ACCRETION IN PROTOPLANETARY DISKS: THE IMPRINT OF CORE PROPERTIES

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ABSTRACT

In this Letter, we present a theoretical scenario to explain the steep correlation between disk accretion rates and stellar masses observed in pre–main-sequence stars. We show that the correlations and spread observed in the two best-studied regions, $\rho$ Oph and Taurus, can be reproduced by a simple model of single-star formation from a rotating collapsing core and the viscous evolution of the circumstellar disk. In this model, the rate of rotation of the parent core sets the value of the “centrifugal radius” within which the infalling matter is loaded onto the surface of the disk. As a consequence, the disk accretion rate measured long after the dispersal of the parental core bears the imprint of the initial conditions of star formation. The observed trend results naturally if, at the onset of the collapse, cores of all masses rotate with the same distribution of angular velocities, measured in units of the breakup rotation rate.

Subject headings: accretion, accretion disks — dust, extinction — stars: formation

Online material: color figures

1. INTRODUCTION

Young stars are surrounded by disks for a large fraction of their pre–main-sequence evolution. The accretion of material from such disks controls the disk properties and its evolution with time. Measurements of the mass accretion rate onto the star ($\dot{M}_{\text{acc}}$) were obtained for T Tauri stars (TTSs) in Taurus several years ago, showing a large spread of $\dot{M}_{\text{acc}}$ for stars of similar properties (Gullbring et al. 1998).

The discovery of disks around very low mass stars and brown dwarfs (BDs) and the measurements of the accretion rate in these disks has provided an unexpected result, namely, that underlying the known large spread, there is a steep dependence of $\dot{M}_{\text{acc}}$ on the mass of the central object, roughly as $\dot{M}_{\text{acc}} \propto M^{1.8}$ (Muzerolle et al. 2003; Natta et al. 2004). This correlation only became clear when a sufficiently large interval of stellar mass $M_*$ (roughly 2 orders of magnitude) was accessible to observations.

The physical origin of this correlation is unknown. There have been a number of suggestions that it may be due to mass-dependent stellar properties, such as its X-ray luminosity, which may affect the disk physical conditions and the angular momentum transfer (e.g., Muzerolle et al. 2003; Mohanty et al. 2005; Natta et al. 2006b). Padoan et al. (2005) proposed a scenario of Bondi-Hoyle accretion to explain it. Alexander & Armitage (2006) showed that the observations can be accounted for by disk viscous evolution if the ratio of the disk to stellar mass at the end of the core collapse is fixed, but the viscous timescale is proportional to $1/M_*$; they then interpret the spread of $\dot{M}_{\text{acc}}$ values as an age effect.

In this Letter, we propose a different, somewhat more basic scenario. We follow the collapse of a rotating molecular cloud core and the simultaneous viscous evolution of the resulting disk. When we assume that cores of vastly different mass have similar rotation rates measured in units of their breakup rate, a trend of $\dot{M}_{\text{acc}} \propto M^{1.8 \pm 0.2}$ is naturally reproduced. The width of the correlation can, in this very simple model, be traced back to a spread in core rotation rates. In this way, the $\dot{M}_{\text{acc}}$ measured in the pre–main-sequence phase bears an imprint of the original core properties, as was already discussed qualitatively by Natta et al. (2006b).

2. DATA

Disk mass accretion rates have been measured in many objects in star-forming regions. In two regions, Taurus and $\rho$ Oph, they are known for a large number of objects, ranging in mass from a few solar masses to brown dwarfs. The $\rho$ Oph sample (Natta et al. 2006b) includes almost all the class II objects (i.e., objects with circumstellar disks) in the region, selected from their mid-IR excess; the accretion rate is measured from the luminosity of the infrared hydrogen recombination lines. The Taurus sample is more heterogeneous, including classical TTSs for which the mass accretion rate has been determined from the optical and UV veiling as well as a number of optically selected BDs where it has been derived by fitting the H$\alpha$ profiles with magnetospheric accretion models (see Muzerolle et al. 2005 and references therein) or from the Ca IR lines (Mohanty et al. 2005). The presence of a disk in the BDs is not always known. A comparison of the results in $\rho$ Oph and Taurus can be found in Natta et al. (2006b). The accretion rates turn out to be very similar in the two regions; the relation between $\dot{M}_{\text{acc}}$ and $M_*$ has practically the same slope ($\dot{M}_{\text{acc}} \propto M^{1.8 \pm 0.2}$), and the range of values for any $M_*$ is comparable. The only difference appears in the BD regime, where Taurus seems to lack high accretors. Given the different selection criteria for BDs in the two regions (optical colors vs. infrared excess), and the uncertainty of the $\dot{M}_{\text{acc}}$ estimates in the BDs, it is currently difficult to evaluate the significance of this.

3. MODEL

Our model is quite similar to the model described by Hueso & Guillot (2005, hereafter HG05; see also Nakamoto & Nakagawa 1995). It has previously been used in the context of a theoretical study of the crystallinity of dust (Dullemond et al. 2006). In this section, we describe briefly the model for the
collapsing cloud and disk evolution, and refer for more details to Dullemont et al. (2006) and HG05.

3.1. Collapsing Cloud

We start with a core with temperature $T$, turbulent velocity dispersion $\Delta v$, mass $M_{\text{core}}$, and solid-body rotation rate $\Omega$ (radius $-1$). We assume that the core forms a single star surrounded by a disk. For simplicity, we assume the core to be a singular isothermal sphere (Shu 1977). After onset of collapse (at which time we set our clock to $t = 0$), the infall rate is $M_{\text{infall}} = 0.975 \xi^3 G(M_{\text{core}}/R_{\text{core}})^{3/2}$, where $\xi$ is a factor, the effective sound speed, which combines the thermal and turbulent pressure. In the Shu model here, the infall rate stays steady until the mass $M_{\text{core}}$ has accreted onto the star+disk system, and then it abruptly stops.

The original core has a solid-body rotation rate $\Omega$, which is slower than the breakup rotation rate $\Omega_{\text{break}} = (GM_{\text{core}}/R_{\text{core}})^{1/2}$, where $R_{\text{core}}$ is the radius of the core. According to the singular isothermal sphere model, this radius is $R_{\text{core}} = GM_{\text{core}}/2\xi^2$, so the breakup rotation rate can be written as $\Omega_{\text{break}} = 2\xi^2 GM_{\text{core}}/R_{\text{core}}$.

On collapse, the core will spin up due to the conservation of angular momentum, leading to the formation of a disk. The infalling matter falls onto the disk within the centrifugal radius $R_{\text{centr}}(t)$, which increases with time as $R_{\text{centr}}(t) \propto t^2$ until the end of the infall phase. In the following, we name the final (maximum) $R_{\text{centr}}(t)$ to be the centrifugal radius of the cloud. This radius is $R_{\text{centr}} = \Omega^2 R_{\text{core}}^3 / GM_{\text{core}}$.

$R_{\text{centr}}$ can be expressed in terms of the dimensionless rotation rate $\omega = \Omega/\Omega_{\text{break}}$: $R_{\text{centr}} = \frac{GM_{\text{core}}}{2\xi^2} \omega^2$. (1)

In our calculations, we assume that the range of possible values of $\omega$ is the same for cores of very different mass, or in other words, that the range in ratios of rotational energy over gravitational energy is independent of core mass. This means that small, low-mass cores have lower values of $\omega$ than big, high-mass ones.

An important consequence of this assumption is that, for a given value of $\omega$, larger mass stars form from cores with larger centrifugal radii. This will turn out to play an important role in the $M_{\text{acc}} - M_*$ relation that follows from the model, as we discuss below.

3.2. Disk Formation and Evolution

As matter from the core accretes onto the disk, the disk itself evolves, expanding outward. The surface density $\Sigma(R, t)$ changes with time, while matter continues to fall onto the disk within $R_{\text{centr}}(t)$ (see HG05). The disk evolution continues after the core has disappeared, until it has entirely accreted onto the star. The radial velocity $v_R$ is proportional to the viscosity coefficient $\tau = \alpha k T_\text{mid} / \mu m$, $\Omega_K$. Here $\alpha$ is the parameter of viscosity (Shakura & Sunyaev 1973), which we take to be constant, $T_\text{mid}$ is the midplane temperature, and $\Omega_K$ is the Keplerian frequency. The midplane temperature is determined by taking into account the heating due to viscosity and to irradiation by the central star and by the accretion shock. We include an effective viscosity caused by gravitational instabilities in regions where the Toomre parameter drops below unity.

The evolution with time of the star+disk+core system is discussed in detail in HG05. At time $t_0$, when the core has accreted completely onto the star+disk system, the ratio of the disk to the stellar mass is an increasing function of $R_{\text{centr}}$, its exact behavior depends on the interplay of the infalling matter with the viscous evolution of the disk. If one forces $R_{\text{centr}}$ to be independent of $M_{\text{core}}$, then $M_{\text{disk}}(t_0) \propto M_{\text{core}}$ as expected; if, in equation (2), $R_{\text{centr}} \propto M_{\text{core}}$, we find that the disk mass increases approximately as $M_\ast^2$. The following disk evolution at time $t \gg t_0$ is approximately self-similar (see, e.g., Hartmann et al. 1998), so that at any given time $t \gg t_0$ the accretion rate is to zero order proportional to $M_{\text{disk}}$.

4. RESULTS

4.1. Model Parameters

Since we wish to compare our model results to the Taurus and Ophiuchus samples, we need to choose core properties appropriate for these regions. The average measured line widths (Myers & Benson 1983; Belloche et al. 2001) lead to infall rates of $M_{\text{infall}} \approx 10^{-5} M_\odot \, \text{yr}^{-1}$ ($\tilde{\xi} = 0.35 \, \text{km s}^{-1}$) in Taurus and $M_{\text{infall}} \approx 3 \times 10^{-5} M_\odot \, \text{yr}^{-1}$ ($\tilde{\xi} = 0.5 \, \text{km s}^{-1}$) in Ophiuchus. We shall take these two values as representative for these two star formation regions. The ages of stars in Ophiuchus and Taurus show a peaked distribution with median values of $0.5$ and $\sim 1$ Myr, respectively; with a small tail of objects at older ages (Palla & Stahler 2000). With these typical ages and the mass infall rates chosen above, the star formation timescale is always much shorter than the age of the system. This is consistent with the lack of correlation between spectral type and stellar age in both regions.

With $\tilde{\xi}$ chosen at some representative value, and $M_{\text{core}}$ varied to cover a range of masses between 0.03 and 2.5 $M_\odot$, the only remaining parameters of the model are $\alpha$ and $\omega$. Rotation rates are measured in a limited number of cores, in general more massive than the cores considered here. The measurements are consistent with $\omega$ in the range 0.03–0.5, but there is a large fraction ($\sim 70\%$) of nondetections (Goodman et al. 1993; Belloche et al. 2001). In this Letter, we vary $\omega$ between a very low value (0.01) and a rather large one (0.3) and investigate the effect of this parameter on the $M_{\text{acc}} - M_*$ correlation.

Finally, we chose for the viscosity parameter $\alpha$ the value 0.01, which has been argued to fit well the properties of TTS disks (Hartmann et al. 1998), but it remains a very uncertain parameter because the physics of the anomalous viscosity of disks is not yet fully understood.

4.2. Results for the $M_{\text{acc}} - M_*$ Relation

Figure 1 compares the model results to the observations for Taurus (left panel) and $\rho$ Oph (right panel). Each line corresponds to fixed $\omega$ and fixed $M_{\text{infall}}$ and time, as discussed before. For each $\omega$, the models predict a relation between $M_{\text{acc}}$ and $M_*$ roughly as $M_\ast^{1.8}$, which is in very good agreement with the trend in the data. Lower values of $\omega$ give lower values of $M_{\text{acc}}$ for fixed $M_*$, and we find that values between 0.3 and $\leq 0.01$ can account for the spread of observed $M_{\text{acc}}$ at all $M_*$. The slope of the correlation $M_{\text{acc}} - M_*$ is practically independent of the exact values of any of the model parameters. However, the value of $M_{\text{acc}}$ for any given $M_*$ depends on the value of the parameters. A spread in age, $M_{\text{infall}}$, or $\alpha$ among objects...
in a region introduces a spread in the values of $M_{\text{acc}}^\ast$ for a given $M_\ast$. From our model results, however, we estimate that the observed spread in $M_{\text{acc}}$ is likely dominated by the spread in $\omega$: $M_{\text{acc}}^\ast$ is not a strong function of $M_{\text{ini}}$ or $Q$ (less than linear). It decreases significantly with time (roughly as $t^{-1.7 \ldots 1.8}$), but the observed spread of more than 2 orders of magnitude (in both regions) requires that the objects are homogeneously distributed over a factor $\sim 20$ in age; this is much more than observed, since only few objects in each region have ages so different from the median values (Palla & Stahler 2000).

5. DISCUSSION

The models presented in this Letter account very well for the observed correlation between $M_{\text{acc}}^\ast$ and $M_\ast$ in both star-forming regions. Note that the model parameters have not been adjusted to fit the data but are chosen a priori from independent observational evidence.

The general agreement with the slope $M_{\text{acc}}^\ast \propto M_\ast^{-1.8}$ is recovered for all values of the infall rate, age, etc., as long as $\omega$ is the same for cores of all masses. This is a direct consequence of the dependence of the centrifugal radius on $M_{\text{core}}$ (eq. [2]), as the accretion rate in the disk depends on the mass reservoir in the outer disk. If we assume $R_{\text{centr}}$ independent of $M_{\text{core}}$, we recover the well-known result that $M_{\text{acc}}^\ast$ is roughly proportional to $M_\ast$.

The scenario we propose has a number of implications, which can be tested. First, we assume that the same formation process holds for objects differing in mass by 2 orders of magnitude, from intermediate-mass stars to BDs. If so, cores capable of forming very low mass objects must exist in star-forming regions, with infall rate and $Q$ on average similar to that of more massive cores. Our conclusion that the spread of the measured $M_{\text{acc}}^\ast$ is due to a comparable spread of the angular momentum at the onset of the collapse and that cores of very different mass may rotate at the same fraction of the breakup speed can also be tested by future observations.

Our models predict that the disk mass must depend strongly on the mass of the central object (roughly as $M_\ast^{2}$) and should be tightly correlated with $M_{\text{acc}}$. A significant number of disk mass measurements exist only for the Taurus sample and are shown in Figure 2. They have been derived for TTSs by Andrews & Williams (2005) by fitting submillimeter and millimeter fluxes with simple disk models assuming a normalization of the dust opacity of $10^3$ cm$^2$ g$^{-1}$ at 300 m and a gas-to-dust mass ratio of 100. For BDs, we show the recent measurements of Scholz et al. (2006), normalized to the same value of the opacity. While the distribution of the disk masses as a function of stellar mass does not conflict with the model predictions, the expected correlation with $M_{\text{acc}}$ is not seen in the data. Uncertainties in $\bar{\Omega}$, age and $Q$ will likely spread our models but will not undo the general predicted trend. Therefore, there appears to be a disagreement between the models and the observations in this respect. This may be an argument against our model. However, measurements of disk masses are severely affected by our ignorance of the dust properties (Natta et al. 2006a), of the gas-to-dust ratio, and of their dependence on disk and stellar

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Fig. 1.—Mass accretion rate $M_{\text{acc}}$ as function of the mass of the central object $M_\ast$ in Taurus (left panel) and $\rho$ Oph (right panel). Symbols are measured quantities or upper limits. Each line is a model series for fixed $\omega$, as labeled, varying $M_{\text{ini}}$. In all model series, $M_{\text{ini}}$ and the snapshot time are kept constant ($10^{-7} M_\odot$ yr$^{-1}$ and 1 Myr in Taurus and $3 \times 10^{-8} M_\odot$ yr$^{-1}$ and 0.5 Myr in $\rho$ Oph). [See the electronic edition of the Journal for a color version of this figure.]

Fig. 2.—Disk masses as function of $M_\ast$ (top panel) and of $M_{\text{acc}}$ (bottom panel) for the Taurus sample; binaries unresolved in the millimeter observations have not been included. Only a few of the Taurus BDs shown in the top panel have measured $M_{\text{acc}}$ and appear in Fig. 1 and in the bottom panel. Lines are the same as in Fig. 1. Note that all models practically overlap in the bottom panel. [See the electronic edition of the Journal for a color version of this figure.]
properties. In addition, in the BD case one should note that the
current millimeter detections are still very uncertain and prob-
ably represent the outliers of the real distribution (Scholz et al.
2006).

The very simple models used in this Letter neglect several
important aspects of the star formation process, in particular
the formation from a collapsing core of multiple systems rather
than single stars. A survey of disk accretion rates of binary
TTs in Taurus (White & Ghez 2001) shows that \( M_{\text{acc}} \) of the
primaries does not differ from that of single stars; Figure 1
includes a number of binaries, in which both components are
accreting, and we find that for both primary and secondary
\( M_{\text{acc}} \) is well within the range of single stars with the same mass.

In the context of our models, this is possible if the original
core breaks into fragments that evolve independently, with a
distribution in \( \omega \) similar to that of the cores from which single
stars form. However, we point out that the majority of the
objects in Figure 1 are single, and for them the core-collapse
models we use should be appropriate.

The similarity between the \( M_{\text{acc}}-M_\ast \) properties of Taurus and
Ophiuchus originates, in our model, from a compensation be-
tween older age and lower \( M_{\text{infall}} \) for Taurus. To disentangle
these effects, one needs to measure \( M_{\text{acc}} \) in older star-forming
regions, where the age effect may become important. This will
be challenging, as fewer stars should be accreting at a detectable
rate, and very low mass objects will very likely be below the
detection limit. However, checking if the upper envelope of
\( M_{\text{acc}} \) is consistent with our predictions will be important.

The model we propose explains the properties and evolution
of disk accretion entirely as a result of the initial condition for
star formation and the disk viscous evolution. We neglect other
processes, such as intermittent accretion, photoevaporation,
variability of the X-ray emission from the central star, etc.,
which may affect at some level the snapshot measurements of
\( M_{\text{acc}} \), but we claim that they do not control the basic observed
trends.

6. CONCLUSION

In this Letter, we propose that the steep dependence of the
mass accretion rate on the mass of the central object, seen in
two star-forming regions of different age and properties (Taurus
and \( \rho \) Oph), results from the imprint of the initial conditions
for the formation of the star+disk system. A simple model of
disk formation and evolution from collapsing cores naturally
yields the \( M_{\text{acc}} \propto M_\ast^{1.8} \) relation, provided that cores of all mass
have a similar distribution of rotation rates in units of their
breakup speed. We show also that varying \( \omega \) within a range
consistent with the (few) existing observations could account
reasonably well for the large spread of observed at any
\( M_\ast \), even though other factors may also cause a spread. The
predicted correlation of \( M_{\text{acc}} \) with disk mass is not well repro-
duced by the data; this requires further investigations into the
disk model and the disk mass measurements.

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