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EVOLUTION OF PRE-MAIN SEQUENCE ACCRETION DISKS

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Introduction

The aim of this project is 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 plan to:

• Develop much larger samples of 3-10 Myr-old stars to provide better empirical constraints on protoplanetary disk evolution;

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

• Develop detailed model disk structures consistent with observations to infer physical conditions in protoplanetary disks and to constrain possible grain growth as the first stage of planetesimal formation.

Work during the past year has addressed the above items, as described below.

1. 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.

Two of our prime target clusters lie in the Cep OB2 association, at a distance of approximately 800 pc. Previous studies based on the upper-main sequence turnoff points, and the expansion timescales of molecular gas around the clusters, have suggested that two of the main clusters, NGC 7160 and Trumpler 37, have ages of $\sim 10-15$ Myr and $\sim 3-5$ Myr, respectively Marschall, Comins, & Karshner 1990; Patel et al. 1998). Our goal is to identify the low-mass members of these clusters and other stars in the region to study accretion disk evolution as a function of mass and age, and additionally verify or refine the ages using pre-main sequence tracks.

We have recently completed a study of the massive and intermediate-mass stars in Tr 37, which has just been submitted for publication (Contreras et al. 2002). The photometry and spectroscopy presented 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 (Figure 1). Only three new emission-line stars were found in our sample, resulting in a total of four stars in the cluster with emission lines

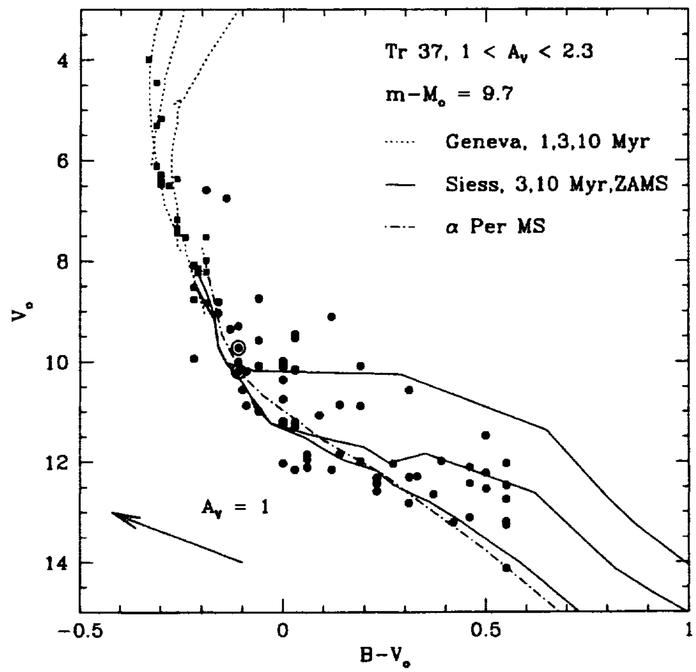

Figure 1: Color-magnitude diagram for probable members of Tr 37. The dotted curves are isochrones for high mass stars with $Z = 0.02$ from Schaller *et al.* (1992) for ages of 1,3, and 10 Myr; the solid curves are isochrones from Siess *et al.* (2000) for 3 and 10 Myr, and the ZAMS; and the dot-dashed line is the dereddened main sequence of the α Per cluster (J. Stauffer, personal communication; see also Pinsonneault *et al.* (1998). Circled objects are the emission-line stars in our survey; the large cross denotes MVA 805, which has no emission lines but exhibits an infrared excess. (MVA 60 = LkHa 349 has an uncertain spectral type and therefore cannot be dereddened; its large B-V=2 indicates that it is probably heavily extincted.)

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 $\gtrsim 1.5M_\odot$).

We obtained CCD photometry in 1999 of Tr 37 NGC 7160 using the 4-shooter mosaic camera on the SAO 1.5m meter telescope on Mt. Hopkins, identified potential members from their position 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. This resulted in the identification of about 35 members of Tr 37 and 20 members in NGC 7160 (Figures 2a and 2b). More could not be done because of bad weather with following Hydra runs.

To improve our selection process, and provide samples with less bias toward CTTS, we are

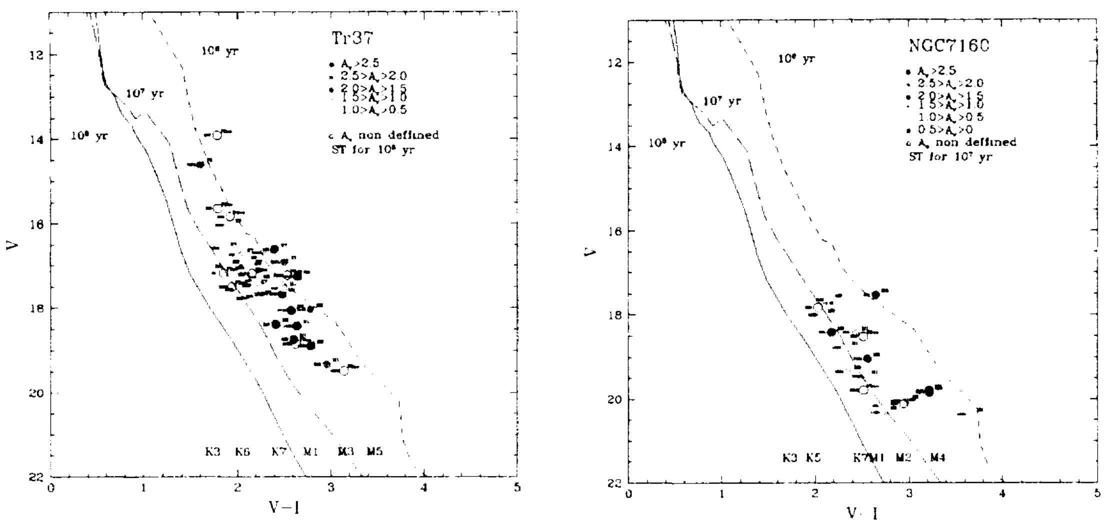

Figure 2: Optical color-magnitude diagram of identified members in Tr 37 (left) and NGC 7160 (right), mostly dependent upon detecting strong Hα emission.

now exploring the use of photometric variability to identify members. As shown by the work of Briceño et al. (2001) in studying the Orion OB1 association, variability is potentially an extremely powerful method for identifying low-mass pre-main sequence stars.

Figure 3a shows magnitude differences for one field in Tr 37 for two nights. This demonstrates that we can potentially detect optical variability above 0.1 mag down to $R \sim 18$ in our short exposures, and a similar result holds for the long exposures down to about $R \sim 20$. This should ultimately enable us to identify variables down to about $0.2 M_{\odot}$ and perhaps even lower for more highly-variable systems. By defining a typical photometric error on each night and then identifying objects with significant variability on more than one night, we have been able to identify more likely members, not biased toward strong emission (Figure 3b). These objects will be targeted with Hydra in July 2002 for spectroscopic confirmation of membership.

We have proposed to use Hydra on the WIYN telescope in the fall of 2002 to spectroscopically identify further members of these two clusters, using the results of our variability study. We hope that we will also be able to use the Hectospec and Hectochelle spectrographs on the converted MMT on Mt. Hopkins in fall 2002 to identify members; this work may be delayed until spring/summer 2003, depending upon the timescale for finishing the F/5 secondary. The use of Hectospec and Hectochelle will greatly increase our ability to provide reasonably complete membership lists to faint magnitudes.

The photometric and spectroscopic reductions are being performed by CfA predoctoral fellow Aurora Sicilia Aguilar as part of her thesis research, to be completed by fall 2003.

NGC 7160 and Trumpler 37 are targets in the PI's guaranteed time observing program with SIRTF to study disk evolution. Nominal launch date for SIRTF is now sometime in 2002. By this point we should have good membership lists, and thus can use the SIRTF data to study the evolution of disk emission throughout the range 3.6μm - 70μm.

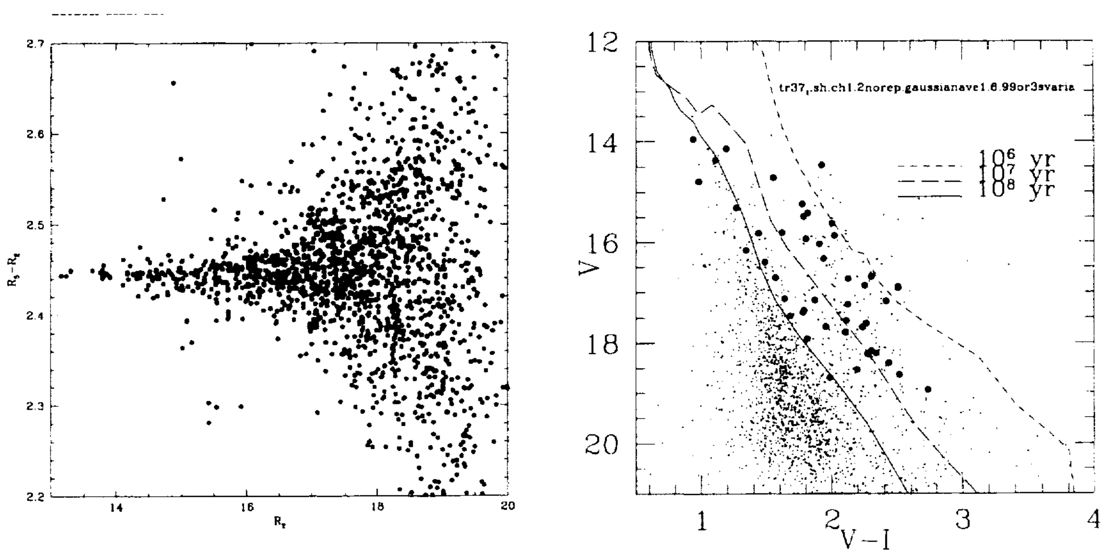

Figure 3: (Left) Typical night-to-night magnitude differences of CCD photometry; using these data to determine typical errors, and searching for objects that exhibit significant variability on more than one night leads to the identification of candidate members for spectroscopic followup (Right).

2. Evidence for a developing gap in a 10 Myr old protoplanetary disk

In a recently-published paper (Calvet *et al.* 2002), we developed a physically self-consistent model of the disk around the nearby 10 Myr old star TW Hya which matches the observed spectral energy distribution and 7mm images of the disk. The model requires both significant dust size evolution and a partially-evacuated inner disk region, as predicted by theories of planet formation. The outer disk, which extends to at least 140 AU in radius, is very optically thick at infrared wavelengths and quite massive ($\sim 0.06 M_\odot$) for the relatively advanced age of this T Tauri star. This implies long viscous and dust evolution timescales, although dust must have grown to sizes of order $\sim$ 1 cm to explain the sub-mm and mm spectral slopes. In contrast, the negligible near-infrared excess emission of this system requires that the disk be optically thin inside $\lesssim$ 4 AU. This inner region cannot be completely evacuated; we need $\sim$ 0.5 lunar mass of $\sim$ 1 μm particles remaining to produce the observed 10μm silicate emission. Our model requires a distinct transition in disk properties at $\sim$ 4 AU, separating the inner and outer disk. The inner edge of the optically-thick outer disk must be heated almost frontally by the star to account for the excess flux at mid-infrared wavelengths. We speculate that this truncation of the outer disk may be the signpost of a developing gap due to the effects of a growing protoplanet; the gap is still presumably evolving because material still resides in it, as indicated by the silicate emission, the molecular hydrogen emission, and by the continued accretion onto the central star (albeit at a much lower rate than typical of younger T Tauri stars). TW Hya thus may become the Rosetta stone for our understanding of the evolution and dissipation of protoplanetary disks.

3. Rapid formation of molecular clouds and stars

In a recently-published paper (Hartmann, Ballesteros-Paredes, & Bergin 2002), we showed how molecular clouds in the solar neighborhood might be formed and produce stars rapidly enough to explain stellar population ages, building on results from numerical simulations of the turbulent interstellar medium and general considerations of molecular gas formation. Observations of both star-forming regions and young, gas-free stellar associations indicate that most nearby molecular clouds form stars only over a short time span before dispersal; large-scale flows in the diffuse interstellar medium have the potential for forming clouds sufficiently rapidly, and for producing stellar populations with ages much less than the lateral crossing times of their host molecular clouds. We identify four important factors for understanding rapid star formation and short cloud lifetimes. First, much of the accumulation and dispersal of clouds near the solar circle might occur in the atomic phase; only the high-density portion of a cloud's lifecycle is spent in the molecular phase, thus helping to limit molecular cloud "lifetimes". Second, once a cloud achieves a high enough column density to form H_2 and CO, gravitational forces become larger than typical interstellar pressure forces; thus star formation can follow rapidly upon molecular gas formation and turbulent dissipation in limited areas of each cloud complex. Third, typical magnetic fields are not strong enough to prevent rapid cloud formation and gravitational collapse. Fourth, rapid dispersal of gas by newly-formed stars, passing shock waves, and reduction of shielding by a small expansion of the cloud after the first events of star formation, might limit the length of the star formation epoch and the lifetime of a cloud in its molecular state. This picture emphasizes the importance of large-scale boundary conditions for understanding molecular cloud formation; implies that star formation is a highly dynamic, rather than quasi-static, process; and that the low galactic star formation rate is due to low efficiency rather than slowed collapse in local regions.

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