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Between Cool Stars and Hot Planets: Origins of Brown Dwarfs

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Abstract. Brown dwarfs, which straddle the mass range between stars and planets, appear to be common both in the solar neighborhood 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. Studies of young sub-stellar objects could provide valuable insight into their formation and early evolution. Here I report on the latest results from our observational programs at Keck, VLT and Magellan on the disk and accretion properties of young brown dwarfs. We find compelling evidence that they undergo a T Tauri phase analogous to that of their stellar counterparts.

1. Introduction

The past several years have seen the identification of a large number of sub-stellar objects in the solar neighborhood and in star-forming regions. Yet their origin remains a mystery. One possibility is that they form like stars do as a result of the turbulent fragmentation and collapse of molecular cloud cores (e.g., Padoan & Nordlund 2003). Another scenario which has gained popularity in recent times is that brown dwarfs are stellar embryos ejected from multiple proto-stellar systems (Reipurth & Clarke 2001; Bate, Bonnell & Bromm 2002).

There are few observational constraints on the formation and early evolution of sub-stellar objects. Since studies of *young* brown dwarfs could provide valuable clues to their origin(s), we have commenced a multi-faceted program to investigate the physical properties of brown dwarfs in star-forming regions and compare them to the much better studied low-mass pre-main sequence stars. We have employed many of the methods developed in the study of T Tauri stars to address the key question of *whether young sub-stellar objects undergo a T Tauri-like phase.*

2. Disk Excess

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 (3.8μm) disk 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).

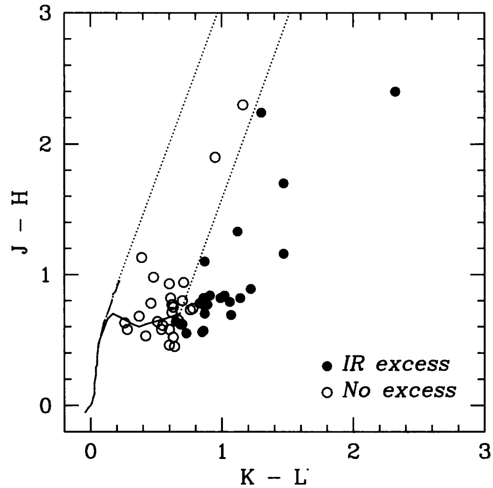

Figure 1. $J - H/K - L'$ color-color diagram for our target sample. Also plotted are the empirical loci of colors for giants (solid) and for main-sequence dwarfs (dashed) from Bessell & Brett (1988) and Leggett et al. (2002) and the reddening vectors (dotted). The filled circles are objects with $E(K - L') > 0.2$.

We find disk fractions of 40%–60% in IC 348, Chamaeleon I, Taurus and Upper Scorpius regions, using a conservative criterion of $K - L' > 0.2$ for the presence of optically thick disks. ChaHα 2, which shows a large $K - L'$ excess (0.97 mag) in our data is a probable close (∼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. 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, Cha I and Upper Sco, which may be slightly older at ∼2-5 Myrs, we find $K - L'$ excess in ∼50% of the targets whereas accretion-like Hα is seen in a smaller fraction of objects (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 (∼5 Myr) σ Orionis cluster, only about a third of the targets show infrared excess. Neither of the two TW Hydrae brown dwarfs (age ∼ 10 Myr) in our sample shows excess.

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 whether brown dwarf disks are truncated as predicted by the ejection scenario.

3. Accretion Signatures

The shape and width of the Hα emission profile is commonly used to discriminate between accretors and non-accretors among T Tauri stars (TTS). Stars exhibiting broad, asymmetric Hα lines with equivalent width larger than 10 Å are generally categorized as classical TTS (CTTS), although this threshold value varies with spectral type. We find that in very low mass (VLM) accretors, the Hα 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).

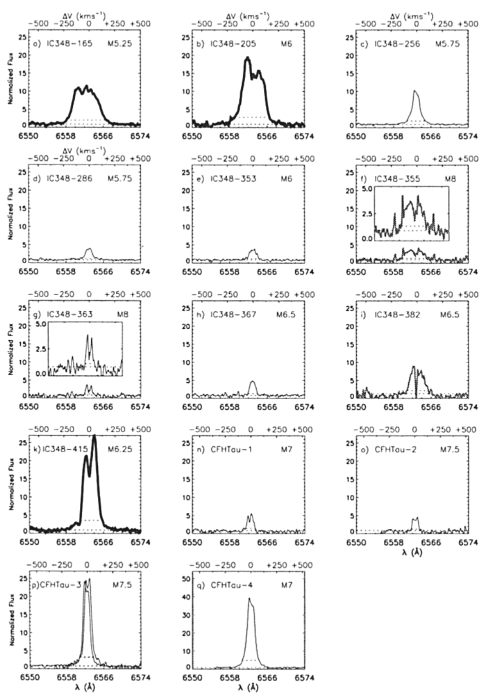

Figure 2. Hα line profiles of IC 348 and Taurus targets. Thick black lines indicate accretors with broad Hα as well as Ca II and O I emission; grey indicates probable accretors, based on the Hα profile-shape and 10% full-width.

We obtained high-resolution Keck and Magellan optical spectra of $\sim$45 objects spanning the range of M5–M8 in several nearby star-forming regions. The vast majority of VLM objects in ρ Ophiuchus were inaccessible to our optical spectroscopy because of significant extinction, presumably due to circumstellar

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as well as interstellar material. However, at least one of our four ρ Oph targets, GY 5, shows an accretion-like Hα profile. We also find evidence for accretion in 5/10 objects in IC 348 (Fig. 2), 3/14 in Taurus, 1/12 in Cha I, and 1/11 Upper Scorpius (Jayawardhana, Mohanty & Basri 2002, 2003). Perhaps somewhat surprisingly, one of the three known brown dwarfs in the 10-Myr-old TW Hydrae association also exhibits a broad, asymmetric Hα line. If confirmed, this detection suggests that accretion, albeit at very low rates, could last a fairly long time in some brown dwarfs (Mohanty, Jayawardhana & Barrado y Navascués 2003).

4. Evidence of an Outflow?

We have recently obtained Magellan low-, medium-, and high-resolution optical spectra of a particularly intriguing young VLM object named LS-RCrA 1, identified by Fernández and Comerón (2001). We confirm both pre-main sequence status and membership in the RCrA region for this object, through the detection of Li I, presence of narrow K I indicative of low gravity, and measurement of radial velocity. The Hα emission profile is very broad, with a 10% full width of 316 kms^{-1} at high-resolution, implying the presence of ongoing accretion. Our spectra also exhibit many forbidden emission lines indicative of mass outflow (Fig. 3), in agreement with the Fernández and Comerón results (Barrado y Navascués, Mohanty, & Jayawardhana 2003).

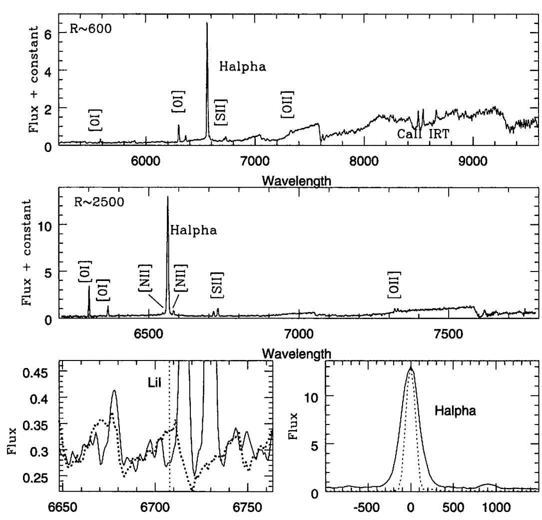

Figure 3. Spectral features of LS-RCrA 1. Upper panel.- Low resolution spectrum. Note the forbidden emission lines. Middle panel.- Medium resolution spectrum. Lower panel.- Zooms on Li I and Hα.

Our optical veiling measurements yield a mass accretion rate between 10^{-10} and 10^{-9} solar masses per year. The presence of prominent outflow signatures at these low accretion rates is initially puzzling. We consider, and discard as improbable, the possibility that these signatures arise in a line-of-sight Herbig-Haro knot unassociated with LS-RCrA 1 itself. However, if LS-RCrA 1 possesses an edge-on disk, a natural outcome would be the enhancement of any outflow signatures relative to the photosphere; we favor this view. A low accretion/outflow rate, combined with an edge-on orientation, is further supported by the absence of high-velocity components and any significant asymmetries in the forbidden lines. An edge-on geometry is also consistent with the lack of near-infrared excess in spite of ongoing accretion, and explains the relatively large Hα 10% width compared to other low-mass objects with similar accretion rates as well as the apparent sub-luminosity of LS-RCrA 1 given its spectral type, distance and age. It would be extremely interesting to confirm the presence of an edge-on disk and a jet/outflow in this system with high-angular-resolution imaging.

5. Conclusion

We have found compelling evidence, in the form of disk excesses and spectroscopic accretion signatures, that young brown dwarfs undergo a T Tauri phase similar to that of solar-mass stars. In one case, there is also a hint of possible mass outflow from a young sub-stellar object; if confirmed, this would further strengthen the analogy with T Tauri stars.

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