whenever

\[ \ell_H \equiv \left( \frac{m_i c^2}{4\pi Z^2 e^2 n_i} \right)^{1/2} \left( \frac{\rho}{\rho_1} \right)^{1/2} \gtrsim 0.2H \]


\[ \partial_t \mathbf{V} - \mathbf{V} \cdot \nabla \mathbf{V} + \nabla \mathbf{p} - \rho \mathbf{g} - \epsilon \mathbf{R} = 0 \]

\[ \partial_t \mathbf{B} + \mathbf{V} \times \mathbf{B} = \epsilon \mathbf{R} \]

\[ \mathbf{R} = \nabla \times \mathbf{B} \]

\[ \mathbf{j} = \nabla \times \mathbf{B} \]

\[ \mathbf{V} \cdot \nabla \mathbf{V} - \nabla \mathbf{p} + \rho \mathbf{g} = \epsilon \mathbf{R} \]
Disc winds
Disc winds
Blandford & Payne paradigm

Ejection

Accretion flow

Need a large scale mean field
Magneto-centrifugal ejection when \( i > 30^\circ \)
Requires \( \beta \equiv \frac{P_{\text{Th}}}{P_{\text{Mag}}} \sim 1 \) [Murphy+ (2010), A&A, 512, 82]

Jet formation
Coexistence of MRI and strong disc winds?

For strongly magnetised discs, the MRI spontaneously evolves into discs winds

Precursor of variability in jets?
Disc winds in weakly magnetised discs

\[ \beta \equiv \frac{P_{\text{Th}}}{P_{\text{Mag}}} = 10^3 - 10^5 \]

- Stratified box simulations with a mean vertical field always show «weak» magnetically driven winds

- Could explain \( M_{\text{Acc}} \sim 10^{-8} M_\odot/\text{yr} \) in «dead» parts of the disc & in outer parts

![Diagram showing wind properties from all fiducial simulations](image)

- **BUT**: some quantitative results (eg mass loss rate in the wind) depend *strongly* on the box size!
Conclusions regarding MHD processes

The MRI is likely to be absent/insufficient in large parts of protoplanetary discs (1 to 10-30 AU)

- Results depend *crucially* on non-ideal MHD effects (controlled by heating/cooling, CRs, FUV, PAHs, dust settling, chemistry...)
- Hall effect will probably not save the MRI
- Weak magneto-centrifugal winds might be the answer (but many numerical artefacts in box simulations)

Global MRI+wind simulations are the next step
Gravitational instability
Gravitational instability

General criteria.

- Criterion for a disc to be gravitationally unstable: \( Q = \frac{c_s \Omega}{\pi G \Sigma} \lesssim 1 \)


- Outcome of GI (fragmentation/gravito-turbulence) depends on the cooling time \( \tau_c \)

\[
\tau_c = 10\Omega^{-1}
\]

\[
\tau_c = 2\Omega^{-1}
\]


- Gravito-turbulence gives

\[
\alpha = \frac{1}{9/4\gamma(\gamma - 1)\Omega \tau_c}
\]
Gravitational instability
fragmentation inevitable?

- Fragmentation condition depends on numerical resolution and is stochastic!

![Turbulence vs. log(number of particles)]

\[ \log(\tau_{\text{cool}}\Omega) \]

\[ \log(\text{number of particles}) \]

\( \tau_{\text{cool}}\Omega = 7 \)

\[ \tau_{\text{cool}}\Omega = 7 \]

\[ \Sigma_{\text{max}}/\Sigma_0 \]

\[ \Omega t \]


Gravito-turbulence might not be *long lived*
Gravitational instability can be active in dense & cold disc regions (outer parts of young discs)

- Outcome of GI still uncertain (resolution sensitivity, stochastic fragmentation). Maybe GI always lead to fragmentation?
- Behaviour & convergence with more realistic cooling function?

Hydrodynamic instabilities
Baroclinic instability

- Driven by the radial entropy gradient $\beta \equiv -\frac{d \ln S}{d \ln R} > 0$ [Klahr & Bodenheimer (2003), ApJ, 582, 869]


- Leads to $\alpha \sim 10^{-3} - 10^{-2}$


Problems with the vortex scenario

- Vortices are unstable in 3D [Lesur & Papaloizou (2009), A&A, 498, 1]

- 3D circulation complicates the picture [Meheut+ (2010), A&A, 516, 31]

- Vortices migrate
GSF instability

- **Vertical shear instability (Goldreich-Schubert-Fricke=GSF)**
- appears in «locally isothermal» discs: $T(R)$
- can give $\alpha \sim 10^{-3}$

Conclusions on hydrodynamical processes

- Hydro candidates are *thermally driven*. Precise heating/cooling computations are needed in order to assess their existence in discs.

- Vortices are an interesting hypothesis since they can trap dust. But uncertainties remain regarding their evolution on long timescales.
Observing transport mechanisms
Non-axisymmetric dust accumulation

- Indication of a large scale vortex at 63 AU
- Vortex at the edge of a gap cleared by a giant planet?
- Problem: a 10 M_{Jup} planet at 20 AU generates a vortex at 40 AU (assuming a $\alpha = 10^{-4}$ disc)
- Alternative scenario: baroclinic vortices?
Turbulence in the inner disc (0.1 AU)?

- Spectrum (black) of V1331 Cyg in the 2.3 µm region (H₂O+CO)
- Model (red) with a 4 km/s line broadening (CO thermal dispersion 0.9km/s)
- Signature of sonic turbulence? (winds excluded: no line asymmetry)
Turbulence in the outer disc?

- CS J=3-2 transition in DM-tau
- Best fit gives a turbulent broadening ~0.11 km/s at 300 AU
- Signature of turbulence at ~50% of the sound speed?

Conclusions on observations

- Non thermal broadening of spectral lines probably due to subsonic motions (could be turbulence, but could also be vortices or wind in the outer disc).
- Indications of large scale vortices. Planet scenario not entirely satisfactory (baroclinic vortices?).

Perspectives:

- Higher resolution observations should make the distinction between small scale structures (~turbulence) and large scale features (vortices, wind)
Conclusions & perspectives

Magnetically dead zones are the current bottleneck in transport theory

- Is the dead zone really magnetically dead? (improve chemistry)
- Need for global wind models including all of the nonideal MHD effects
- Go beyond simplistic thermodynamics: realistic equation of state with radiative transfer (& chemistry ?)