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 much larger samples of 3-10 Myr-old stars to provide better empirical constraints on protoplanetary disk evolution; measured disk accretion rates in these systems; and constructed detailed model disk structures consistent with observations to infer physical conditions such as grain growth in protoplanetary disks.

i. Cluster survey- ground-based data

We are completed our observational program to identify star clusters with ages of 3-10 Myr which are sufficiently populous to provide good statistical information on disk properties as a function of stellar mass and age. We have identified two such clusters, Tr 37 and NGC 7160, which lie in the Cep OB2 association at a distance of approximately 900 pc.

We recently completed a study of the massive and intermediate-mass stars in Tr 37 (Contreras et al. 2002, AJ, 124, 1585). The photometry and spectroscopy help to refine the membership, reddening ($A_V \sim 1.5 \pm 0.5$), and distance modulus ($m - M = 9.7 \pm 0.2$) to this cluster. Only three new emission-line stars were found in our sample, resulting in a total of four stars in the cluster with emission lines and spectral type earlier than G. One of these emission-line stars, LkHα 349, is probably not a member of the central cluster, as it lies within a dark globule on the periphery of the H II region IC 1396. Three of the four emission line stars show near-infrared excesses characteristic of circumstellar disks. Thus, at an age of about 3 Myr, as estimated from the expansion age of molecular material around the cluster, emission-line phenomena driven by disk accretion are extremely rare through spectral types F (masses $\gtrsim 1.5 M_\odot$).

Using CCD photometry from 4-shooter mosaic camera on the SAO 1.5m meter telescope on Mt. Hopkins, we identified candidate cluster members from their positions in the color-magnitude diagram, and then obtained followup spectroscopy for these candidates using the Hydra multifiber bench spectrograph on the WIYN telescope on Kitt Peak. Using Hα emission and Li I absorption indicators, we were able to identify low-mass members in these clusters and confirm the ages discussed above. The paper reporting these results has been published (Sicilia-Aguilar *et al.* 2004).

Followup observations using the new Hectospec multiobject spectrograph on the MMT on Mt. Hopkins were obtained in fall 2004. These observations allowed us to rapidly survey

the clusters to fainter targets and to do better subtraction nebular emission, to identify all of the weak-emission T Tauri members of these clusters. As shown in Figure 1, the cluster members are found within a fairly well-defined radius around the central O6 star. We find no statistically significant difference in the positions of the diskless or non-accreting WTTS and the disk-accreting CTTS, which might have been expected if the O star had evaporated much of the disks in its vicinity. This paper has been accepted for publication (Sicilia-Aguilar *et al.* 2005b).

ii. Infrared excesses in Tr 37

As part of the effort to understand protoplanetary dise evolution in young clusters, described in the previous section, we have obtained Spitzer Space Telescope Observations of Tr 37 and NGC 7160. The Infrared Array Camera (IRAC) data has been reduced and analyzed. The four IRAC bands, spanning the range from 3.6 μm to 8 μm, are ideal for detecting infrared excess emission from inner disks to extremely sensitive levels. In addition, we have 24 μm observations from the MIPS instrument on Spitzer for both clusters.

We found that the frequency of disks, as indicated from infrared excess emission, is about 40% in Tr 37 and about 5 - 10% in NGC 7160, in reasonable agreement with extrapolations from data on other regions. The frequency of disks among intermediate-mass stars is much lower; we find objects which appear to be debris disks in Tr 37, which would make them the youngest ($\sim 3-4$ Myr) such systems known.

The infrared excesses of the CTTS in Tr 37 are systematically lower than typically observed in the younger (1-2 Myr) Taurus CTTS (Figure 3), and the shorter-wavelength IRAS excesses tend to be lower relative to the 24μm excess. This behavior is consistent with the idea that grain growth and/or settling, especially in inner disk regions, should proceed over a few Myr timescale in most protoplanetary disks. A scientific paper has been written on the above project and will be submitted for publication shortly (Sicilia-Aguilar *et al.* 2005c). This paper completes the thesis reseach of Aurora Sicilia-Aguilar.

iii. Disk accretion

In (Muzerolle *et al.* 2003) we studied disk accretion in very low mass stars. Using limits on continuum veiling and modelling Hα line emission which arises in magnetospheric accretion columns, we showed that very low mass T Tauri stars accrete at very low rates, $10^{-12} < \dot{M} < 10^{-9} \mathrm{M}_{\odot}\,\mathrm{yr}^{-1}$, with a clear dependence on mass.

The mass dependence of accretion was more explicitly examined in a recently published paper (Muzerolle *et al.* 2004) in which we added results from intermediate-mass stars. Over the entire range from $0.04-4\mathrm{M}_{\odot}$, we find increasing mass accretion rates with increasing mass. The overall trend is roughly $\dot{M} \propto M^{2.3}$, with a large scatter at each mass. The physical origin of this relation is not clear; standard viscous accretion disk models predict some correlation but not as steep a relation as we find. We suggest that X-ray ionization of the disk may provide an additional mass-dependent effect on the angular momentum transport needed for accretion; this possibility needs to be explored with further theoretical and observational work.

iv. Herbig Ae/Be stars

In Hernandez *et al.* 2004, we presented a study of the optical spectra of Herbig Ae/Be stars, the intermediate-mass counterparts of the low-mass T Tauri stars. Accurate spectral types were presented and compared with observed optical photometry to confirm previous findings of high values of total-to-selective extinction ($R_V \sim 5$). Using higher values of R_V than often adopted, we find that the vast majority of HAe/Be stars appear younger, more consistent with being pre-main sequence objects.

v. McNeil's nebula

In Briceno *et al.* 2004 we presented a study of the newly-discovered eruptive young star in McNeil's nebula. We derive photometry spanning the preoutburst state and the brightening itself, which is a unique record including 14 epochs and spanning a timescale of about 5 years. We constrain the beginning of the outburst at some time between 2003 October 28 and November 15. The light curve of the object at the vertex of the nebula, the likely exciting source of the outburst, reveals that it has brightened 5 mag in about 4 months. The timescale for the nebula to develop is consistent with the light-travel time, indicating that we are observing light from the central source scattered by the ambient cloud into the line of sight. We also show recent FLWO optical spectroscopy of the exciting source and of the nearby HH 22. The spectrum of the source is highly reddened; in contrast, the spectrum of HH 22 shows a shock spectrum superposed on a continuum, most likely the result of reflected light from the exciting source reaching the HH object through a much less reddened path. The blue portion of this spectrum is consistent with an early B spectral type, similar to the early outburst spectrum of the FU Orionis variable star V1057 Cygni. These observations constitute a unique dataset for understanding eruptive phenomena in early stellar evolution.

vi. Orion nebula kinematics and accretion

In Sicilia-Aguilar *et al.* (2005a) we presented results from high-resolution spectra of 237 stars in the Orion Nebula cluster (ONC) obtained during two engineering runs with the Hectochelle multifiber echelle spectrograph on the 6.5 m MMT. The ONC is the nearest populous young (age 1 Myr) cluster and is therefore an important object for studies of the evolution of protoplanetary disks. Using the high spectral resolution of Hectochelle, we are able to distinguish stellar accretion and wind emission-line profiles from nebular emission lines and identify accreting members of the cluster from Hα profiles with greater accuracy than previously possible. We find 15 new members on the basis of Li 6707 absorption and Hα emission. Line profiles of Hα of some objects that are not too contaminated by nebular emission show features characteristic of mass inflow and ejection. We also present rotational velocities as part of an initial investigation into angular momentum evolution of very young stars, confirming a difference between classical T Tauri stars and weak-line T Tauri stars that had been found from period analysis. Finally, we present an initial study of the radial velocity dispersion of the brighter stars in the central cluster. The very small dispersion derived, $\leq 1.8 kms^{-1}$, is in good agreement with estimates from proper motions.

Papers supported by this grant

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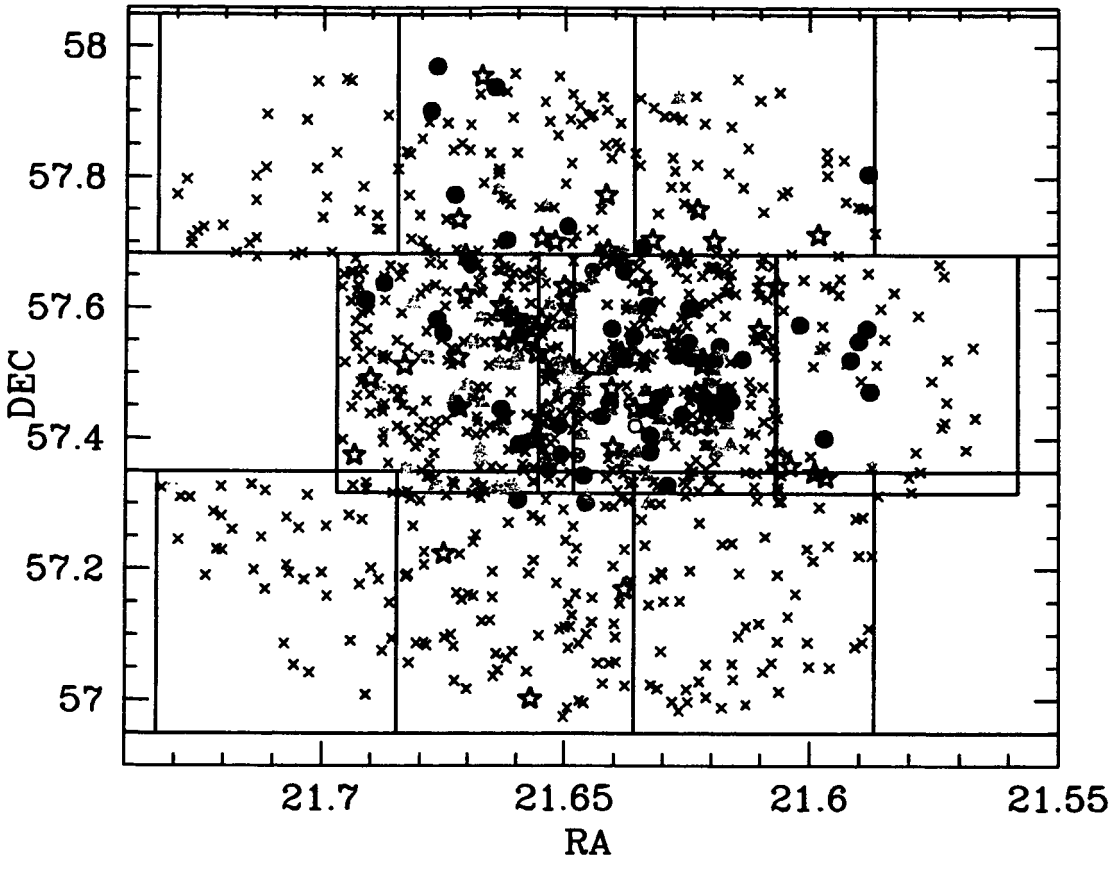

Figure 1: Spatial distribution of stars in Tr 37, as inferred from ground-based data. Large star: O6 central star HD206267. Small stars: B and A stars. Crosses: non-members as determined from Hectospec. Circles: CTTS. Triangles: WTTS. From Sicilia-Aguilar *et al.* 2005b.

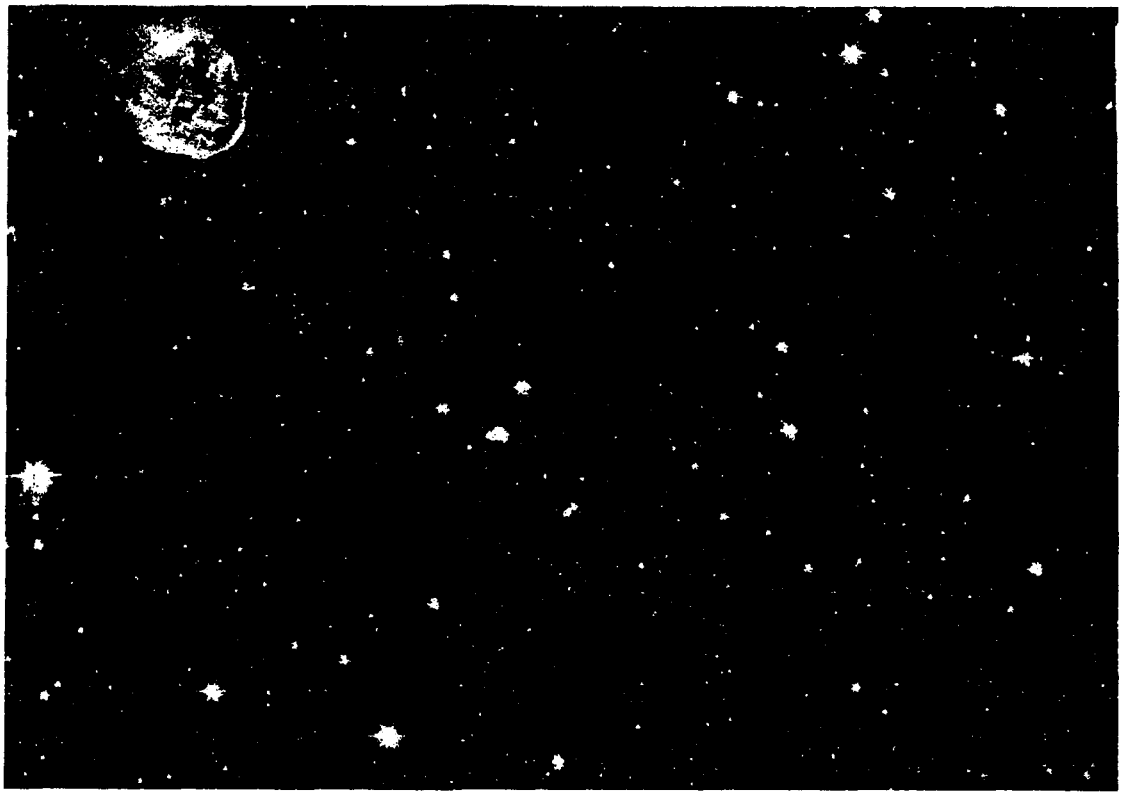

Figure 2: Channel 1 (3.6 μm) mosaic image from the IRAC instrument on Spitzer Space Telescope of the young cluster Tr 37. The extended object to the upper left is a dusty globule of molecular gas which harbors very young stars.

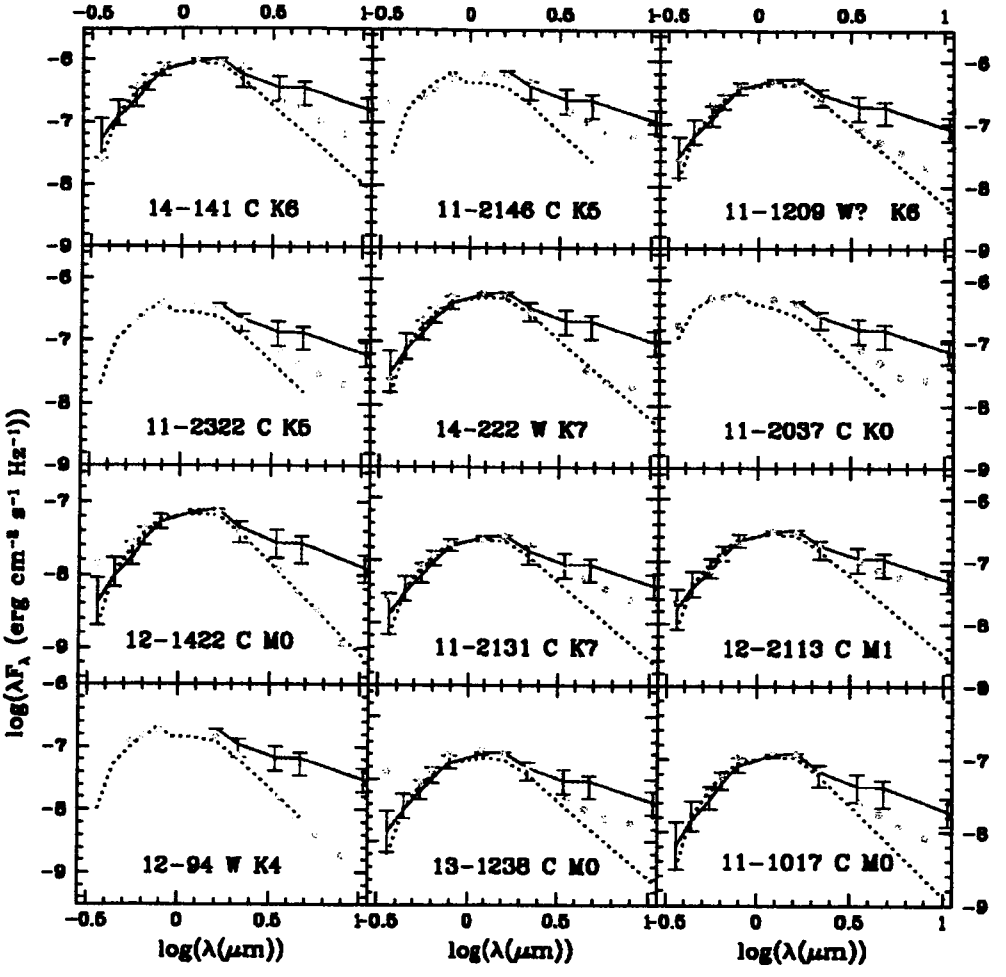

Figure 3: Spectral energy distributions of young stars in Tr 37 detected in all bands with IRAC. The excesses are generally lower than those observed in the 1-2 Myr-old Taurus stars (curve with errorbars) (see text)