OBSERVATIONAL CLUES TO BROWN DWARF ORIGINS

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Abstract
Over the past year, we have conducted a multi-faceted program to investigate the origin and early evolution of brown dwarfs. Using high-resolution Keck optical spectra of ~30 objects near and below the substellar boundary in several star-forming regions, we present compelling evidence for a T Tauri-like accretion phase in young brown dwarfs. Our systematic study of infrared L'-band (3.8μm) disk excess in ~50 spectroscopically confirmed young very low mass objects reveal that a significant fraction of brown dwarfs harbor disks at a very young age. Their inner disk lifetimes do not appear to be vastly different from those of disks around T Tauri stars. Taken together, our findings are consis-
tent with a common origin for most low-mass stars, brown dwarfs and isolated planetary mass objects.

Introduction

Brown dwarfs, which straddle the mass range between stars and planets, appear to be common both in the field and in star-forming regions. Their ubiquity makes the question of their origin an important one, both for our understanding of brown dwarfs themselves as well as for theories on the formation of stars and planets.

In the standard framework, a low-mass star forms out of a collapsing cloud fragment, and goes through a “T Tauri phase”, during which it accretes material from a surrounding disk, before arriving on the main sequence. There is ample observational evidence now to support many key aspects of this picture for young solar-mass stars. Whether the same scenario holds for objects at and below the sub-stellar limit is an open question. Studies of young sub-stellar objects could provide valuable clues to address that question.

To that end, over the past year, we have undertaken a multi-faceted study of very low mass (VLM) objects in star-forming regions and their immediate circumstellar environment. Here we report on our investigations of accretion signatures and disk excess in young brown dwarfs.

1. Accretion Signatures

The shape and width of the H$_\alpha$ emission profile is commonly used to discriminate between accretors and non-accretors among T Tauri stars (TTS). Stars exhibiting broad, asymmetric H$_\alpha$ lines with equivalent width larger than 10 Å are generally categorized as classical TTS (CTTS), although this threshold value varies with spectral type. Recently White & Basri (2003) have suggested that a full-width > 270 kms$^{-1}$ at 10% of the peak emission is a better empirical indicator of accretion, independent of spectral type. However, we find that in VLM accretors, the H$_\alpha$ profile may be somewhat narrower than that in higher mass stars. We propose that low accretion rates combined with small infall velocities at very low masses can conspire to produce this effect, and adopt $\sim$ 200 kms$^{-1}$ as a more appropriate, yet conservative, threshold (see Jayawardhana, Mohanty & Basri 2003 for further discussion).

We obtained high-resolution Keck optical spectra of $\sim$30 objects spanning the range of M5–M8 in IC 348, Taurus, Upper Scorpius and $\rho$ Ophiuchus star-forming regions. Putting together now all the young objects near or below the substellar boundary ($\sim$ M5 and later) with published high-resolution optical spectra (Jayawardhana, Mohanty & Basri 2002;
Brown Dwarf Disks and Accretion

(2003 and references therein), we have 4 objects in ρ Ophiuchus, 10 in IC 348, 14 in Taurus and 11 in Upper Scorpius. Of these, optical spectral signatures of accretion are found in 1 object in ρ Oph (GY 5), 5 in IC 348 (IC 348-165, 205, 355, 415, 382; Fig. 1), 3 in Taurus (CIDA-1, GM Tau, V410 Anon 13) and 1 in Upper Sco (USco 75), adopting an accretion cutoff of \( \sim 200 \text{ km s}^{-1} \) in 10% width of the H\( \alpha \) line. The vast majority of ρ Oph VLM objects were inaccessible to our optical spectroscopy because of significant extinction, presumably due to circumstellar as well as interstellar material. Thus, our (small) ρ Oph sample is heavily bi-

![Figure 1. H\( \alpha \) line profiles of IC 348 and Taurus targets. Spectra shown have been smoothed by a 3-pixel boxcar; continuum and full width at 10% of the peak levels are marked by dotted lines. Thick black lines indicate accretors with broad H\( \alpha \) as well as CaII and OI emission; grey indicates probable accretors, based on the H\( \alpha \) profile-shape and 10% full-width. Insets zoom in on objects with low peak-flux and noisy continua, to clearly show the H\( \alpha \) detection. For CFHT-3, two spectra are shown, separated by a year; note the similarly strong emission both times. For CFHT-4, note the change in Y-axis scale; the peak flux in this object is much higher than in any other target in our sample.](image-url)
ased against possible accretors, and should not be used to estimate the accreting fraction. Considering the other three clusters, which are much less affected by this bias, we find that \( \sim 50\% \) of the VLM objects show disk accretion at an age \( \leq 2 \) Myr (IC 348), \( \sim 20\% \) at age \( \sim 3 \) Myr (Taurus), and \( \leq 10\% \) by \( \sim 5 \) Myr (Upper Sco). While there are uncertainties in the cluster ages, IC 348 is likely to be younger than Taurus and Upper Sco. Thus, we appear to be seeing a decrease in the fraction of accreting young sub-stellar objects with increasing age.

Interestingly, three of our \( \sim M6 \) IC 348 targets with broad H\( \alpha \) also harbor broad OI (8446Å) and CaII (8662Å) emission (Fig. 2), and one shows broad HeI (6678Å) emission; these features are usually seen in strongly accreting classical T Tauri stars.

Our results constitute the most compelling evidence to date that young brown dwarfs undergo a T Tauri-like accretion phase similar to that in low-mass stars.

2. Disk Excess

Excesses at infrared wavelengths provide readily a measurable signature of dusty disks around late-type objects. Using the ESO Very Large Telescope, Keck I and the NASA Infrared Telescope Facility, we have carried out a systematic study of infrared \( L' \)-band (3.8\( \mu m \)) disk

Figure 2. Line profiles of OI (8446Å) and CaII (8662Å) in three IC 348 objects. Arrows indicate line-center. These spectra have been smoothed by a 4-pixel boxcar.
excess in a large sample of spectroscopically confirmed objects near and below the sub-stellar boundary in several nearby star-forming regions (Jayawardhana et al. 2003). Our longer-wavelength observations are much better at detecting disk excess above the photospheric emission and are less susceptible to the effects of disk geometry and extinction corrections than JHK studies (also see Liu, Najita & Tokunaga 2003).

We find disk fractions of 40%–60% in IC 348, Chamaeleon I, Taurus and Upper Scorpius regions. Based on ISO observations, Natta & Testi (2001) have already shown that ChaHo 1, ChaHo 2 and ChaHo 9 harbor mid-infrared spectral energy distributions consistent with the presence of dusty disks. ChaHo 2, which shows a large $K - L'$ excess (0.97 mag) in our data is a probable close ($\sim 0.2''$) binary with roughly equal-mass companions (Neuhäuser et al. 2002). It is possible that a few of our targets harbor infrared companions that contribute to the measured excess, but this is unlikely in most cases. The disk fractions we report for IC 348 and Taurus are lower than those found by Liu, Najita & Tokunaga (2003). This is primarily because we use a more conservative criterion of $K - L' > 0.2$ for the presence of optically thick disks whereas Liu et al. consider all objects with $K - L' > 0$ as harboring...
disks. In IC 348, our disk fraction is comparable to that derived from Hα accretion signatures in high-resolution optical spectra (Jayawardhana, Mohanty & Basri 2003). However, in Taurus and Upper Sco, which may be slightly older at \( \sim2-5\) Myrs, we find \( K - L' \) excess in \( \sim50\% \) of the targets whereas only three out of 14 Taurus VLM objects and one out of 11 Upper Sco sources exhibit accretion-like Hα (Jayawardhana, Mohanty & Basri 2002; 2003). This latter result suggests that dust disks may persist after accretion has ceased or been reduced to a trickle, as also suggested by Haisch, Lada & Lada (2001).

In the somewhat older (\( \sim5\) Myr) σ Orionis cluster, only about a third of the targets show infrared excess. Neither of the two brown dwarf candidate members of the \( \sim10\)-Myr-old TW Hydrae association (Gizis 2002) shows excess. Gizis (2002) reported strong Hα emission (equivalent width \( \approx300\) Å) from one of the TW Hydrae objects, the M8 dwarf 2MASSW J1207334-393254, and suggested it could be due to either accretion or chromospheric activity. Given the lack of measurable \( K - L' \) excess in this object, accretion now appears less likely as the cause of its strong Hα emission. Our findings in the σ Ori and TW Hya associations, albeit for a small sample of objects, could mean that the inner disks are clearing out by the age of these groups. Similar results have been found for T Tauri stars in the TW Hydrae association (Jayawardhana et al. 1999).

Our results, and those of Muench et al. (2001), Natta et al. (2002), and Liu, Najita & Tokunaga (2003) show that a large fraction of very young brown dwarfs harbor near- and mid-infrared excesses consistent with dusty disks. While the samples are still relatively small, the timescales for inner disk depletion do not appear to be vastly different between brown dwarfs and T Tauri stars. Far-infrared observations with the Space InfraRed Telescope Facility and/or the Stratospheric Observatory For Infrared Astronomy will be crucial for deriving the sizes of circum-sub-stellar disks and providing a more definitive test of the ejection hypothesis for the origin of brown dwarfs.

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