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Signatures of accretion in protostellar disks

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ABSTRACT

To be written

Subject headings: accretion, accretion disks — stars: formation

1. Introduction

For many years, observational constraints on dynamical models of protostellar disks were limited to broad-band spectral-energy distributions (SEDs), accretion rates as determined from excess emission on the blue side of the stellar photospheric emission, and inferences concerning the primordial solar nebula based on the present solar system. The recent harvest of infrared molecular spectra from observatories such as *Spitzer*, *Herschel*, Keck, and the VLT promises by the sheer number of bits involved to provide much more detailed constraints to modelers, if only one can interpret these new data intelligently **References here**.

A longstanding dynamical question is the nature of the mechanism responsible for extracting angular momentum from the accreting material. The main suspect is turbulence driven by the magnetorotational instability (MRI), but a difficulty with this mechanism is the very low ionization fraction of the disk gas, so that coupling to magnetic fields may be insufficient for MRI **many references here**. At distances of a few tenths to a few AU from the accreting low-mass protostar, it is believed that stellar X-rays and other nonthermal sources of ionization support MRI only in near-surface layers of the disk having typical column densities at 1 AU of order $10\,\mathrm{g\,cm^{-2}}$, much less than the total disk column(Gammie 1996; Glassgold et al. 1997; Bai & Goodman 2009, and references therein).

1.1. Energetics

As is well known, a razor-thin disk intercepts one quarter of the stellar luminosity, and The stellar flux impinging on one side of the disk at radius $r \gg R_*$ is $F_*(r) \approx L_* R_*/6\pi r^3$,

R_* and L_* being the photospheric radius and luminosity. The correction $2R_*/3r$ to the inverse-square law accounts for the grazing incidence of the rays. On the other hand, a disk accreting steadily at rate $\dot{M}$ radiates $F_{\rm acc} = 3GM\dot{M}/8\pi r^3$ in addition to any reprocessed stellar light. Since both fluxes scale as r^{-3}, there is a characteristic mass accretion rate at which the heat of accretion equals the irradiation. This is

$$\dot{M}_{\rm eq} = \frac{4}{9\pi}\frac{R_* L_*}{GM_*} \approx 4.5\times10^{-9}\left(\frac{L_*}{L_\odot}\right)\left(\frac{R_*}{R_\odot}\right)\left(\frac{M_\odot}{M_*}\right)\,\dot{\rm M}_\odot\,{\rm yr}^{-1}. \tag{1}$$

The typical accretion rate for classical T+Tauri stars is $\sim 10^{-8}\,\dot{\rm M}_\odot\,{\rm yr}^{-1}$, though with wide scatter and with strong dependence on the protostellar mass, $\dot{M} \propto M_*^2$ (Hartmann et al. 1998; Muzerolle et al. 2005; Fang et al. 2009). That eq. (1) should predict observed accretion rates is probably no coincidence. By selection, T Tauri have not yet reached the main sequence, so that their luminosities derive from gravitational contraction. It is therefore natural that their accretion timescales $M_*/\dot{M}$ should be comparable to their Kelvin-Helmholtz times.

However, protostellar disks are probably not flat but rather flaring, i.e. the vertical density scale height (H) increases faster than linearly with radius, and a flaring disk intercepts more of the stellar light than a flat disk would. Consequently, beyond a few stellar radii in the disk, the accretion power is locally rather small compared to the reprocessed emission. To illustrate this, the effective temperature corresponding to an accretion rate of $10^{-8}\,\dot{\rm M}\,{\rm yr}^{-1}$ onto a solar-mass star is only $85\,r_{\rm AU}^{-3/4}\,{\rm K}$. Infrared spectral-energy distributions clearly require higher temperatures than this, as can be achieved by a self-consistently flaring, passively reprocessing disk (Chiang & Goldreich 1997). Only in the boundary layer between the disk and the star should the accretion strongly outshine the reprocessed light, which is why boundary-layer emission is used to measure accretion rates.

As already noted, it would be useful to find emission that could be directly associated with accretion at larger radii, particularly at $r \sim 1\,{\rm AU}$ where MRI is most problematic. The net frequency-integrated emission coming from these larger radii is not very useful as an accretion diagnostic because of the dominant reprocessed light.[1] However, molecular lines observed in some systems appear to require that some fraction of the gas at $r \lesssim 1\,{\rm AU}$ is much hotter than would occur in a passively reprocessing disk if it radiated locally as a black body (Salyk et al. 2008; Carr & Najita 2008). The emitting gas is probably many density scale heights from the disk midplane, where the density is relatively low and cooling inefficient. To model the hot gas properly, one has to consider individual heating, cooling, and line-forming processes in some detail; the assumption of local thermodynamic

[1]except when the accretion rate temporarily rises far above $10^{-8}\,M_\odot\,yr^{-1}$, as may be the case in FU Orionis systems **references here**.

equilibrium (LTE) is inadequate. One finds that the main part of the stellar light, with a color temperature $\sim$ 4000–5000 K, cannot explain the high gas temperature. Instead, in a passively reprocessing model, the hot gas depends upon far-ultraviolet (and perhaps also X-ray) excesses in the stellar spectrum. Because T Tauri stars are chromospherically active, these excesses are strong but typically still less than one percent of the bolometric luminosity. Therefore, if the accretion process can efficiently heat the low-density, high-altitude gas, it might produce a signature in the molecular emissions that could be distinguished from purely passive reprocessing. This has been the motivation for our study.

1.2. Plan of the paper.

We use the ProDiMo code to model the microphysics of the disk gas, including non-LTE level populations, gas-dust interactions, radiative transitions, and radiative transfer. The features of this code are well documented by its authors (Woitke et al. 2009; Kamp et al. 2010; Woitke et al. 2011), though it is still actively developing. ProDiMo comes "out of the box" with a simple prescription for accretion heating, but this is characterized by a constant effective viscosity, corresponding to a constant heating rate per unit mass (dependent upon shear rate but independent of density and altitude) **They have since added a different treatment for the viscous heating by assuming an alpha parameter, computing the dissipation at a given radius based on Mdot, then distributing the heating in altitude as ρ^2.**

2. Disk Modeling with ProDiMo

2.1. ProDiMo

Insert a description of the code, the knobs tweaked, and extra modules (notably Xray) here.

2.2. Disk Structure

The structure of a disk is determined in ProDiMo entirely through five parameters: the mass of the disk $M_{\rm disk}$, the mass of the star $M_\star$, the inner radius of the disk $R_{\rm in}$, the outer radius of the disk $R_{\rm out}$, and the radial power law index of the column density ϵ as defined by:

$$\Sigma\left(r\right)=\Sigma_0 r^{-\epsilon}. \tag{2}$$

We emulate the MMSN as described by Hayashi **add ref** by taking $\Sigma_0 = 1700\,\mathrm{g\,cm^{-2}}$ and $\epsilon = 1.5$. If we set $R_{\rm in} = 0.25$ AU and $R_{\rm out} = 200$ AU, consistent with previous ProDiMo modeling of TW Hya **citation?**, then we can infer the mass of the disk by the relation

$$M_{\rm disk} = 2\pi \int_{R_{\rm in}}^{R_{\rm out}} \Sigma\left(r\right) r \mathrm{d}r, \tag{3}$$

which yields $M_{\rm disk} = 0.033 M_\odot$.

Finally, we follow Bai & Goodman (2009) and take $M_\star = 1 M_\odot$. Hence, all five necessary structural parameters have been determined.

3. Simulation Results

In this section, we present a suite of ProDiMo simulations that probe the effects of different heating mechanisms on the molecular line emission of the disk.

3.1. Baseline Model

Outline

- Dust abundance, why baseline of 10^{-4}
- Discuss assumptions on chemistry, what is included, what is not (may go in ProDiMo section above, but needs written either way)
- Discuss X-ray luminosity (should "baseline model" have any X-ray at all?)

Make table with ProDiMo parameters

Make grid of standard disk structure plots

3.2. Viscous Heating Models

Outline

- Discuss HT heating model and its implementation in ProDiMo
- Discuss effects on disk temperature
- Discuss effects on SED (continuum + line emission), showing ratio plots with baseline model
- Emphasize differences that could be observable

3.3. X-Ray Heating

Outline

- As above, but with emphasis on contrasts with viscous heating model, esp. observables

3.4. UV Heating

3.5. Effects of Dust Abundance and Settling

4. Conclusion

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