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# Structure and emission of magnetized accretion disks

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*To the memory of Francesco, to his restless curiosity and joy of life*

**Abstract.** The magnetic field from the molecular core is dragged into the protoplanetary disk during the phase of gravitational collapse. If the field remains frozen to the gas, the magnetic field would be amplified in the center and would produce a catastrophic magnetic braking preventing the formation of the observed rotationally supported disks. Instead, processes like ambipolar diffusion and ohmic dissipation reduce the magnetic field that ends up in the star plus disk system. The level of disk magnetization is not yet known although observations with ALMA and VLA in the near future should provide an estimate of the mass-to-flux ratio, a key parameter for the structure and emission of magnetized disks. Here we discuss the vertical structure and emission of magnetized disk models whose radial structure was studied by Shu and collaborators.

**Key words.** ISM: magnetic fields – Stars: formation – Protoplanetary disks

## 1. Introduction

During the recent years several groups have tried to establish the conditions under which magnetic fields from the parent cloud core can be dissipated to prevent a catastrophic magnetic braking and form a rotationally supported protoplanetary disk (see, e.g. review of Lizano & Galli 2015). Several recent papers focus on the formation of the first Larson core and the early disk stages (e.g., Masson et al. 2016; Hennebelle et al. 2016, Machida et al. 2016). Nevertheless, the expected level of magnetization for a fully developed star plus disk system has not yet been established. In the near future, one expects ALMA to be able to measure the magnetic field directly through Zeeman splitting of CN lines and determine the value of the mass-to-flux ratio in the star plus disk system. In non-dimensional form this ratio is written as $\lambda_{\rm sys} = 2\pi G^{1/2}(M_* + M_d)/\Phi$, where $M_*$ and $M_d$ are the star and disk masses, $G$ is the gravitational constant, and $\Phi$ is the magnetic flux. In the meantime, it is useful to study the structure and emission of disks with different levels of magnetization.

Shu et al. (2007) modeled the radial structure of magnetized disks threaded by a poloidal magnetic field dragged form the parent cloud core during the phase of gravitational collapse. These disks have two diffusive processes: viscosity $\nu$ that redistributes angular momentum and allows matter to accrete, and resistivity $\eta$ that allows matter to slip through magnetic field lines. Lubow et al. (1994) found that, to achieve a steady state between the advection and diffusion of the magnetic field, the Prandtl

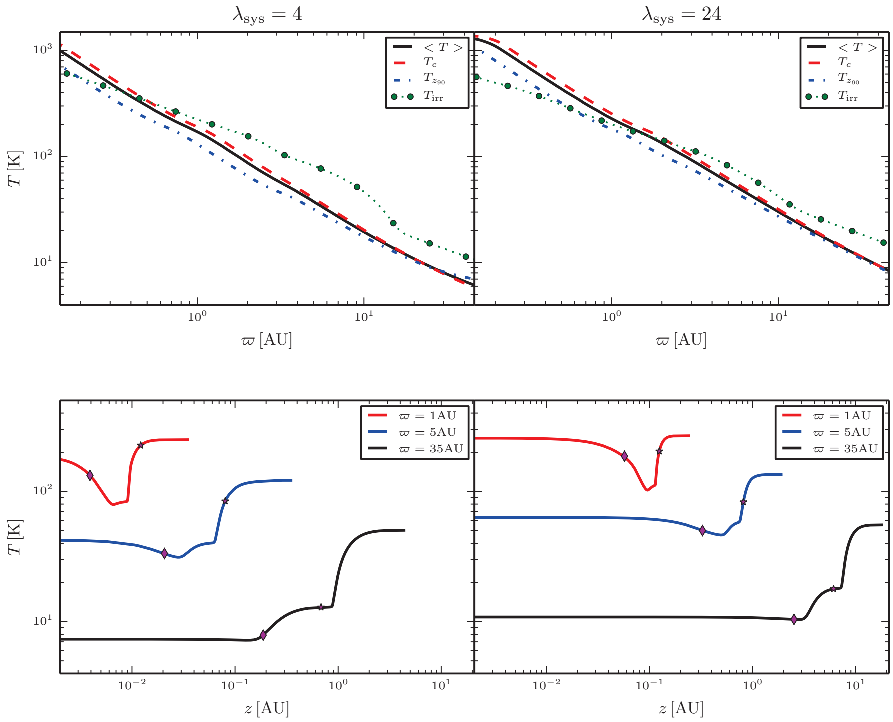


**Fig. 1.** T Tauri disks with mass-to-flux ratios $\lambda_{\rm sys}$ = 4 and 24. The upper panels show the radial temperature profiles: the solid black lines correspond to the mass weighted temperature $< T >$; the red dashed lines show the mid-plane temperature $T_c$; the blue dot-dashed lines show the temperature at the mass surface $z_{90}$; the green dot lines show the temperature at the irradiation surface $z_{\rm irr}$. The lower panels show vertical temperature profiles at different radii. The star symbol indicates the location of the $z_{\rm irr}$ and the diamond symbol indicates the location $z_{90}$.

number must be $P = \nu/\eta \sim 1/A >> 1$, where $A$ is the disk aspect ratio. In addition, these disks rotate with sub Keplerian speeds because the magnetic tension contributes to the radial force balance. Below we briefly discuss the structure and emission of these magnetized disks.

## 2. Vertical structure and emission

Lizano et al. (2016) studied the vertical structure of magnetized accretion disks subject to both viscous and resistive heating and irradiated by the central star. They considered three different types of disks around a low mass protostar, a T Tauri star, and an FU Ori star. They modeled disks with different levels of magnetization measured by the mass-to-flux ratio $\lambda_{\rm sys}$. They found that strongly magnetized disks with $\lambda_{\rm sys}$ = 4 are highly compressed by the magnetic pressure. In T Tauri disks the compression produces an aspect ratio $z/\varpi \sim 0.01$, ten times smaller than the value inferred from observations, indicating that a large amount of magnetic field has to be dissipated during the process of disk formation. Tapia and Lizano (2017) studied the emission of magnetized disks with $\lambda_{\rm sys}$ = 4, 12, 24 (see their Table 2). They calculated the spectral energy distribution (SED) and the antenna temperature profiles convolved with the highest resolution beam of ALMA (1 mm) and VLA (7 mm). They found that weakly magnetized disks (high $\lambda_{\rm sys}$) emit more than strongly magnetized disks (low $\lambda_{\rm sys}$) because the former are

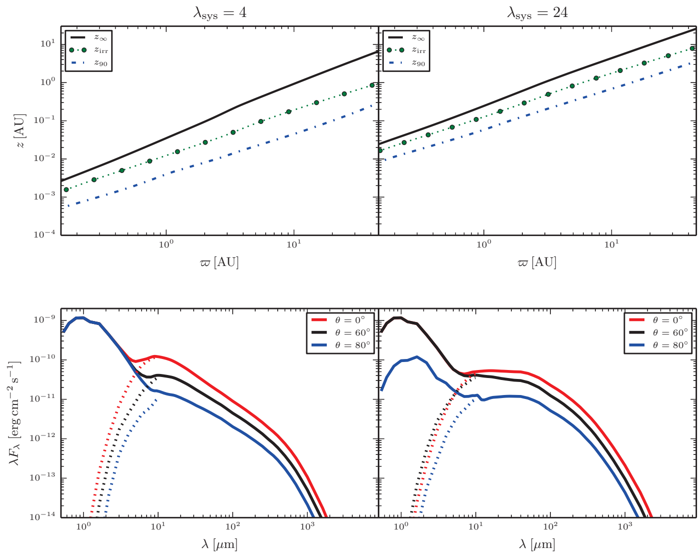


**Fig. 2.** In the upper panels the black solid lines show the surface of the disk $z_\infty$; the green dot lines show the irradiation surface $z_{\rm irr}$; the blue dot-dashed lines show the disk mass surface $z_{90}$. The lower panels show the SED of the star plus disk system at different inclination angles $\theta$. The dotted lines show the disk contribution.

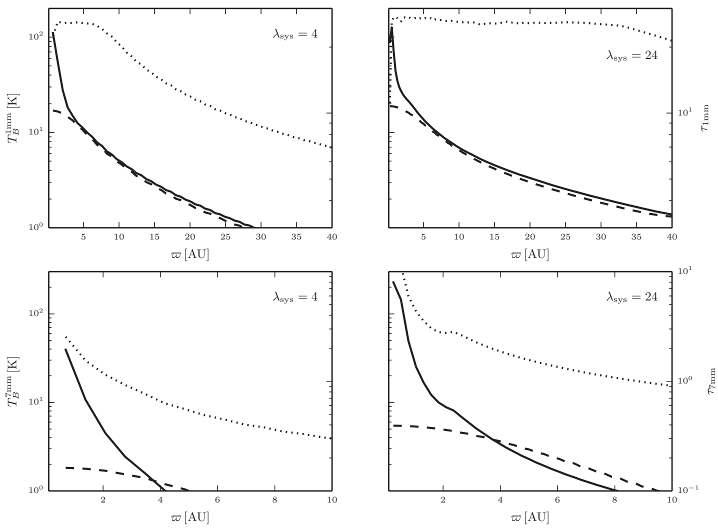


**Fig. 3.** Averaged antenna temperature $T_B$ and optical depth $\tau_\lambda$ profiles. The 1 mm and 7 mm profiles are shown in the upper and lower panels, respectively. The disk models have an inclination of $\theta = 60°$. The antenna temperature is averaged over ellipsoidal annuli with an eccentricity $\epsilon = \sin\theta$. The solid lines in each panel correspond to the antenna temperature profiles. The dashed lines correspond to the antenna temperature profiles convolved with the ALMA beam at 1 mm, $\theta_{ALMA} = 0.034''$, and the VLA beam at 7 mm, $\theta_{7\,mm} = 0.043''$, respectively. The dotted lines correspond to the optical depth, the values are shown in the left axis in each panel.

denser, hotter, and have larger aspect ratios, receiving more irradiation from the central star. These results are clear when one compares models with different levels of magnetization.

In the following figures we consider a strongly magnetized T Tauri disk with $\lambda_{\rm sys} = 4$ and a weakly magnetized T Tauri disk with $\lambda_{\rm sys} = 24$. The mass of the star is $M_* = 0.5 M_\odot$, the stellar radius is $R_* = 2 R_\odot$, the mass of the disk is $M_d = 0.03 M_\odot$, the disk accretion rate is $\dot{M}_d = 10^{-8} M_\odot {\rm yr}^{-1}$, and the viscosity coefficient is $D = 0.01$ (see discussion about this coefficient in Section 3.1 of Shu et al. 2007). The disk properties are shown in Table 2 of Tapia & Lizano (2017). To calculate the emission we assume a distance of 140 pc. The upper panels of Fig 1 show radial temperature profiles and the lower panels show vertical temperature profiles at different radii. One can see that the weakly magnetized disk is hotter than the strongly magnetized disk. The upper panels of Figure 2 show different disk surfaces: $z_\infty$, $z_{\rm irr}$, and $z_{90}$ (see caption). These surfaces are highly compressed in the strongly magnetized disk with $\lambda_{\rm sys} = 4$. The lower panels of this figure show the SEDs. The weakly magnetized disk with $\lambda_{\rm sys} = 24$ shows a partial occultation of the central star at a large inclination angle $\theta = 80^\circ$ due to the flaring of the outer disk. The upper panels of Fig 3 show the 1 mm and 7 mm averaged antena temperature profiles and the optical depth profiles. This figure shows that the weakly magnetized disk emits more and has a higher optical depth than the strongly magnetized disk. The magnetorotational instability (MRI) is assumed to be the source of the viscosity in accretion disks (e.g., Balbus & Hawley 1998). To operate, the MRI requieres a minimum level of ionization, too low ionization produces zones dead to the MRI. In these dead zones, the viscosity would have very low values, generating low accretion rates and low heating. Recently, Glassgold et al. (2017) modeled the deep-down ionization of accretion disks considering electrons, atomic ions, molecular ions, and negatively charged grains. These results can be used to determine the degree of ionization of the magnetized disks discussed here and the existence of dead zone regions. Such dead zones would affect the disk structure and heating, and therefore, its emission. These types of models will be the subject of a future study.

## 3. Conclusions

We discuss the structure and emission of protoplanetary disks threaded by a poloidal magnetic field dragged from the parent cloud core during the process of disk formation. We examine how the level of magnetization affects the structure and emission of these disks.

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