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Accretion, jets and disk-locking in the brown dwarf domain

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Abstract. We demonstrate that in accreting ultra-low mass stars and brown dwarfs, the CaII λ8662 emission line flux yields a robust quantitative estimate of the mass accretion rate ($\dot{M}$), providing an easier $\dot{M}$ determination technique than detailed Hα line-profile modeling. With optical high-resolution spectra, we derive $\dot{M}$ from CaII fluxes for young ultra-low mass objects down to nearly the deuterium-burning (planetary-mass) limit. Our results, combined with prior studies of higher-mass classical T Tauri stars (CTTs), show that $\dot{M}$ decreases steeply with (sub-)stellar mass, roughly as $\dot{M} \propto M_*{}^2$ (albeit with considerable scatter). A similar relationship has been suggested by previous studies; we extend it to nearly the planetary regime. We also find forbidden [OI] λ6300 emission in the $\sim$ 10 Myr-old, M8 accreting brown dwarf 2MASS 1207-3932, making this the oldest and one of the lowest-mass brown dwarfs with a mass outflow. Finally, in CTTs, accretion and jets are often linked to disk-locking. Using v*sin* i derived from our high-resolution spectra, we show that the same phenomenon arises in the ultra-low mass regime as well: accretors near and below the sub-stellar boundary appear to be preferentially slow rotators compared to non-accretors. These results suggests that ultra-low mass stellar and sub-stellar objects pass, in their youth, through a T Tauri phase completely analogous to that observed in higher-mass stars, bolstering the idea of a common formation mechanism in the two mass regimes.

Key words. low-mass stars and brown dwarfs – accretion and jets – disk-locking

1. Introduction

Ongoing accretion has now been identified in a number of objects near and below the hydrogen-burning limit (Jayawardhana, Mohanty & Basri 2002, 2003; Mohanty, Jayawardhana & Barrado y Navascués 2003; Muzerolle et al. 2003; Natta et al. 2004). To investigate disk accretion in detail in very low mass stars and brown dwarfs, our group has conducted, over the past two years, the largest high-resolution optical spectroscopic survey to date of such objects in nearby star-forming regions and young clusters. A summary of our general results is presented by Jayawardhana et al. in these proceedings. In the present article, we focus on some of the physical processes involved in accretion in the ultra-low mass regime. Specifically, we demonstrate the

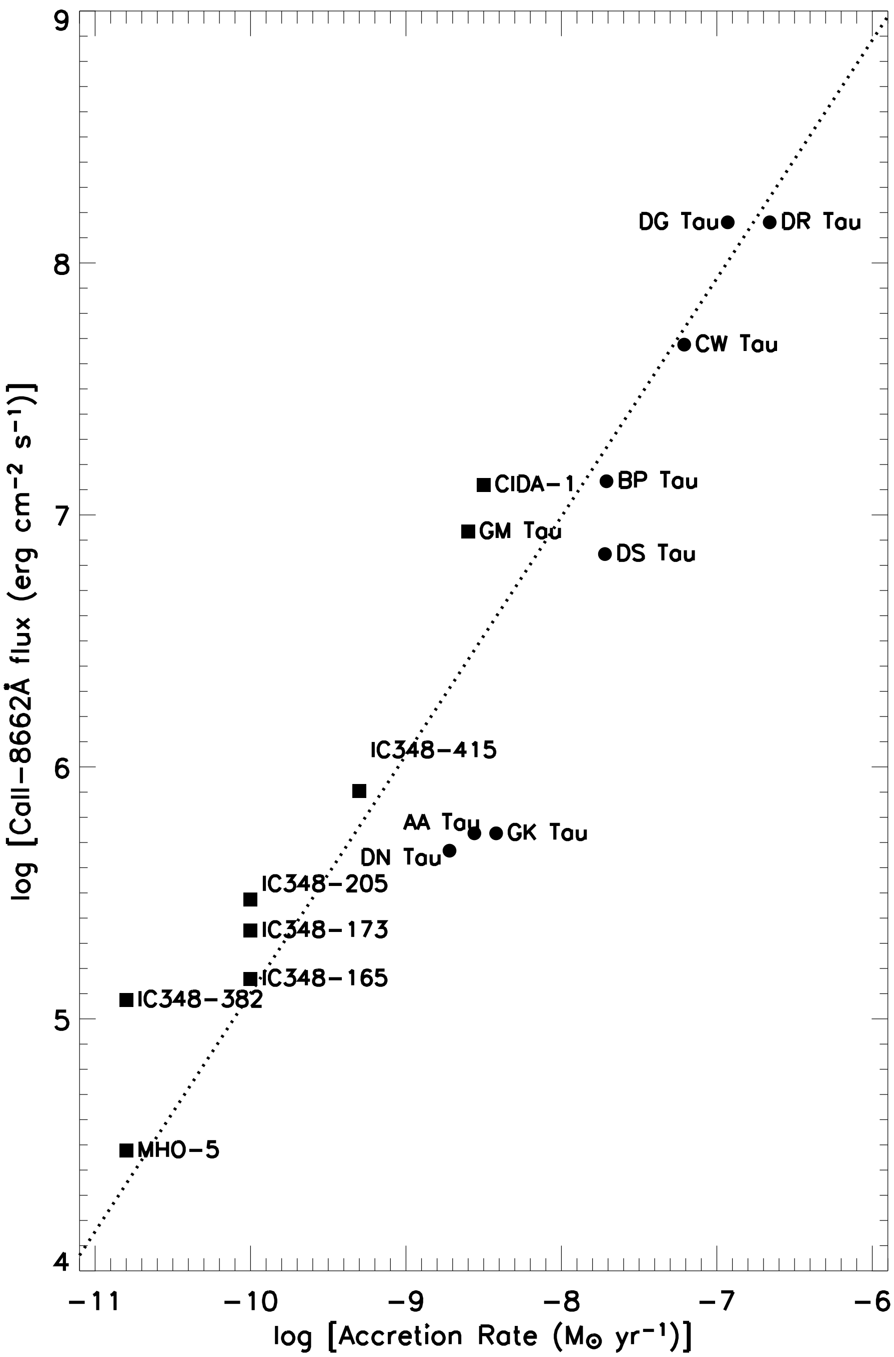

Fig. 1. CaII λ8662 flux vs. $\dot{M}$, for CTTs (all with $\dot{M}>10^{-8.5}$ $M_{\odot}yr^{-1}$) and ultra-low mass accretors. The two quantities correlate remarkably well.

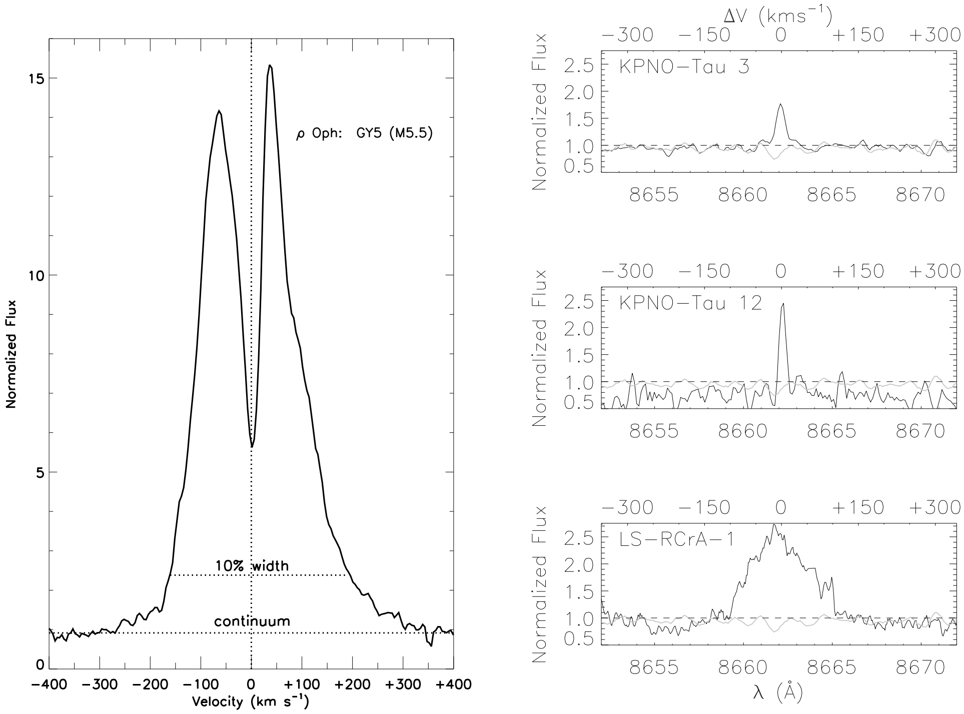

Fig. 2. *Left*: Hα profile for the low mass accretor GY5. The 10% full-width is >> 200 kms^{-1}, signifying accretion; the line is also asymmetric, as often seen in accreting CTTs. *Right*: CaII emission in some of our low mass stellar and substellar accretors. For comparison, the grey line is the photosphere of a young non-accretor, showing no CaII emission.

viability of using CaII emission line fluxes to derive accretion rates ($\dot{M}$), investigate the relationship between $\dot{M}$ and the mass of the central object, and show that disk-locking appears to play a role in ultra-low mass stars and brown dwarfs. A detailed description of our analysis can be found in Mohanty, Jayawardhana & Basri 2004.

2. Accretion Rates

In CTTs, $\dot{M}$ is often derived from the optical or UV "veiling" (i.e., from the luminosity of the excess continuum emission produced by the accretion shock). In ultra-low mass objects, however, the accretion rates are usually much lower than in CTTs (as we explore in the next section), leading to negligible veiling. Under the circumstances, $\dot{M}$ in these objects is most often derived from a detailed modeling of the accretion-related Hα emission line profile (Muzerolle et al. 2003; hereafter M03). Such modeling, however, is laborious and time consuming; consequently, it is very useful to identify an easier technique for $\dot{M}$ determination.

One possible solution is to use CaII emission fluxes. In CTTs, the emission flux in the CaII infrared triplet (IRT) lines is known to correlate very well with the accretion rate inferred via other means (Muzerolle, Hartmann & Calvet 1998; hereafter MHC98). If this correlation also extends to the ultra-low mass regime, then these line fluxes, which can be computed straightforwardly (see below), can be used to directly determine $\dot{M}$ without a detailed modeling of the Hα profile.

To investigate this possibility, we examine the relationship between $\dot{M}$ and CaII flux in a sample comprising both CTTs and accreting ultra-low mass objects. For the former, $\dot{M}$ have been derived by MHC98 from veiling measurements; for the latter, $\dot{M}$ are inferred from Hα profile-modeling by M03. For all objects, we have also calculated the emission flux in the λ8662 component of the CaII IRT, by combining the equivalent widths quoted by MHC98 and M03 with estimates of the underlying photospheric continuum flux appropriate to the spectral types (line flux = equivalent width $\times$ continuum flux $\times$ [1 + veiling]; the veilings are also quoted by MHC98 and M03, and are mostly zero for the ultra-low mass targets, as mentioned earlier).

The resulting relationship between $\dot{M}$ and CaII flux is shown in Fig. 1. Clearly, the two quantities are remarkably well correlated all the way from CTTs to the substellar domain, over more than 4 orders of magnitude in both line flux and accretion rate. A linear fit yields: $\log[\dot{M}] = 1.05 \times \log[\mathrm{CaII}\ (\lambda 8662)\ \mathrm{flux}] - 15.25$. Thus, with this relationship, measurement of CaII λ8662 fluxes alone can indeed provide an easy yet robust estimate of accretion rates.

Our new large sample of young ultra-low mass objects (described in the contribution by Jayawardhana et al.) contains a number of accretors which evince CaII emission. It is noteworthy here that we do not identify the *presence* of accretion through CaII emission. Instead, as described by Jayawardhana et al., we use the shape of the Hα profile for this purpose – a full-width $>\sim 200$ kms^{-1} at 10% of peak emission indicates accretion (Fig. 2a). This is important since, while we find CaII λ8662 emission only in accretors in our sample, not all accretors evince emission in this line. Thus, a separate indicator of accretion is required: the simple Hα width diagnostic fulfills this purpose. However, in those accretors that *do* exhibit CaII (the majority; Fig. 2b), a quantitative estimate of the accretion rate can be obtained easily from the $\dot{M}$–CaII flux relationship noted above, without detailed Hα profile-modeling. We have derived $\dot{M}$ this way for objects ranging down to the lowest mass accretors known to date – down to a spectral type of M9, or ~15 Jupiter masses: nearly the planetary mass boundary. Our results demonstrate that accretion occurs over the entire range of substellar masses.

3. Accretion Rate versus Mass

We have derived masses for all our accretors through comparison to the latest theoretical evolutionary tracks. In Fig. 3, we plot accretion rates against mass for both our ultra-low mass sample as well as higher mass CTTs from studies by other investigators. While there is considerable scatter in the $\dot{M}$ at any given mass, the data clearly show that the accretion rate, on average, falls off steeply with declining mass. A formal fit to the data yields $\dot{M} \propto M_*^{1.85}$; given the scatter, this is consistent with the approximate relationship $\dot{M} \propto M_*^{2}$, all the way from solar-mass stars to the lowest mass brown dwarfs. Similar results have previously been obtained by Natta et al. 2004 and M03. Our results not only confirm their findings, but also extend the relationship to the entirety of the sub-stellar domain, down to nearly planetary masses. The physical reason behind this fall-off in $\dot{M}$ with M_*, however, remains unclear. It may be that a decrease in ionizing flux emitted by cooler, lower mass objects lowers the degree of ionization in the surrounding disk, which in turn affects the disk viscosity (thought to be related to the Balbus-Hawley magneto-rotational instability) and thus the disk-accretion rate. Whether this suggestion is viable remains to be seen.

4. Jets, Accretion and Disk-Locking

In addition to accretion, mass outflows have now also been identified in some ultra-mass stars and brown dwarfs, analogous to the outflowing winds and jets often seen in CTTs. For instance, Fernando & Comeron (2001) and Barrado y Navascués, Mohanty & Jayawardhana (2004) have found forbidden lines indicative of a jet in LS-RCrA-1, an object close to the sub-stellar boundary. We have now also identified forbidden [OI] λ6300 emission in the accreting brown dwarf 2MASS 1207-3932, located in TW HyA (Mohanty, Jayawardhana & Basri 2004). With

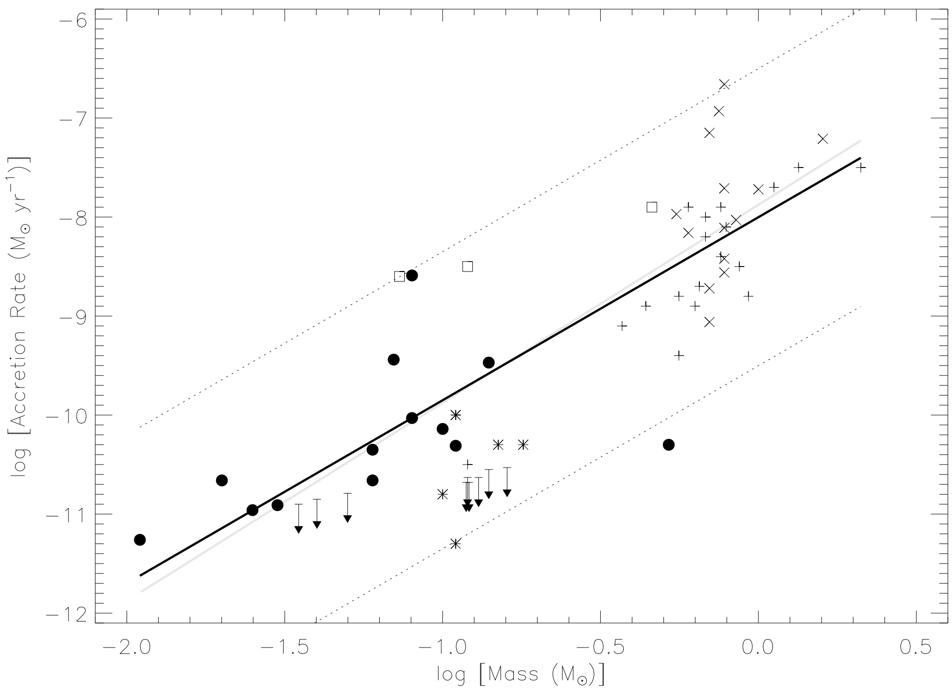

Fig. 3. Accretion rate versus mass, from solar-type stars down to nearly planetary masses. $\dot{M}$ drops sharply with M_*. The solid black line is the formal fit to the data, $\dot{M} \propto M_*^{1.85}$; the solid grey line is $\dot{M} \propto M_*^2$, consistent with the data; the dashed lines are our fit shifted by ±1.5dex to indicate the scatter. Symbols indicate different studies (filled circles and upper limit arrows from this study; see Mohanty, Jayawardhana & Basri 2004).

an age ~10 Myr, mass ~35 Jupiters (spectral type M8), and known accretion signatures (Mohanty, Jayawardhana & Barrado y Navascués 2003), this is the oldest, and one of the lowest mass, sub-stellar accretors known to evince a mass outflow. Jets and outflows therefore certainly occur in the ultra-low mass domain.

Now, in CTTs, accretion and outflows are expected to regulate the angular momentum of the central object. In particular, CTTs, which are undergoing disk-accretion, are often empirically seen to be preferentially slow rotators compared to non-accreting weak-line T Tauri stars (WTTs). In the X-wind theory of accretion, this arises due to magnetically mediated star-disk interactions: the stellar magnetosphere threads the inner edge of the disk; accreting disk material is channeled in by the field lines; the excess angular momentum of the infalling material is extracted by the field, and channeled out to the disk footpoints of the field lines, thereby driving a jet/outflow; the central star is forced, by this field-disk interaction, to corotate slowly at the slow angular Keplerian velocity of the inner disk edge.

In Fig. 4, we show that exactly the same process appears to operate in ultra-low mass objects as well. In particular, very low mass stars and brown dwarfs that are undergoing disk accretion are clearly seen to be preferentially slow rotators compared to non-accreting objects. We conclude that not only do accretion and outflow occur near and below the Hydrogen-burning limit, just as in CTTs, but

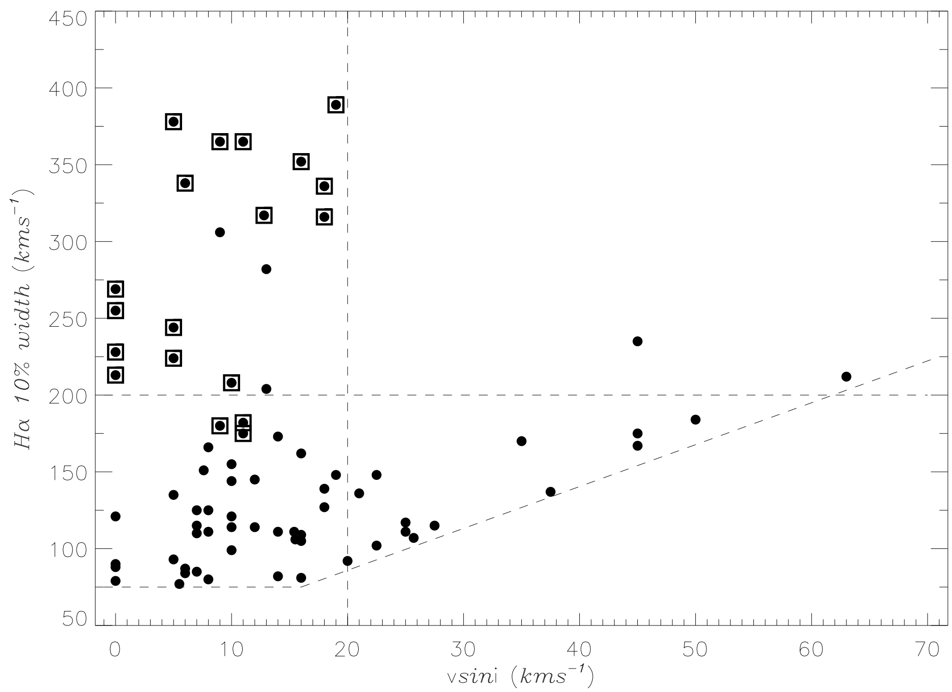

Fig. 4. Hα 10% width (accretion indicator) vs. v*sin* i. All objects with 10% width >∼ 200 kms^{-1} are accretors, except the 2 with v*sin* i >40 kms^{-1}, whose Hα is simply rotationally broadened. Surrounding squares indicate other accretion/outflow indicators as well, e.g., emission in CaII or [OI]. Accretors are preferentially slow rotators, while non-accretors have a range of rotation velocities. A similar phenomenon is seen in T Tauri stars.

the physical processes underlying these phenomena are similar to those in CTTs.

5. Conclusions

Our study implies that: *(1)*: CTTs-like accretion is common in the ultra-low mass regime, and can also be accompanied by CTTs-like jets/outflows; *(2)*: accretion rates can be directly inferred from CaII fluxes; *(3)*: these rates decrease sharply with mass, roughly as $\dot{M} \propto M_*{}^2$ all the way from solar-mass stars to nearly planetary masses; *(4)*: disk-locking appears to operate in ultra-low mass accretors, just as in CTTs. These phenomenological similarities suggest a common formation mechanism for higher mass stars and ultra-low mass stellar and sub-stellar objects.

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