Jets and Outflows in Protoplanetary Disks

Raquel Salmeron[(1)]*, Arieh Königl*[(2)] *& Mark Wardle*[(3)]
(1) Research School of Astronomy & Astrophysics and Research School of Earth Sciences, ANU
(2) Dept. Astronomy & Astrophysics, University of Chicago
(3) Dept. Physics, Macquarie University

Introduction

Jets and winds are commonly associated with accreting astrophysical sources. Their ubiquity, and the apparent correlation between accretion and outflow signatures in these systems [1], suggest that they play a key role in regulating accretion [2].

They are thought to be launched centrifugally from the disk surfaces via the stresses of open magnetic field lines that thread the disk [3]. However, in protoplanetary disks the ionization fraction is low and the ability of the field to couple to the gas (and drive a wind) is severely limited. It is essential, therefore, that realistic wind models incorporate the detailed ionization structure and conductivity properties of the gas.

Here we present wind solutions that include, for the first time, all magnetic diffusion mechanisms (Ambipolar, Hall and Ohmic), calculated via a a realistic ionization profile. These models can be used to study planet formation and assess the chondrule-forming properties of disk winds.

Disk wind models

Our wind solutions are based on the magnetocentrifugal mechanism for wind launching [3]. The modelling procedure, based on [4], is as follows:

-We solve the mass and momentum conservation equations for the neutrals and the induction equation for the evolution of the magnetic field. The current density obeys Ampere and Ohm’s laws (see ‘For the mathematically minded’, right panel).

-The disk is isothermal and geometrically thin. The gas is in steady-state, nearly-Keplerian motion and the density is vertically stratified.

-We calculate a realistic ionization profile, with contributions from X-rays, cosmic rays and radioactive decay. All magnetic diffusion mechanisms (Ohmic, Hall and Ambipolar) are included (see ‘Disk Ionization’ and ‘Magnetic Diffusivity’, lower central panel).

Numerical Method

The system of equations (see right panel) are integrated vertically upward from the midplane (z = 0) and the height of the sonic point and values of the variables there are estimated. The solution is integrated backwards to a fitting point and iterated until it converges. This disk solution is matched onto a global (self-similar) wind solution [3], by imposing the Alfvén critical point constraint.

For the mathematically minded

Non-ideal MHD equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathrm{V}) = 0 \qquad \frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{V} \times \mathbf{B}) - c \nabla \times \mathbf{E}'$$

$$\frac{\partial \mathbf{V}}{\partial t} + (\mathbf{V} \cdot \nabla)\mathbf{V} + \frac{c_s^2}{\rho}\nabla \rho + \nabla \Phi - \frac{\mathbf{J} \times \mathbf{B}}{c\rho} = 0 \qquad \mathbf{J} = \frac{c}{4\pi} \nabla \times \mathbf{B}$$

$$\mathbf{J} = \sigma_{\|}\mathbf{E}'_{\|} + \sigma_{\mathrm{H}}\hat{\mathbf{B}} \times \mathbf{E}'_{\perp} + \sigma_{\mathrm{P}}\mathbf{E}'_{\perp}$$

$\sigma_{\|}$, σ_H and σ_P are the Pedersen, Hall and field-aligned conductivity terms. In the ambipolar diffusion limit, $\sigma_{\|} >> \sigma_P >> \sigma_H$ and σ_P is specified via the parameter η

Model parameters

$a_0 = v_{\mathrm{Az},0} / \mathrm{c_s}$	The midplane ratio of the Alfven speed to the sound speed. It measures the magnetic field strength.
η	The ratio of the Keplerian rotation time to the neutral-ion momentum exchange time (the magnetic coupling), taken to be spatially constant.
$\varepsilon \equiv -\mathrm{v}_{r0} / \mathrm{c_s}$	The normalized inward radial speed at the midplane.
$c_\mathrm{s} / v_\mathrm{K} = h_\mathrm{T} / r$	The ratio of the tidal scale height to the radius, a measure of the disk geometric thinness.
$\varepsilon_\mathrm{B} \equiv -cE_\phi / c_\mathrm{s} B_z$	The normalized radial drift speed of the magnetic field lines.

Wind driving protoplanetary Disks

Disk winds - Overview

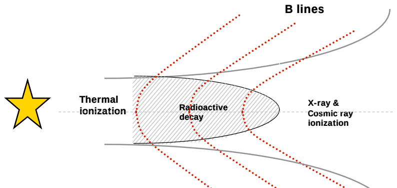
Disk winds are energetic outflows that emerge in two opposite directions along the disk rotation axis and become well collimated and highly supersonic as they propagate away from the source.

They tap the rotational kinetic energy of the disk and are accelerated centrifugally via magnetic stresses [3]: Matter at the disk surface is flung out along the open magnetic field lines that thread the disk (see diagram below) if they are inclined at a sufficiently large angle (> 30°) to the rotation axis (the ‘bead-on-a-wire’ effect).

Such outflows represent a possible means of transporting the excess angular momentum of the disk vertically outwards, enabling matter to accrete, as opposed to the radial transport that is commonly invoked in viscous disk models.

Wind driving disks - 1. Schematic diagram

A not-to-scale cartoon of a protoplanetary disk, showing typical values of the gas temperature (T), hydrogen number density (n_H) and electron fraction ($x_e = n_e/n_H$) at the midplane of the disk for R = 0.1, 1 and 10 AU from the central protostar. The main ionization sources at different locations and typical topology of the open magnetic field lines that thread the disk are also indicated.



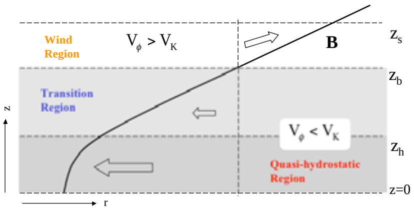
R (AU)	0.1	1	10
T (K)	1000	300	100
n_H (cm^{-3})	10^{16}	6×10^{14}	10^{12}
x_e		7×10^{-13}	2×10^{-9}

Wind driving disks - 2. Vertical structure

Three different zones can be identified [4]:
In the **quasi-hydrostatic layer** next to the disk midplane (z=0), the magnetic field lines (B) are radially bent and azimuthally sheared. The neutral gas loses angular momentum to the field, which enables it to accrete.

Above, in the **transition layer**, the magnetic energy density becomes dominant as the gas density decreases. The field is nearly force free and the B lines are locally straight.

Since the gas angular velocity decreases with radius, the field lines (which move with a constant angular velocity and bend radially outwards) eventually overtake the matter and fling it out centrifugally. This is the **wind region**, the base of the wind.



Adapted from [ref]. Representative field line and fluid poloidal velocity (arrows). Z_h denotes the disk scale. Z_b is the base of the wind z_s is the sonic point. V_ϕ is the azimuthal fluid velocity and V_K is the Keplerian velocity.

Disk Ionization

The main ionization sources outside the innermost ~ 0.1 AU from the central object are non-thermal: Interstellar cosmic rays, X-rays and UV radiation emitted by the magnetically active protostar and the decay of radioactive elements present in the disk (see schematic diagram, left panel).

In the inner regions of the disk (e.g. at 1 AU, Fig. 1), the electron fraction is very low because the ionizing sources are excluded or heavily attenuated. As a result, the conductivity of the gas is low and magnetic activity may be suppressed.

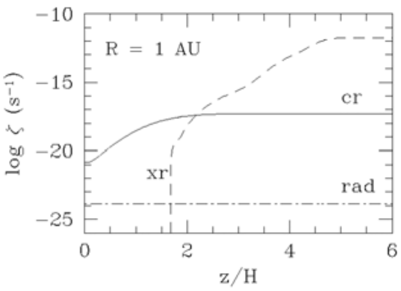


Figure 1. Ionization rate (s^{-1}) contributed by cosmic rays (curve labeled ‘cr’), X-rays (xr) and radioactive materials (rad) as a function of height, for a minimum-mass solar nebula disk [ref] at 1 AU from the central object. Note that cosmic ray ionization is attenuated with respect to the interstellar rate for z/H < 2 and X-rays are excluded from the disk for z/H < 1.7.

Magnetic diffusivity

In the dense, weakly ionized environments typical of protoplanetary disks, the conductivity of the gas is strongly stratified and can be very low. As a result, the diffusion between the magnetic field and the neutral gas is important. Three regimes can be identified (Fig. 2):

Ambipolar Diffusion. This mechanism is typically dominant in low density regions (e.g. near the surface in protoplanetary disks). The magnetic field is frozen into the ionized component of the fluid and drifts with it through the neutrals.

Hall Diffusion. This mechanism dominates at intermediate densities. It is characterized by a varying degree of coupling amongst charged species. Typically ions are tied to the neutrals and electrons remain frozen into the magnetic field.

Ohmic Diffusion. The magnetic field can not be regarded as being frozen into any fluid component and the diffusivity is a scalar. This regime dominates close to the midplane in the inner regions of protoplanetary disks [5].

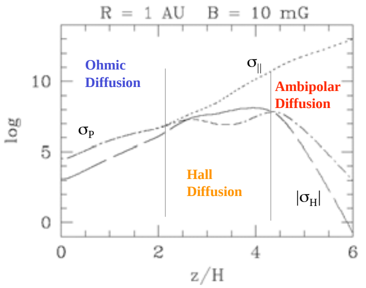


Figure 2. Dependence of the conductivity terms ($\sigma_{\|}$, σ_P and σ_H) with height for R = 1 AU and B = 10 mG. For z/H < 2 the magnetic diffusion is resistive. There is then a central section where Hall diffusion dominates while for higher z ambipolar diffusion is dominant.

Illustrative solution

Fig. 3 shows a local disk solution that matches onto a global (self-similar) wind solution [3]. In the ‘Disk Region’ (to the left of the vertical line) the radial velocity is negative (towards the star, e.g. the material is accreting), and the vertical velocity is small. In contrast, in the ‘Wind Region’, all fluid velocity components are positive and increasing strongly with height.

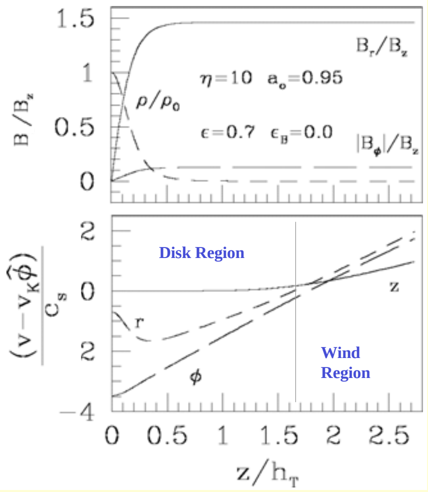


Figure 3. Vertical structure of a strongly magnetized, wind-driving protoplanetary disk. *Top*: Normalized radial and azimuthal components of the magnetic field (B_r and B_ϕ) and fluid density (ρ). *Bottom:* All velocity components, with respect to the Keplerian velocity (v_K) and normalized by the sound speed (c_s). The self-similar wind solution [3] parameters are: $\kappa = 3.2 \times 10\text{-}4$, $\lambda = 395$ and $\xi_b' \equiv B_{r,b}/B_z = 1.46$. The curves terminate at the sonic point (z_s).

Applications & Future Work

Planet formation has so far been studied in the context of viscous accretion disk models. However, the particular dynamical properties of wind driving disks are likely to affect planet growth & migration and could lead to new insights into these mechanisms.

Despite their recognized efficiency in extracting disk angular momentum and gravitational potential energy, and significant advances in the theoretical understanding and realistic simulation of these jets, the suitability of these winds as an environment for **chondrule formation** has not been examined. The realistic treatment of the microphysics in our models make them ideal for the analysis of the chondrule-forming properties of these jets.

Using semi-analytic and numerical results we have constructed a model of steady-state disks that includes vertical **angular-momentum transport** by a wind as well as radial transport induced by the magnetorotational instability (MRI, [6]). This model can be used to evaluate the fractions of angular momentum transported by these two mechanisms, respectively, as a function of position in protoplanetary disks.

References

[1] Hartigan et al., 1995, ApJ, 452, 736.
[2] Konigl A., 1989, ApJ, 342, 208.
[3] Blandford R. D., Payne D.G., 1982, MNRAS, 199, 883.
[4] Wardle M. & Königl A., 1993, ApJ, 410, 218.
[5] Wardle M., 2007, Ap&SS (in press)
[5] Salmeron, R., Königl A. .& Wardle M., 2007, MNRAS, 375, 177