Basics of protoplanetary disc structure and dynamics II

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O Dust dynamics

- Radial drift
- **Settling**
- Winds
	- Photoevaporation & MHD disc winds
	- MHD wind basics
	- **Impact on the secular evolution**

● Wind-dust interaction

Dust & gas dynamics

Dust grains dynamic 101

The dust grain is coupled to the gas through a drag:

$$
m_{\text{grain}} \frac{d\vec{v}_{\text{grain}}}{dt} = -\frac{m_{\text{grain}}}{\tau_s} (\vec{v}_{\text{grain}} - \vec{v}_{\text{gas}})
$$

This introduces the gain's stopping time $\tau_{_S}$

In disks, one introduces the Stokes number: $\mathrm{St} = \tau_{\scriptscriptstyle S} \Omega_K$

Relating *St* to the grain size

Assumes spherical grains. Fluffy grains typically modelled assuming an « effective » density

Stokes number in actual discs

- Generally speaking, St increases with radius and altitude above the midplane
- **1mm size spherical** grains have St=1 @ 30 AU

Dust radial drift

As a rule of thumb, grains always drift towards high gas pressure regions

Dust vertical settling

Grains should settle towards the midplane on a timescale $\tau_{\text{setting}} \simeq z/\dot{z} \simeq [\Omega_K St]^{-1}$

- By 1 million years, all grains with $St > 10^{-3}$ @ 100 AU should have settled
- Something's happening to prevent settling of low « ish » St…

Dust turbulent diffusion

On can treat the grain population as a « fluid » and write an equation on the dust density

[Dubrulle +1995]

$$
\frac{\partial \rho_d}{\partial t} = \frac{\partial}{\partial z} \left(z \Omega_K^2 \tau_s(z) \rho_d \right) + \frac{\partial}{\partial z} \left[D_z \rho_g \frac{\partial}{\partial z} \left(\frac{\rho_d}{\rho} \right) \right]
$$
\nTerminal velocity of dust grains

\n

Dust layer thickness

Result of the advection-diffusion equation for dust grains

$$
\rho_d(z) = \rho_d(0) \exp\left(-\frac{z^2}{2H_d^2}\right) \text{ with } \frac{H_d}{H} = \frac{1}{\sqrt{1 + \frac{\frac{St_0 \Omega_K H^2}{D_z}}{D_z}}}
$$
\nIn the large St limit\n
$$
H_d = H \sqrt{\frac{D_z}{St_0 \Omega_K H^2}}
$$

- Typical values for vertical dust diffusion
	- *MRI: D_z/Ω_KH² ≃ 5 × 10^{−3} (Fromang & Papaloizou 2006)*
	- VSI: $D_z/\Omega_K H^2 \thicksim 0.2$ (Dullemond et al. 2022, but see also Stohl & Kley 2017)

• Gl:
$$
D_z/\Omega_K H^2 \simeq 10^{-2}
$$
 (Riols et al. 2020)

NB: D_z and α can be very different!

Comparing dust settling models to observations

[e.g. Villenave+2020, 2024] VSI is excluded from regions where we observe strong settling

Vertical shear instability with multiple dust grains

Time=4869.5693

[Lesur & Latter 2025]

Photo-evaporation

 $\mathcal{D}_\mathcal{A}$, and the disc surface by the disc surface by the disc surface by higher surface by $\mathcal{D}_\mathcal{A}$

Launched at radii larger than [Shu+1993,

*M*wind ≃ 10−9*M*⊙/yr

0 50 100 150 200

 $\frac{1}{20}$ $[Sellek + 2024]$

0

15

 10^1 10^2 10^3 10^4 Gas Temperature / K

 $10^2\,$

 Ξ

 $10³$

 $10^4\,$

 $_{\rm Gas}$ Temperature / K

*T*gas*/T*dust

0 50 100 150 200

 $\hat{1}0$ 10^{25} 2^3 11 12 12

cial simulation. The latter is defined as $\frac{1}{\sqrt{2}}$

Fig. 5: The gas density (left), gas temperature (centre) and ratio of gas and dust temperatures (right) after 200 orbits of the fidu-

the dashed lines show streamlines at regular intervals. The grey lines in the right-hand panel show to talk column density of the right-hand panel show to the right-hand panel show to the right-hand panel show to the right

*T*gas PRIZMO , , *T*DIAD)/*T*dust PRIZMO , . The solid purple line is the sonic surface, while

at the outer edge of the wind. However, the self-shielding of H2

can help protect it once it accumulates a column of

 1996; Richings et al. 2014). Given the approximate density of 105 cm3 and a molecular fraction of 106,

C

Draine & Bertoldi

(

0

What is perhaps more surprising in the amount of H2 present in the amount of H2 pr the outer parts of the wind. Figure 6 shows that its abundance

rapidly grows to around 10 per cent around

 \blacksquare

 \mathcal{L}

50

17 au and the national street and the street street and the street street and the street street and the street

N

⇡

column density of

100万
1000

R (au)

A. D. Sellek et al.: X-ray photoevaporation with PLUTO+PRIZMO

Hollenbach+1994]

A. D. Sellek et al.: X-ray photoevaporation with PLUTO

 \mathcal{L}

 $\frac{1}{2}$

 $\#V$

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MHD disk wind (MDW)

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er
a a molecular fraction of 101 outside the H-H2 transition of 101 outside the H-H2 transition, can also **Driven** by the accretion energy released by the $\frac{1}{2}$
and $\frac{1}{2}$ only 103 au. Hence, self-shielding can contribute to the steady of the steady self-steady and the steady self-1013cm2. Once the wind reaches the wind reaches are the conce the wind reaches are the conce the wind reaches a $\frac{1}{2}$ in the wind at 10s and 10s inside the H-H2 transition, the column density can only be \bigcirc disk

6500

B

e
a
9 Requires a large-scale B field [Ferreira & Pelletier 1993,1995]

 $\overline{1}$

A little experiment

Internals of magnetic breaking

Back to the accretion problem

$$
\frac{\partial \Sigma}{\partial t} + \frac{1}{R} \frac{\partial}{\partial R} R \overline{\rho v_r} + \left[\rho v_z \right]_{z=-h}^{+h} = 0
$$

$$
\sum_{k=0}^{\infty} \sum_{k=0}
$$

A wind introduces 2 new parameters: *ζ* and *λ*

Two « flavours » of MHD wind

A sample of MHD disc winds

Fig. 2. Flow topology in the fiducial run (ambipolar diffusion only $\Lambda_A = 1$). Top row: poloidal streamlines (white) and log of the sonic Mach number. Bottom row: poloidal field and log of density, normalised so that the midplane density at $R = 1$ is unity. Note that the colour scales are identical between the columns. From left to right the disc magnetisation increases: $\beta = 10^5$; 10^3 ; 35. The green lines denotes critical lines of the flow: Alfv'enic (plain) and fast magnetosonic (dot-dashed). The green dashed line represents the disc "surface" where the flow becomes ideal, arbitrarily located at *z* = 3.5*h* for all of the solutions.

Relating accretion, ejection and field strength B .
F

where the last equation is the continuity results from the continuity equation as \mathbb{N}/\mathbb{N} suming ∂*t*Σ = 0. It is easy the show that the ejection efficiency is Mass accretion is mostly controlled by the magnetic field intensity and depends *only weakly* on Σ

directly connected to the transport coefficients:

where the first equality assumes \mathcal{R} is negligible while the second while the sec σ in the scaling found in the fiducial run (Fig. 3). This image is implied in the fig. 3). This image is implied to the fig. σ

Mass loss rate is approximately equal to mass accretion rate.

The big unknown for a predictive theory is $B_z(R,t)$

Impact on disc evolution

In MHD disk winds, the angular momentum is « extracted » vertically, so there *e dis* no radial expansion *discussion of secular secular 377*

Figure 6. Examples of the evolution of the surface density for the analytical solutions presented in this work. The first three left-hand panels are for constant α solution 3.3) in the case of viscous (wind-driven band-driven (wind-driven and pure wind-driven is for a \sim 0.41 \times 0. **Figure 6.** Examples of the evolution of the surface density for the analytical solutions presented in this work. The first three left-hand panels are for constant α \ldots Of finay σ there is (faily α Dar zuz i), and pure wind-driven α … or maybe there is (Yang & Bai 2021)

Dust Dynamics in wind-driven disc Dust Settling

Observed dust settling is compatible with a wind-driven accretion disc ble with the 0.87-2.9 mm dust continuum emission measured by ALMA \Box a wind-driven accretion disc \Box the \Box \mathcal{I} or the contract with \mathcal{I} or \mathcal{I} and \mathcal{I} and \mathcal{I} are profile is represented by a blue line. The set of \mathcal{I}

AU.

number. The orange area corresponding to the orange area corresponding to the range of profiles compatible of p
The range of profiles compatible profiles compatible compatible of profiles compatible profiles compatible pro

x-axis unit is in AU, the conversion is about 1*H* ' 2.5 AU at *R* = 30

Dust grain entrainment

- Maximum entrained dust size ~a few μ m region where 99 % of the mass loss occurred.
- Mostly in the inner regions (dust settling outside) and is caused by wind-driven strengths and is caused by w We observe a contribution of gas through the inner cavity when α is the inner cavity when α observed in the right panel of $\mathcal{L}_{\mathcal{A}}$ settling
- Appears as a faint conical emission in synthetic observations C Appears as a fairm conical emist respectively. In the case of a purely magnetically driven

drag force between $\mathsf H$ band image

0.1 *μ*m

1 *μ*m

Gas density & magnetic field lines Ambipolar-only disc (R>10 AU)

COME

 $9.9e-01$

Temporal evolution

²⁵

Spontaneous structure formation in « windy » disc

Common ingredients are

- Γ Λ Γ Ambipolar diffusion (valid for R>~5AU)
- $\left| \right|$ colour and the poloidal magnetic field magnetic field $\left| \right|$ contours) in black, (b) the surface density normalized to the initial radial radial radial radial radial radia distribution, !ⁱ [∝] *^r*−1*/*2, and the vertical magnetic field strength at the mid-plane normalized to its initial distribution, *Bz*, *ⁱ* [∝] *^r*−5*/*4, (c) the radial velocity (black) of neutrals (black) and international international international international international i (d) the density-weighted vertical average of the radial velocity (km s−1) a poganotic field (fogeil field⁾) Ω Ω Ω Ω Ω Ω Ω $\mathcal{L} \cap \mathcal{L} = \{ \alpha \}$ and $\alpha \in \mathcal{L}$ if $\alpha \in \mathcal{L}$ and $\alpha \in \mathcal{L}$ $B\ge a$ few mG @ 10 AU ($\beta \lesssim 10^4$) $R = 10 \, \text{GeV}$ and $R = 20 \, \text{GeV}$ Large scale magnetic field (fossil field?) $\ddot{}$

A feedback loop

This drags poloidal magnetic field lines towards the gap until magnetic pressure equilibrium is reached

The magnetic pressure deficit triggers an ion drift towards the « gap »

MHD-driven rings are observable $\overline{}$

[Riols+2020]

 MHD wind opentonal to MHD wind opentonal to MHD p_{ref} is a larger than the velocity associated with the velocity associated with the velocity p_{ref} MHD wind spontaneously create visible dust ring structures

The aim of this Section is to produce symplectic images of this Section is to produce synthetic images derived

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radial turbulent dial turbulent dial turbulent dialectic concentration. We then expect concentration of dust co

Summary

Supplementary material

Planet-disc-wind interaction in action

[Wafflard-Fernandez & Lesur 2024]RWI-generated A Planet's wake Planet's gap vortices (spiral shock) 0.4 -2 0.2 log(RHO) $N \theta.0$ -0.2 -0.4 -5 circumplanetary 3Mj, $\beta_0 = 10^7$ disc 1Θ 0.75 $.00.$ 1.25 1.75 2.00 2.25 2.50 1.50 R -1 The Idefix code -1 Θ

Gap opening by embedded planet in a windy disk

↵⌫ ⁼ ^hW*R*i h*P*i **External Allen Dianate still onan ganel a. Of the see panel a. Of the see panel a. Of the see panel a. Of the s** with a di⊄erence in density in density in the planet in
The planet in the planet i \sim 110 Planets still open gaps

dw) contributions:

We are able to retrieve the inner and outer planet wakes in all

and Maxwell (↵*^M*

 \mathcal{A} distinct to this aximuthal asymmetry, there is also a two-fold radial ra

where *R* and *R* are respectively related to the R are related to the R are respectively related to the R and and Maxwell components of the radial stress. We also define a dimensionless parameter ↵dw, similar to the one introduced in shoe region could generate a positive or negative contribution in \sim total gravitational to the gas one that \sim due to a static corona str planets (*Mp Mj*) and highly magnetized disk (⁰ = 103), in ado opening exiterian and de Gap opening criterion and depth depends on the field strength and radial depth asymmetry.

Gap morphology

groups of diaerent planet masses. The top plot of each group has the lowest magnetization, whereas the highest

The Magnetised gaps become asymmetric as time goes on E2 two Magnetised gaps become asymmetric as time goes on

episodes in the run *Mj-*³ that will be discussed in Section 3.2.3. Stronger field amplifies the effect

Wafflard-Fernandez & Lesur 2024

A collapsing core

- Chemical network to account for non-ideal effects [Ohmic & Ambipolar]
- Setup inspired from Masson et al. (2016):
	- Start from a uniformly rotating supercritical $\overline{\bigcirc}$ $1 \,$ M_{\odot} core
	- initial $R_{\rm core}$ = 2500 au

Barotropic EOS :
$$
T \propto T_0 \sqrt{1 + \left(\frac{n}{n_{cr}}\right)^{4/5}}
$$

$$
n_{cr} = 10^{11} \text{ cm}^{-3} \Leftrightarrow 1^{st} \text{ hydrostatic core}
$$

• Anisotropic infall and a flattening of the core • Field line deformation that acquire the classic hourglass shape

• Field line dragging

Let's zoom in

Long timescale evolution

edge-on view Top view [Mauxion+2024]

 $n\ (\rm cm^{-3})$

10⁰ 10¹ 10² 10³

Constraining the large scale field

B must decay by \sim 10² at 10 AU from class 0 to class II