RevMexAA (Serie de Conferencias), **3**, 97–100 (1995)

CAN α-DISKS DRIVE WINDS CENTRIFUGALLY?

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RESUMEN

Estudiamos el arrastre de un campo magnético externo uniforme por el flujo en un disco de acreción delgado y turbulento. La acreción en el disco se debe a la viscosidad turbulenta dada por la prescripción estándar en términos del parámetro α. Trabajamos en la aproximación cinemática ignorando los posibles efectos del campo magnético sobre el flujo que lo arrastra. Obtenemos soluciones para dos tipos de discos en estado estacionario: un disco protoplanetario viscoso y un disco "estándar" como aquellos que rodean a estrellas compactas. La habilidad del disco para arrastrar al campo depende principalmente del número de Prandtl magnético asociado con la turbulencia, $\mathcal{P}_t$. En ambos casos estudiados, el disco será incapaz de arrastrar al campo hasta alcanzar una configuración conducente a la generación de vientos, a menos que el número de Prandtl sea reducido artificialmente por dos ordenes de magnitud de su valor esperado $\mathcal{P}_t = 1$.

ABSTRACT

We study the capability of turbulent accretion disks to drag an external magnetic field to a configuration favorable for driving winds centrifugally. This is done by modeling the interaction of the large scale flow in a geometrically thin accretion disk with an externally imposed, uniform, vertical magnetic field. Turbulent viscosity in the disk is given by the standard α parameterization and axial symmetry is assumed. No attempt is made to include the back-reaction of the field on the disk dynamics. Solutions are obtained for two types of disks: a so-called "standard" steady-state model of a disk around a compact star, and a steady-state model of a viscous protoplanetary disk. The ability of the disk to drag the field to a wind favorable configuration depends primarily on the value of the magnetic Prandtl number for turbulent motions, $\mathcal{P}_t$. In both cases studied, no wind can be driven unless the Prandtl number is artificially reduced by about two orders of magnitude from its fiducial value of $\mathcal{P}_t = 1$.

Key words: **ACCRETION, ACCRETION DISKS – MAGNETIC FIELDS – MHD – ISM: JETS AND OUTFLOWS**

1. INTRODUCTION

Two features commonly associated with very young solar-type stars are circumstellar accretion disks and bipolar outflows. It is believed that accretion disks surround many compact stars, such as white dwarfs and neutron stars. In most theoretical studies, the accretion process, i.e., the transport of angular momentum outwards and inward mass accretion onto the central star, is considered to be caused by turbulence and/or magnetic fields in the disk. This process is widely, almost exclusively, dealt with by adopting the formalism of standard turbulent α-disks.

On the other hand, bipolar outflows are thought to arise from winds generated at the disk's surface. The most extensively studied mechanism for driving such winds is the so-called magneto-centrifugal acceleration. In this model winds can be driven centrifugally if the magnetic field lines make an angle greater than 30 degrees with the rotation axis as they come out of the disk. Previous wind models have assumed that such a favorable field configuration has already been reached, somehow.

In this paper we study the possibility that such a condition is achieved as the accretion flow in a turbulent disk drags in an external magnetic field. We seek to determine whether these two widely used frameworks, turbulent accretion disks and centrifugally driven winds, are compatible. In § 2 we enumerate the basic characteristics and assumptions of our models. Results are presented in § 3 and we conclude by discussing some implications of our results.

2. THE MODELS

Two disk models are used to illustrate our results. They represent extreme cases in the degree of ionization. We first study dragging in a steady-state accretion protoplanetary disk. In it, the opacity is provided by dust grains and the corresponding disk structure is taken from the tables of Stepinski, Reyes-Ruiz, & Vanhala (1993). Such disks have a very low internal temperature and thermal ionization is only possible in regions very near the central star. The outer part of the disk can also be ionized by penetrating cosmic rays and the decay of short-lived radioactive elements. Equilibrium is assumed between such ionization sources and recombination of electrons onto grains and ions.

We also study the case of a so-called standard accretion disk, such as those around compact objects. The disk is assumed to be optically thick with a Kramer opacity law (see Frank, King, & Raine 1985). Due to their high temperature, such disks can be considered "perfectly" ionized, inasmuch as the ohmic diffusivity is much less than the turbulent diffusivity.

In addition to the assumption of axial symmetry in our models, the following important assumptions are also made:

- No disk dynamo, or any other magnetic instability, is operating inside the disk.
- In calculating the degree of ionization, we consider a best-case scenario of single size, one cm dust grains. This minimizes the recombination of charged particles onto dust grains. We also assume the ionization degree is constant from the midplane to the surface of the disk.
- There is no wind coming off the disk (yet), hence vacuum is assumed outside. Consistent with thin disk approximations, the velocity field is taken to be $(V_r, V_{kepler}, 0)$, with V_r obtained from the continuity equation and independent of z.
- No back reaction of the dragged magnetic field on the gas dynamics is considered.
- The turbulent magnetic diffusivity, η_t, is proportional to the turbulent viscosity, ν_t, which is given by the α parametrization. The proportionality constant, a new parameter $\mathcal{P}_t = \eta_t/\nu_t$, is expected to be ≈ 1 from MHD turbulence theory (Ruzmaikin, Shukurov, & Sokoloff 1988).

3. RESULTS

3.1. Protoplanetary Disk

Results shown in Figure 1 correspond to a disk with disk parameters, $M_\star = M_\odot$, $\dot{M} = 10^{-6} M_\odot$ yr^{-1}, and $\alpha = 0.01$. The dependence of the relevant disk properties on such parameters is weak and the ability of the disk flow to bend the field lines depends essentially on the value of $\mathcal{P}_t$. A wind favorable configuration, i.e., an inclination of the field lines greater then 30 degrees, can only be reached for extreme values of $\mathcal{P}_t \lesssim 0.01$, and only in the innermost, well-ionized regions of the disk. In the outer parts of the disk, due to the low degree of ionization, even if turbulent magnetic diffusivity is artificially reduced, the ohmic diffusivity is too high to allow any significant dragging. The "bunching-up" of field lines, where they can be dragged, results in an amplification of the field with respect to its value "at infinity".

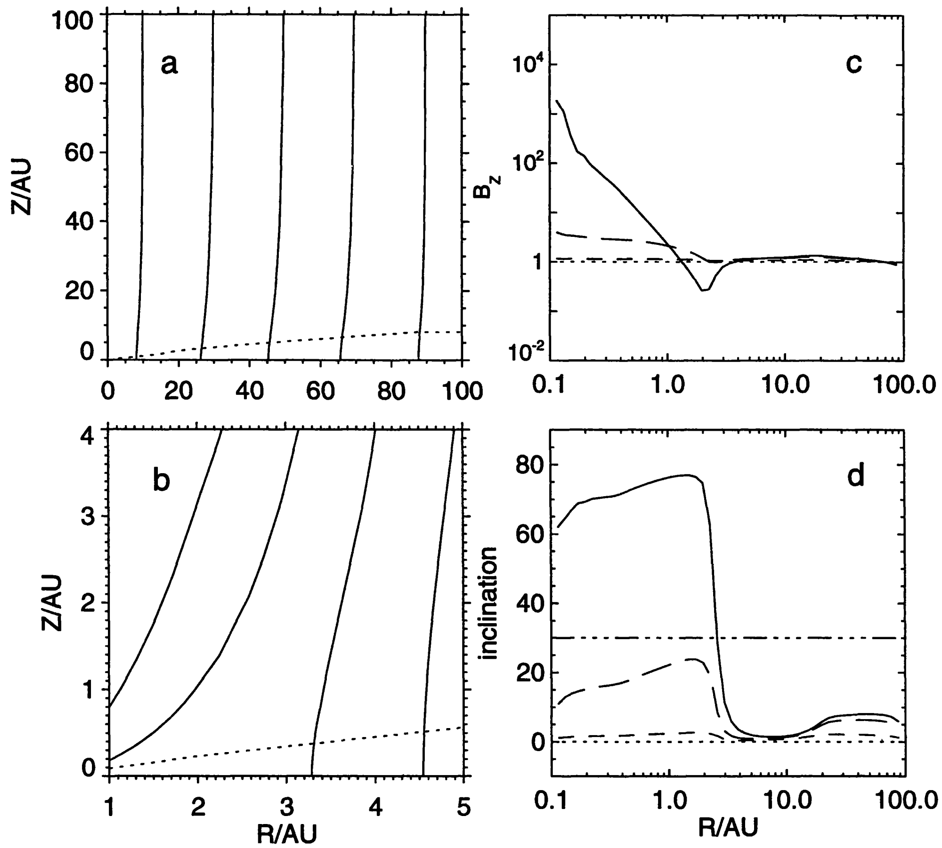

Fig. 1. Properties of the steady-state magnetic field resulting from dragging an initially uniform vertical field by the flow in a viscous protoplanetary disk. Different line styles correspond to different values of magnetic Prandtl number: $\mathcal{P}_t = 1$, short dash; $\mathcal{P}_t = 0.1$, long dash; $\mathcal{P}_t = 0.01$, solid line. (a) Global view of the magnetic field for the case of $\mathcal{P}_t = 0.01$. (b) A close-up of an inner portion of a disk to show the structure of the poloidal field near the region of low ionization. (c) Radial profile of the magnetic field at the disk's midplane. The magnitude of field is measured in units of B^∞, the dotted lines, drawn for visual reference, indicate $B = B^\infty$. (d) Inclination angle, i, between the field lines and the normal to the disk measured at disk surface, as a function of distance from the star. Dotted and triple-dot-dashed lines are for visual reference indicating $i = 0$, and $i = 30°$, respectively.

3.2. Standard Disk

Following Frank et al. (1985) we adopt the following disk parameters for a disk around a compact, non-magnetic star, $M_\star = M_\odot$, $\dot{M} = 10^{16}$ g s^{-1} and $\alpha = 0.1$. Once a particular disk model has been chosen, the problem depends entirely on the magnetic Prandtl number. Results are shown in Figure 2. Again, a field configuration conducive to wind generation can only be reached for very small values of $\mathcal{P}_t \lesssim 0.01$. Since magnetic diffusion is now entirely given by the magnetic turbulent diffusivity, the reduction of the Prandtl number affects similarly all disk regions. Hence, for such low values of $\mathcal{P}_t$, winds can be driven from the whole disk as indicated by the high inclination of field lines in Figure 2d. In cases of very low $\mathcal{P}_t$, dragging may lead to dynamically significant amplification of the field. In such a case however, our kinematic approximation no longer holds.

4. CONCLUSIONS

For fiducial values of $\mathcal{P}_t \approx 1$, launching centrifugal winds from viscous accretion disks is impossible if the magnetic field is solely resultant from dragging an externally imposed field. If somehow $\mathcal{P}_t \ll 1$, driving the

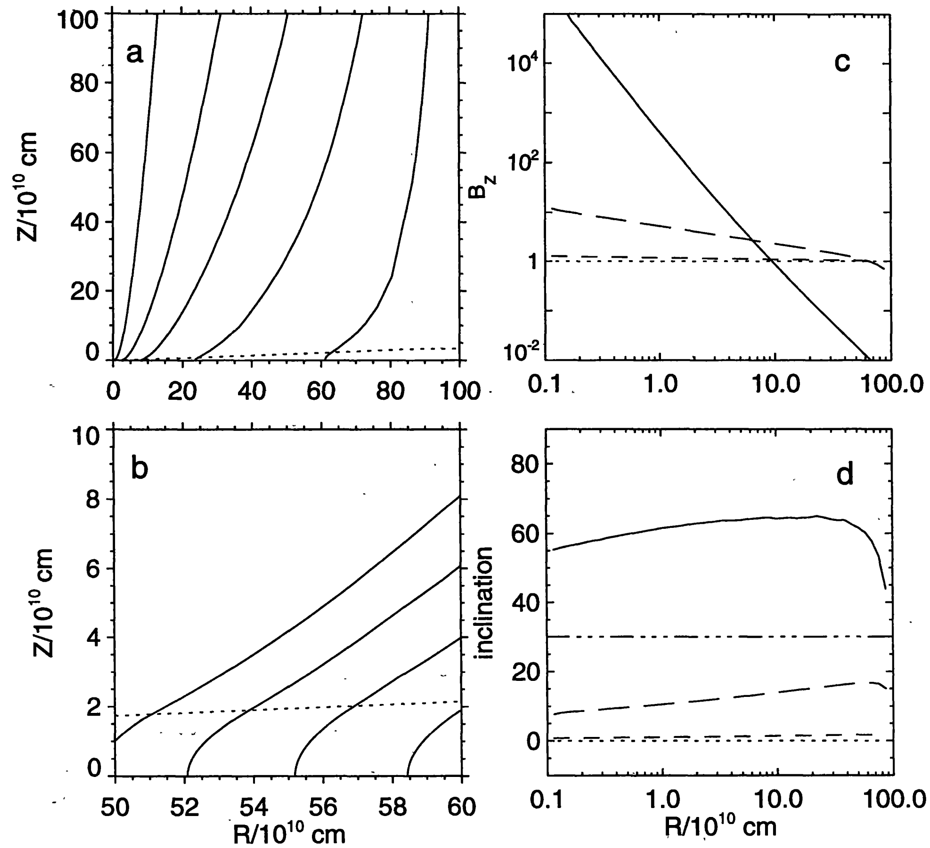

Fig. 2. Same as in Figure 1 but for dragging by a standard accretion disk. A close-up in panel b shows the structure of the poloidal field inside the disk and outside the disk, near its surface.

wind is possible. In such a case however, a consistent treatment of the back reaction of the magnetic field on the disk dynamics is necessary.

Given that bipolar outflows and accretion disks are almost a ubiquitous feature of YSO's, our results indicate the necessity for a revision of the simple, hand-waving idea of field dragging to achieve wind launching configurations. We believe that, if accretion disks are taken to be α-disks, then alternative scenarios must be sought for magnetic field and/or wind generation. One particular possibility currently under consideration is the generation of an open disk magnetic field by a dynamo mechanism.

Alternatively, if the concept of centrifugally driven winds is to be maintained, our results suggest that the structure of protoplanetary disks may be entirely different from standard α-disks.

REFERENCES

Frank, J., King, A., & Raine, D. 1985, in Accretion Power in Astrophysics (Cambridge: Cambridge Univ. Press)
Ruzmaikin, A. A., Shukurov, A. M., & Sokoloff, D. D. 1988, in Magnetic Fields of Galaxies (Dordrecht: Kluwer)
Stepinski, T. F., Reyes-Ruiz M., & Vanhala H. A. T. 1993, Icarus, 106, 71