The accretion disk paradigm for young stars

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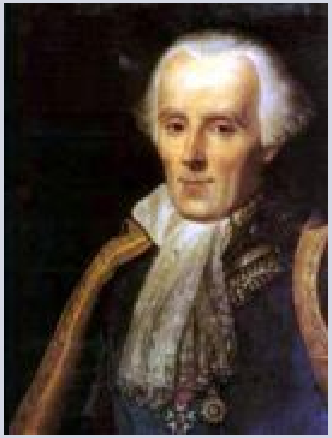
Talk outline

- Disclaimer
- Historical perspective
- The accretion disk paradigm shift
- Some remarks on a few of the many advances and unsolved issues

Early ideas on star and planet formation



Immanuel Kant (1755), Pierre-Simon Laplace (1796):

the Sun and planets coalesce under the influence of gravity from a flattened and rotating gaseous nebula.

Alfred H. Joy (1882-1973)

A.H. Joy in 1972

"It is difficult to be certain which was Joy's most far-reaching contribution, but the T Tauri stars are his most famous monument."

George Herbig (1974)

T Tauri variables

"Eleven irregular variables have been observed […] The distinctive characteristics are:
(1) irregular light variations of about 3 mag.,
(2) spectral type F5-G5 with emission lines *resembling the solar chromosphere*,
(3) low luminosity,
(4) association with dark or bright nebulosity".

A.H. Joy, ApJ 102, 168 (1945)

T Tauri stars were not immediately recognized as young, solar-type stars.

Viktor A. Ambartsumian (1908-1996)

V.A. Ambartsumian in 1961
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Among many important contributions to astrophysics, he introduced the concepts of stellar (OB and T) associations in 1947 and recognized that they were sites of ongoing star formation.

It took a few years before this idea, which was at the time bold and speculative, was generally accepted.

First models

Jesse L. Greenstein (1950, PASP 62, 156):

"It seems improbable that the short-lived association of these stars with a cloud of interstellar matter can change the actual energy generation in the interior. The veiling continuum and the emission lines must be produced in a circumstellar fringe or extended chromosphere".

Greenstein's model

based on gas accretion as the star crosses the molecular cloud

- Kinetic luminosity of the accreting matter as the star moves at 10 km/s through a molecular cloud with density 10^4 per cm^3 is a few 10^{-4} L_{sun}, insufficient for explaining emission properties.
- The dynamics of an accreting molecular gas envelope might be controlled by magnetic forces if the magnetic field is high enough (analogy with solar prominences), leading to high densities and velocities in the envelope. The same mechanism could produce flares.

On T Tauri and dMe flares

Burbidge, G.R., Burbidge, E.M., 1955, (The Observatory, 75, 212):

"To sum up, we wish to divide the stars showing flaring into two main categories:

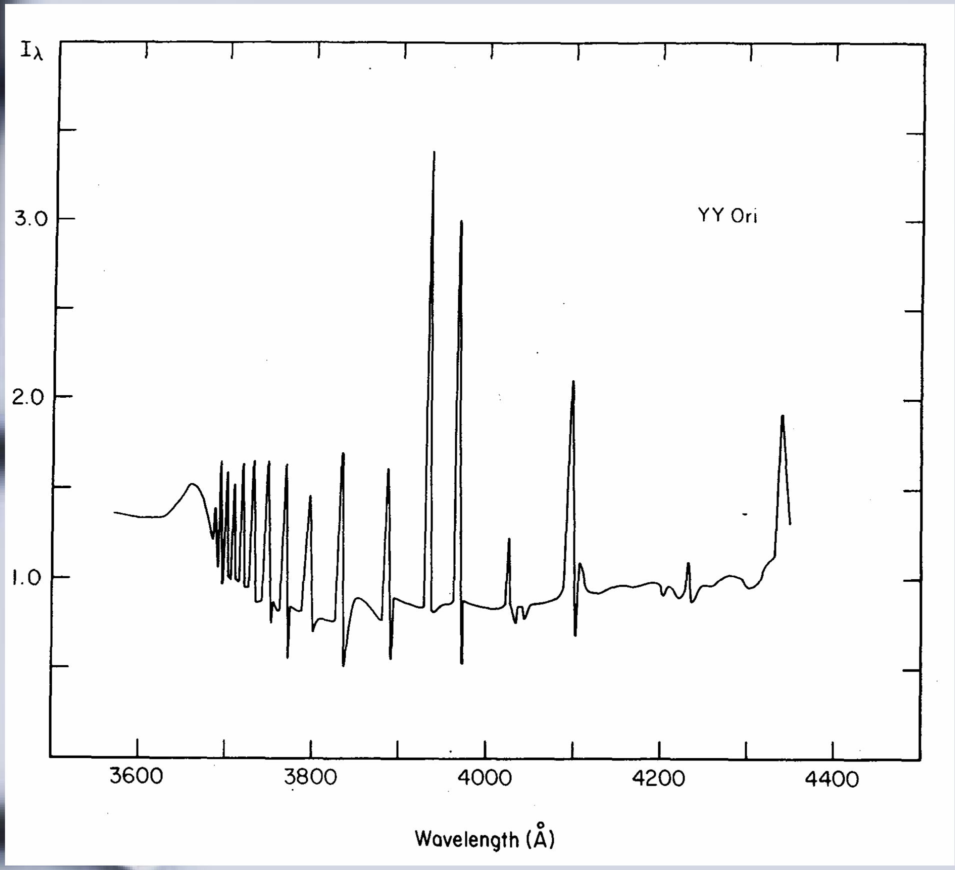
(a) The T Tauri and related objects in which MHD processes outside the star are responsible;

(b) The dMe flare stars in which internal MHD processes are responsible".

1960s: growing evidence of mass motions in T Tauri star envelopes

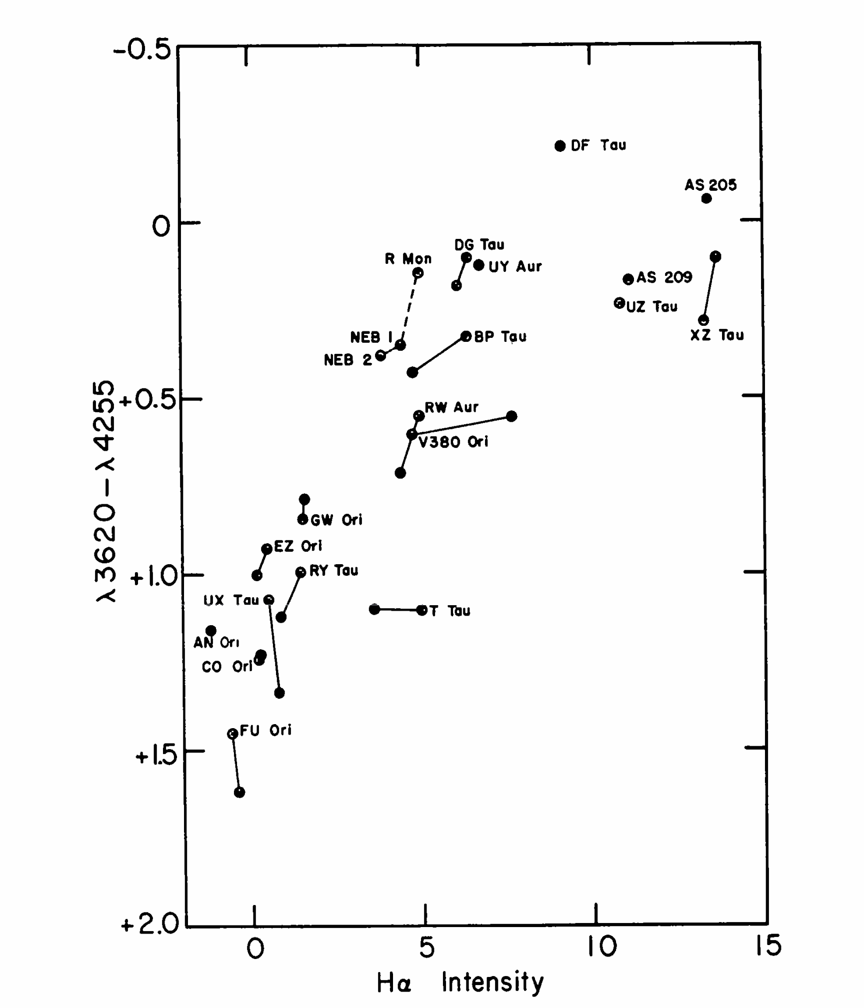
- **George H. Herbig** (1962, Adv. Astr. Astrophys., 1, 47-103) reviews scarce high-resolution spectroscopic data and concludes "*Mass ejection by T Tauri stars […] seems to be such a common trait of the family that it must find some natural explanation in the contractional process*".
- **Leonard V. Kuhi** (1964, PhD thesis and ApJ 140, 1409) models line profiles of several TTSs and finds mass loss rates of ~ 3 10^{-8} Mo/yr for T Tau and RY Tau.

1960s: discovery of YY Orionis stars



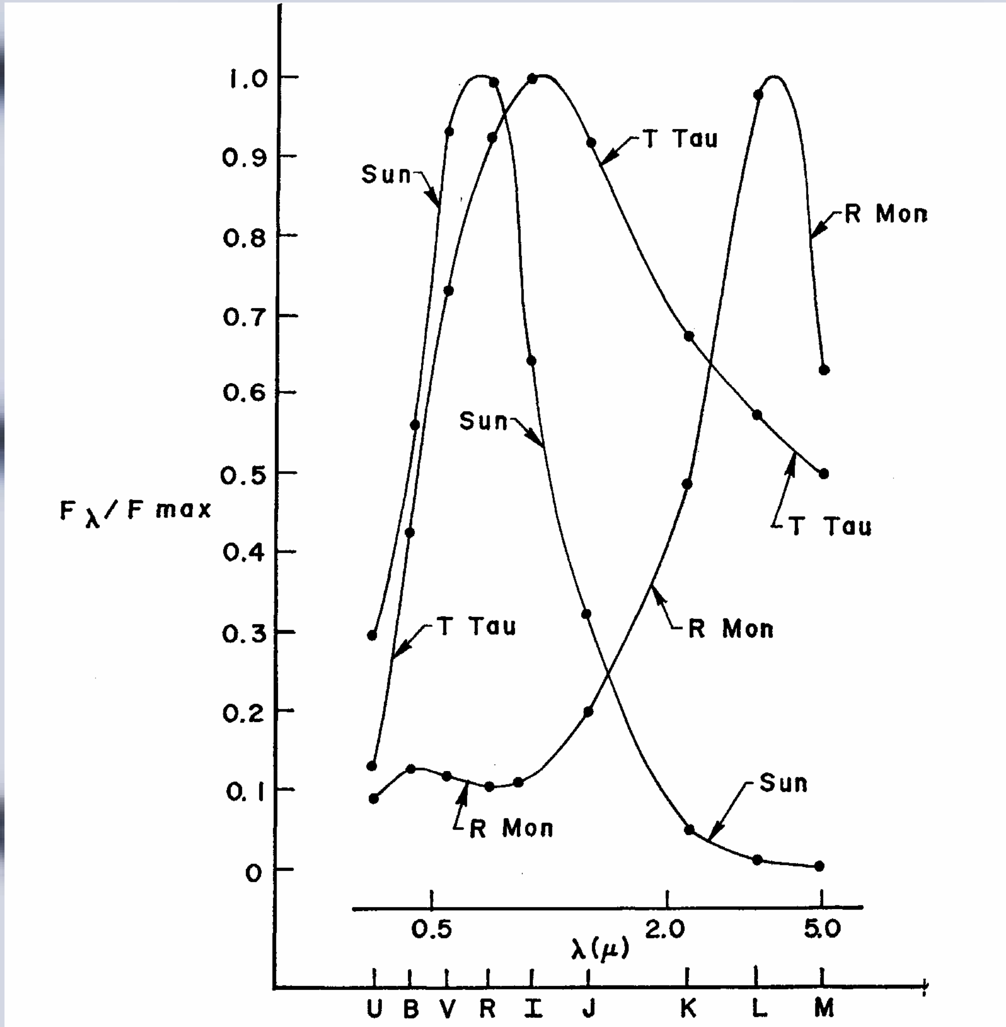
Merle F. Walker (1963, AJ 68, 298) reports red-displaced (by 200-400 km/s), highly variable absorption components in the Balmer lines of YY Ori and other faint Orion stars with UV excess. He suggests that *"the presence of the excess continuous emission may have some connection with this possible infall of material".*

Nature of the UV excess in TTSs



Kuhi (1966, PASP 78, 430) finds a correlation between UV excess and Hα intensity and concludes that the UV excess is due to Balmer emission.

Late 1960s: discovery of near-IR excess in TTSs



Eugenio Mendoza (1966, ApJ,143, 1010):

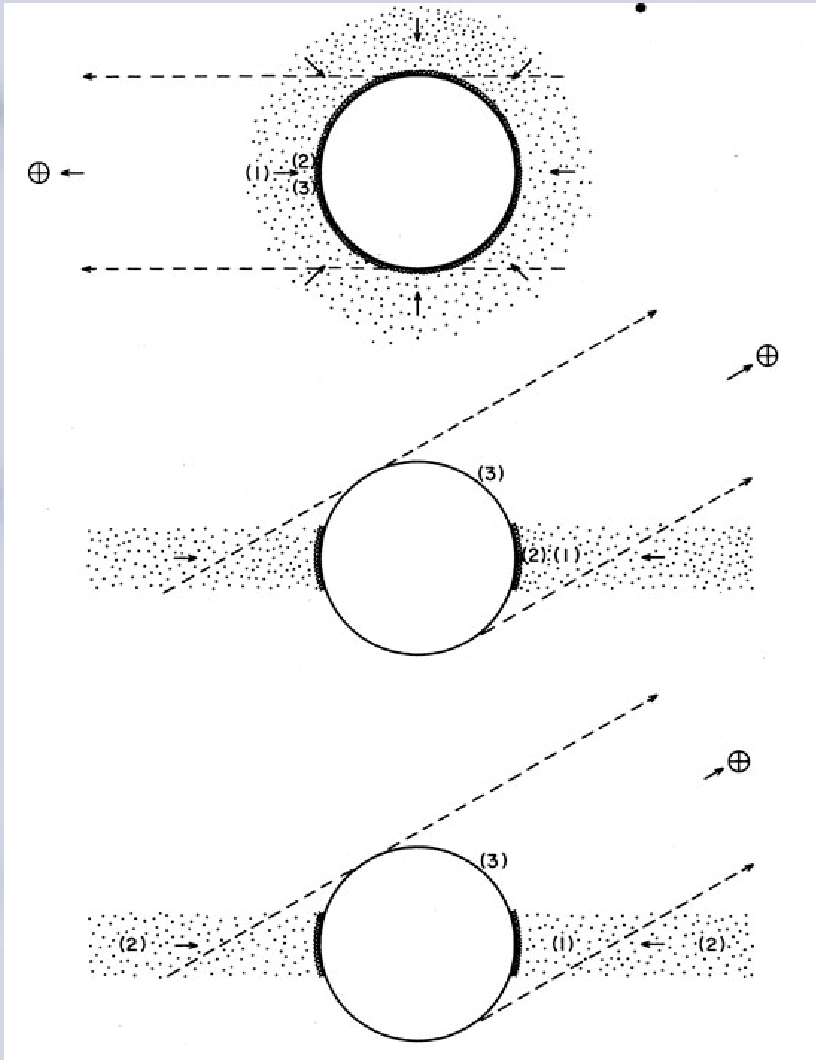
"The study is not complete but the results are so surprising that a preliminary report is called for".

1960s: summary

At the end of the 1960s, there is evidence that T Tauri stars:

- are pre-main sequence and solar-type,
- are variable at all wavelengths,
- are veiled by a blue continuum,
- may have UV and/or near-IR excesses,
- display wind and sometimes infall signatures.

Early 1970s: true pioneers



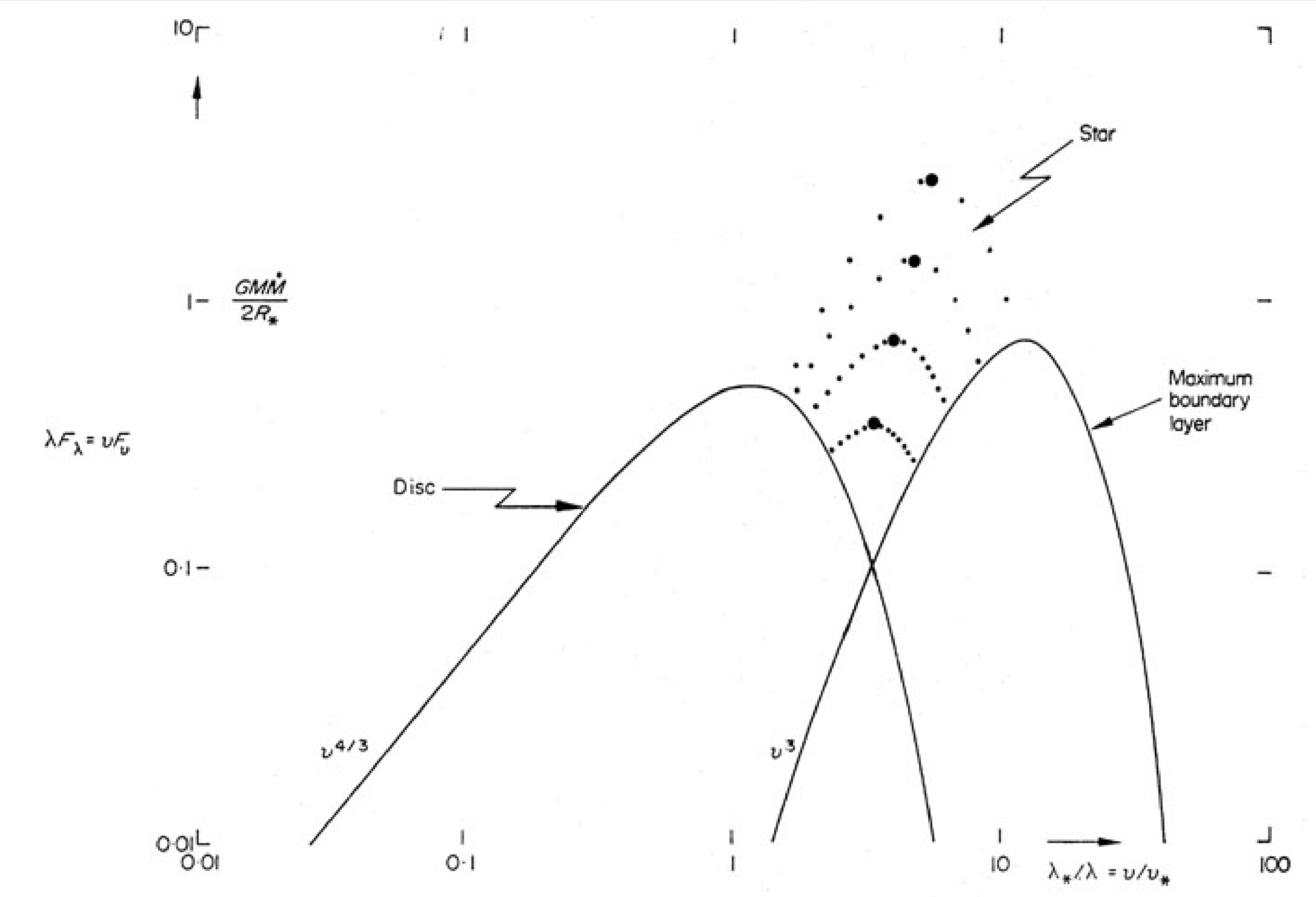
1972: M. F. Walker (ApJ 175, 89) introduces a disk model to explain the spectroscopic properties of YY Ori stars.

(1) region where the red-displaced absorption lines originate;

(2) region where the emission lines originate;

(3) region where the late-type stellar absorption spectrum originates.

1974: Lynden-Bell & Pringle accretion disk model



1976: Roger Ulrich's infall model

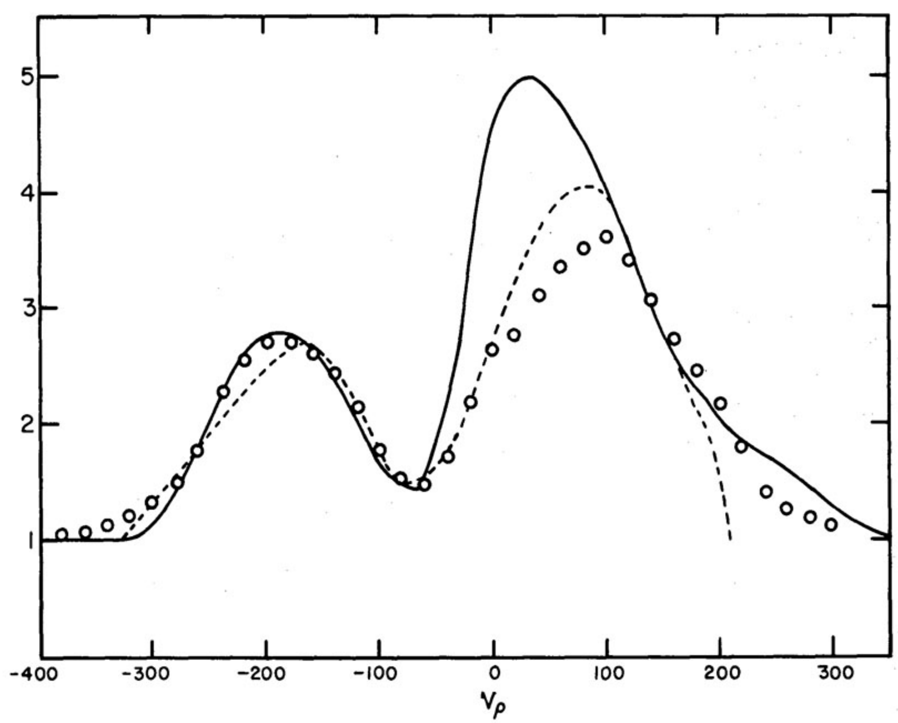


FIG. 13.—Comparison of a computed line profile (———) to the Hα profile observed from RY Tau, EC 1519 (○ ○ ○) and to the profile (– – –) computed by Kuhi (1964) for the outflow model. Parameters used for infall profile were $\tau_0 S_L = 21 B_\nu$, $i = 55°$, and $r_d/R = 10$.

Velocity field and density law in the envelope are derived from a kinematic approach to the gravitational collapse with rotation. Balmer lines are assumed to be formed *only* in shocks at the stellar surface. Type III P Cygni profiles may result depending on parameters chosen.

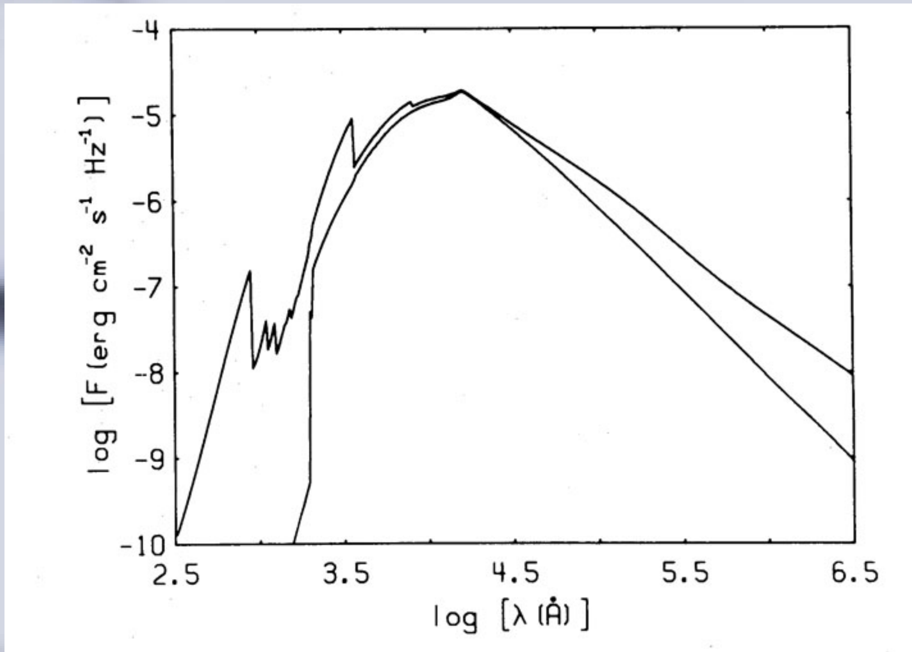
1976 Geneva IAU Symposium No. 75 "Star Formation"

- LBP accretion disk model mentioned only in passing in the review talks on theory by R. Larson and L. Mestel.
- Attempts to relate observations of YY Ori and T Tau stars to results of the collapse computations by Larson and others.
- Deep-chromosphere models for TTSs are discussed.
- The focus of the discussions among T Tauri experts is on the infall vs. outflow controversy.
- Herbig calls for decisive observations and concludes: "After all, when the historians of science look back on our times with the perspective of the years, all that we do today will certainly be seen to have been either wrong, or irrelevant, or obvious".

The explosion of the observational knowledge base in the early 80s

- Discovery of bipolar CO outflows (Snell, Loren, and Plambeck, 1980, ApJL 239, L17).
- IUE mission: UV excess of young stars extends to far-UV, MgII line emission, etc. (1981, Giampapa et al, ApJ 251, 113)
- *Einstein* X-ray Observatory: TTS X-ray luminosity ~ 10^{30-31} erg/s (1981, Feigelson & De Campli, ApJ 243, 89)
- Discovery that Herbig-Haro objects are highly collimated jets (Mundt & Fried, 1983, ApJL 274, L83)
- Discovery that H-H objects and bipolar molecular outflows are often associated (Edwards & Snell, 1984, ApJ
- Mid-IR ground-based observations lead to a new characterization of YSOs based on their IR properties (1984, Lada & Wilking, ApJ 287, 610)
- IRAS observations show that the IR excess of TTSs extends to the far-IR with power-law SEDs typically $\lambda F_\lambda \sim \lambda^{-1}$ (1985, Rucinski, AJ 90, 2321).

Meanwhile, theory moves forwards: I. the deep chromosphere model



- Advocated by Herbig, Kuhi, and others. Detailed models by Cram (1979, 234, 949), Calvet, Basri, and Kuhi (1984, ApJ 277, 725) and others.
- Model assumes that the chromospheric temperature minimum is located at τ_c~0.1-0.3 instead of τ_c~10^{-3}-10^{-4} as in the Sun.
- Can account for bulk properties of emission line spectrum and Balmer emission.
- Cannot account for Balmer decrement, line shapes, IR excess.

II. Wind models

- De Campli (1981, ApJ 244, 124) discusses the energetic constraints for generating a strong T Tauri wind.
- He shows that the wind luminosity of a thermally driven wind with mass-loss rate ~ 10^{-8} M_o/yr exceeds the stellar luminosity, but that Alfven-wave driven winds are more efficient and may account for moderately strong T Tauri winds.
- Detailed models were given by De Campli (see ref. above), Hartmann, Edwards, and Avrett (1982, ApJ 261, 279), and Lago (1984, MNRAS 210, 323).

III. Stellar structure

Appenzeller & Dearborn (1984, ApJ 278, 689) find from computation of pms stellar structure models that variable magnetic fields can cause visual brightness variations in the star that are comparable in range (up to 3.5 mag) to what is observed in TTSs.

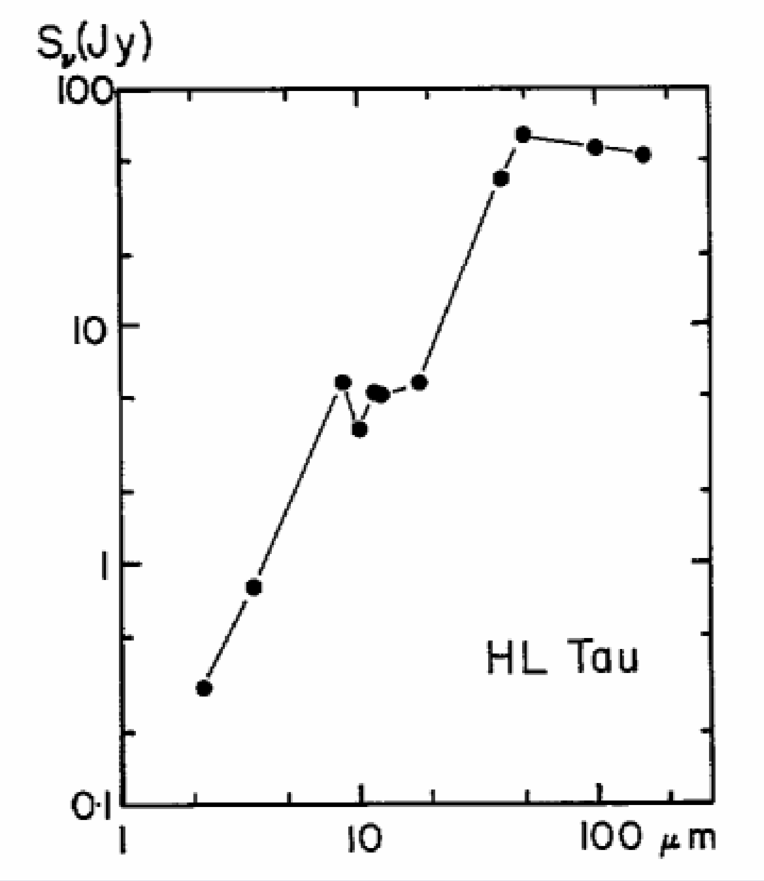
State of affairs in 1985

A promising TTS model would combine

- a magnetically active star
- with a deep chromosphere
- and an Alfven-wave driven wind.

- but this involves strong constraints on the stellar magnetic field
- and what about the IR excess?
- and what about spectroscopic evidence of infall?

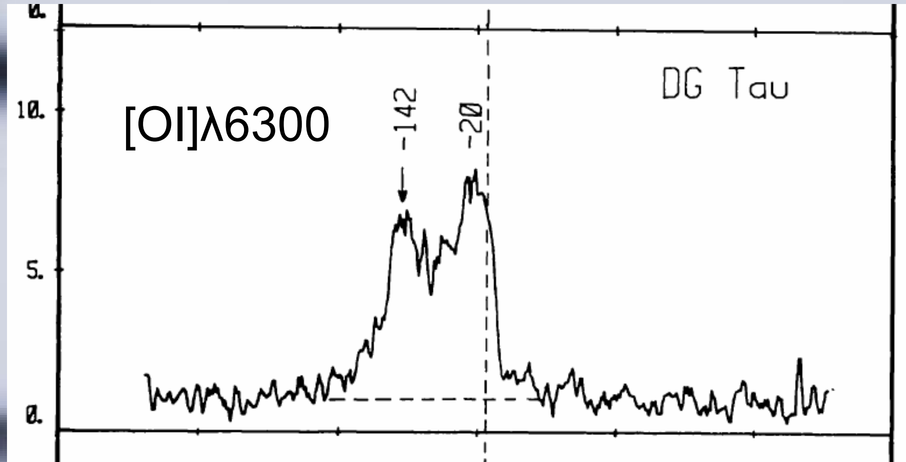
The return of the disks

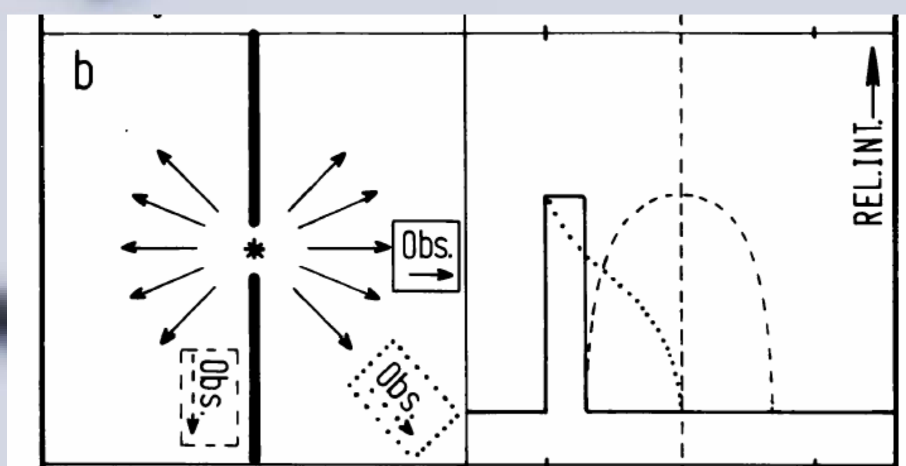


M. Cohen (1983, ApJL 270, L69) suggests that the TTS HL Tau is surrounded by a dusty disk. Main arguments:

- peculiar SED
- 3.1 μm ice feature
- 10 μm silicate absorption
- 13% linear polarization

The return of the disks (cont'd)





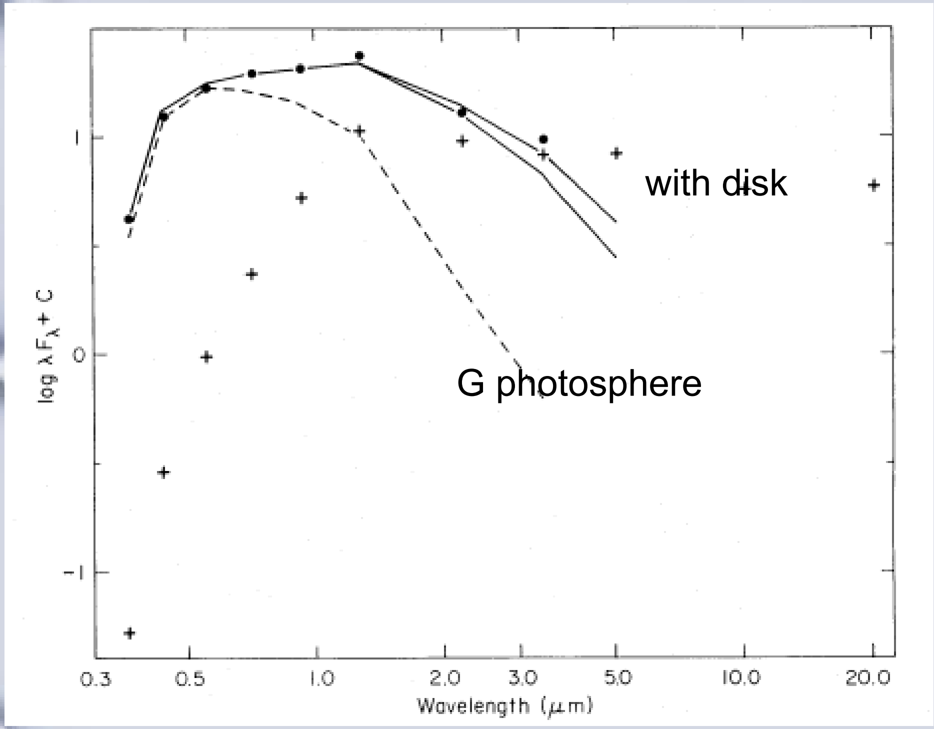
Appenzeller, Jankovics & Oestreicher (1984, A&A 141,108) show that:

- Forbidden lines are often blue-displaced in TTSs;
- they can be interpreted as being formed in collimated outflows partially occulted by dusty "screens".

First spectroscopic evidence of optically thick disks around TTSs.

FUOrs as accreting pms stars

V1057 Cyg



Hartmann & Kenyon (1985, ApJ 299, 462) show that FUOr outbursts can be explained as episodes of strong mass accretion from a disk. Emission from the hot, optically thick accretion disk dominates the system light at maximum.

Aside

Scott Kenyon’s 1983 PhD thesis was on “The nature of symbiotic stars”.

These interacting binary systems include an evolved red giant and a hot companion surrounded by an accretion disk.

The LBP disk model was applied very successfully to model disks in symbiotic systems as early as 1974.

1986 Heidelberg IAU Symposium No. 122 "Circumstellar matter"

Can be considered the moment when the disk hypothesis for TTSs re-emerges successfully.

- F. Shu presented there his ongoing work (with F. Adams, C. Lada, S. Lizano) on the 4 stages of pre-main sequence evolution.
- R. Mundt discussed the now large body of data concerning molecular outflows and optical jets;
- M. Cohen discussed the possible role of disks in bipolar outflows observed in many different types of stars;
- F. Walter discussed the X-ray selected, "naked" TTSs;
- U. Finkenzeller and G. Basri reported evidence of inflowing material in moderately active TTSs;
- I compared observed SEDs of TTSs with simple models of stars interacting with accretion disks.

1986-1990: exploring the new paradigm for TTSs

- Thomas Kuhn showed that most advances in science, both small and large, are discontinuous shifts in ideas.
- A shift to a new paradigm occurs after a sufficiently large body of contradictions between observations and theory has accumulated, making it impossible to continue along the same line of thought as previously.

Why an accretion disk?

The main problem that the disk hypothesis solves concerns the energetics of TTSs:

The disk offers a reservoir of potential energy that can be tapped to power phenomena associated with these stars (emission excesses at all wavelengths, jet and wind).

Lex parsimoniæ: the presence of a disk and its interaction with the star account for most exotic properties of young stars.

Remark: active vs. passive disks

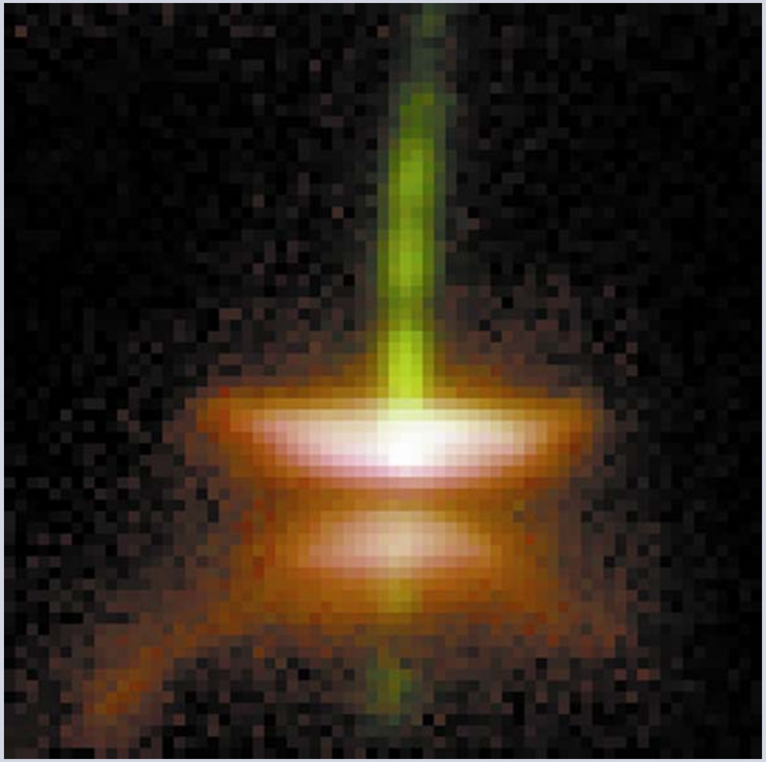
A passive disk only reprocesses the luminosity of the star – no real gain as far as energetics are concerned.

TTSs with "classical" characteristics (emission lines, veiling, UV excess, etc.) must therefore be surrounded by, and interacting with, actively accreting disks.

Some of the early contributions that led to a consensus about the disk paradigm

- Adams, Lada, Shu (1987, ApJ 312, 788): empirical/theoretical classification of YSOs; global picture of star formation
- Kenyon and Hartmann (1987, ApJ 323, 714): flaring, passive disks; detailed models of FU Ori disks;
- Edwards, Cabrit, Strom, Heyer, Strom, Anderson (1987, ApJ 321, 473): studies of forbidden and Hα line emission in TTSs; complementary of Appenzeller et al (1984, A&A 141, 108);
- Basri, Bouvier, myself (1988 ApJ 330, 350; 1989 ApJ 341, 340) detailed models of TTS SEDs, suggestion of magnetospheric accretion in DF Tau;
- Adams, Shu, Lada (1988, ApJ 326, 865): models of TTS with flat IR-spectra;
- Strom, Strom, Edwards, Cabrit, Skrutskie (1989, AJ 89, 1451): first estimates of disk lifetime;
- Cabrit, Edwards, Strom, Strom (1990, ApJ 354, 687): first evidence for a connection between accretion and ejection;
- Koenigl (1991, ApJL 370, L39): first model of magnetospheric accretion.

Several years later, observers told us that young stars looked the way they were supposed to ☺



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Advances and issues: disk mass

- SED models have reached a high degree of physical realism (vertical structure integration taking viscous heating and reprocessing of stellar radiation into account, multi-component dust models, etc. (Dullemond and collaborators, D'Alessio and collaborators, Lachaume et al, Pinte et al, and others).
- These detailed models of radiative transfer in disks indicate that grain growth in disks and settling to the midplane of the largest particles is needed to account for sub-mm and mm SED.

Advances and issues: disk mass (cont'd)

- Disk observations up to 7mm show evidence for a grain size distribution with radii up to several cm. There is clear evidence in many disks of a population of "sand and peebles" (Natta et al in their PPV review).
- Since the opacity of dust is strongly dependent on its size, the masses of disks remain very uncertain.
- Example: for the HK Tau B disk, models of scattered light emission assuming ISM dust grains result in a mass of $\sim 6\ 10^{-5}\ M_o$, while an SED model with a distribution of particle sizes results in a mass of $\sim 6\ 10^{-2}\ M_o$ (D'Alessio et al 2001).

Advances and issues: mass accretion rates

- A number of methods have been used over the years to derive the mass accretion rates from the optical spectrum for large stellar samples (Basri and collaborators, Hartigan and collaborators, Gullbring et al, and others).
- These estimates show a scatter of a factor of 10, the origin of which is fairly well understood (see Gullbring et al, 1998 ApJ 492, 423). Furthermore there is an uncertainty of typically a factor 3 on individual mass accretion rates.
- The current consensus is to use the lower values of the mass accretion rates; they provide for a consistent picture of disk evolution (a disk of mass 0.01 M_{sun} is an adequate reservoir to feed a star during 10^6 years at a rate of 10^{-8} Mo/yr).

Advances and issues: mass accretion rates (cont'd)

- However, the Gullbring et al mass accretion rates were pushed down by construction:

  - photospheric flux from the J filter instead of I (see recent paper by White and Hillenbrandt)

  - particularly low visual extinction values, etc.
- One goal was to reconcile accretion rates with the relatively small disk masses that were inferred in the 1990s, but these were probably systematically underestimated.
- Revisiting mass accretion rates with modern accretion column models and radiative transfer tools will be very useful.

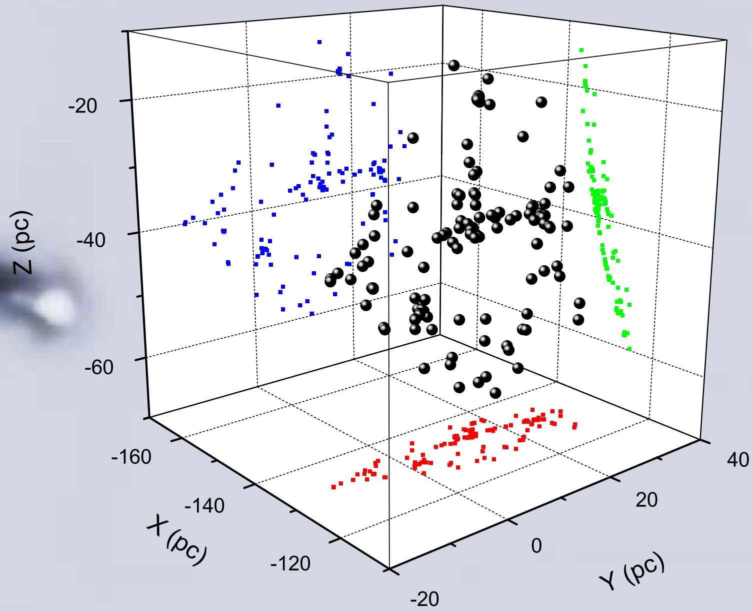
Advances and issues: the nature of WTTSs

- Evolution from CTTS to WTTS is usually taken for granted, although not proven yet. The observed mass and age overlap in HRD is understood to be a consequence of a large scatter in disk properties due to different initial conditions in the star forming cores.
- In order to study the relationship between CTTSs and WTTSs in more detail, one needs better estimates of their stellar properties.

Advances and issues: the nature of WTTSs (cont’d)

- Work in progress: investigation of the properties of the *kinematic* members of the Taurus-Auriga T association.
- Bertout & Geneva (2006, A&A 460, 499) found 94 bona fide members of the Taurus moving group and derived individual parallaxes for 67 of these objects, which presumably represent a more homogeneous sample than is usual for TTS population studies.

Locations of TTSs in Taurus-Auriga: populating the entire cloud



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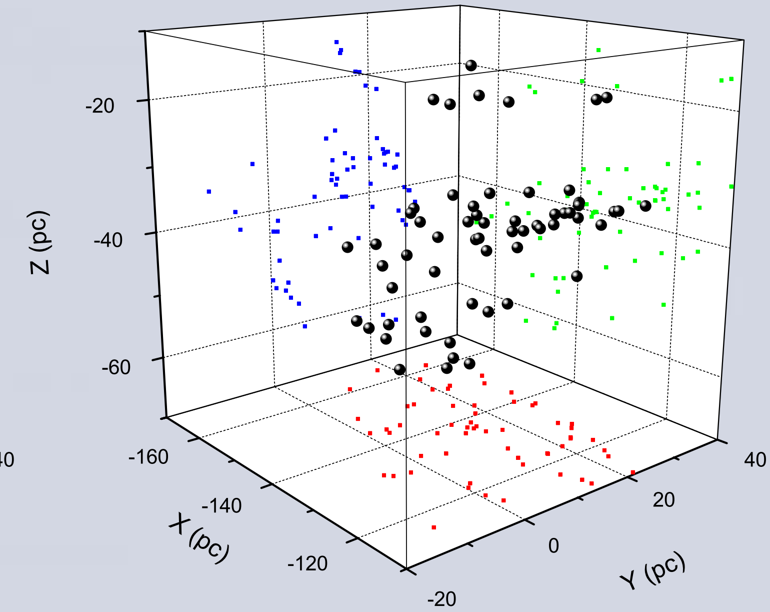

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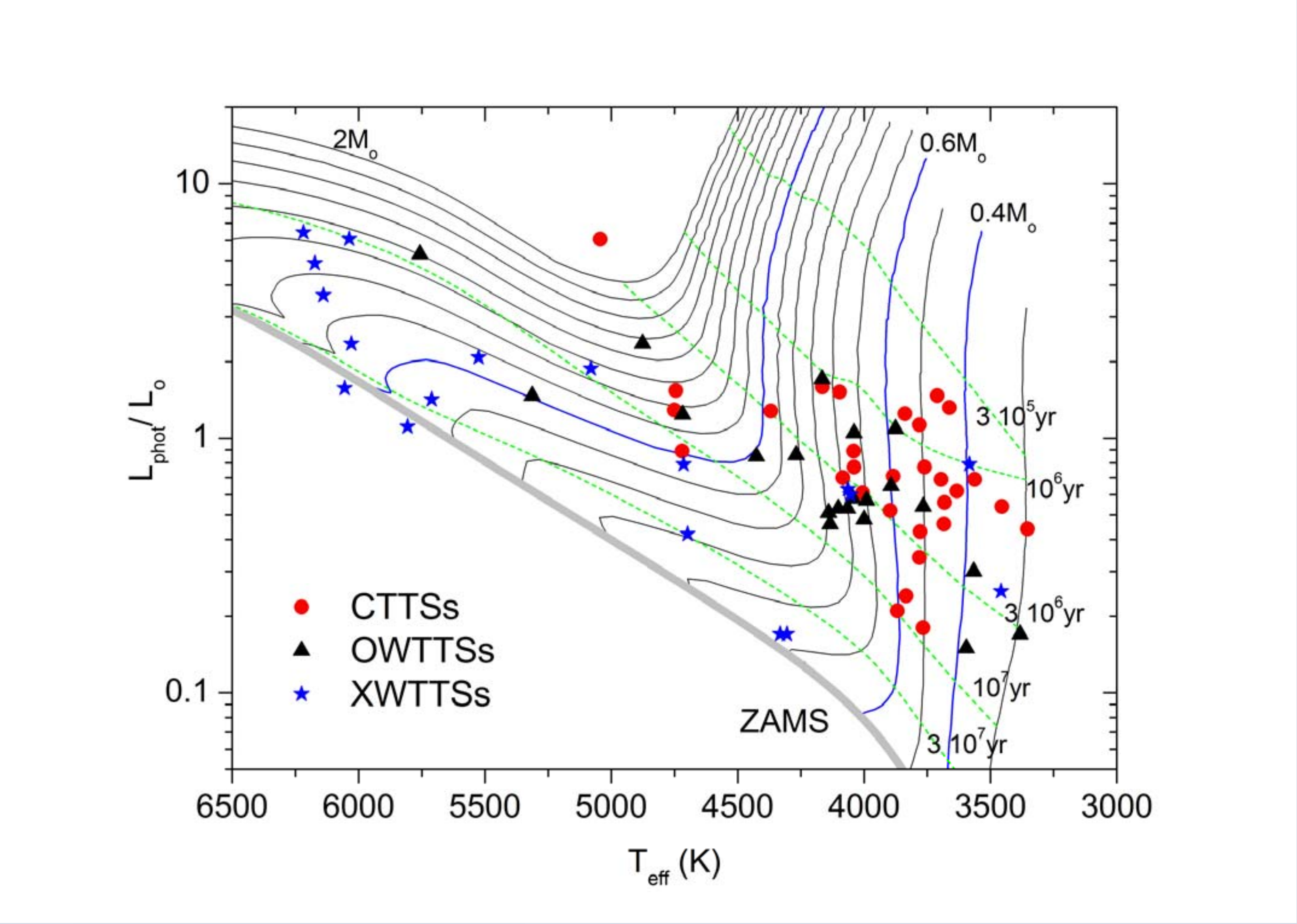
New hint for evolution from CTTSs to WTTSs
(Bertout, Cabrit & Siess, in progress)



From CTTSs to WTTSs

If there are no hidden biases in the sample, then:

- Low-mass CTTSs (0.4 - 0.6 M_{sun}) span an age range from 3 10^5 to 10^7 yr.
- Most higher-mass CTTSs (0.6 - 1.3 M_{sun}) are younger than 3 10^6 yr.
- This appears compatible with the recent finding (Muzerolle et al, Natta et al) that mass accretion rates are $\propto M_{star}^{2.1}$ over 2 decades in mass. The lifetime of a disk around a $1M_{sun}$ star is ~4 times shorter than the lifetime of a disk surrounding a $0.5M_{sun}$ star (provided the disks had similar masses to start with).
- A detailed assessment of this result is under way.

Conclusion

- No lack of topics where work is needed!
- I look forward to hearing about the most recent advances in disk physics presented during this meeting.