EVOLUTION OF PRE-MAIN SEQUENCE ACCRETION DISKS

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Introduction

The aim of this project was to develop a comprehensive global picture of the physical conditions in, and evolutionary timescales of, pre-main sequence accretion disks. The results of this work will help constrain the initial conditions for planet formation.

To this end we:

• Developed detailed calculations of disk structure to study physical conditions and investigate the observational effects of grain growth in T Tauri disks;

• Studied the dusty emission and accretion rates in older disk systems, with ages closer to the expected epoch of (giant) planet formation at 3-10 Myr; and

• Began a project to develop much larger samples of 3-10 Myr-old stars to provide better empirical constraints on protoplanetary disk evolution.

1. Viscous disk structure

We have been calculating protoplanetary disk models for detailed testing against observations. In FY 98 we presented methods by which detailed vertical as well as radial disk structure can be calculated for α disk models (D'Alessio et al. 1998). These models self-consistently included the heating from the stellar radiation field as well as viscous energy dissipation.

As a first step, we calculated steady viscous accretion disk models assuming that the dust in these disks is well-mixed with the gas and has the properties of ISM dust. In a published paper (D'Alessio et al. 1999), we constructed a grid of models for comparison with observations. . In the inner disk, the central temperature is raised due to radiative trapping of viscous energy dissipation. However, in the outer disk, stellar irradiation dominates the disk heating. The irradiation heating causes two effects; (a) a vertical temperature inversion, with the upper layers being hotter than the disk midplane; and (b) very much hotter disk temperatures throughout the vertical structure than would occur from viscous dissipation alone. This extra irradiation heating causes the disk to become significantly vertically thick at size scales of 100 AU or more, i.e. the disk is strongly "flared".

Figure 1 shows a comparison of the predicted emission from the model disk compared with the median spectral energy distribution of T Tauri stars in the Taurus molecular cloud. It can be seen that the model does reasonably well, considering its simplicity. In detail, there is too much emission at wavelengths of 100 μm, due to the disk being too thick, and thus absorbing too much light from the central star. Other observational tests indicate that the disk is too thick - for example, scattered light images of disks indicate flatter disk structure than predicted here. These results can be accomodated if dust grains grow and settle toward the disk midplane, as expected from quite general considerations (Weidenschilling & Cuzzi 1993). Indeed, grain growth is probably required to explain the magnitude of mm-wave dust emission; the model fails badly in this region, not because it probably doesn't have enough mass ($M(disk) \sim 0.01\mathrm{M}_{\odot}$), but because the ISM dust opacity is too low by about an order of magnitude.

2. Disk emission in the TW Hya association

A group of young, active stars in the vicinity of TW Hydrae has recently been identified as a possible physical association with a common origin. Given its proximity (50 pc), age (10 Myr), and abundance of binary systems, the TW Hya association (TWA) is ideally suited to studies of the diversity and evolution of circumstellar disks. In Jayawardhana et al. (1999b) we presented mid-infrared observations of 15 candidate members of the TWA group, 11 of which have no previous flux measurements at wavelengths longer than 2 mum. We report the discovery of a possible 10μm excess in CD -33°7795, which may be due to a circumstellar disk or a faint and as yet undetected binary companion. Of the other stars, only TW Hya, HD 98800, Hen 3-600A, and HR 4796A-all of which were detected by IRAS-show excess thermal emission. Our 10μm flux measurements for the remaining members of the association are consistent with photospheric emission, allowing us to rule out dusty inner disks. These findings suggest that the timescale for disk dispersal or coagulation is generally less than 10 Myr for most low-mass stars.

We also (Jayawardhana 1999a) obtained mid-infrared observations with high spatial resolution of the nearby late-type young binary system Hen 3-600. The binary, at a distance of 50 pc, is probably a member of the TWA Our images made it possible for the first time to determine which star in the pair, separated by 1.4", harbors the mid-infrared excess detected by IRAS. In the near-infrared, where the radiation is primarily photospheric, Hen 3-600A (M3) and Hen 3-600B (M3.5) have a flux ratio of 1.6. At 4.8, 10.8, and 18.2 mum, the primary becomes increasingly dominant over the secondary, suggesting that most of the circumstellar dust in the system resides around Hen 3-600A. Comparison of the spectral energy distribution (SED) of Hen 3-600A to the median SED of classical T Tauri stars suggests that its disk may be truncated by the secondary and provides tentative evidence for a central disk hole. The distribution of dust in the Hen 3-600 system shows that similar stars in a binary system can have very different protoplanetary disk properties at a given age.

3. Accretion in the TW Hya association

The rate of decrease of the disk mass with time of a viscous disk (and therefore the mass accretion rate) is related to the rate of expansion of the disk. In Hartmann et al. (1998) we conducted an initial exploration of disk evolution in T Tauri stars using the similarity solutions discussed by Lynden-Bell and Pringle (1974) for the condition that the viscosity has a power-law radial dependence and is independent of time, and constrained by observations of disk masses and our mass accretion rates (§1.1). We found that we could cover the observed range of disk properties among the Taurus pre-main sequence stars using initial disk masses $M_d \sim 0.1 - 0.01 M_\odot$ and viscosities characterized by a roughly constant α parameter, $\alpha \sim 10^{-2}$; the latter is consistent with current estimates for the Balbus-Hawley mechanism (Stone et al. 1996; Brandenburg et al. 1996).

Better tests of this picture of disk accretion require larger samples of significantly older stars. We have begun a program to identify star clusters with ages in the appropriate range for improved studies of protoplanetary disk evolution (see §4). In the meanwhile, we have begun studies of a few older stars in the TW Hydra Association (see §2) which are still actively accreting at an age of about 10 Myr.

In Muzerolle et al. (2000) we presented high-resolution optical spectra of suggested members of the TW Hydrae association with significant Hα emission. Only two objects, TW Hydrae and Hen 3-600A, are still actively accreting, as evinced by the ballistic infall signature of their broad Hα emission profiles. Figure 2 shows line profiles for these stars, compared with theoretical models of the type we developed to explain the line profiles in younger T Tauri stars (Muzerolle et al. 1998a,b,c).

The magnetospheric infall paradigm predicts the formation of an accretion shock on the stellar surface, as matter from the accretion flow merges with the star. The emission from this shock produces veiling of the absorption lines in the optical, and becomes very conspicuous at UV wavelengths, where it stands out against the low photospheric fluxes. The detailed shock structure and emission models for TTS by Calvet & Gullbring (1998) account very well for the observed excess emission in the Taurus CTTS. In Figure 3 we compare a shock model with the observed UV and optical continuum of TW Hya. We have taken UV spectra of TW Hya from the IUE archive, choosing low resolution data with the highest signal to noise. To obtain fluxes in the optical range, we calculated the mean and sigma of the 59 (Cousins system) $UBVRI$ observations of Rucinski and Krautter (1983); the 2-sigma range at each band is indicated.

The UV excesses of TW Hya and Hen 3-600A enable us to make a quantitative estimate of the accretion rates in these objects. Figure 3 shows that the shock model reproduces the TW Hya optical/UV SED remarkably well, explaining both the ultraviolet fluxes and the observed veiling at $\sim$ 7000 Å of $\sim$ 0.2 - 0.3. The accretion shock carries an energy flux $F = 3 \times 10^{11}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$, and has a filling factor $f = 0.3$ % of the stellar surface; these values are similar to those found in the 1 Myr Taurus T Tauri stars (Calvet & Gullbring 1998). The small value of the filling factor is also consistent with hot spot models of the photometric variability (Mekkaden 1998). The accretion luminosity is $L_{acc} = F \times f 4\pi R_*^2 = 0.012\,L_\odot$. Using the known mass and radius, we then obtain a mass accretion rate, from $L_{acc} = GM_*\dot{M}/R_*$, of

$\sim 4 \times 10^{-10}\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$. A range of variability at ultraviolet wavelengths similar to that observed in the U band would result in a range of a factor of 2 around this value.

Our results show that the same mechanism which drives accretion in the younger, relatively well-understood Taurus CTTS also operates in the older CTTS TW Hya and Hen 3-600A. Thus, some young stars are able to maintain magnetically-controlled disk accretion, and have enough circumstellar material to accrete, for up to 10 Myr. The mass accretion rates we derive for TW Hya and Hen 3-600A are at least an order of magnitude lower than the mean value in 1 Myr regions such as Taurus (Gullbring et al. 1998; Hartmann et al. 1998; Calvet et al. 2000; see Fig. 4). In fact, our estimate for Hen 3-600A is the lowest pre-main sequence accretion rate yet determined. Hartmann et al. (1998) calculated similarity solutions of accretion disk evolution in TTS. Their fiducial model predicts a decrease of accretion rate with time, with $\dot{M} \sim 5 \times 10^{-10}\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$ at an age of 10 Myr, in agreement with our measurements for the TWA CTTS.

The low mass-transfer rates of the accreting stars, plus the absence of either accretion or dusty disk emission, indicate that disk evolution to larger bodies is mostly completed before an age of 10 Myr. However, there are significant differences in the properties of individual objects of the same age. We note that one common theory for disk dissipation - UV photoionization/photodissociation (Hollenbach et al. 2000) - is inconsistent with the fact that TW Hya has maintained an optically thick disk for 5-10 Myr despite having a significant UV excess.

4. Cluster study of disk evolution

As mentioned in the previous section, one of the principal limitations in trying to constrain processes in the expected epoch of (giant) planet formation (3-10 Myr) is the lack of good samples of stars in this age range. We have begun a major observational program to identify star clusters with ages in this range which are sufficiently populous to provide good statistical information on disk properties as a function of stellar mass and age.

This program has been underway for approximately 1.5 years. Four promising clusters have been identified, and optical and near-infrared photometry have been identified for these objects. The goal now is to separate stellar members from the background and foreground objects. This will be done primarily through optical spectroscopy and photometric variability. We have optical spectra for some stars in two northern clusters, obtained on the KPNO 4m and at the WIYN telescope, and we are in the process of using these spectra to identify some of the brighter members. We have observing time on the CTIO 4m in April 2000 to obtain spectra of candidates in two of our southern clusters. Limited repeat photometry is now being reduced to see if we can identify further (fainter) members from photometric variability. We expect to make major progress on this project in the fall 2000- spring 2001 timeframe, when we can use the multifiber optical spectrographs on the converted MMT on Mt. Hopkins, and we will propose followup photometric variability studies.

These cluster samples, plus other objects from the literature, will form the basis of a guaranteed-time observing program with SIRTF.

5. Reviews

During the reporting period, two review papers were written. A review of disk accretion was written for Protostars and Planets IV (Calvet et al. 2000). In addition, a review comparing accretion processes in low- and intermediate mass stars was also completed (Hartmann 1999).

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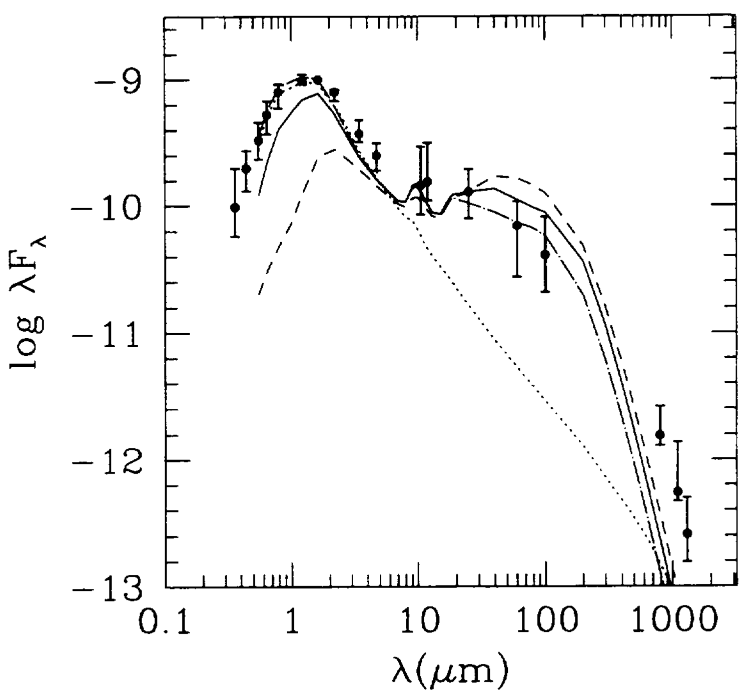

Figure 1: SED of the fiducial model at an inclination angle $i = 60°$ relati ve to the line of sight, for three disk radii $R_d = 30$ AU (dot-dashed line), 100 AU (solid line), and 300 AU (dashed line). The median observed SED (points) and quartiles (error bars) and the disk model irradiated as a flat disk (dotted line) are also shown. From D'Alessio et al. (1999).

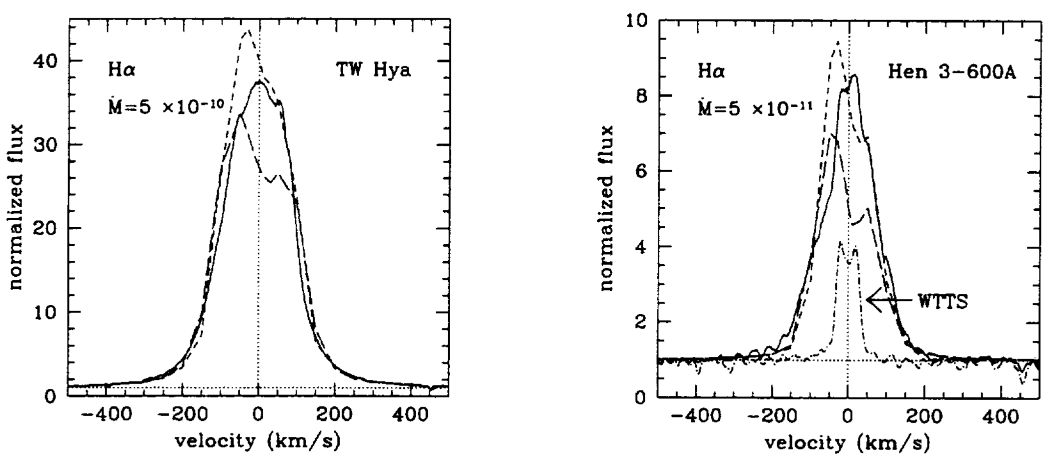

Figure 2: Hα profiles of TW Hydrae and Hen 3-600A (solid lines). The velocity scale for Hen 3-600A is based on the dominant component of the spectroscopic binary. Magnetospheric accretion models are overplotted in the dashed lines, with the following parameters. TW Hya: $M_* = 0.7\,\mathrm{M}_\odot$, $R_* = 1\,\mathrm{R}_\odot$, $T_{eff} = 4000\,\mathrm{K}$, $\dot{M} = 5\times10^{-10}\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$, $R_{mag} = 5 - 5.5\,\mathrm{R}_*$, $T_{max} = 12,000\,\mathrm{K}$, $V_{rot} = 23\ \mathrm{km\,s}^{-1}$. Hen 3-600A: $M_* = 0.2\,\mathrm{M}_\odot$, $R_* = 0.9\,\mathrm{R}_\odot$, $T_{eff} = 3500\,\mathrm{K}$, $\dot{M} = 5\times10^{-11}\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$, $R_{mag} = 3 - 3.7\,\mathrm{R}_*$, $T_{max} = 12,000\,\mathrm{K}$, $V_{rot} = 23\ \mathrm{km\,s}^{-1}$. The short- and long-dashed lines represent models with inclination angles of 45° and 60°, respectively. For comparison, the Hα profile of the WTTS TWa 10 is shown (dot-dashed line in the Hen 3-600A plot); note the narrow linewidth. From Muzerolle et al. (2000).

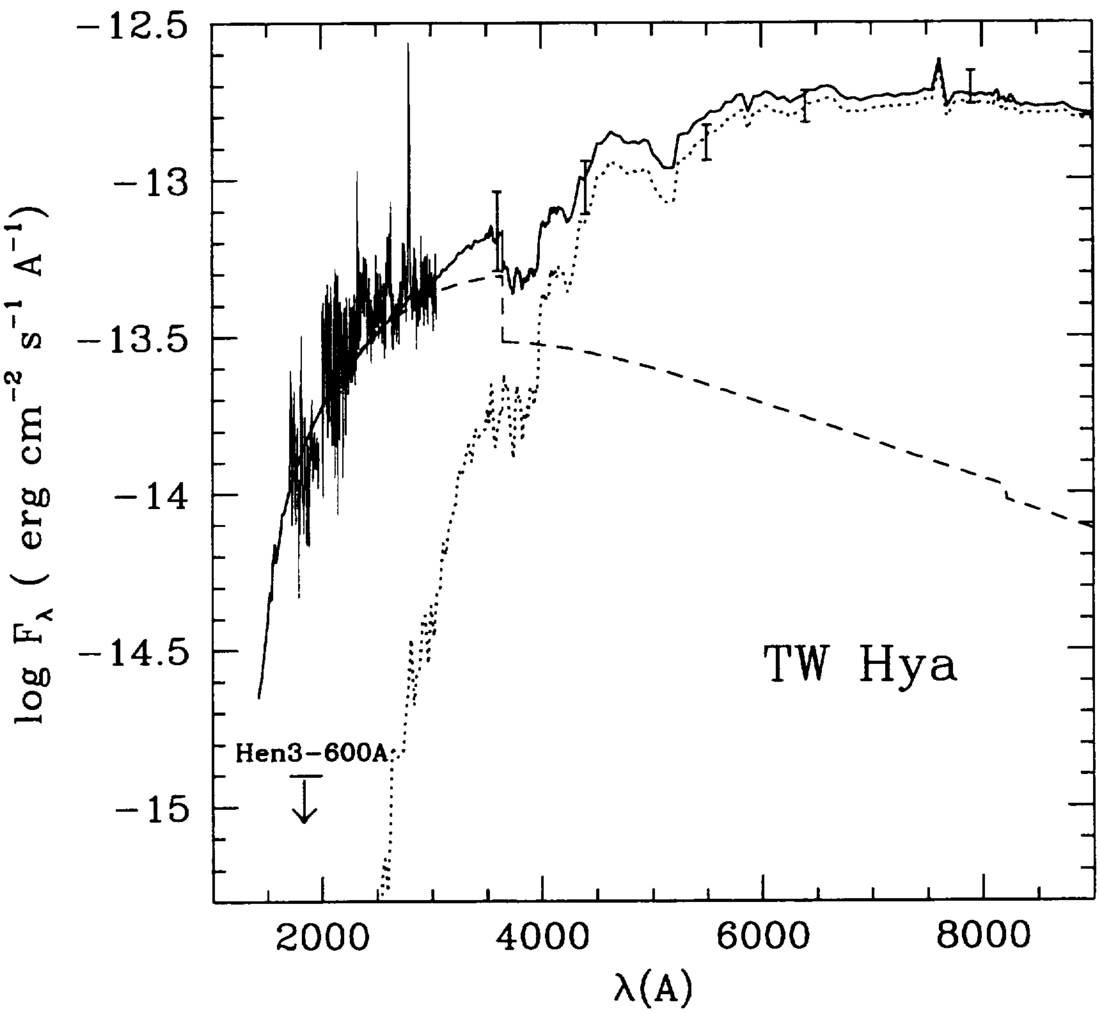

Figure 3: Ultraviolet and optical fluxes of TW Hya. UV fluxes (light solid curves) are from the IUE archive (spectra LWR05966 and SWP23471). Error bars show the range of optical variability, from Rucinski & Krautter (1983). From the colors, we derive a visual extinction of zero, consistent with the absence of an associated molecular cloud. An upper limit to the UV flux of Hen 3-600A, derived from a noisy IUE spectrum (SWP3666), is also shown. A composite (heavy solid line) of a 4000 K photosphere (dotted line) and an accretion shock model (dashed line) fits the observed fluxes and provides a veiling at 7000 Å of 0.27, in good agreement with measurements from echelle spectra. From Muzerolle et al. (2000).

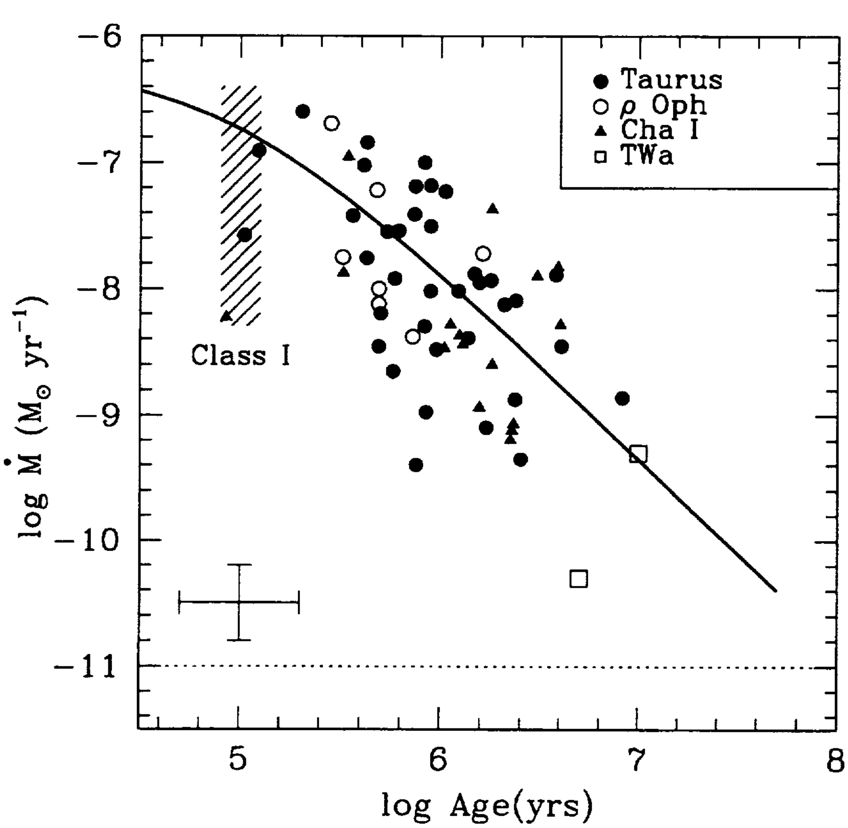

Figure 4: The distribution of mass accretion rates as a function of age, for CTTS in a variety of star forming regions (cf. Calvet, Hartmann, & Strom 2000). TW Hya and Hen 3-600A are indicated by the open boxes. The fiducial model from the viscous disk similarity solutions of Hartmann et al. (1998) is indicated by the solid line. Model parameters include an initial disk mass $M_d(0) = 0.1\,M_\odot$, characteristic radius $R_1 = 10\,\mathrm{AU}$, and viscosity parameter $\alpha = 10^{-2}$. The shaded area labeled "Class I" represents the approximate range of accretion rates for Class I objects in Taurus and ρ Oph, as inferred from Brγ line luminosities (see Muzerolle et al. 1999c). The error bars indicate typical uncertainties in ages from the HR diagram, and typical uncertainties in accretion rates due to variability. The dotted line marks the approximate accretion rate below which our models predict no observable broad Hα emission. From Muzerolle et al. (2000).