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JET EMITTING VS. STANDARD ACCRETION DISKS

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Abstract.
The structure of accretion disks is a fundamental issue regarding star and planet formation. Many theoretical studies, focusing on different aspects, have been conducted in the context of the Standard Accretion Disk (SAD) model, where no jet is present. We aim at calculating the structure of YSO accretion disk in an approach that takes into account the presence of the protostellar jets. The radial structure of this Jet Emitting Disk (JED) should then be compared to that of standard accretion disks. The analytical treatment used in this work is very similar to that of standard accretion disks but is using the parameter space of the Magnetised Accretion-Ejection Structures (MAES) to include the effects of the jet on the disk. In this framework, the analytical expressions of key quantities, such as mid-plane temperatures, surface densities or disk aspect ratio can be derived. It is found that JED are both thinner and lighter than SAD. The way this may affect planet formation and migration is briefly addressed.

1 Introduction

Accretion disks are ubiquitous in the Universe. From the theoretical point of view, accretion disks have been extensively studied in the context of the Standard Accretion Disk model (SAD) (Pringle & Rees, 1972; Shakura & Sunyaev, 1973; Pringle, 1981), be it for Active Galactic Nuclei (AGN) or Young Stellar Objects (YSO). Despite the many refinements included in the current models, the basic idea of the *standard* theory is still that of the first seminal papers: the gas inward motion is ensured by the radial turbulent transport of angular momentum from the inner to the outer parts of the disk.

However, it now appears very clearly that disk accretion onto a central object and bipolar ejections (observed in AGN, X-ray binaries, YSO or brown dwarfs) cannot be disentangled. It is believed that accretion powers the jets which, in turn, vertically remove part of the disk angular momentum allowing accretion to proceed. Despite the advances in the standard theory of accretion disks, the latter does not provide any explanation to the production of jets.

In the remaining of this paper, we will focus on YSO only. Several models have been developed to explain the jets seen in TTauri stars. Stellar winds have been invoked (Sauty et al., 2002) and may be present in the inner parts of the jets but cannot sustain the observed mass rates (Ferreira et al., 2006). To date, two accretion powered wind models exist: i) the X-wind model (e.g. Shu et al., 2000) and the ii) extended disk wind model (e.g., Ferreira, 1997). Both models are based on the same mechanism, the so-called magneto-rotational launching (Blandford & Payne, 1982). They only differ by the origin and configuration the magnetic field threading the disk and the size of the launching region. Higher angular resolution observations are needed to provide a definite answer regarding the process(es) at play. However, Ferreira et al. (2006) have gathered indirect evidence that appears to favor extended disk wind theories. About 30% of TTauri stars present bipolar ejection. This percentage increases to 100% for Class 0 objects, the earliest stage of star formation. If the jets are indeed accretion powered then the jets must affect the structure of the underlying region of the disk responsible that launches them. Therefore, the standard theory of accretion disk cannot be used in this region where part of the angular momentum is also vertically transported away.

In this work, the structure of Jet Emitting Disk (JED) and is calculated and compared to that of SAD. The paper is organised as follows:

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- In Sec. 2, we briefly present the framework of the Magnetized Accretion Ejection Structures (MAES) and how it is included in the calculation of the disk structure.
- The results, and in particular a comparison between the two (jet emitting and standard) types of accretion disks, are presented in Sec. 3.
- Before concluding, Sec. 4 raises a few issues and focusses on the possible implications of the existence of JED with regard to planet formation and migration.

2 Theoretical background

The Magnetised Accretion Ejection Structures model (Ferreira, 1997; Ferreira & Casse, 2004) has been developed so as to treat consistently both the accretion disk and the jet it generates. This differs drastically from the more classical approach for extended disk winds (initiated by Blandford & Payne, 1982) where the disk is only treated as a boundary condition, hence forbidding any quantification of the effect of the MHD wind on the disk. As for the standard theory of accretion disks, the MAES model is based on turbulent viscosity to which is supplemented a turbulent driven resistivity for the transport of the magnetic field. They are both phenomenologically parametrised using the standard *alpha*-prescription (Shakura & Sunyaev, 1973).

We are interested in deriving the radial structure of a JED, i.e. a disk that is launching a jet. We make the assumption of a geometrically thin, optically thick steady-state disk, rotating at Keplerian velocity, i.e. with a frequency $\Omega_K = \sqrt{GM_\star/r^3}$. We also assume that the accretion rate $\dot{M}_a$ does not depend from the distance to the central object. This is justified since solutions to the MAES problem give $\dot{M}_a \propto r^\xi$, with the ejection index $\xi \sim 10^{-3}$– 5×10^{-1} (Casse & Ferreira, 2000). We also assume the gas and the dust to be well coupled, at the same temperature, and that the mixture behaves as an ideal gas. The approach presented hereafter is common to most accretion disk structure studies but for the fact that the problem is parametrised in order to have the key MAES parameters to appear in the equations. Different values of these parameters will correspond either to the SAD or to the JED configuration.

Integrated over the thin disk, the hydrostatic equilibrium of the disk defines its scale height h. Using the perfect gas equation of state, the aspect ratio of the disk $\epsilon = h/r$ reads:

$$\epsilon^2 = \frac{k_B T_0}{\bar{\mu} m_p \Omega_K^2 r^2} , \tag{2.1}$$

where k_B is the Boltzmann constant, $\bar{\mu}$ the mean molecular weight of the gas and m_p the proton mass.

Defining u_0 to be the inward radial velocity of the flow, one can simply calculate the density as

$$\rho_0 = \frac{\dot{M}_a}{4\pi r h u_0} = \frac{\dot{M}_a}{4\pi \Omega_K r^3} \frac{1}{m_s \epsilon^2} , \tag{2.2}$$

where m_s is the sonic Mach number. The latter is found to be of the order of unity in MAES solutions whereas SAD inward motions are largely subsonic.

The heating term Q^+ can be written in a generic form as

$$Q^+ = f \times \frac{GM_\star \dot{M}_a}{8\pi r^3} , \tag{2.3}$$

where f represents the fraction of gravitational potential energy that is used to heat the gas. For this work, the gas is only locally heated by viscous effects and any other source of heating, such as irradiation, are discarded. We will take $f_{\mathrm{SAD}} = 1$ when calculating the SAD for comparison to the JED. For the latter, however, most of the potential energy escapes with the jet and only a small fraction contributes to the viscous heating. In the MAES context, it can be shown (Casse & Ferreira, 2000) that

$$f_{\mathrm{JED}} \approx \epsilon \ll 1 , \tag{2.4}$$

meaning that there is much less energy available for the disk heating than in the SAD model.

As for the cooling, we assume that the disk radiates like a black body with an effective temperature $T_{\rm eff}$, which leads to (Hubeny, 1990)

$$Q^- = \sigma T_{\rm eff}^4 \approx \frac{3\sigma}{8\tau} T_0^4 \ , \tag{2.5}$$

where the optical depth $\tau \approx \kappa \rho_0 h$ links the effective temperature $T_{\rm eff}$ to the mid-plane temperature T_0 *via* the opacity of the gas κ. For the latter, we adopt the standard $\kappa = \bar{\kappa} \rho_0^a T_0^b$ prescription, where $\bar{\kappa}$, a and b are taken from Bell & Lin (1994) and adjusted to the relevant opacity regime.

Equaling the heating and cooling terms established previously, one can express all disk quantities as a function of the distance to the central star. In particular using Eq. (2.1) and (2.2), the disk height scale, density (hence surface density $\Sigma = 2h\rho$) and temperature are determined analytically.

3 Results

Any disk quantity (see above) is obtained under the form

$$X(r) = f(M_\star, \dot{M}_a, \bar{\kappa}) \; r^{\eta(a,b)} \ , \tag{3.1}$$

where the normalizing function depends on the problem parameters and the exponent η on a given opacity regime.

Disk winds rely on the existence of a large scale magnetic field threading the disk. One important result obtained by the MAES model is that the solutions require a magnetic field close to equipartition ($B^2/\mu_0 P \in [0.1, 1]$). This characteristic, confirmed by numerical simulations (Zanni et al., 2007), allows us to give an estimate of the magnetic field strength from our knowledge of the density and temperature of the gas in the JED.

The results are given in Fig. 1. The miplane temperature (upper left), surface density (upper right), disk aspect ratio (lower left) and magnetic field strength (lower right) are plotted as a function of the distance to the central object. We chose the inner truncation radius to be located at 0.04 AU. The solid lines correspond to the JED whereas the dashed line is for a SAD. The latter does not appear in the magnetic field panel as the standard theory of accretion disk is a purely hydrodynamical approach.

All quantities scale, by construction, as broken power laws, each segment corresponding to a given opacity regime of Bell & Lin (1994). Disks with high accretion rates also have the higher temperatures and need to take into account more opacity regimes. For large $\dot{M}_a$, icy dust dominates the cooling of the outer parts whereas it is molecular cooling that control the most inner regions. Note that for the JED, the solution is stopped beyond the distance where it becomes optically thin to its own radiation, hence invalidating Eq. (2.5). The higher the accretion rate, the wider the valid radius range. For a SAD, the optically thick approximation holds throughout the spatial domain.

It is of interest to compare, for a given accretion rate, the SAD and JED disk structure. On the figure, this is illustrated for the highest accretion rate only, so as to prevent overlapping curves but these results hold for smaller accretion rates. The SAD solution has been obtained using the standard value $\alpha_v = 10^{-2}$ for the turbulence prescription (Shakura & Sunyaev, 1973). It is found that standard disks are warmer, denser and thicker than their JED equivalent[1]. The effect of the jet torque is particularly important for the disk surface density: the JED and the SAD differ by two orders of magnitude.

From the equipartition property of the MAES solutions, we have estimated the magnetic field strength of the JED (Fig. 1d). The observation of magnetic fields is a very difficult task and no measurements have been obtained so far in disks where the system is known to drive jets. However, Donati et al. (2005) have managed to measure the magnetic field strength in the disk of FUOr, a very strong accreting object with $\dot{M}_a \sim 10^{-5} {\rm M}_\odot$ yr^{-1}. They found a value of $B \sim 1$ kG at 0.05 AU from the star, which is larger than what equipartition requires, one order of magnitude larger than our JED value. As no jet is observed in FUOr, this is consistent with the analytical and numerical models of MAES which have shown that a field close to—but smaller than—equipartition was required to launch a jet (Zanni et al., 2007).

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[1] This stays true for higher and smaller value of α_v.

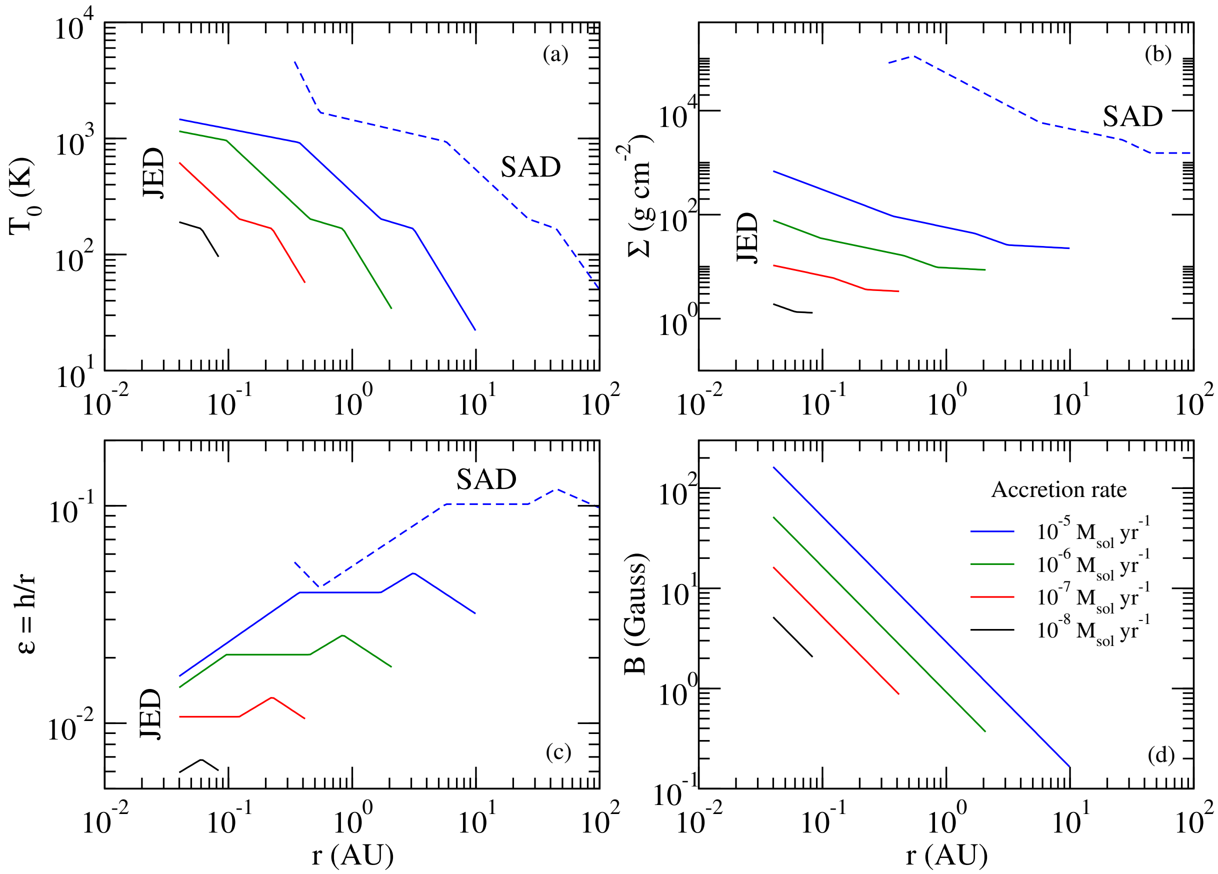

Fig. 1. Radial variation of key disk quantities. *Upper-left:* mid-plane temperature. *Upper-right:* Surface density. *Lower-left:* Aspect ratio of the disk. *Lower-right:* Magnetic field intensity. Accretion rates from 10^{-8} to $10^{-5} M_\odot$ yr^{-1} are considered. Solid lines correspond to a JED and the dashed line to a SAD (at $10^{-5} M_\odot$ yr^{-1}).

The structure of jet emitting disks is very different from that of standard accretion disks. Their emission properties should also be different and are further investigated elsewhere (Combet & Ferreira, submitted)[2] .

However, some possible effects on planet formation and migration are inferred below.

4 Discussion

The initial conditions for planet formation depend on the disk structure and physical properties. It has been shown in the previous section that the latter are very different between from a JED to a SAD. We discuss, hereafter, two of the possible consequences that a jet emitting region of the disk may have on planet formation.

Gammie (1996) was the first to present the idea of *layered accretion disks*where the upper part of the disk is ionized—via collisions, cosmic rays or X-rays—and some embedded inner part remains neutral. The latter, termed *dead zone* is then decoupled from the magnetic field, hence to the MRI[3] induced turbulence, and stays quiescent. We have shown in the previous section that jet emitting disks were both thinner and lighter than standard disks. As a consequence, JED are likely to be more ionized than SAD as radiation from the central star and cosmic rays should penetrate them more deeply. The calculation of the actual ionization degree of JED is postponed to a forthcoming study, which should give a quantitative answer to the possibility of a dead

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[2] The main point is that the spectral energy distribution of a disk will present a “hole” if a JED occupies the disk’s inner regions (and a SAD the outer regions) compared to the case of a SAD being present on the entire spatial range.

[3] The Magnto-Rotational Instability is, to date, the best candidate to generate and sustain the required level of turbulence in accretion disks.

zone in a JED. Dead zones appears to be a very important ingredient with regard to dust settling (Fromang & Papaloizou, 2006; Ciesla, 2007) and thus to planet formation. It is then relevant to wonder if JED could host the earliest stages of planet formation.

Jet emitting disks, and in particular the transition between an inner JED to an outer SAD may also have important consequences on type I planet migration. Indeed, Masset et al. (2006) have shown that a surface density jump in the disk could trap planetesimals at the location of the transition. Once a planetesimal is in the trap, the resonances it creates may stop the migration of other bodies on larger orbits. As seen in Fig. 1b, the transition between an inner JED to an outer SAD would naturally provide such a density jump. The location of this planetary trap would then be that of the jet outer radius.

5 Conclusion

The existence jets and the very likely launching from accretion disks invalidate the use of the standard theory for the launching region. The results of the MAES model have been used along a very simple analytical formulation that allow to take into account the jet in the disk structure calculation. We showed that strong differences exist between the two types of disks: jet emitting disks have been found thinner, lighter and cooler than standard disks at the same accretion rate. This may have important consequences on planet formation and migration and should be further investigated.

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