MHD Modelling of Protostellar Disk Winds and Jets

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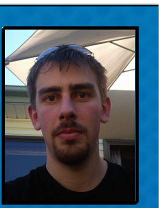


Abstract

One of the outstanding challenges in star formation is the angular momentum problem. Angular momentum transport is required to allow a cloud core to collapse to form a star [1]. Angular momentum in the initial collapsing cloud prevents the majority of material falling directly onto the protostar, instead settling into a circumstellar disk around it. Angular momentum must then be redistributed to allow material to accrete.

Radial transport of angular momentum is accomplished via the magnetorotational instability (MRI; [2]). Vertical angular momentum transport has generally been attributed to centrifugally driven winds (CDWs) from the disk surfaces (e.g. [3], [4]). Both modes of transport depend on the strength of the local magnetic field, parametrised by the ratio of the vertical Alfven speed to the isothermal sound speed, a_0. MRI is expected to dominate in the presence of weak fields ($a_0 \ll 1$) [5], whereas CDWs require a strong field ($a_0 \lesssim 1$).

Here we present calculations of the structure of strongly magnetised protostellar disks ($a_0 = 1$), with midplane density and temperature as in the minimum-mass solar nebula model ([6]) around a solar-mass star, focusing on the regions of these disks that may launch a CDW from their surfaces. These models explore the effect of the magnetic diffusivity in protostellar jet launching, and the connection between the disk properties and the large-scale features of jets.

Method

Parameters:

- $\mathbf{a_0}$: Magnetic field strength (Alfvén speed/sound speed at the midplane,)
- $\mathbf{\Lambda_0}$: Degree of coupling between the neutrals and magnetic field,
- $\boldsymbol{\varepsilon}$: Normalised inward radial speed at the midplane,
- $\boldsymbol{\eta}$: Diffusivity regime, characterised by the normalised Ohm, Hall and ambipolar diffusivities ($\boldsymbol{\eta_O}$, $\boldsymbol{\eta_H}$ and $\boldsymbol{\eta_A}$ respectively).

1D disk wind solutions [4, 7, 8]:
The governing equations are integrated in the z direction from the disk midplane up to the sonic point ($v_z = c_s$)

1+1D disk wind solutions:
The total mass flux $\dot{M}$, determines the outer extent of the wind-driving region of the disk, satisfying the inequality $\boldsymbol{\varepsilon\Lambda_0 < v_K/2c_s}$ [10]. The wind-driven mass loss, $\dot{M}_w(r)$, is calculated and subtracted from $\dot{M}$, giving an accretion rate, $\dot{M}_a(r)$. This is solved radially inwards, until no physically viable wind solution exists.

Protostellar winds and accretion

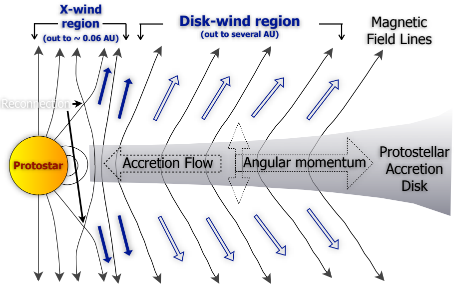


Figure 1. Schematic, not-to-scale diagram of a protostellar disk, showing the radially extended 'disk-wind' and 'X-wind' regions [9].

Centrifugally driven winds [4], [10]

Centrifugally driven winds can be divided into three distinct zones:

- A quasi-hydrostatic zone where the bulk of the matter is concentrated and most of the field-line bending takes place. In this region, the neutral gas looses angular momentum to the magnetic field.
- A transition zone where the inflow gradually diminishes with height and the field becomes locally straight.
- An outflow zone that corresponds to the base of the wind. The magnetic field lines overtake the matter and propel it out centrifugally.

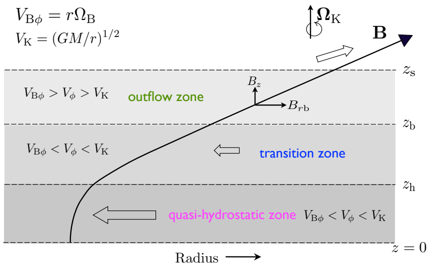


Figure 2. Schematic, not-to-scale diagram of a CDW [4]

Radial extent of wind launching region

Successful wind-launching radii, given different $\dot{M}$ for pure ambipolar and Hall diffusion regimes. Model parameters are $a_0 = 1.0$ and $\Lambda_0 = 5.0$ [see right panel above]. The Hall regime dominates at the midplane at radii between 1-10 AU, whereas the ambipolar regime is dominant at >10 AU [8].

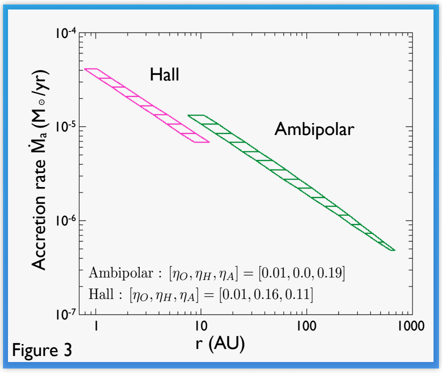


Figure 3

The ratio $\dot{M}_w/\dot{M}_a$

An important observational constraint on disk-jet systems is the ratio of the mass lost in the wind to the mass accreted onto the central protostar. Typical ratios for a bipolar jet are in the range 0.1 to 0.2 [11]. Figure 4 shows the radial dependence of this ratio from our models.

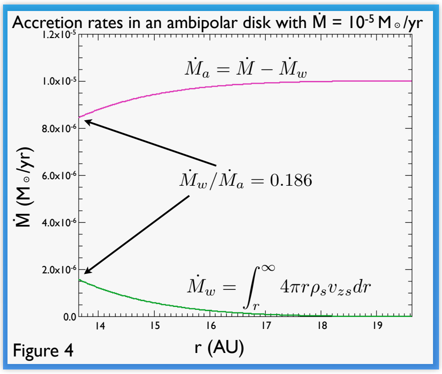

Accretion rates in an ambipolar disk with $\dot{M} = 10^{-5}\,M_\odot$/yr

Figure 4

Two sided $\dot{M}_w/\dot{M}_a$ for different $\dot{M}$ and regime (see Figure 4)

Regime	$\dot{M} = 1.00\times10^{-6}$	$\dot{M} = 3.16\times10^{-6}$	$\dot{M} = 1.00\times10^{-5}$	$\dot{M} = 3.16\times10^{-5}$
Ambipolar	0.101	0.153	0.186	0.226
Hall	0.124	0.152	0.189	0.222

Disk structure

One plus one-dimensional wind-driving disk solutions for $\dot{M}_a = 10^{-5}\,M_\odot$/yr in the ambipolar and Hall regimes are shown in the figures below. The white lines show the boundaries of the three wind zones (see Figure 2). The arrows depict the poloidal velocity field and the pink lines trace the magnetic field geometry.

Figure 5. Ambipolar Regime

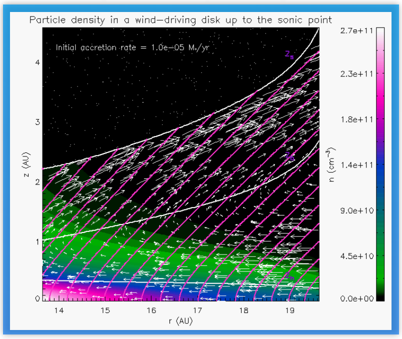
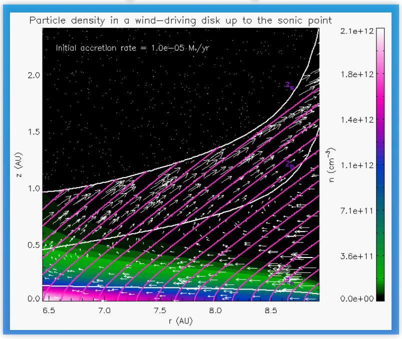


Figure 6. Hall Regime



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Conclusions

- Centrifugally driven winds may only exist over a range of disk radii and this range moves outward with decreasing total mass flux $\dot{M}$.
- For a given radii, increasing the relative contribution of the Hall to ambipolar diffusivity results in a lower disk accretion rate.
- $\dot{M}_w/\dot{M}_a$ in our models compares well with two sided, real disk ratios (0.1 to 0.2).
- $\dot{M}_w/\dot{M}_a$ increases with $\dot{M}$ in both ambipolar and Hall regimes (see table, right column).
- One plus one-dimensional disk structure is consistent with schematic structure of wind-driving disks (left column).