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The role of angular momentum transport in establishing the accretion rate–protostellar mass correlation

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HIGHLIGHTS

- We model the mass accretion rate to stellar mass correlation.
- Gravitational torques are parameterized in terms of Toomre's Q criterion.
- The observed spread in mass accretion rates from 0.2–3.0 M⊙ is reproduced.
- Model populations are found to be coincident with their observational counterparts.

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ABSTRACT

We model the mass accretion rate $\dot{M}$ to stellar mass M_* correlation that has been inferred from observations of intermediate to upper mass T Tauri stars—that is $\dot{M} \propto M_*^{1.3\pm0.3}$. We explain this correlation within the framework of quiescent disk evolution, in which accretion is driven largely by gravitational torques acting in the bulk of the mass and volume of the disk. Stresses within the disk arise from the action of gravitationally driven torques parameterized in our 1D model in terms of Toomre's Q criterion. We do not model the hot inner sub-AU scale region of the disk that is likely stable according to this criterion, and appeal to other mechanisms to remove or redistribute angular momentum and allow accretion onto the star. Our model has the advantage of agreeing with large-scale angle-averaged values from more complex nonaxisymmetric calculations. The model disk transitions from an early phase (dominated by initial conditions inherited from the burst mode of accretion) into a later self-similar mode characterized by a steeper temporal decline in $\dot{M}$. The models effectively reproduce the spread in mass accretion rates that have been observed for protostellar objects of $0.2\,M_\odot \leq M_* \leq 3.0\,M_\odot$, such as those found in the ρ Ophiuchus and Taurus star forming regions. We then compare realistically sampled populations of young stellar objects produced by our model to their observational counterparts. We find these populations to be statistically coincident, which we argue is evidence for the role of gravitational torques in the late time evolution of quiescent protostellar disks.

1. Introduction

Protostellar disks are a ubiquitous outcome of the rotating collapse of dense molecular cloud cores in the standard paradigm of low-mass star formation (e.g., Terebey et al., 1984; Shu et al., 1987). Their existence has been confirmed around young stellar objects across a broad range in mass—from objects in the brown dwarf regime, to those with masses of up to $2-3\,M_\odot$ (e.g., Beckwith et al., 1990; Andrews and Williams, 2005)—as well as in a wide variety of star forming environments (e.g., Lada and Wilking, 1984; O'Dell and Wen, 1994; McCaughrean and O'Dell, 1996).

Numerical simulations of collapsing cloud cores reveal that disks can form within $\sim 10^4$ yr from the onset of core collapse (Yorke et al., 1993; Hueso and Guillot, 2005). These early so-called Class 0 systems are difficult to study observationally as they are still embedded within their progenitor cloud cores (André et al., 1993). Numerical simulations (e.g., Vorobyov and Basu, 2005b, 2006, 2010, 2015) suggest that the earliest periods ($\sim$0.5 Myr) of disk formation are rather tumultuous, as infall from the parent cloud core induces gravitational instability–driven mass accretion. Depletion of the gas reservoir by this mechanism then gives way to a much more quiescent period of accretion in which gravitational torques act to transport mass inward while transporting angular momentum outward (Gammie, 2001; Lodato and Rice, 2004; Vorobyov and Basu, 2007). Indeed, the subsequent Class I and II phases are respectively marked by a decline in the rate of accretion

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from the surrounding natal environment, and its eventual cessation (Vorobyov and Basu, 2005a). Hence, it is during the Class II phase, once the central star is optically visible, that the disk properties are most easily amenable to observational investigation.

One result to emerge from observational studies of young stellar objects and their disks is the correlation between protostellar mass M_* and the inferred accretion rate $\dot{M}$ from the disk, for which the power law exponent is typically estimated to be $\beta \sim 1.5 - 2.0$ (e.g., Muzerolle et al., 2005; Herczeg and Hillenbrand, 2008; Rigliaco et al., 2011). Although this correlation appears to hold across multiple orders of magnitude in both M_* and $\dot{M}$, fitting the accretion rates of brown dwarfs and T Tauri stars together may be misleading. In the brown dwarf regime, as well as for low mass T Tauri stars (i.e., those objects with mass $M_* < 0.2\,\mathrm{M}_\odot$), a least squares fit yields $\beta = 2.3 \pm 0.6$. For intermediate and upper mass T Tauri stars ($M_* > 0.2\,\mathrm{M}_\odot$), the equivalent fit yields a value for β of 1.3 ± 0.3; suggestive that different physical mechanisms may be responsible for accretion across the sequence of protostellar masses (Vorobyov and Basu, 2008).

Studies by Alexander and Armitage (2006) and Hartmann et al. (2006) have sought to explain the $\dot{M} - M_*$ scaling in the context of viscous models for the disk evolution, wherein the turbulent viscosity has ad hoc spatial dependence of the form $\nu \propto r^{\xi}$. Dullemond et al. (2006) link the disk evolution to the properties of the parent cloud core, providing a self-consistent basis for the results of their study. However, their models require that the ratio of rotational to gravitational energy be uniform across all cloud core masses. Rice and Armitage (2009) have even attempted to (weakly) incorporate the additional effects of magnetic fields (in high temperature regions of the disk) in quasi–steady state models, but were also unable to fully account for the observed correlation.

In this paper we present a study of the quasi–steady state evolution of viscous circumstellar disks surrounding young stellar objects, following the cessation of mass accretion onto the protostar-disk system (definitively Class II objects). These disks inherit initial conditions roughly consistent with the results of numerical simulations of the earlier burst phase (e.g., Vorobyov and Basu, 2005b; 2006; 2010; 2015), and undergo diffusive evolution wherein angular momentum redistribution is driven by self-gravity, which we parameterize in terms of an effective kinematic viscosity (following Lin and Pringle, 1987). We add to this a simplified argument for angular momentum conservation that correlates disk size with protostellar mass at the start of our simulations. With these assumptions, we are able to reproduce many features of the observed correlation between $\dot{M}$ and M_* for young protostellar systems.

Recent observations of disks using near-infrared polarization imaging (Liu et al., 2016) have found that disks around four recently outbursting (FU Ori) sources have large-scale (hundreds of AU) spiral arms and arcs that are consistent with models of gravitational instability. Added to previous near-infrared detections of spiral structure in smaller disks (e.g., Hashimoto et al., 2011; Muto et al., 2012; Grady et al., 2013), there is a growing realization that meaningful spiral structure, arcs, and gaps exist in Myr-old disks (see the review by Tamura (2016) on the SEEDS survey by the Subaru telescope). New efforts are being made to use gravitational instability driven disk evolution models to predict the near-infrared scattered light patterns as may be seen by the Subaru or Gemini telescopes, or the millimeter dust emission patterns that may be seen with the ALMA telescope (Dong et al., 2016). Furthermore, numerical simulations are also being extended to include long-term residual infall from the molecular cloud to the disk (even after the parent cloud core may have dissipated), which may be needed to keep gravitational instability active after several Myr (Vorobyov et al., 2015; Lesur et al., 2015). Our model in this paper studies gravitational torque driven evolution in a simplified manner. It does not however include residual mass infall from the cloud, which may be a subject of future work.

In this paper we seek to characterize the bulk of transport within the disk through the action of gravitational torques, in the same spirit as the models of e.g., Armitage et al. (2001) and Zhu et al. (2009); 2010). Our aim is to explain the global behavior of disks in which the mass accretion rate is predominantly set by the action of gravitational torques acting through most of the disk. Other accretion mechanisms may be necessary in the innermost sub-AU regions of the disk, possibly introducing short-term time variability. The above studies typicaly invoke the magnetorotational instability (Balbus and Hawley, 1991) as the transport mechanism in the hot inner disk, however it is worthwhile to keep in mind that the region $0.1 - 1.0\,\mathrm{AU}$ from the star is generally thought to be the outflow driving zone (e.g., Garcia et al., 2001; Krasnopolsky et al., 2003) from which significant amounts of angular momentum and mass are carried away from the disk.

2. Disk model

We construct a model for the temporal evolution of self-gravitating, axisymmetric thin disks on a radial grid with logarithmic spacing, and consisting of $N = 256$ annular elements. Discretization of the radial grid allows us to write the relevant partial differential equations as sets of ordinary differential equations, with one equation for each coordinate position in r. The spatial derivatives are approximated using second-order accurate central differencing. Integration of the system through time is handled using a variable order Adams–Bashforth–Moulton solver (e.g., Shampine, 1994).

2.1. Viscous evolution of an axisymmetric thin disk

Combining together the fluid equations for mass and momentum conservation yields a diffusion-like equation that governs the temporal evolution of the disk surface mass density $\Sigma(r, t)$ (e.g., Lynden-Bell and Pringle, 1974; Pringle, 1981):

$$\frac{\partial \Sigma}{\partial t} = -\frac{1}{r}\frac{\partial}{\partial r}\left[\left(\frac{\partial}{\partial r} r^2 \Omega\right)^{-1} \frac{\partial}{\partial r}\left(\nu r^3 \Sigma \frac{\partial \Omega}{\partial r}\right)\right], \tag{1}$$

where $\Omega(r, t)$ is the disk angular frequency (obtained assuming centrifugal balance), and ν is the effective kinematic viscosity (detailed in Section 2.2).

A precise determination of Ω requires a thorough accounting of the contribution to the gravitational potential made by the disk itself, which can be calculated explicitly using the elliptic integral of the first kind (e.g., Binney and Tremaine, 2008). However, the central point-mass dominates the system's gravitational potential, with the contribution from the disk increasing Ω only slightly. For the sake of computational convenience we thus adopt a simplified procedure by approximating the total gravitating mass at a radius r to be

$$M(r, t) = M_*(t) + 2\pi \int_{r_{\rm in}}^{r} \Sigma\, r'\, \mathrm{d}r', \tag{2}$$

in which $r_{\rm in}$ denotes the innermost radius of the simulation domain (and the assumed disk inner edge).

The action of (1) is to transport material within the disk to ever smaller radii, while a small fraction of disk material is simultaneously transported to larger radii, thereby preserving the system's total angular momentum. For these simulations, the disk edge $r_{\rm edge}$ is always $\ll r_{\rm out}$, the computational domain's outer boundary. Thus, material that exits the simulation can only do so through $r_{\rm in}$. We impose a free outflow boundary condition there, and any material crossing $r_{\rm in}$ is assumed to be accreted onto the central protostar, which we model as a point mass.