T Tauri Phase of Young Brown Dwarfs

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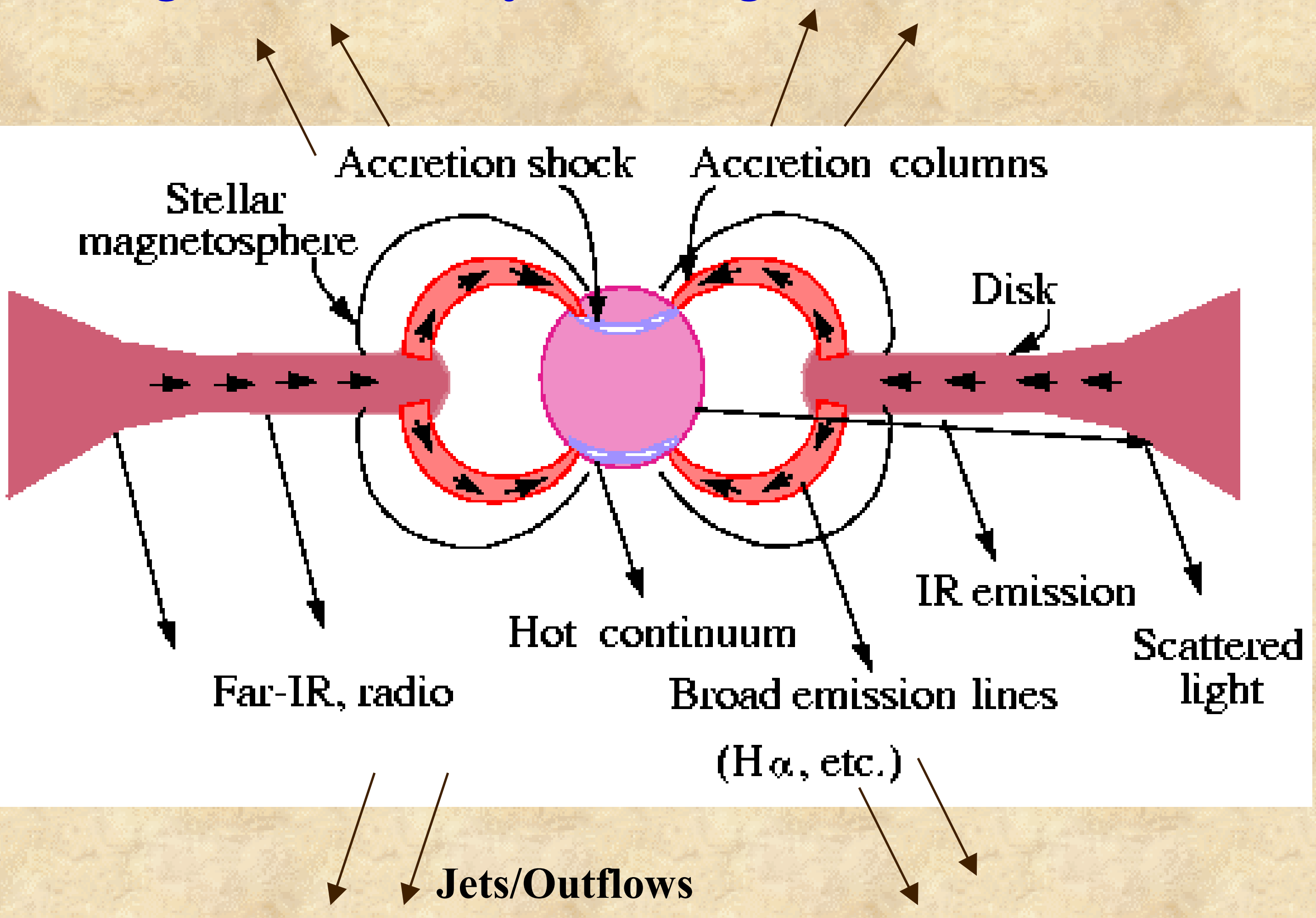
Key Observational Question:

Do Young Sub-Stellar Objects undergo a T Tauri-like Phase?



Investigating Young Brown Dwarfs: A Multi-Faceted Approach

* Measurements of Disk Excess
* Search for Spectroscopic Signatures of Accretion
* Disk Mass Estimates from mm Fluxes
* Looking for Evidence of Jets/Outflows
* Determination of Sub-Stellar Physical Properties

  (Mohanty et al. 2004a; Mohanty, Jayawardhana & Basri 2004b)
* Studies of Angular Momentum Evolution ($v \sin i$, photometric periods)
* Probes of Activity ($H\alpha$, X-rays, radio)

Disk Excess Measurements

Sample

Objects with *known spectral types later than M5* in nearby star-forming regions

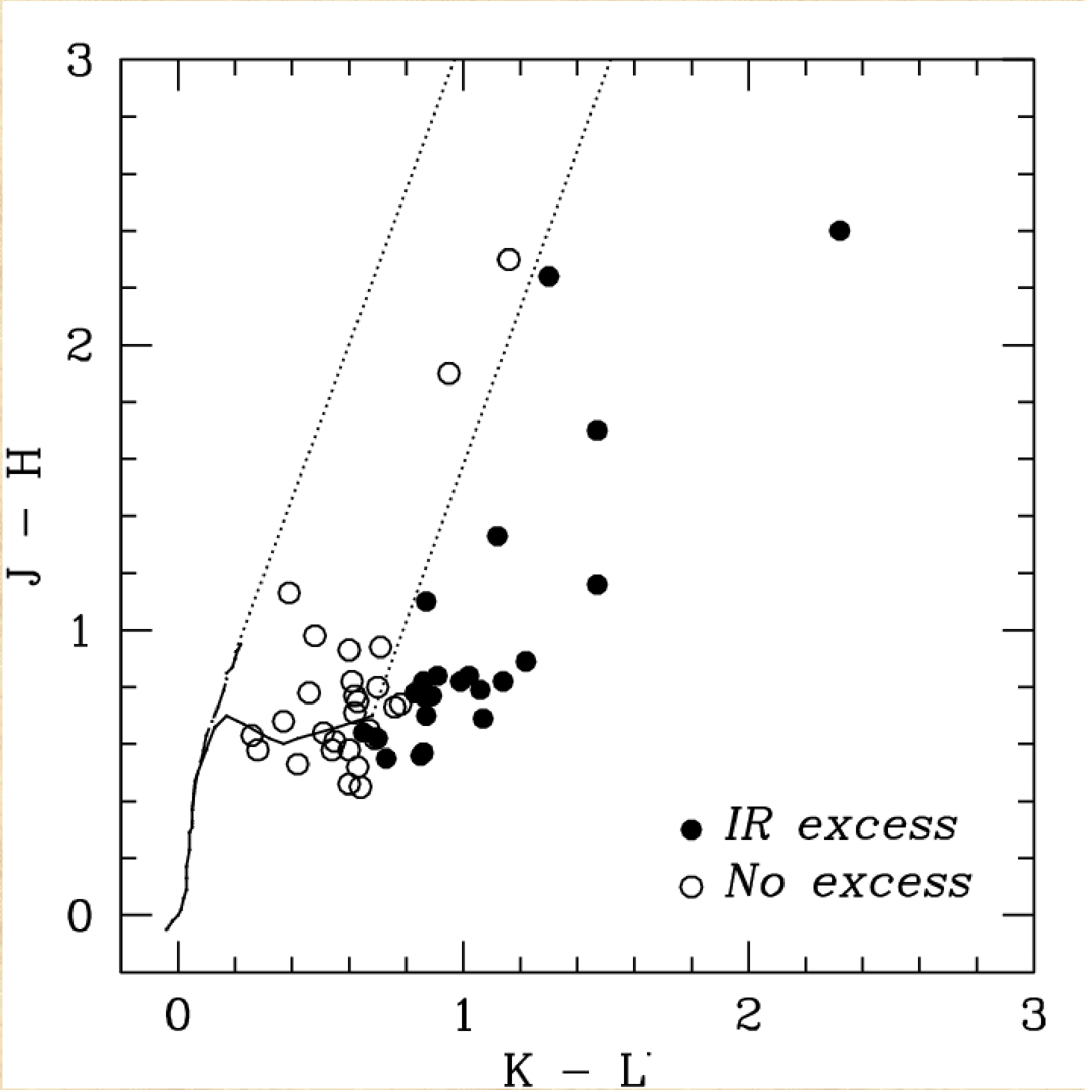
Total: 50+

Observations

JHKL' photometry at VLT, Keck and IRTF

Supplemented with 2MASS JHK

K-L' is a more reliable measure of disk fractions (Haisch, Lada & Lada 2001): less susceptible to geometric effects, smaller extinction corrections, easily measurable above photospheric emission



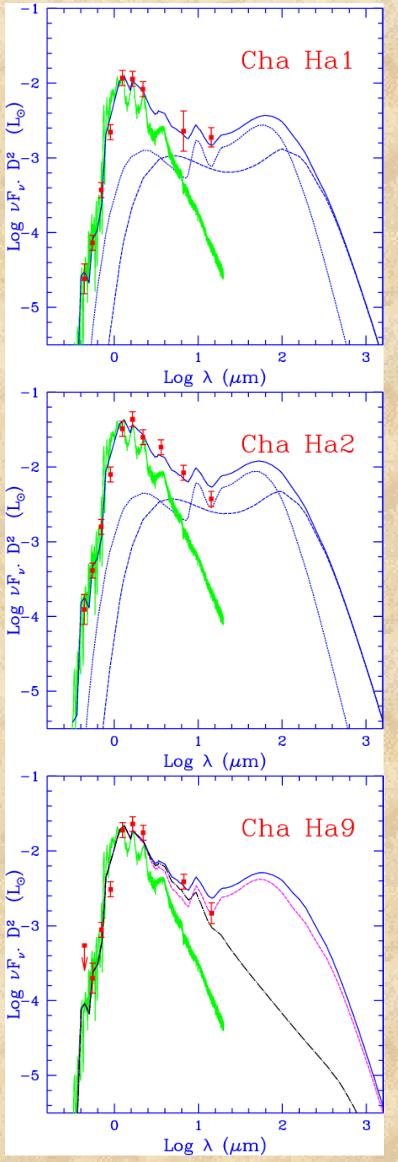
Jayawardhana, Ardila, Stelzer & Haisch (2003)

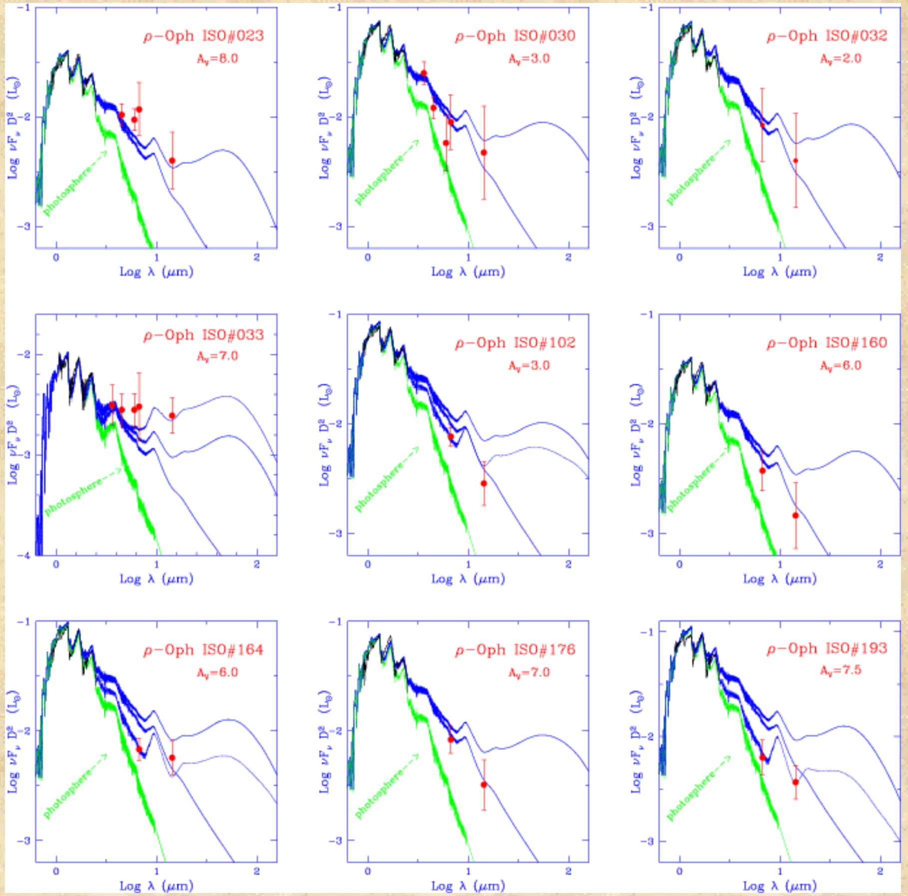
Disk Fractions by Region

Region	Fraction	Est. Age
ρ Oph	6/7	< 1 Myr
IC 348	3/6	~2 Myr
Taurus	5/9	~1-3 Myr
Cha I	8/15	~1-3 Myr
Upper Sco	4/8	~3-5 Myr
σ Ori	2/6	~5-7 Myr
TW Hya	0/2	~10 Myr

Jayawardhana, Ardila, Stelzer & Haisch (2003)

ISO Measurements of Disk Excess at 7μm & 14μm: Chamaeleon I and ρ Oph

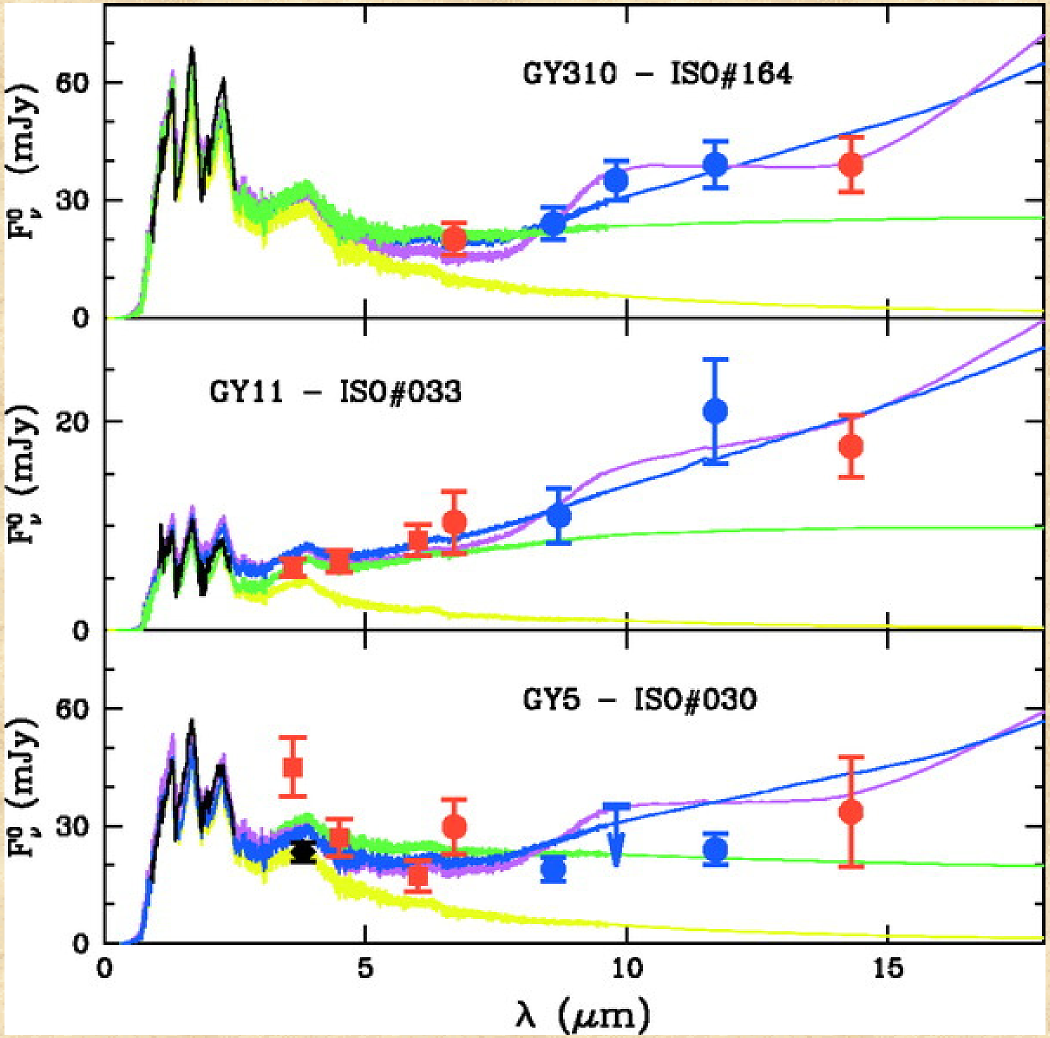




Comeron et al. (1998); Natta & Testi (2001); Natta et al. (2002)

Constraining the Disk Geometry: *Ground-based* Mid-IR Observations

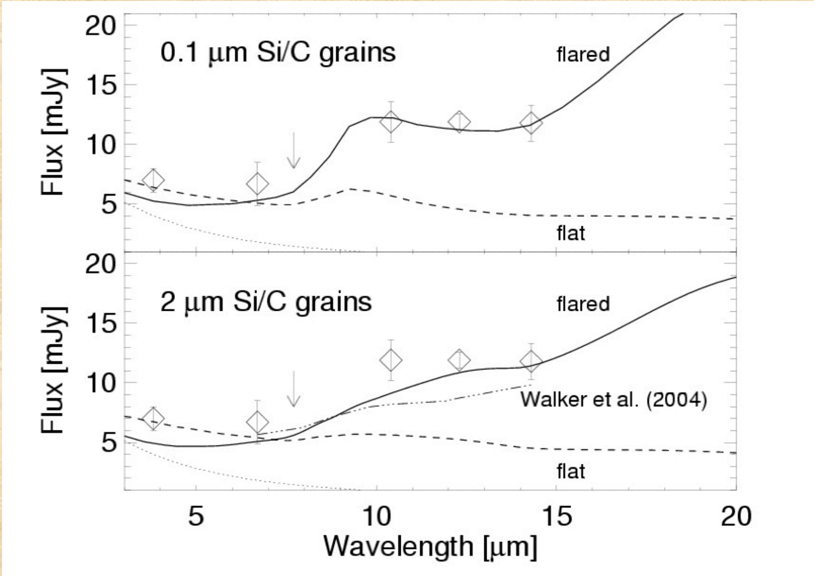
- Flared disks in GY 310 and GY 11
- Inner disk holes of a few (sub-)stellar radii in all three
- Possible silicate feature in GY 310



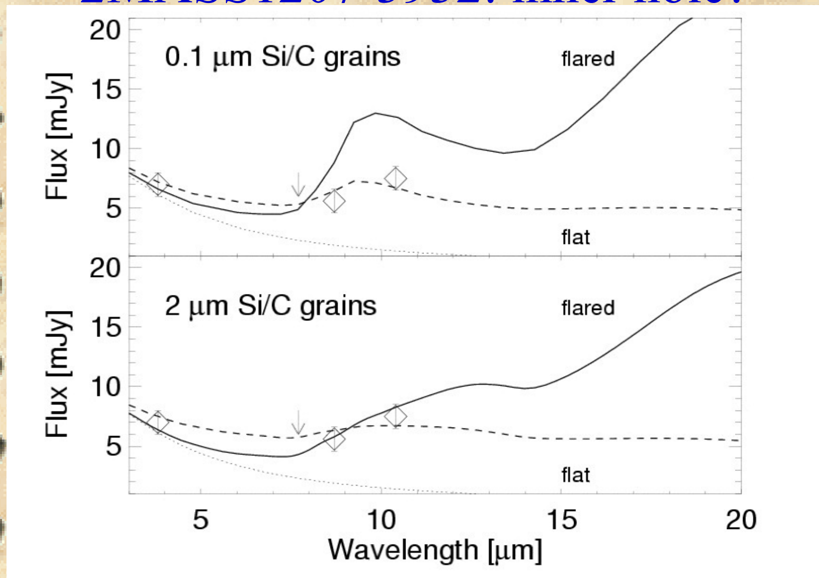
Mohanty, Jayawardhana, Natta, et al. (2004)

Constraining the Disk Geometry: Ground-based Mid-IR Observations

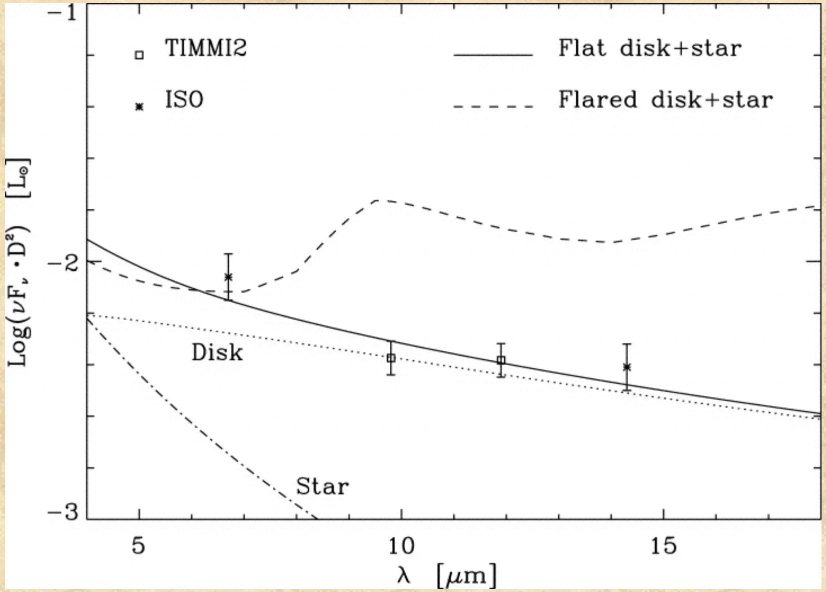
Cha Hα 1: flared disk



2MASS1207-3932: inner hole?



Cha Hα 2: flat disk

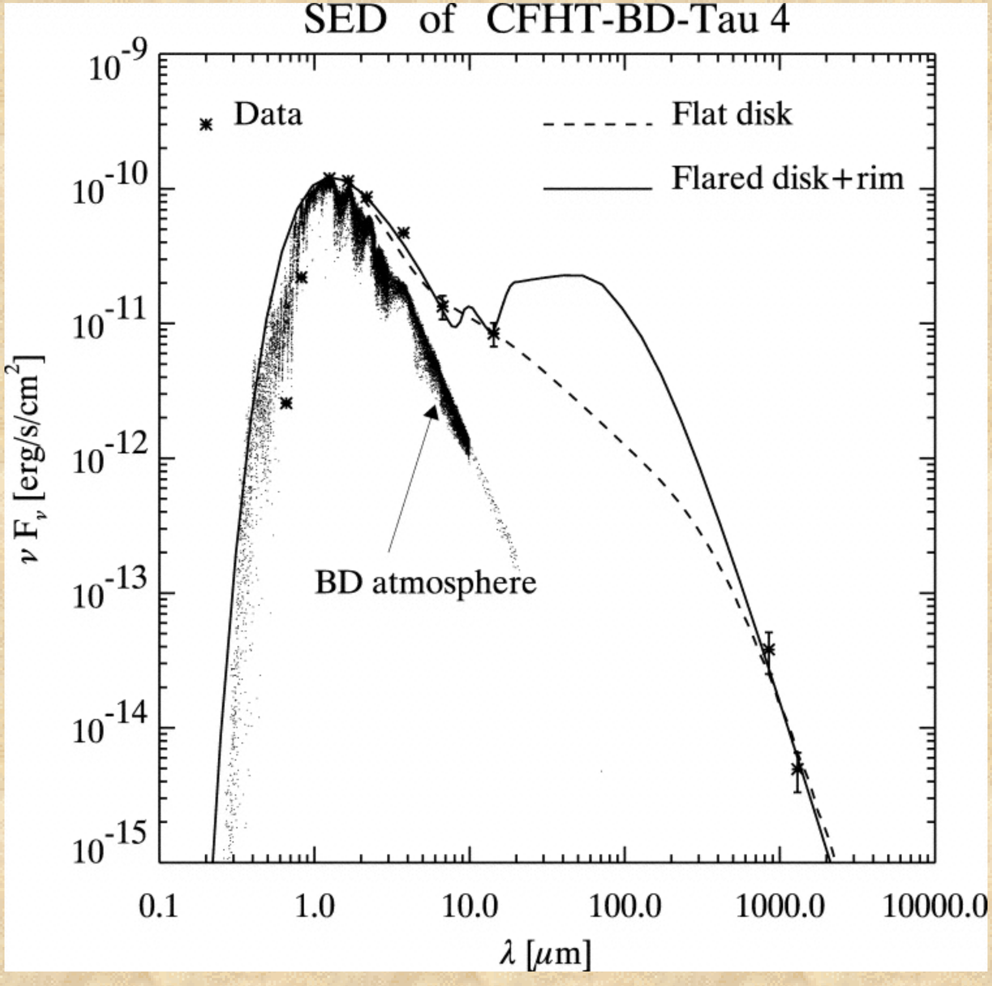


Apai et al. (2003);

Sterzik et al. (2004)

Planet formation potential?
Millimeter Observations of Cold Dust

(CFHT BD-Tau 4 and IC 348 613)



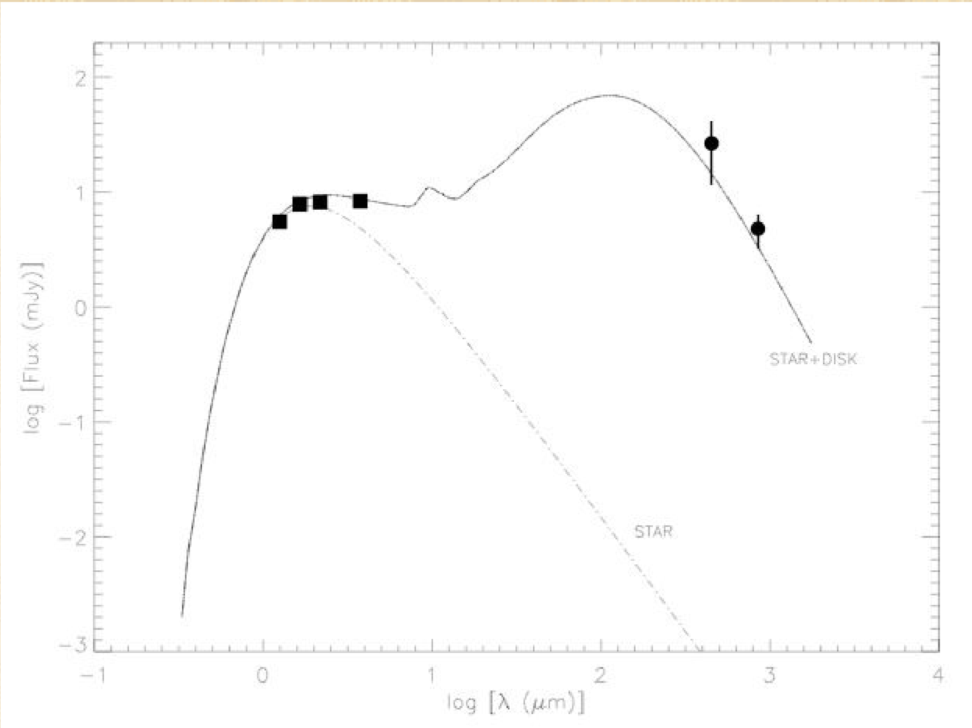
A few Earth masses of dust (assuming dust opacities similar to TTS disks)

Assuming gas-to-dust ratio of 100, disk mass ~a few % of BD mass

Pascucci et al. (2003); Klein et al. (2003)

Millimeter Observations of Cold Dust

(KPNO Tau 3)



~1 Earth mass of dust (assuming dust opacities similar to TTS disks)

Assuming gas-to-dust ratio of 100, disk mass ~1 % of BD mass

On-going survey at JCMT

Mohanty, Jayawardhana, Matthews, et al., in prep.

Spectroscopic Signatures of Accretion

Sample

Objects with *known spectral types later than M5* in Upper Scorpius, ρ Ophiuchus, IC 348, Taurus, Chamaeleon I, and TW Hydrae

Total ~ 82 (!), including 41 "brown dwarfs" (M6.5 and later)

Observations

High-resolution optical spectra at Keck and Magellan

R~33,000 (HIRES), R~20,000 (MIKE)

Hα line profiles in high-resolution spectra is a good diagnostic of accretion (also OI, HeI, CaII in some cases)

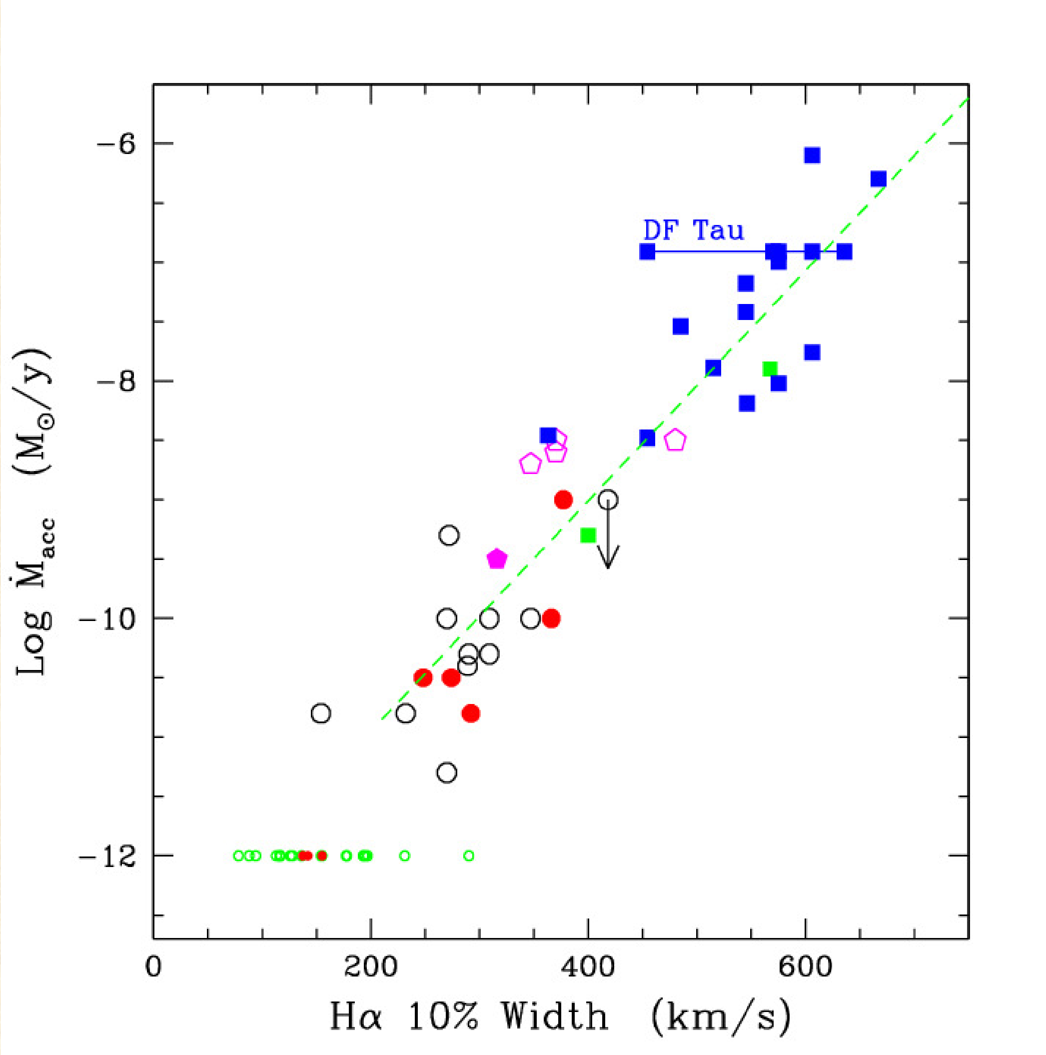
Hα Criterion for Accretion

* Hα EW > 10A are usually categorized as CTTS
* But this threshold value varies with spectral type
* Hα line width at 10% of the peak may be a better indicator
* Nearly free-falling flow between disk inner edge and star
* For brown dwarfs at a few Myr,

adopted accretion threshold: ~200 km/s (+ other diagnostics)

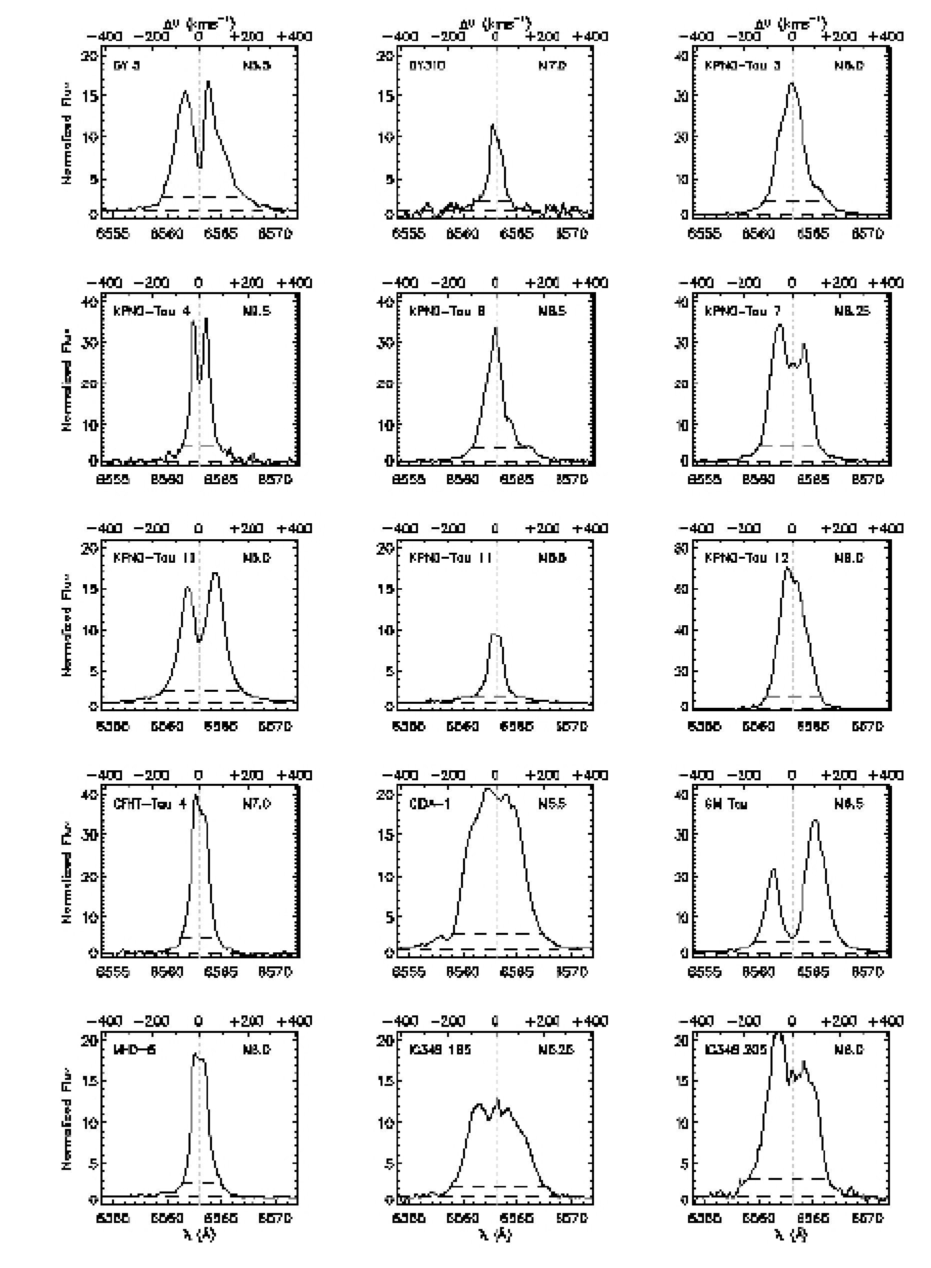
(Jayawardhana, Mohanty, & Basri 2003)

Accretion Rate vs. Hα 10% Width



Natta et al. (2004)

Hα line profiles of some accretors



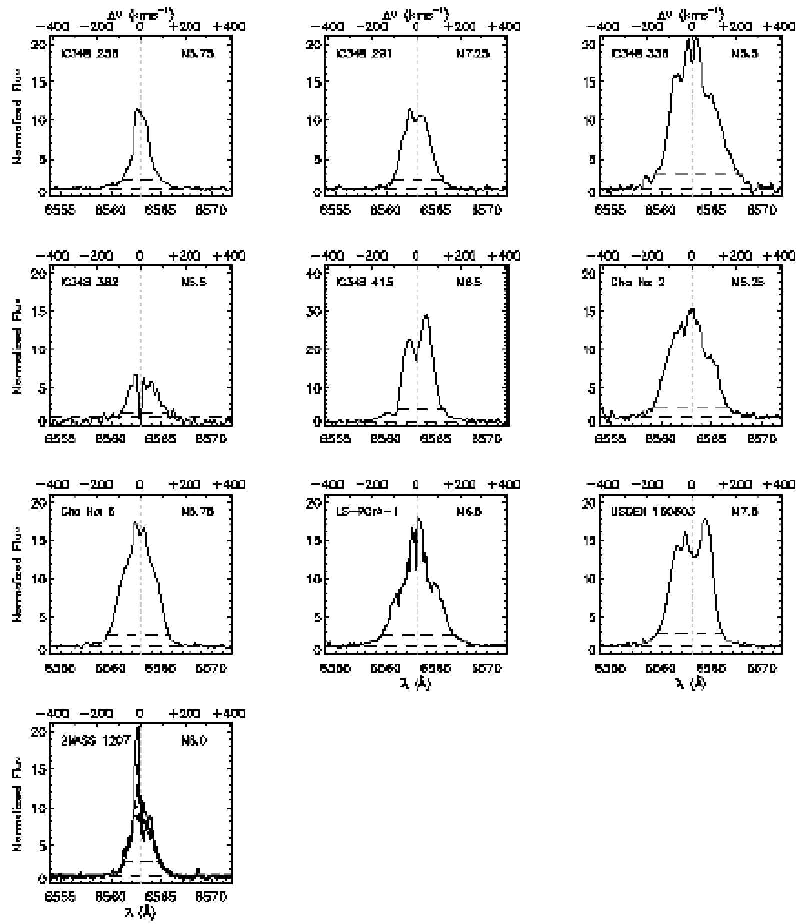
Jayawardhana, Mohanty & Basri (2002, 2003);

Mohanty, Jayawardhana & Basri (2005)

also see White & Basri (2003);

Muzerolle et al. (2003)

Hα line profiles of More accretors



Mohanty, Jayawardhana & Basri (2005)

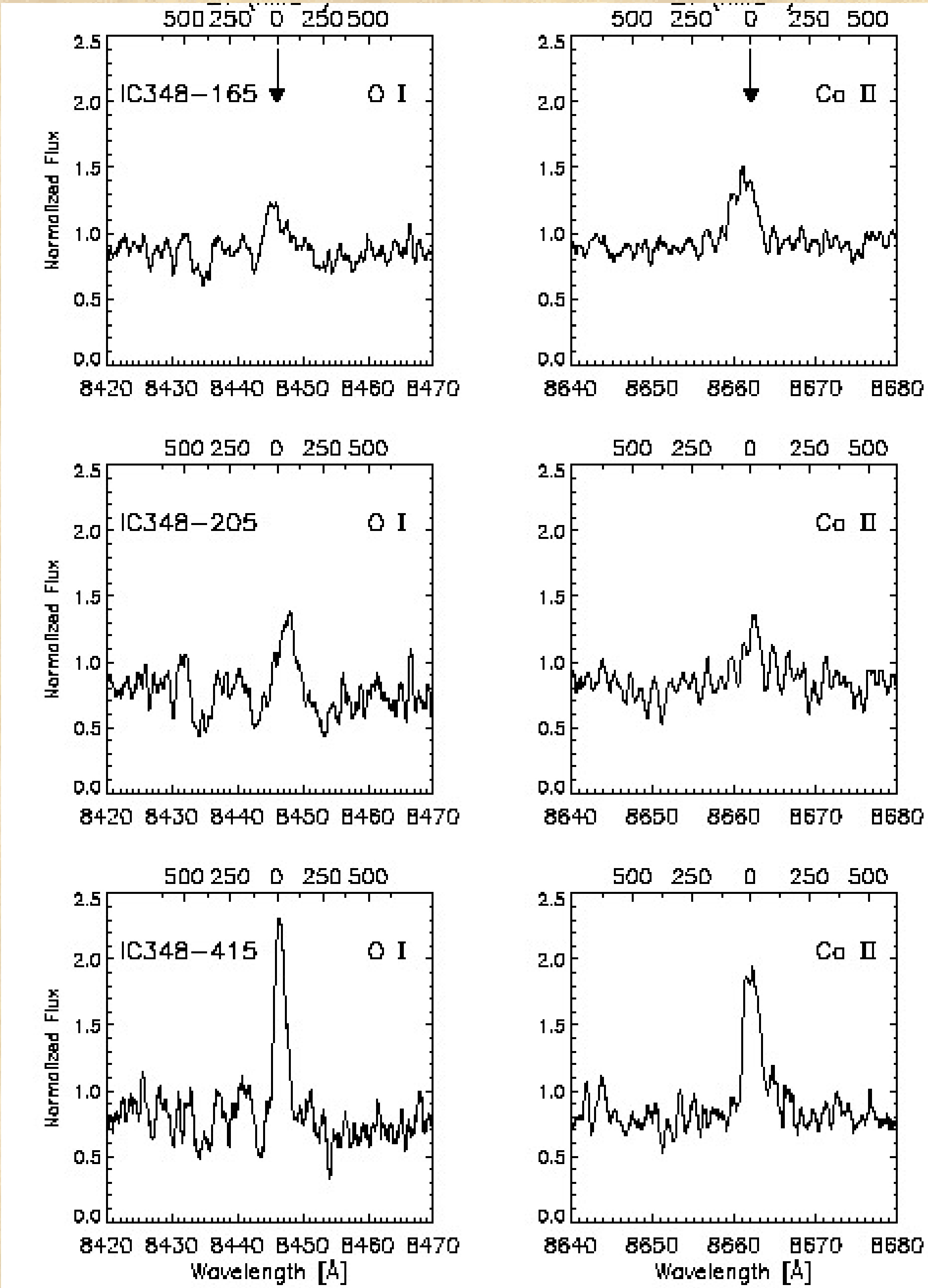
OI (8446A) and

CaII (8662A)

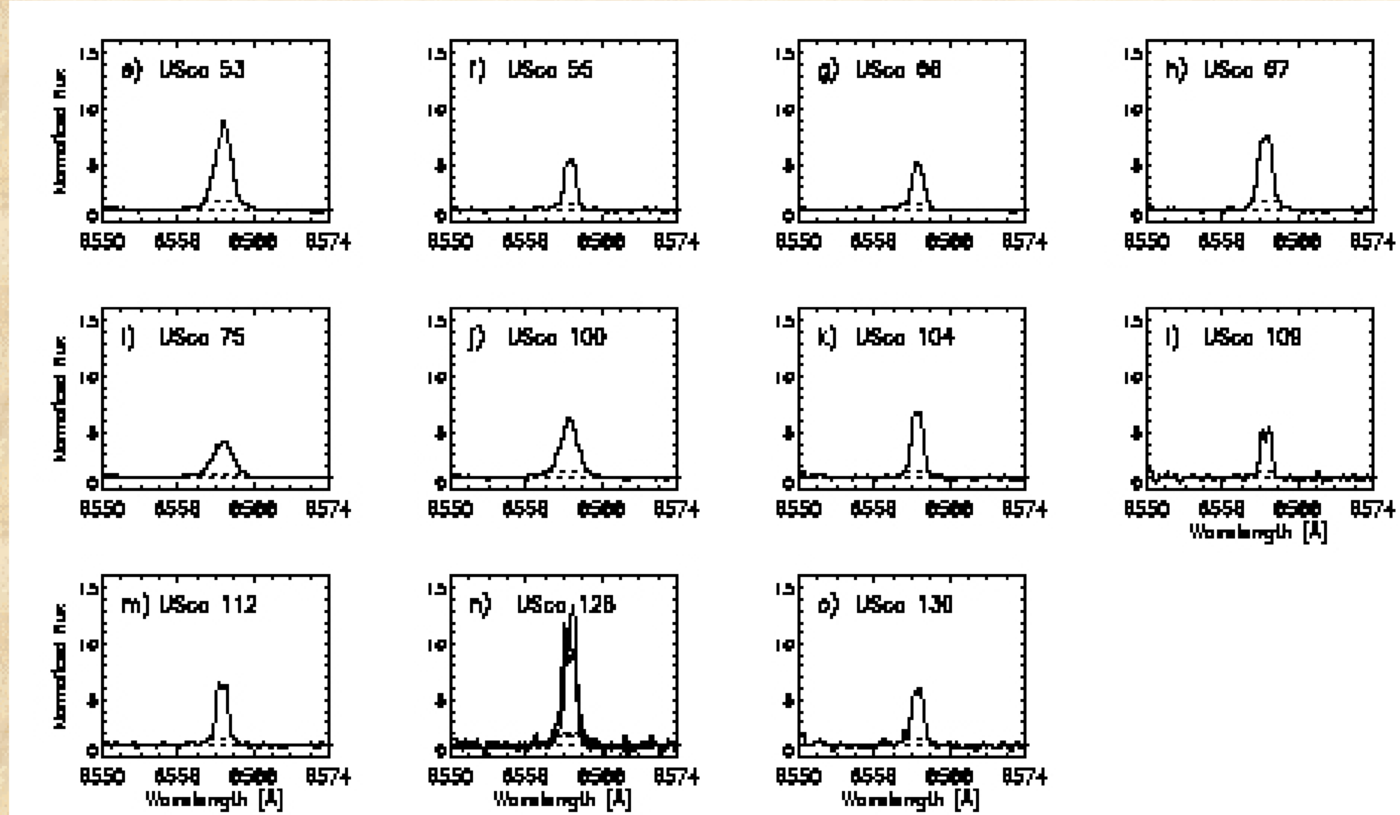
line profiles for three accretors in IC 348

Broad HeI (6678A) line also seen in IC 348-165

Jayawardhana, Mohanty & Basri (2003)

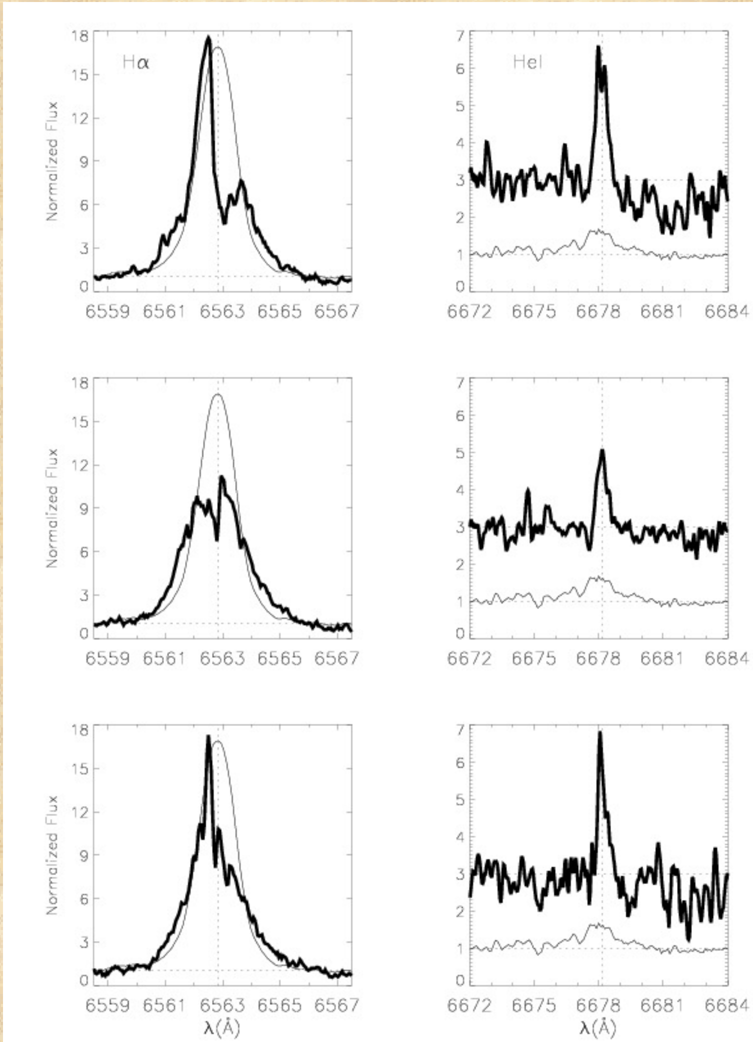


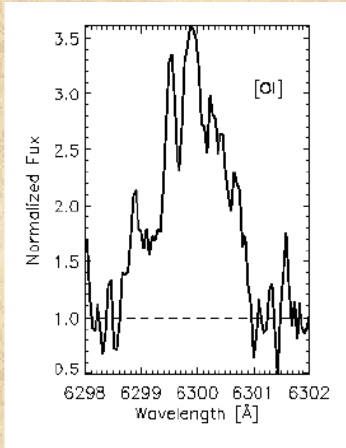
Hα line profiles for Upper Sco (~5 Myr)



Jayawardhana, Mohanty & Basri (2002)

Hα, He I and [OI] emission in 2MASS 1207-3932 in the TW Hydrae Association





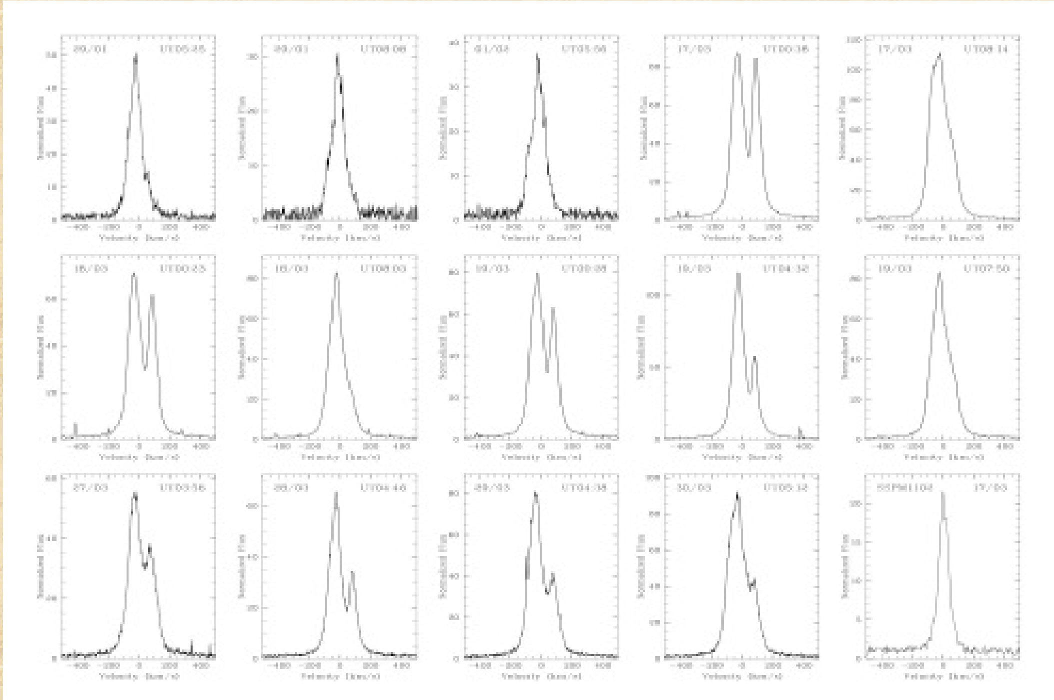
Accretion and winds/outflow in BDs can persist for up to ~8 Myrs

Mohanty, Jayawardhana & Barrado y Navascués (2003)

Mohanty, Jayawardhana & Basri (2005)

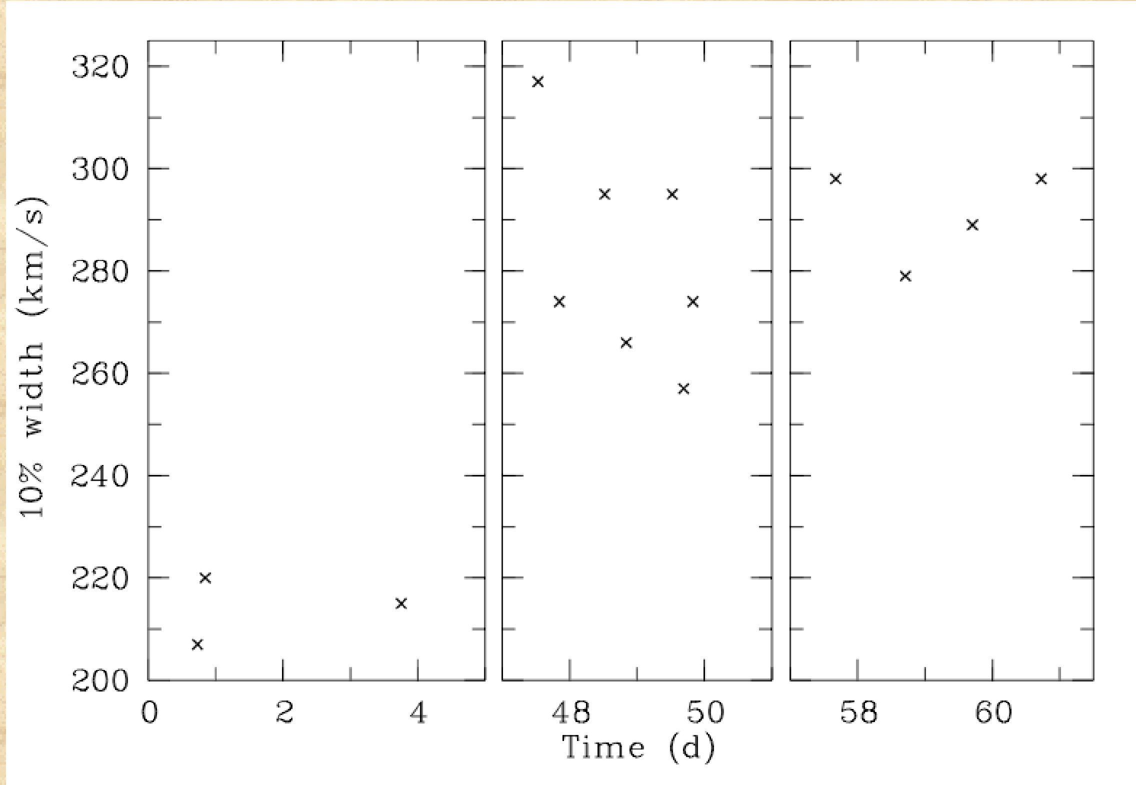
Emission Line Variability in 2MASS 1207-3932: Hα

- 14 high-resolution optical spectra from Magellan, 2005 Jan-Mar
- Variability on timescales of weeks as well as hours
- Redshifted absorption coming into and out of view on ~ rotation period
- Accretion disk close to edge-on?
- Looking into an accretion funnel when line is double-peaked?



Scholz, Jayawardhana & Brandeker (2005)

Emission Line Variability in 2MASS 1207-3932: Hα



Accretion rate appears to change by 5-10x over ~6 weeks

Scholz, Jayawardhana & Brandeker (2005)

Fraction of Accretors

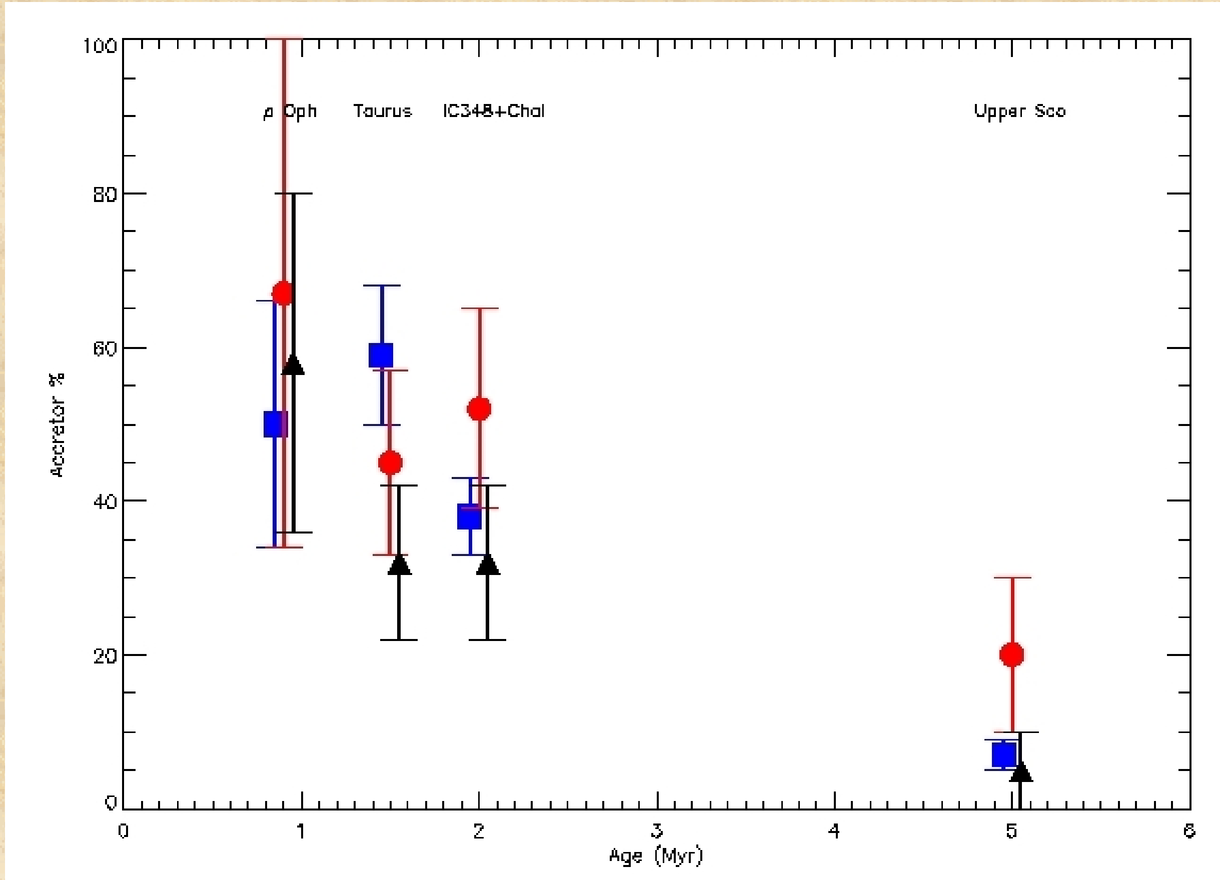
Region	Fraction	Est. Age
ρ Oph	6/9	< 1 Myr
Taurus	12/30	~1 Myr
IC 348 & Cha I	10/32	~2 Myr
Upper Sco	1/20	~5 Myr
TW Hya	1/4	~8 Myr

In Taurus, Cha I and Upper Sco, several objects with K-L′ excess do not show accretion-like Hα profiles

→Disks persist after accretion rates have dropped?

2MASS1207-3932 in TWA: accretion and mid-IR excess, no L′ excess

Fraction of Accretors as a Function of Age: Comparison with higher mass stars



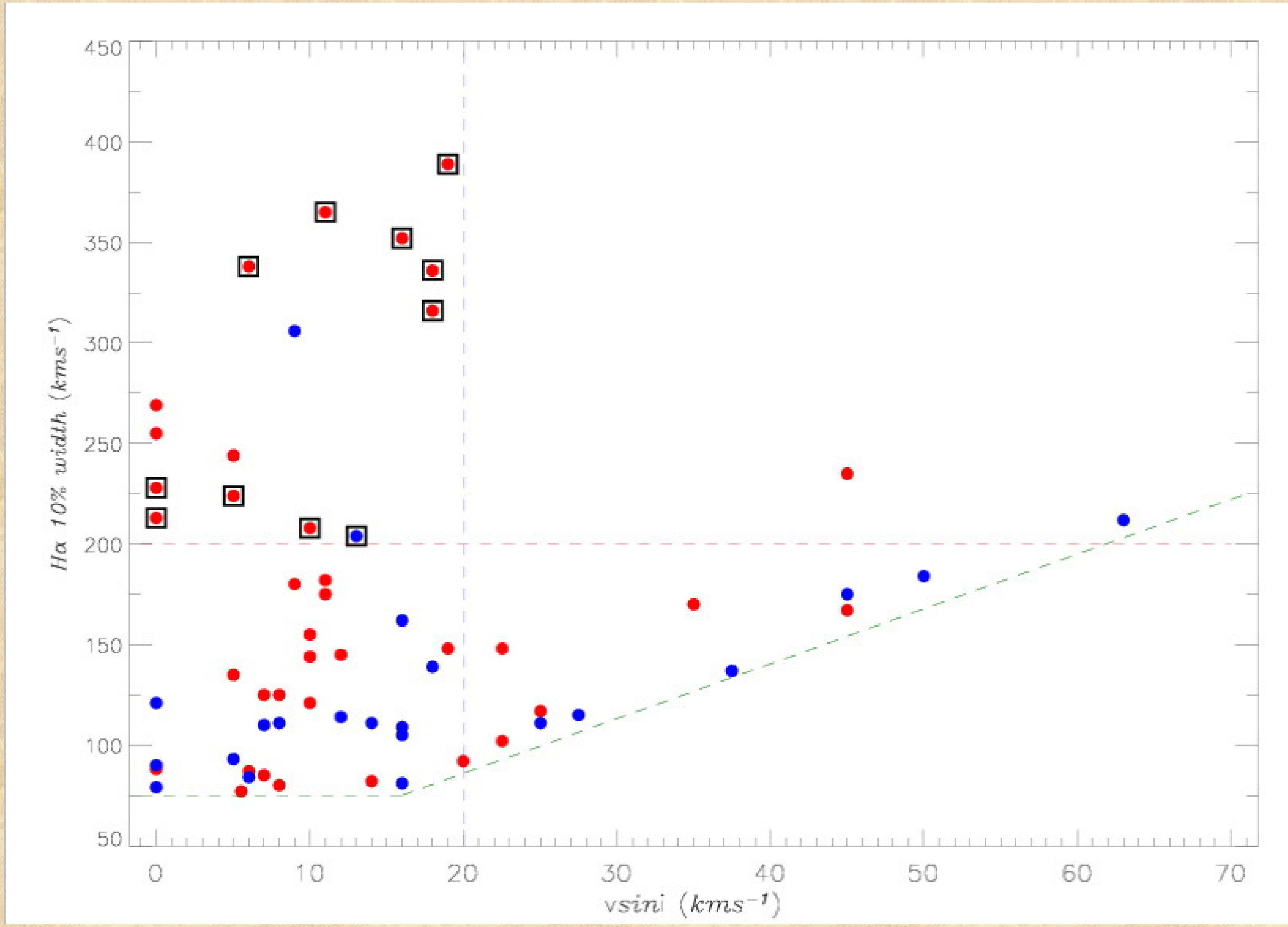
Blue squares: K0-M4 stars using BM03

Red circles: VLM objects using BM03

Black triangles: VLM objects with our high-res. analysis

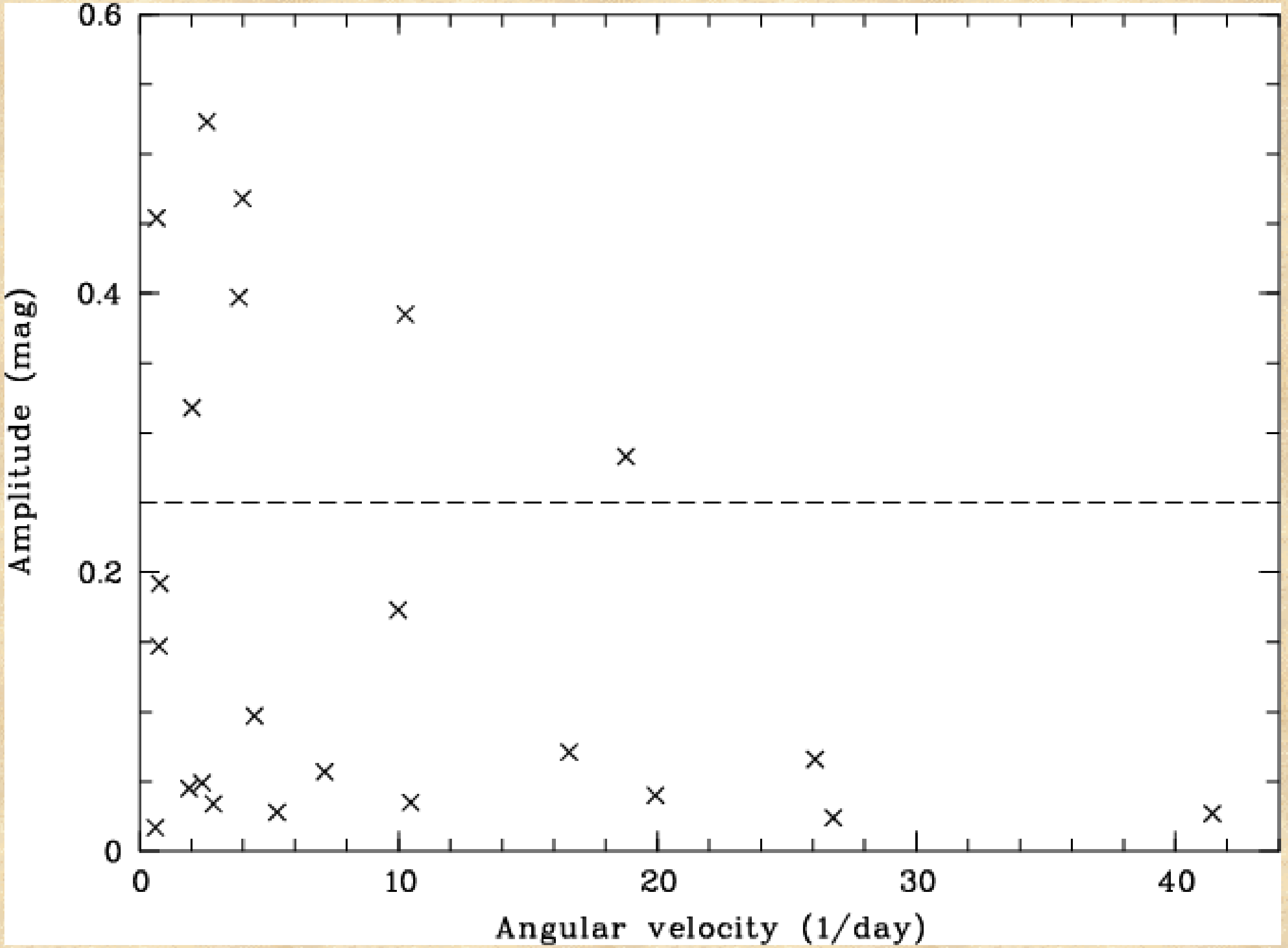
Mohanty, Jayawardhana & Basri (2005)

Rotation-Disk Connection?



Basri, Mohanty & Jayawardhana, in prep.

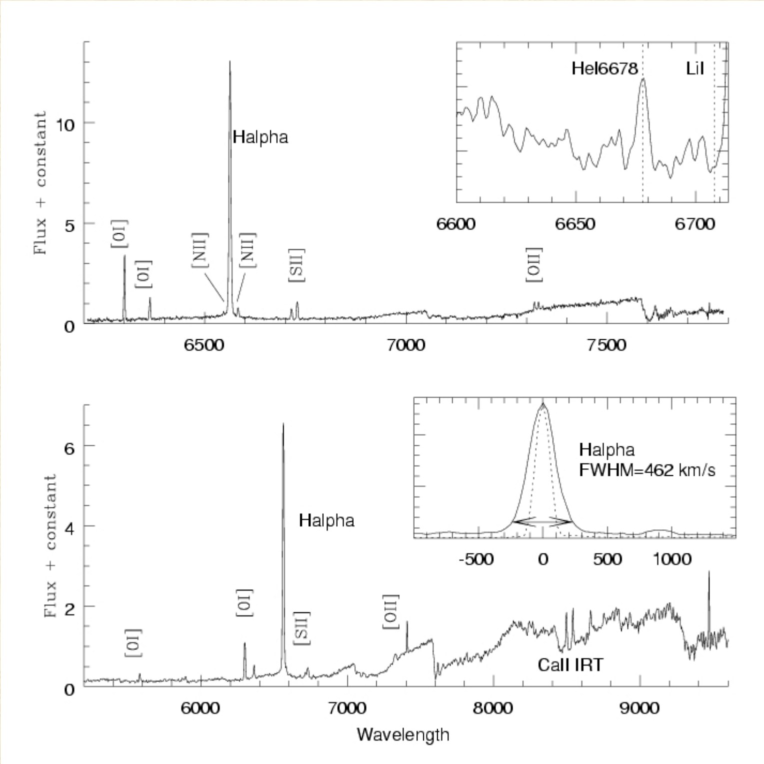
Rotation-Disk Connection?



Scholz & Eisloffel (2004)

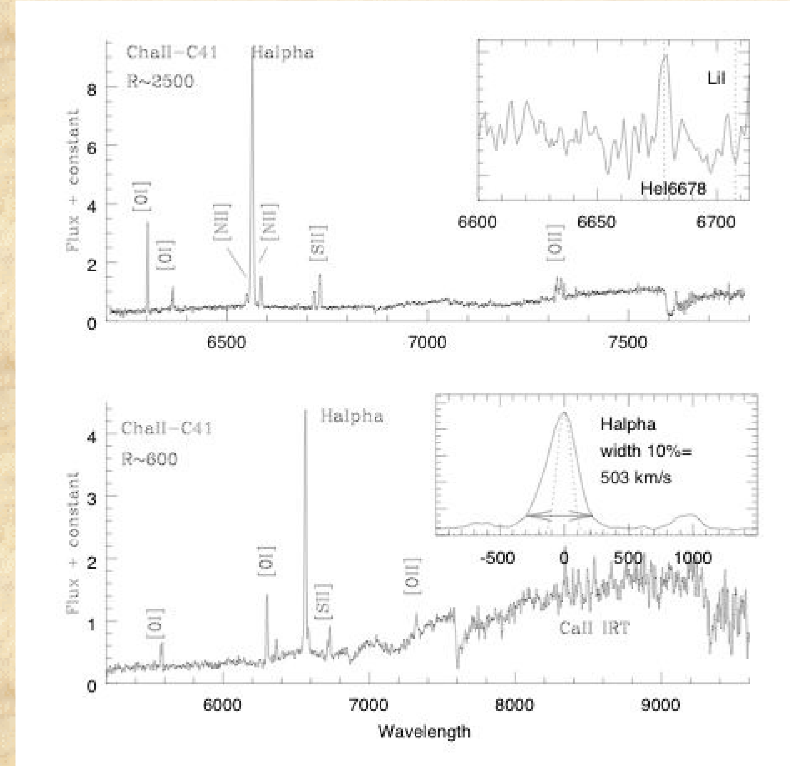
Outflows in the VLM Domain?

LS RCrA 1



Fernandez & Comeron (2001);
Barrado y Navascués, Mohanty & Jayawardhana (2004)

Cha II-C41



Barrado y Navascués, & Jayawardhana (2004)
also see Natta et al. (2004); Muzerolle et al. (2003)

Conclusions

* A large fraction of young sub-stellar objects harbor K-L′ excess consistent with optically thick disks

* Mid-IR and mm observations suggest a range of disk geometries and dust properties similar to those of TTS

* Many brown dwarfs show signs of accretion at very young ages

* Disks appear to persist after accretion rates have dropped below measurable levels (e.g., Upper Sco)

* Inner disk lifetimes of brown dwarfs do not appear to be vastly different from those of T Tauri stars

* Accretion related variability seen in 2M1207 on timescales of both hours and weeks --support for magnetospheric accretion

* Tantalizing hints of outflows in several VLM objects

Compelling Evidence for a T Tauri Phase in Young Sub-Stellar Objects

Implication

Does this imply a common formation mechanism for isolated sub-stellar objects and low-mass stars?

Quite Possibly.

(Even some `planemos' may form the same way as stars do…

D-burning limit shouldn't matter for formation: Chabrier 2003)

But, it may be too early to rule out the ejection scenario and other models for the origin of at least some brown dwarfs.