Spectra of the T Tauri Stars

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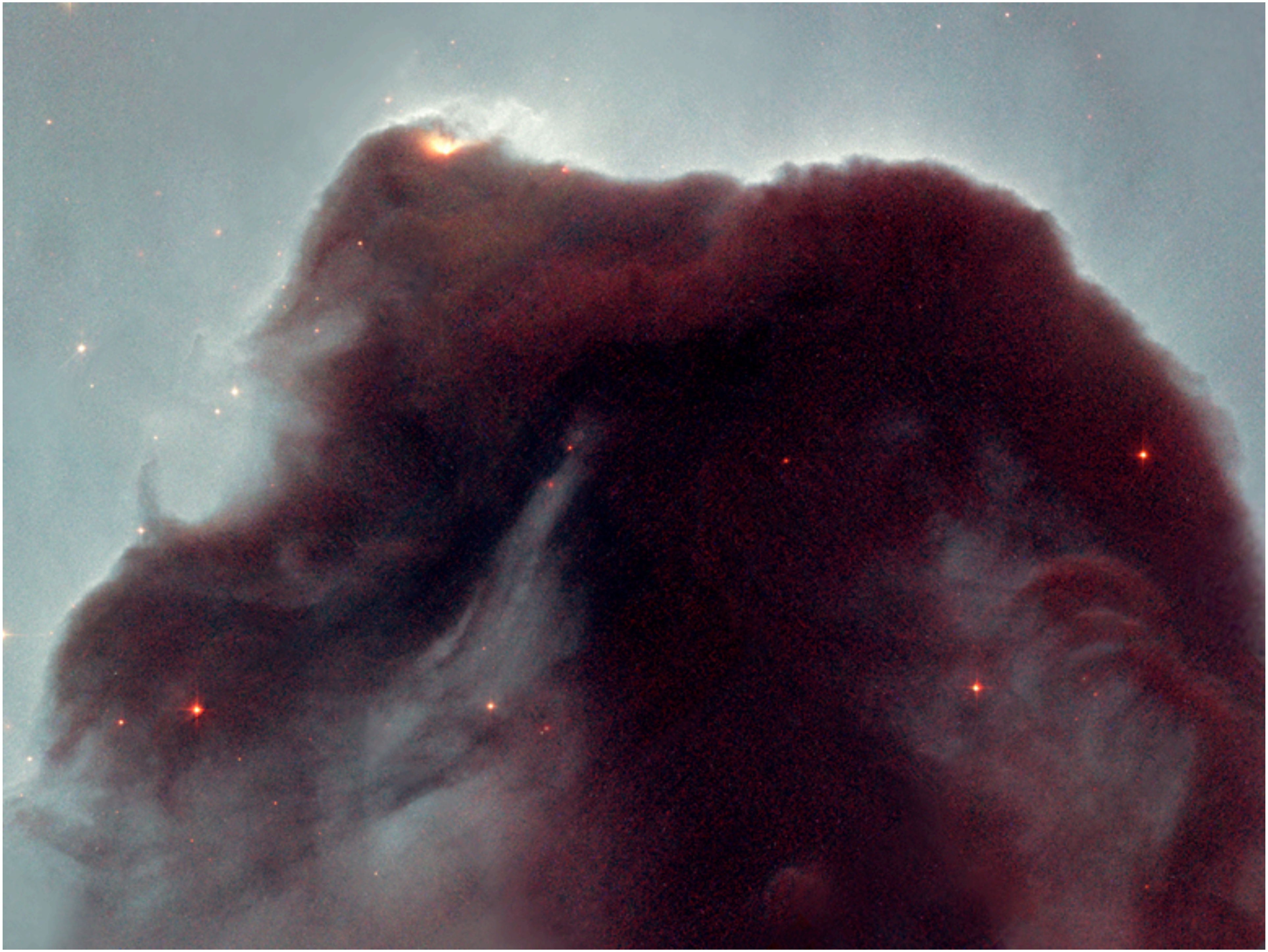
“We had the sky up there, all speckled with stars, and we used to lay on our backs and look up at them, and discuss about whether they was made or only just happened. Jim he allowed they was made, but I allowed they happened; I judged it would have took too long to make so many. Jim said the moon could 'a' laid them; well, that looked kind of reasonable, so I didn't say nothing against it, because I've seen a frog lay most as many, so of course, it could be done.”

Mark Twain - *Adventures of Huckleberry Finn*

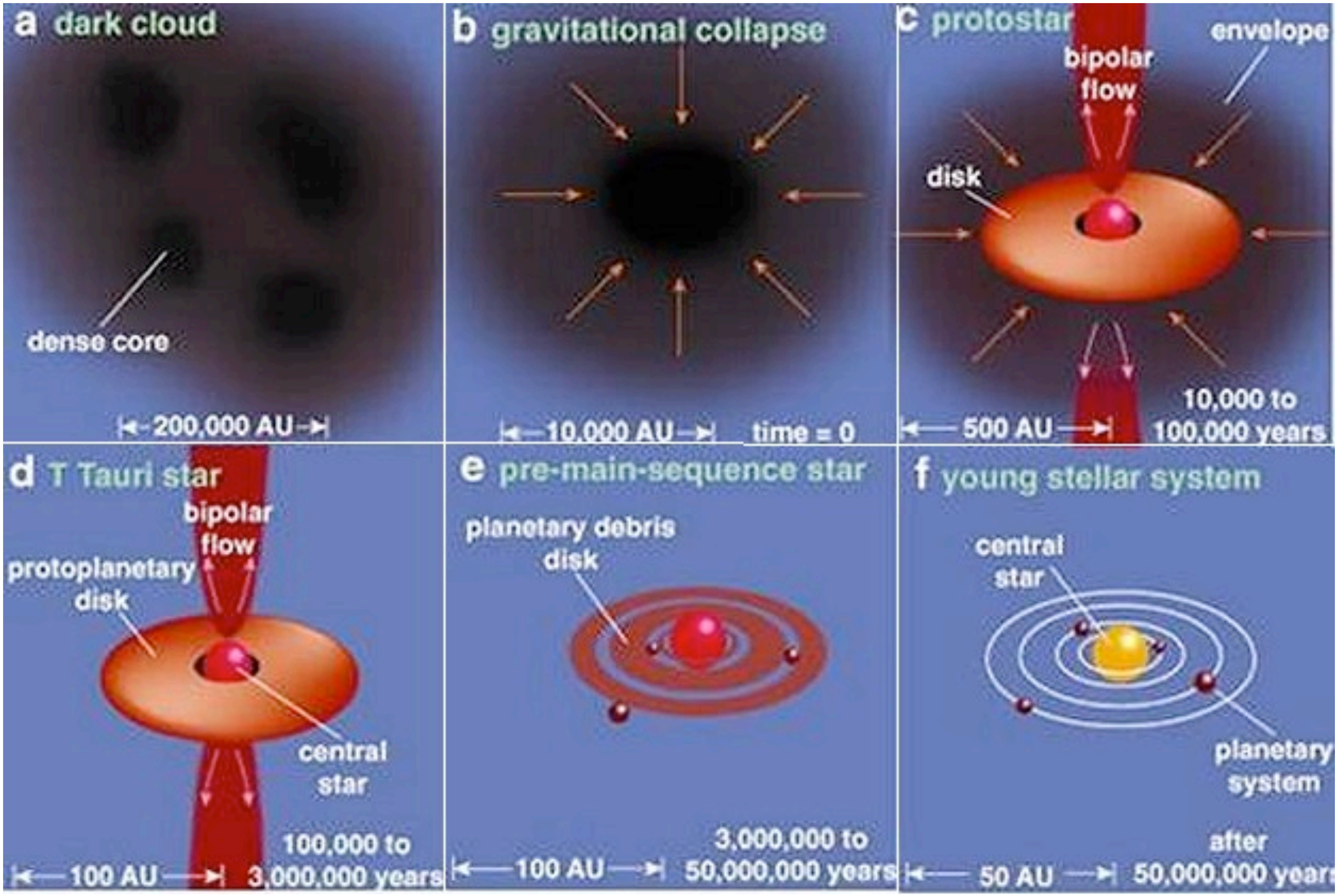
The Stars of Joy

The T Tauri and RW Aurigae stars form a small but important group which deserves more attention than it has yet received. Some of the stars are apparently connected with or obscured by shells or wisps of nebulosity. The light-changes are rapid and entirely irregular. When the nebulous clouds are distant from the stars the character of the spectrum is not greatly affected and various spectral types are represented, but when the clouds or shells are near by or in contact with the star a characteristic bright line spectrum appears in connection with an absorption spectrum of G type. The emission lines of ionized calcium (H and K) are extremely strong, and sharp bright lines of *H*, *Fe* II, *Fe* I, *Sc* II, *Ca* I, *Mg* I, and *He* I have been identified. None of the usual nebular lines is present. The absorption spectrum indicates that these stars are dwarfs of the main sequence.

A.H. Joy, 1942, PASP, 54, 15



Some Context



Taxonomy. I.

- Continuum Stars
  - Very strong Line Emission
  - No photospheric absorption
- **Classical** T Tauri Stars (cTTS)
  - Strong Line Emission
  - Photospheric absorption lines, often weak
- **Naked** or Weak T Tauri Stars (nTTS, wTTS)
  - Emission lines of chromospheric strength
  - Essentially normal absorption spectra

Taxonomy. II.

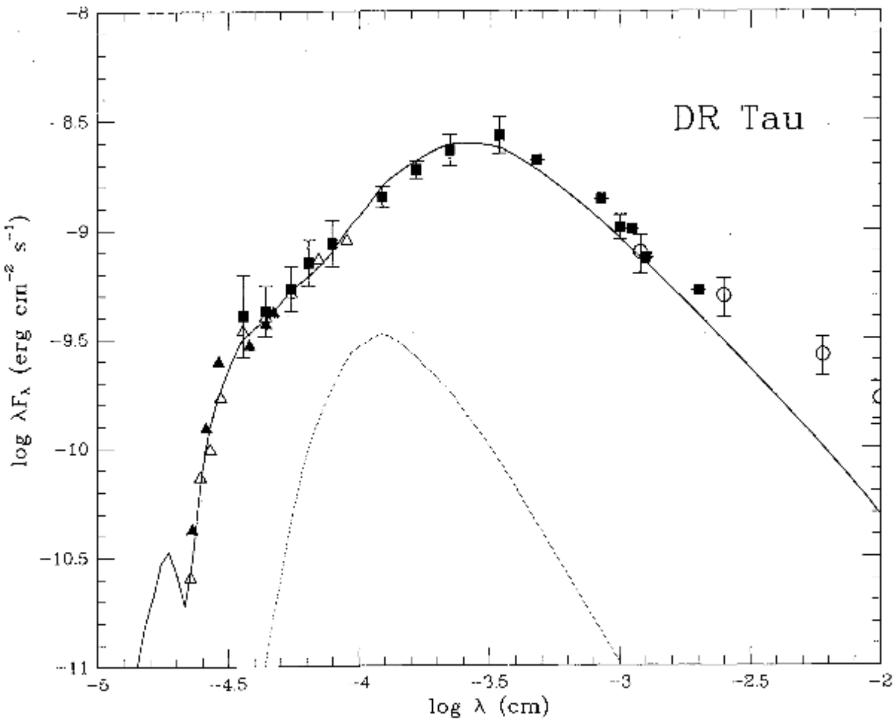
Based on $\alpha = d(\log\lambda F_\lambda)/d(\log\lambda)$,

$2\mu m < \lambda < 25\mu m$ (Lada 1987)

- **Class 1**: $0 < \alpha < 3$, $80K < T_{bol} < 650K$
- **Class 2**: $-2 < \alpha < 0$ = cTTS
- **Class 3**: $-3 < \alpha < -2$ = nTTS
- **FSS**: $-0.3 < \alpha < 0.3$ encompass class 1,2

- **Class 0** (André et al. 2000)
  - $T_{bol} < 80K$
  - $L_{smm}/L_{bol} > 0.005$

Spectral Energy Distributions



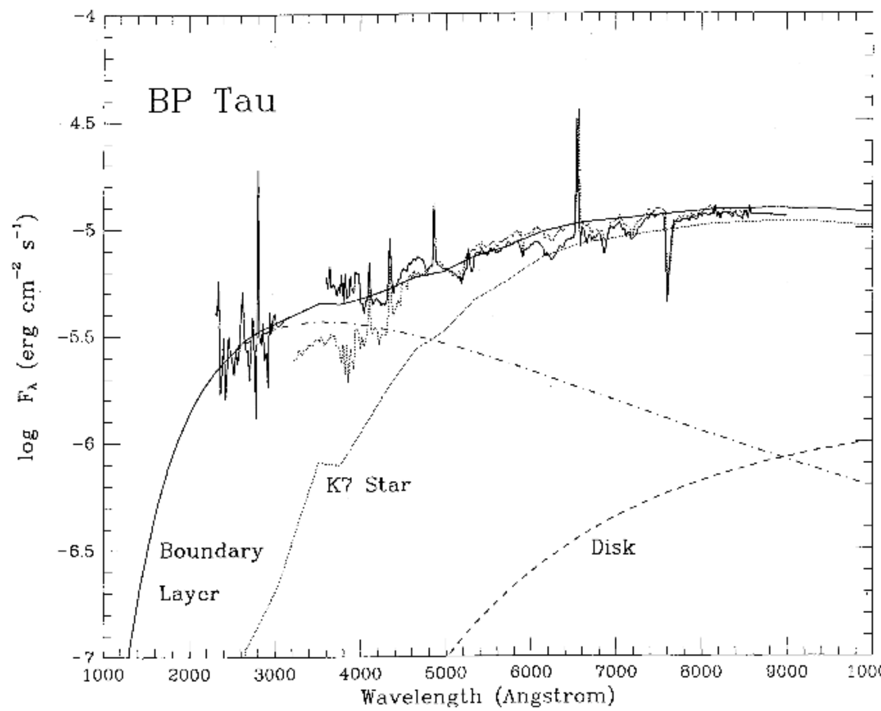


FIG. 6a

Extreme cTTS
Class 2

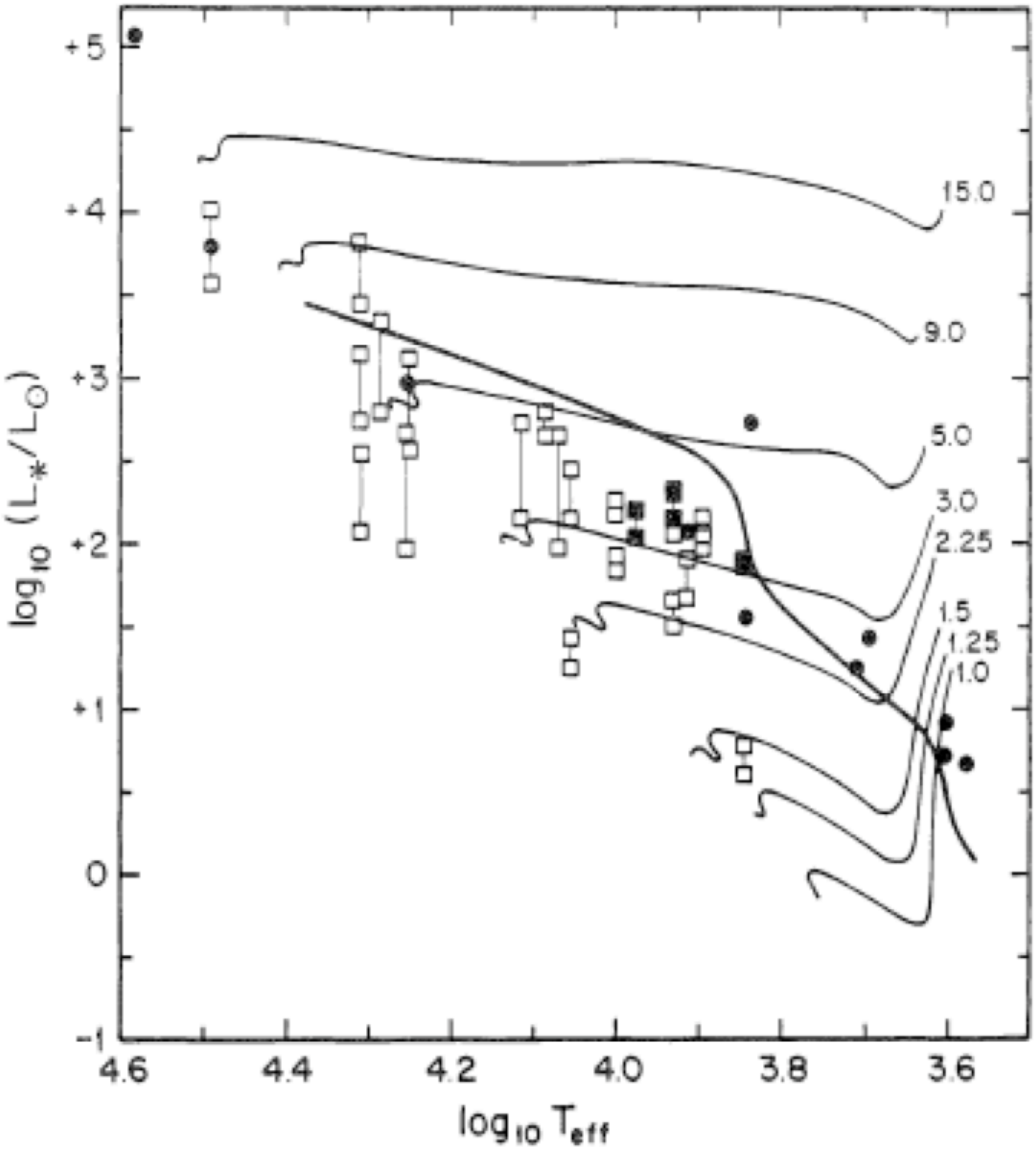
cTTS
Class 2

Bertout, Basri & Bouvier 1988

Birthline

- Protostar structure set by mass accretion rate from opaque envelope
- T_{core} reaches 10^6 K; D-burning initiated
- Deuterium acts as a thermostat
- R~M until ^{2}D depleted
- Quasi-static contraction starts

(Stahler 1983, 1988; Palla & Stahler 1993)



Palla & Stahler, 1993, ApJ, 418, 414

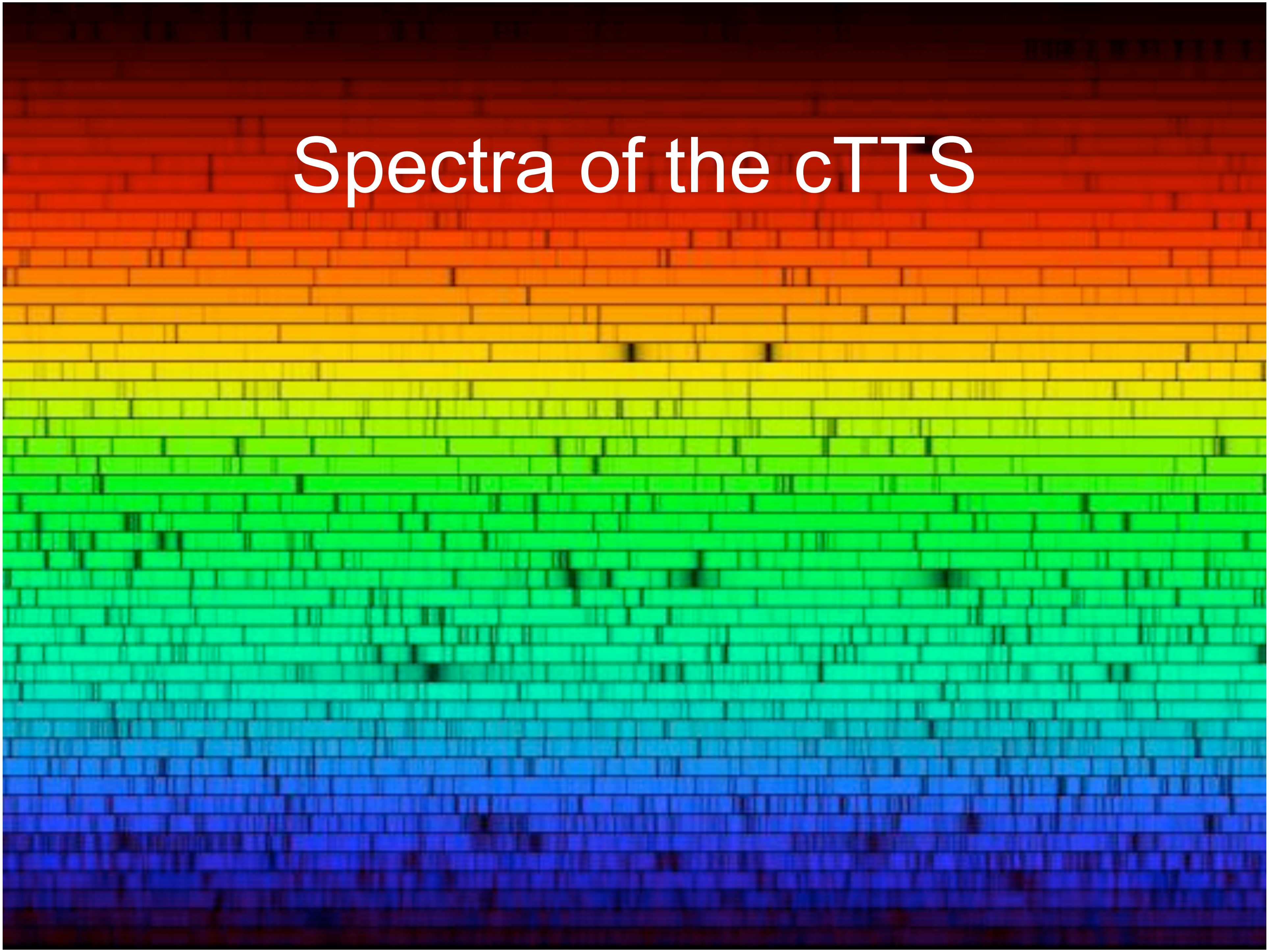
The Hayashi Track

- Luminosity driven by gravitational contraction (Kelvin-Kelmholtz)
- Envelope is fully convective
- Temperature almost independent of luminosity due to H^- opacity
- Nearly vertical evolution in H-R diagram
- When T_{core} reaches ~10^7K, H-burning initiated; radiative core forms and contraction halts (Henyey track).

Taxonomy. III.

- **Class 0 and 1** protostars: pre-birthline
- **Continuum** stars: close to the birthline?
- **Class 2** stars (cTTS): on the Hayashi track
- **Class 3** stars can be on the Hayashi or Henyey tracks, or on the ZAMS

Spectra of the cTTS



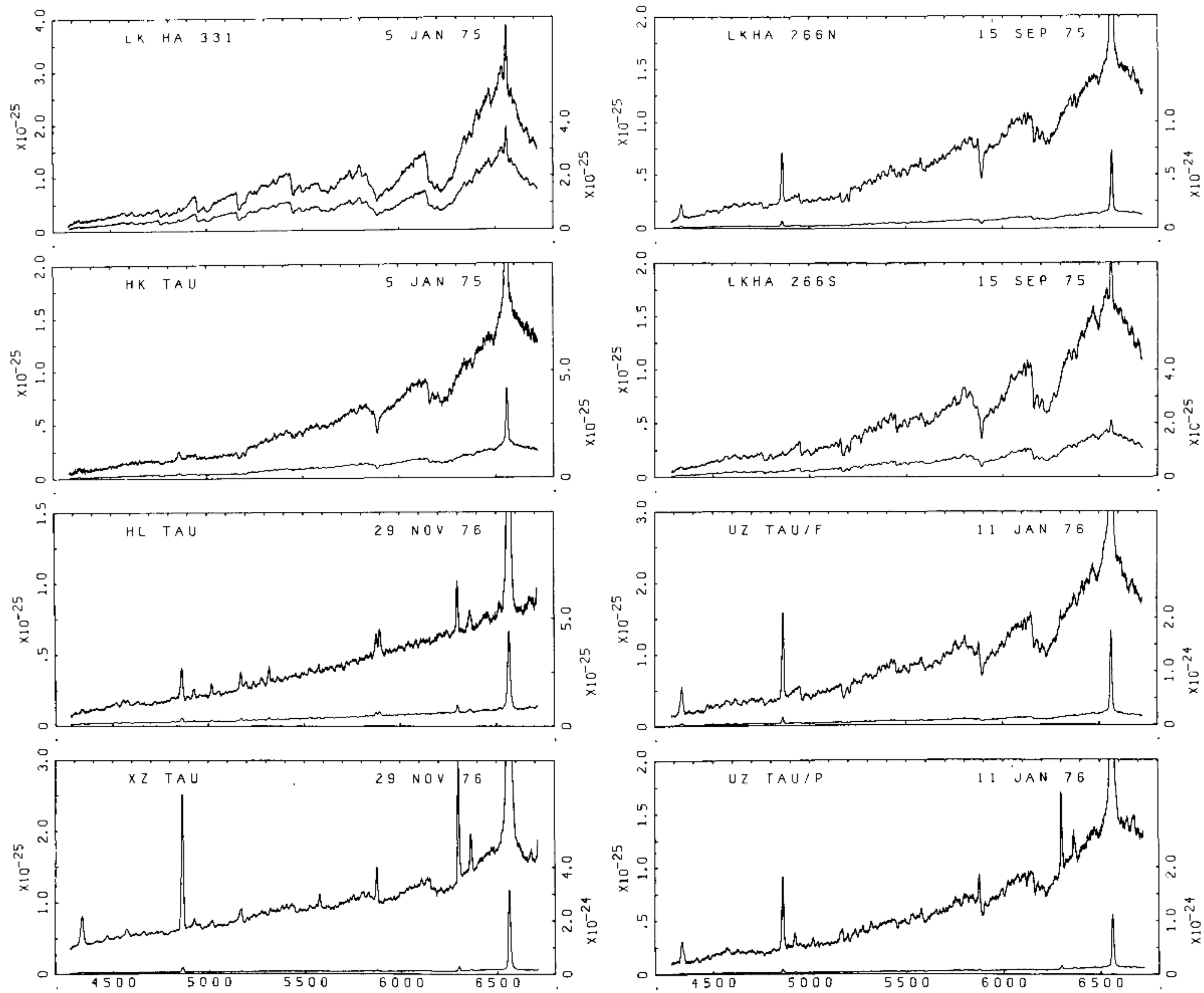


FIG. 23—*Continued*

Cohen & Kuhi, 1979, ApJS, 41, 743

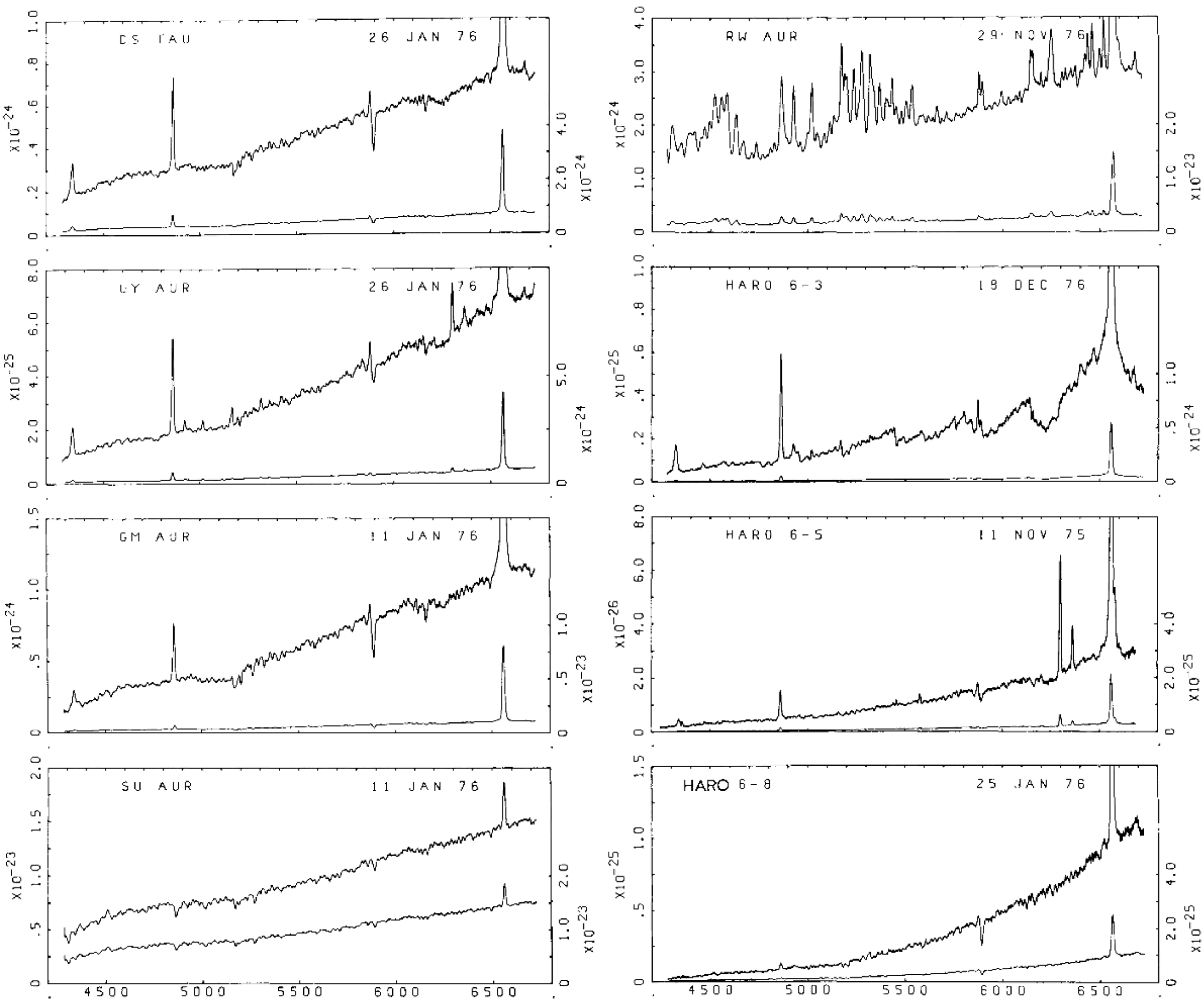
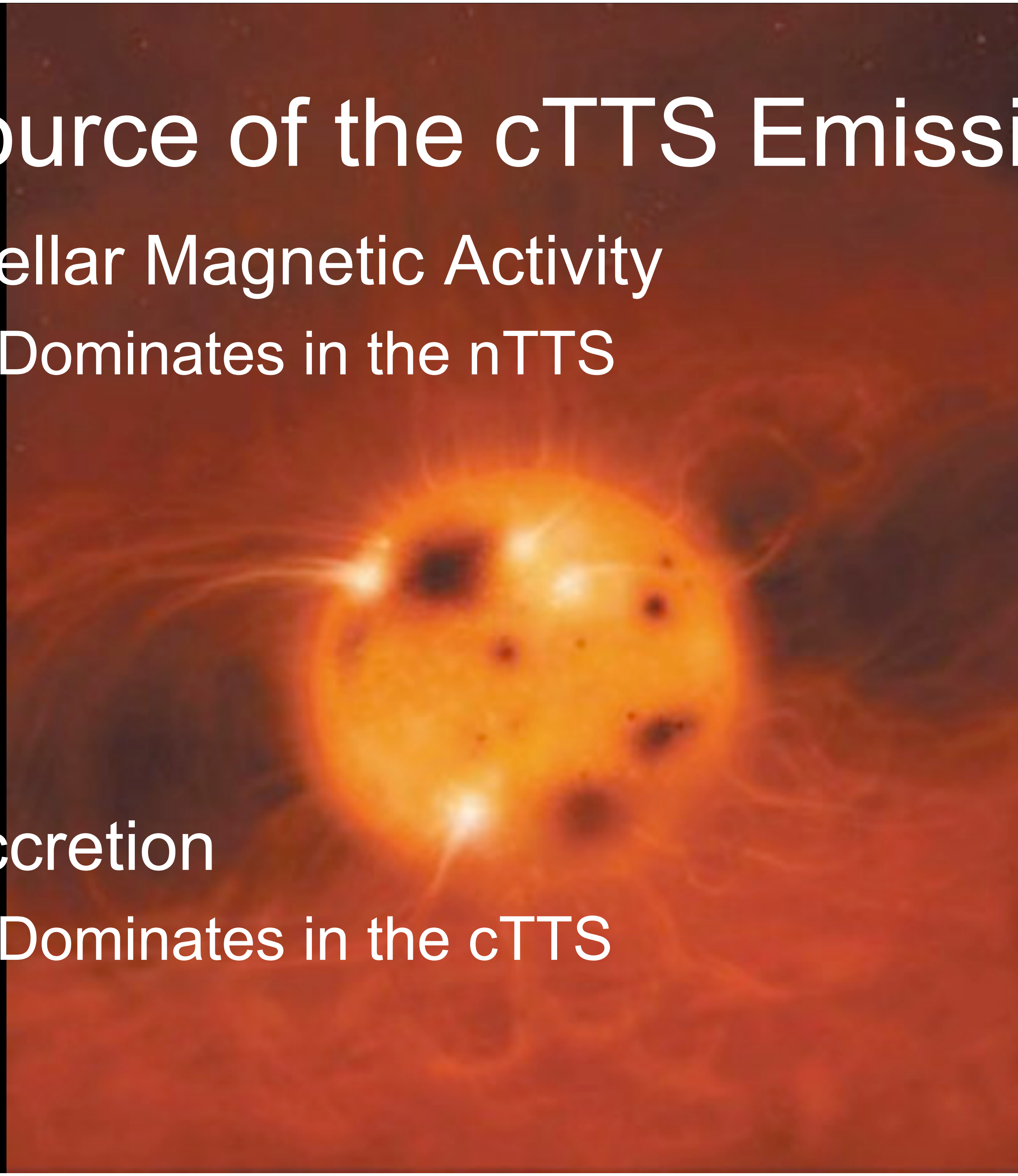


FIG. 23—*Continued*

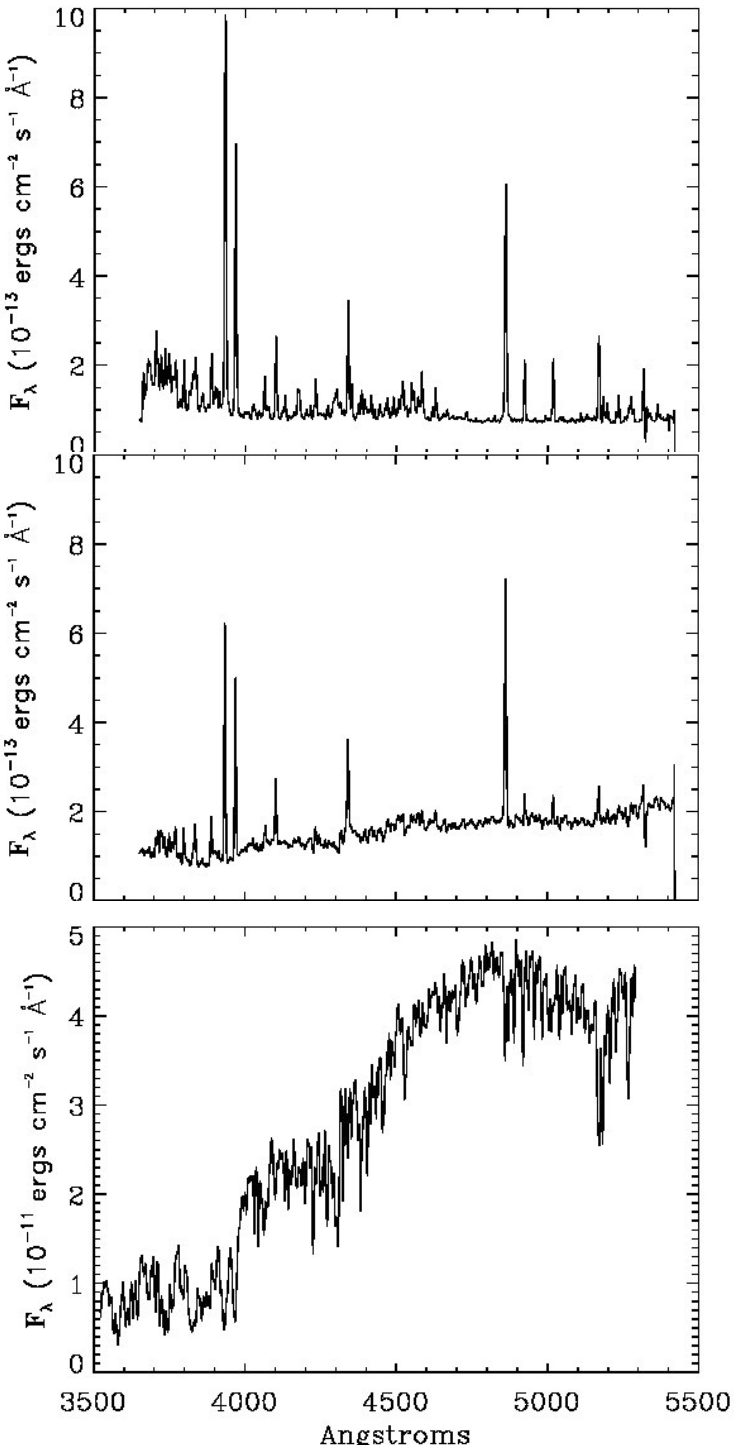
Source of the cTTS Emission



- Stellar Magnetic Activity
  - Dominates in the nTTS
- Accretion
  - Dominates in the cTTS

Three K Stars

- ε **Eri**, K2V
  - Moderately active
  - For comparison only
- **T Tauri**, K0
  - The prototype
  - Not particularly variable
- **RU Lupi**, K7
  - Extremely active

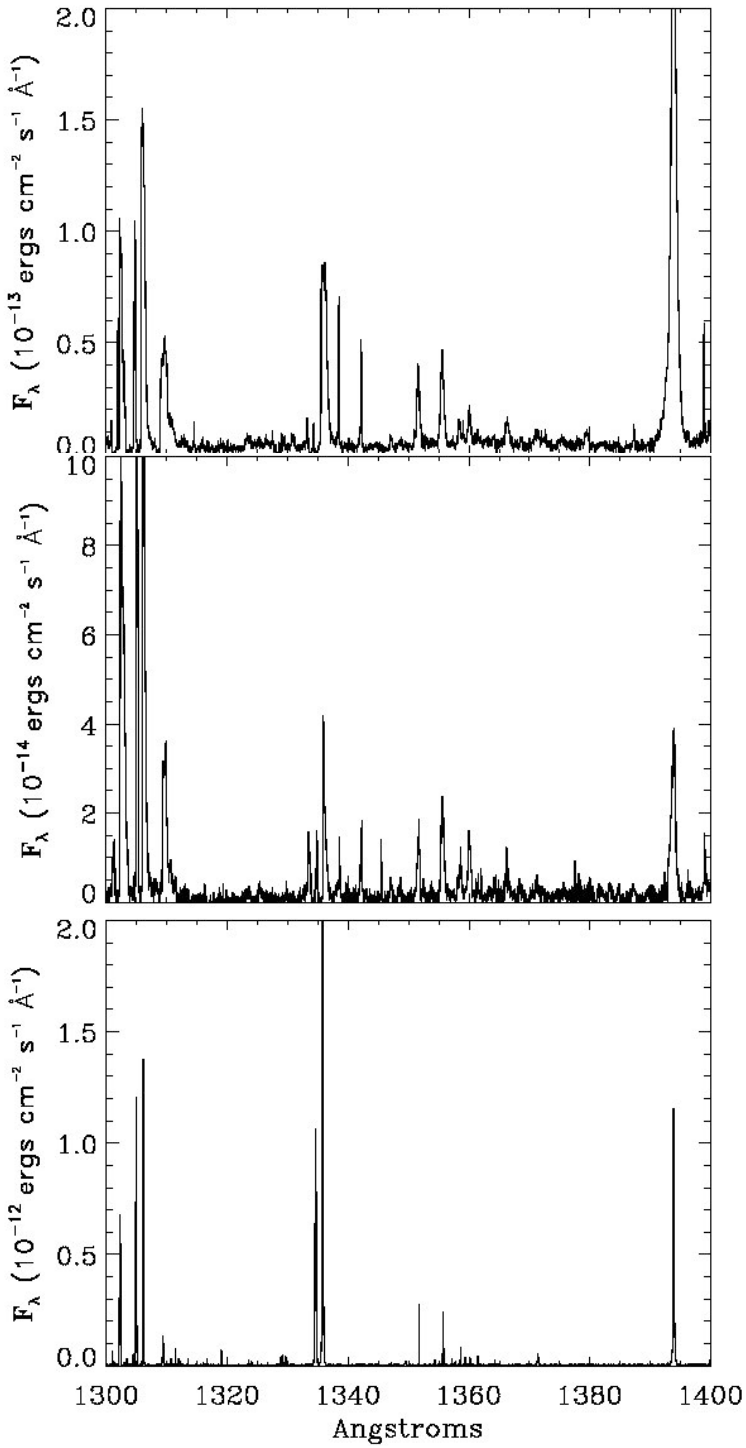


Optical (blue)

RU Lup

T Tau

ε Eri



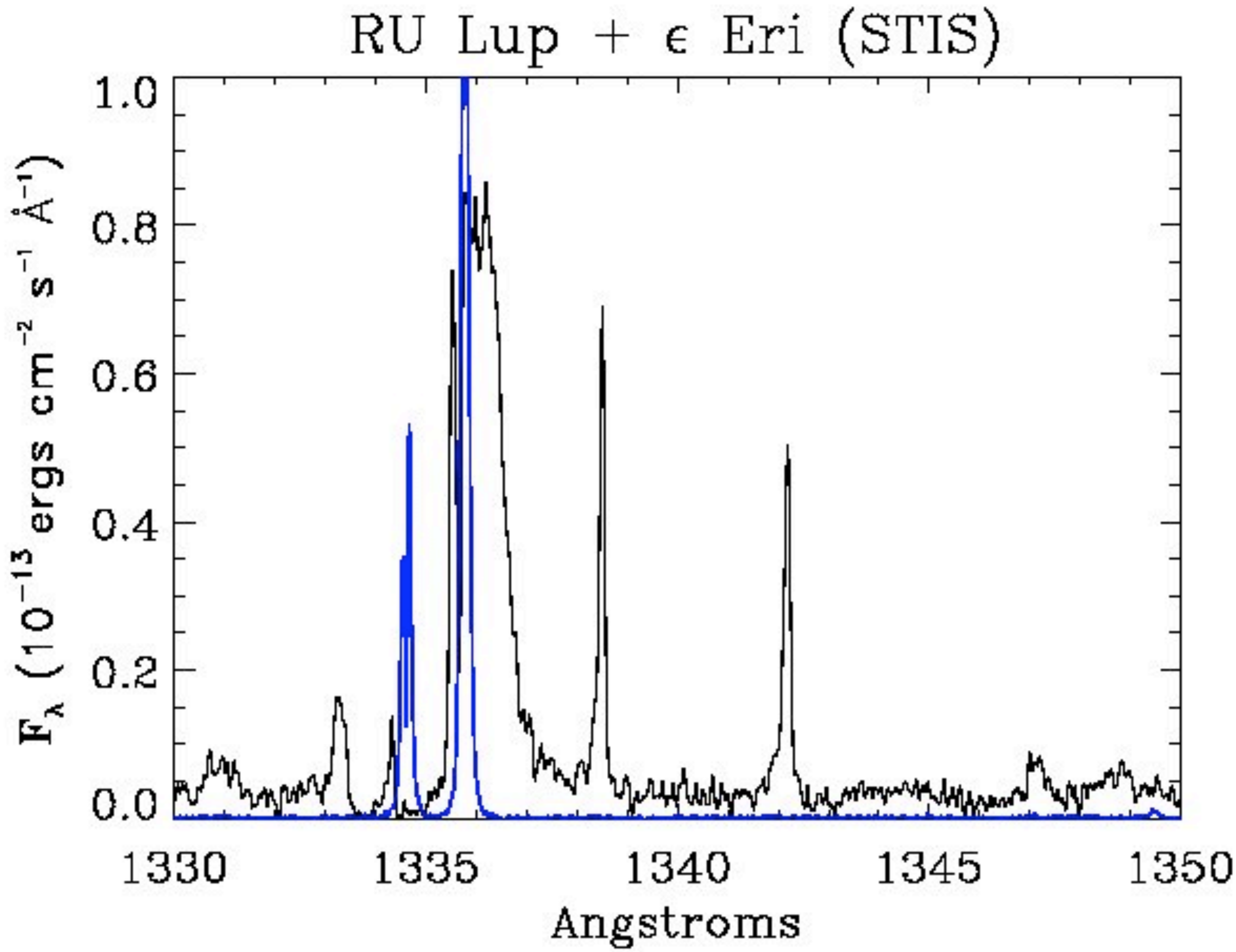
UV (1300-1400Å)

RU Lup

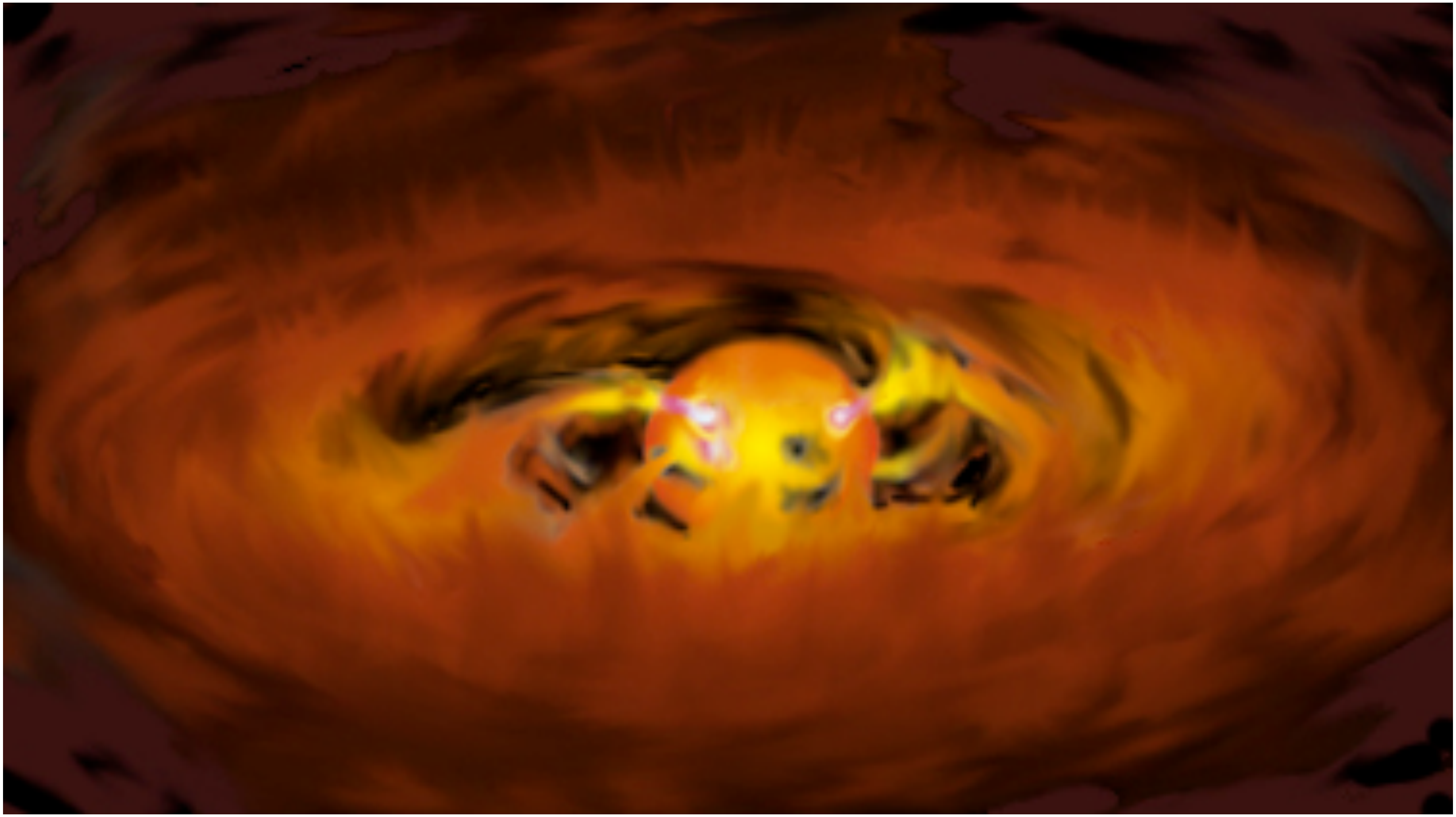
T Tau

ε Eri

UV Comparison



Accretion

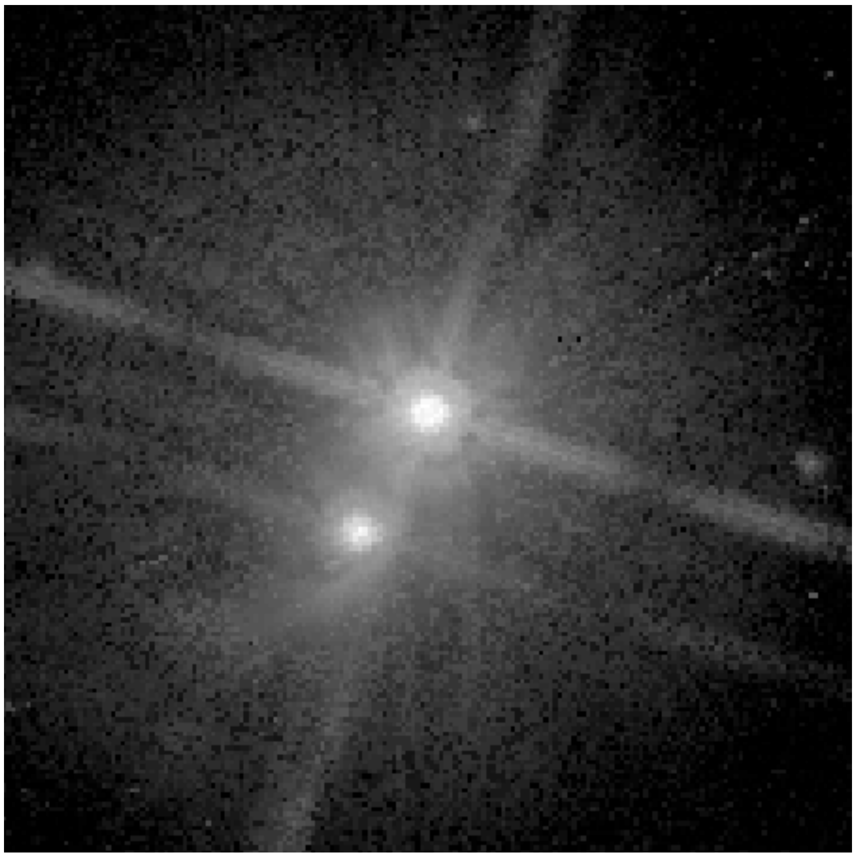


Channeled by magnetic funnels from the Keplerian co-rotation radius

Consequences of Accretion

- Free-fall velocities to ~300 km/s
- Emission wings if seen off star
- Inverse P Cygni profiles if projected on star
- Surface shock (T up to 10^6 K)
- Shock continuum modelled as ~8000K slab

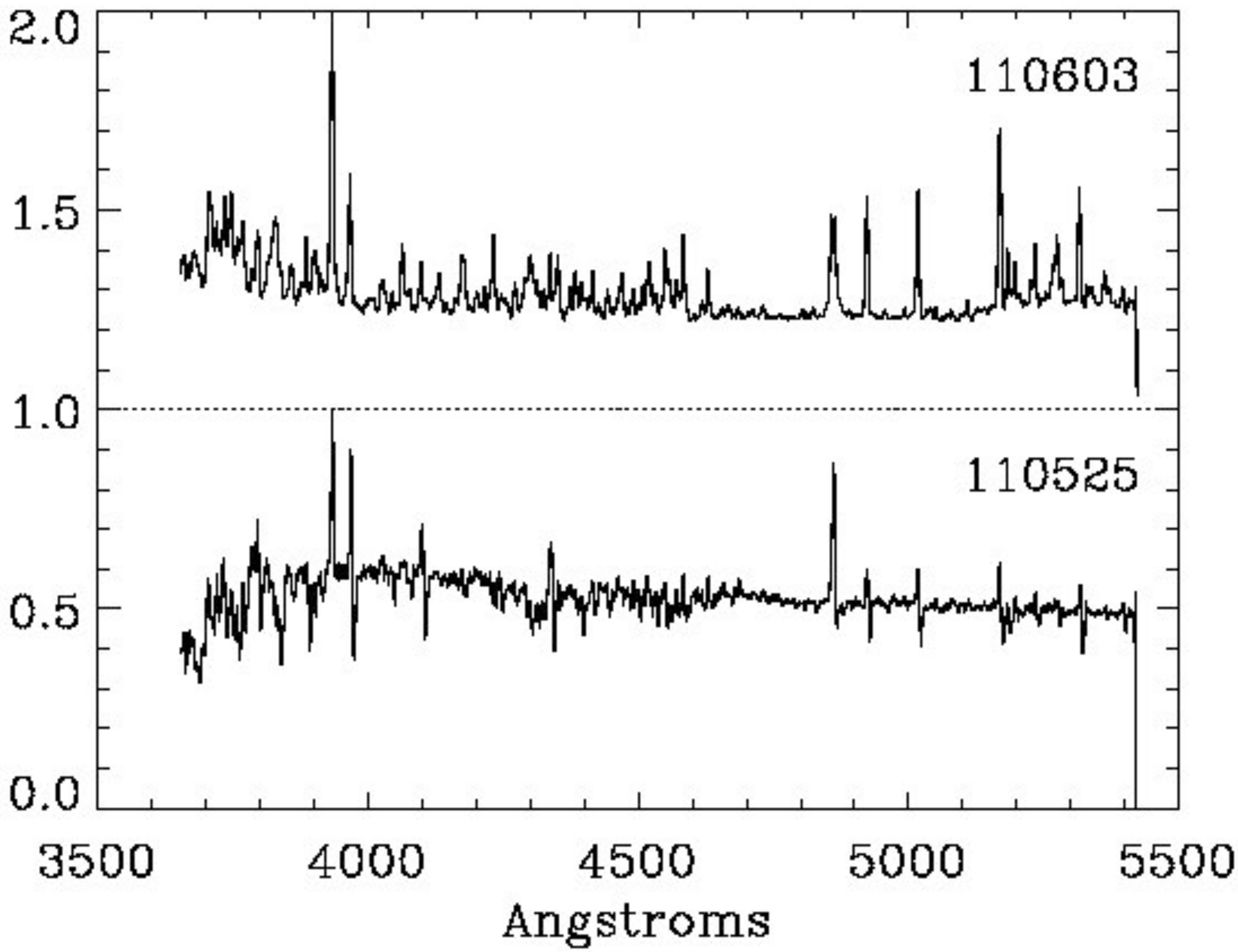
S CrA



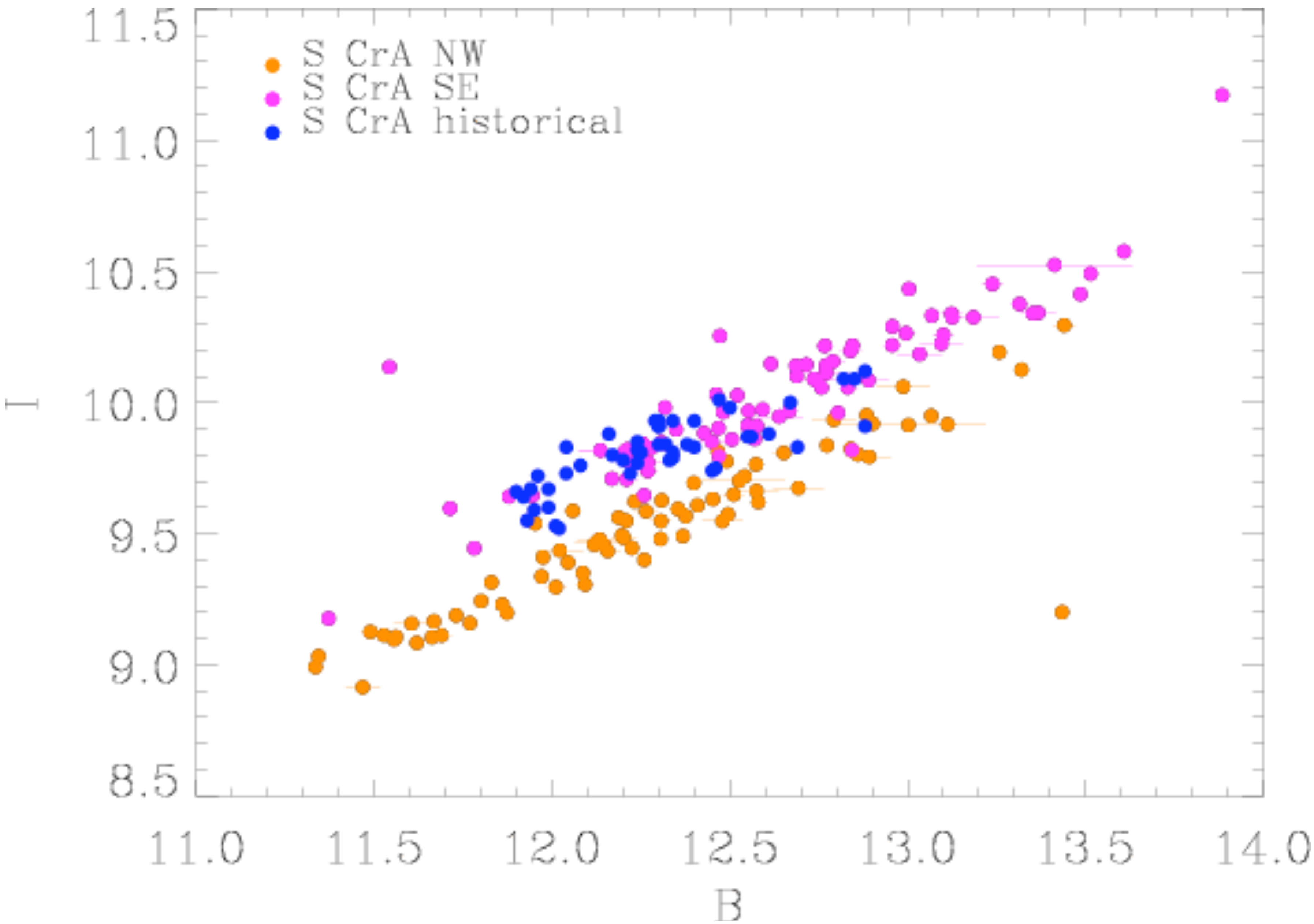
WFPC2 F814W

- 1.3 arcsec pair (~170 AU)
- No change in PA in 70 years

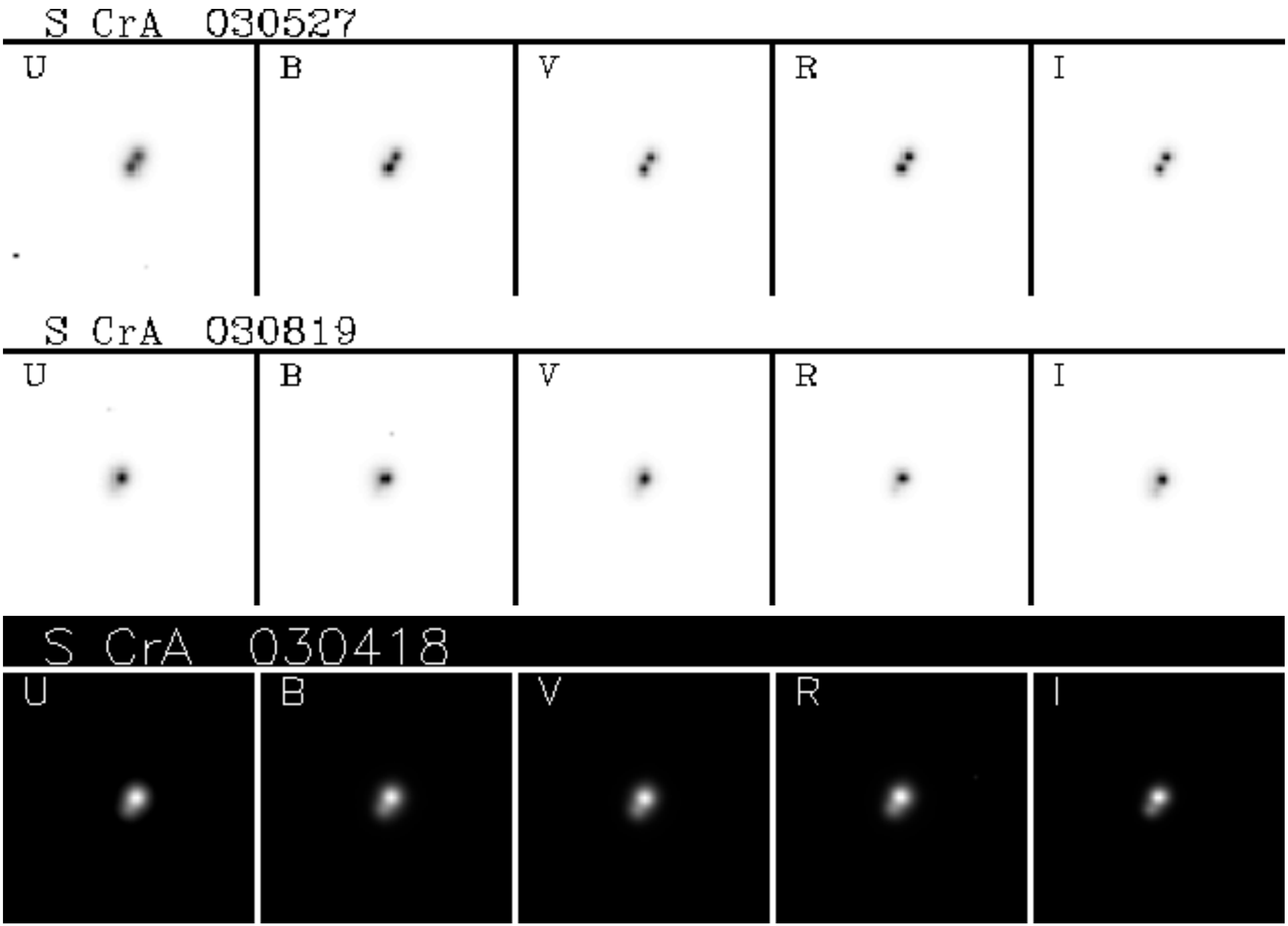
Accretion in S CrA



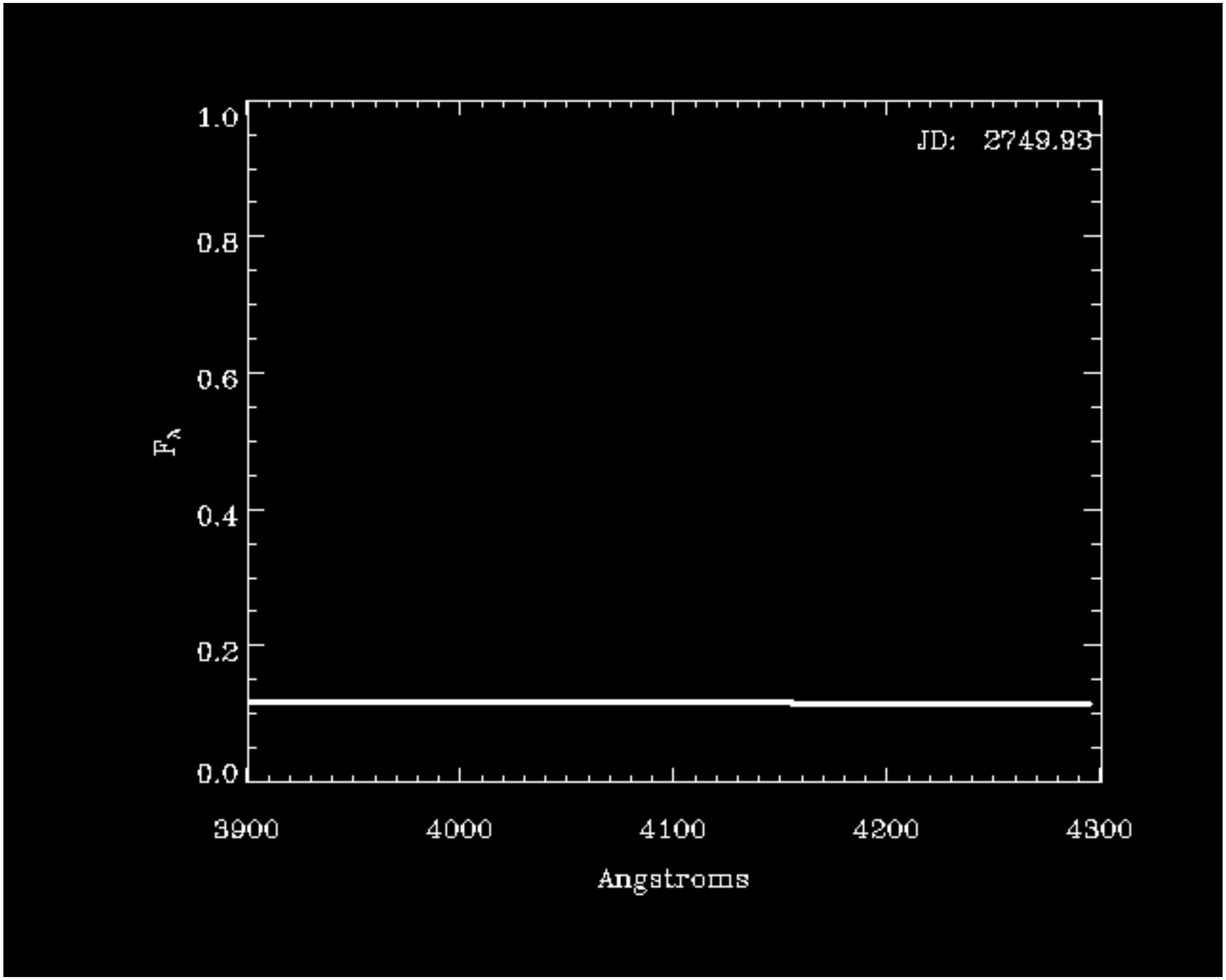
Accretion in S CrA



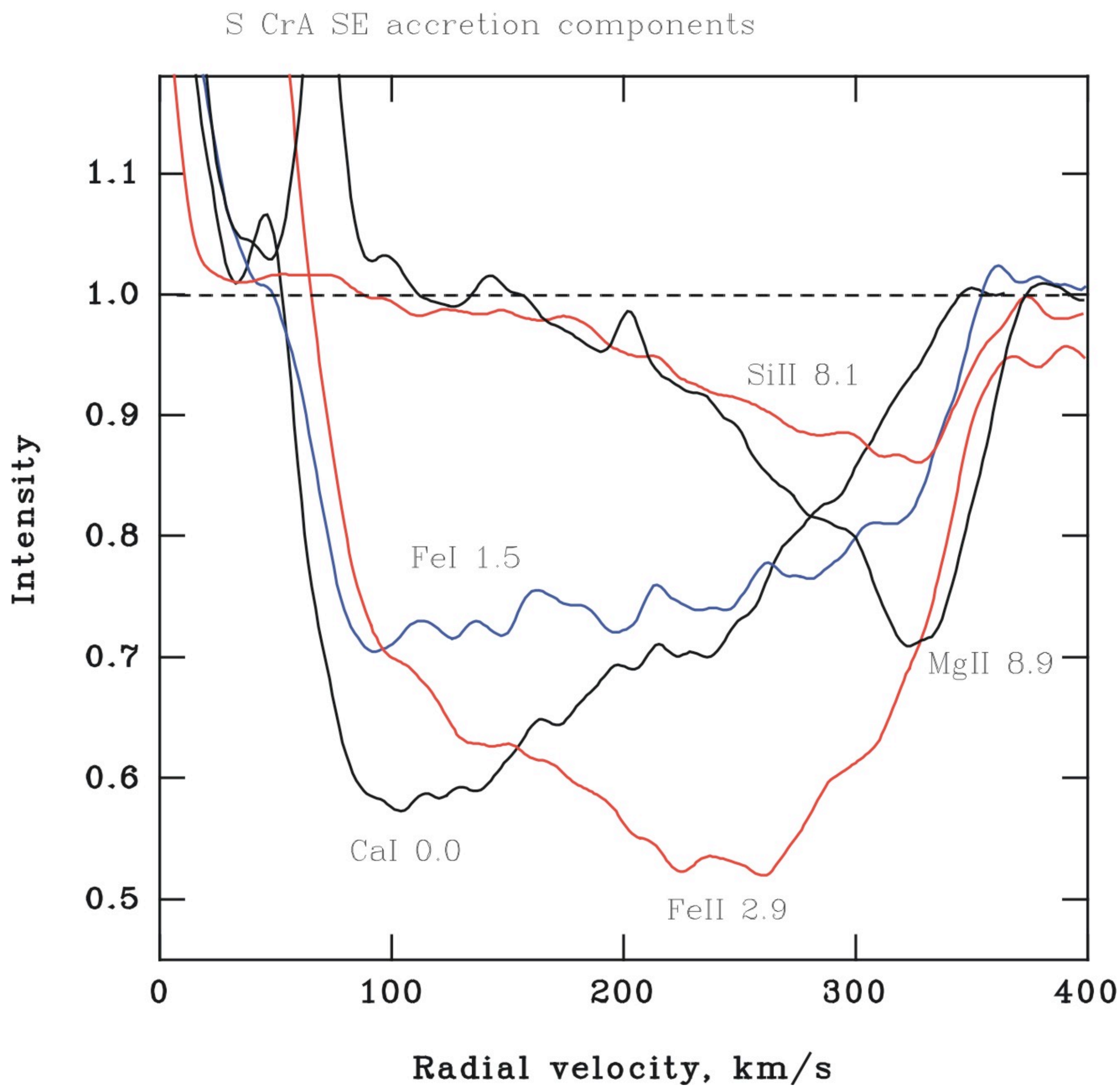
Accretion in S CrA: photometry



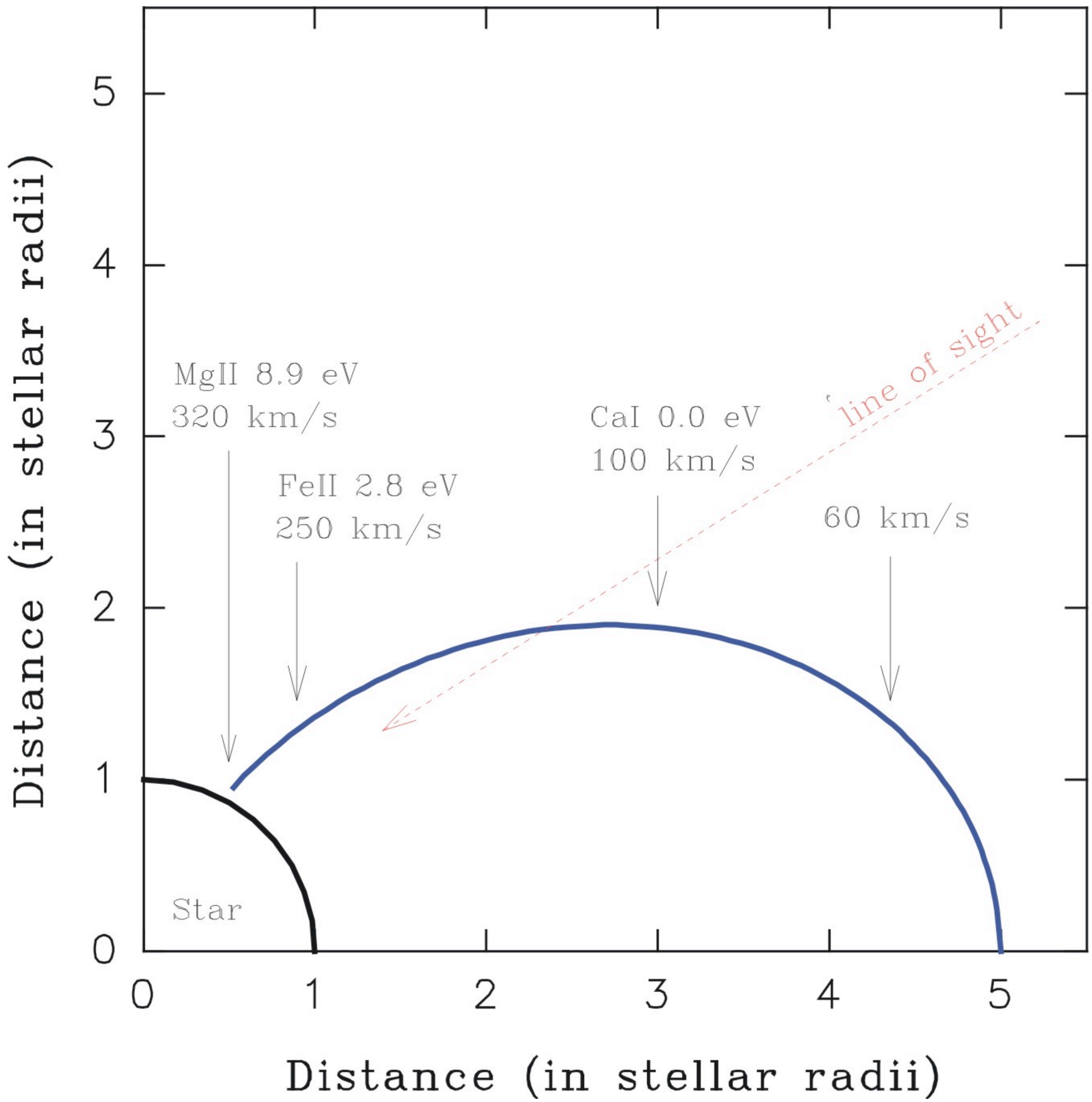
Accretion in S CrA: spectroscopy



Accretion flows in S CrA SE



S CrA SE Model



Accretion Continuum

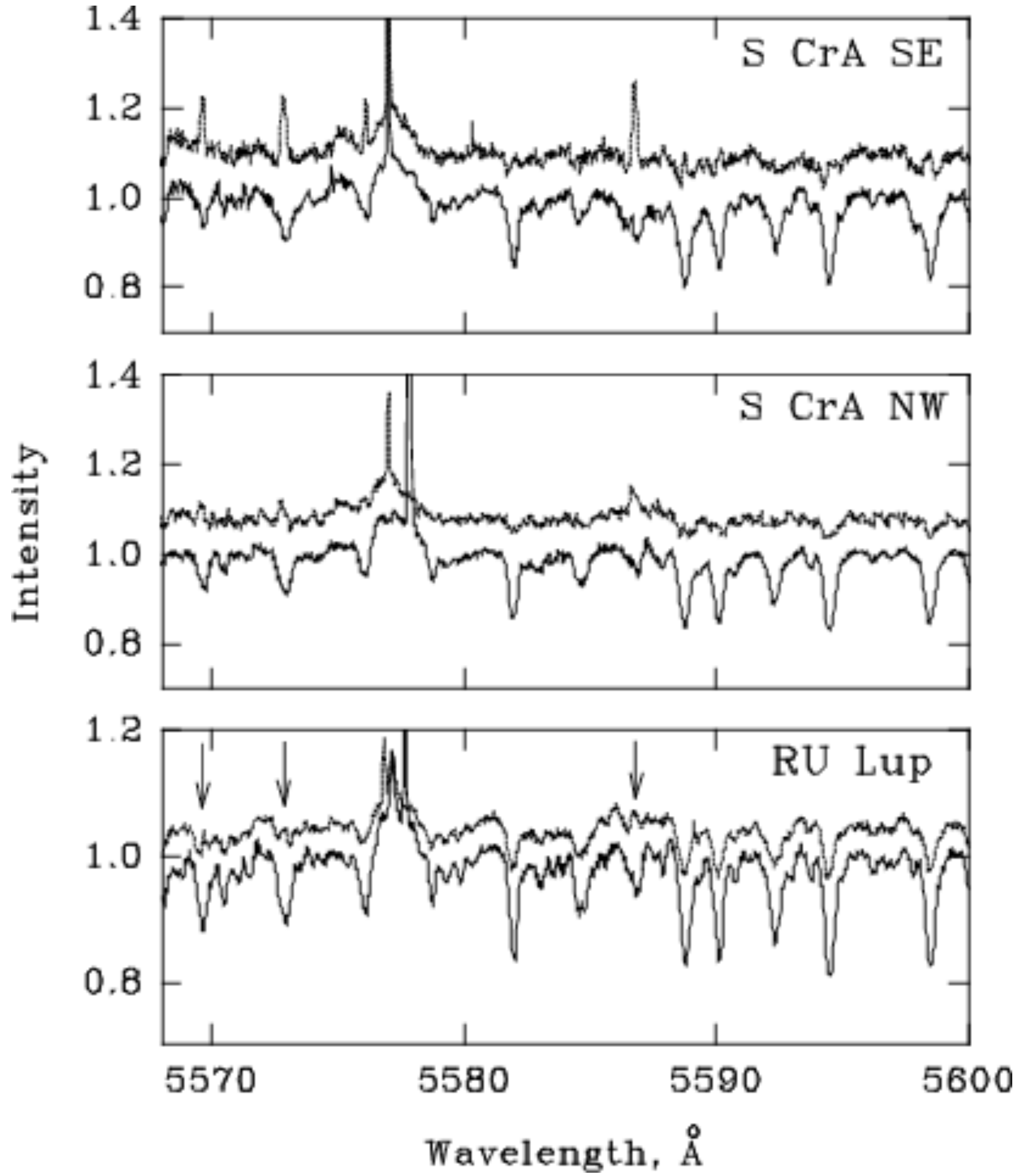
- UV excess ~8-10 $x10^3$ K BB with 2% ff.
- Luminosity consistent with GM/R dm/dt
- Modeled as an optically thick slab.
- Formerly called the Boundary Layer

- Accretion cannot explain the 10^7K corona.

Veiling

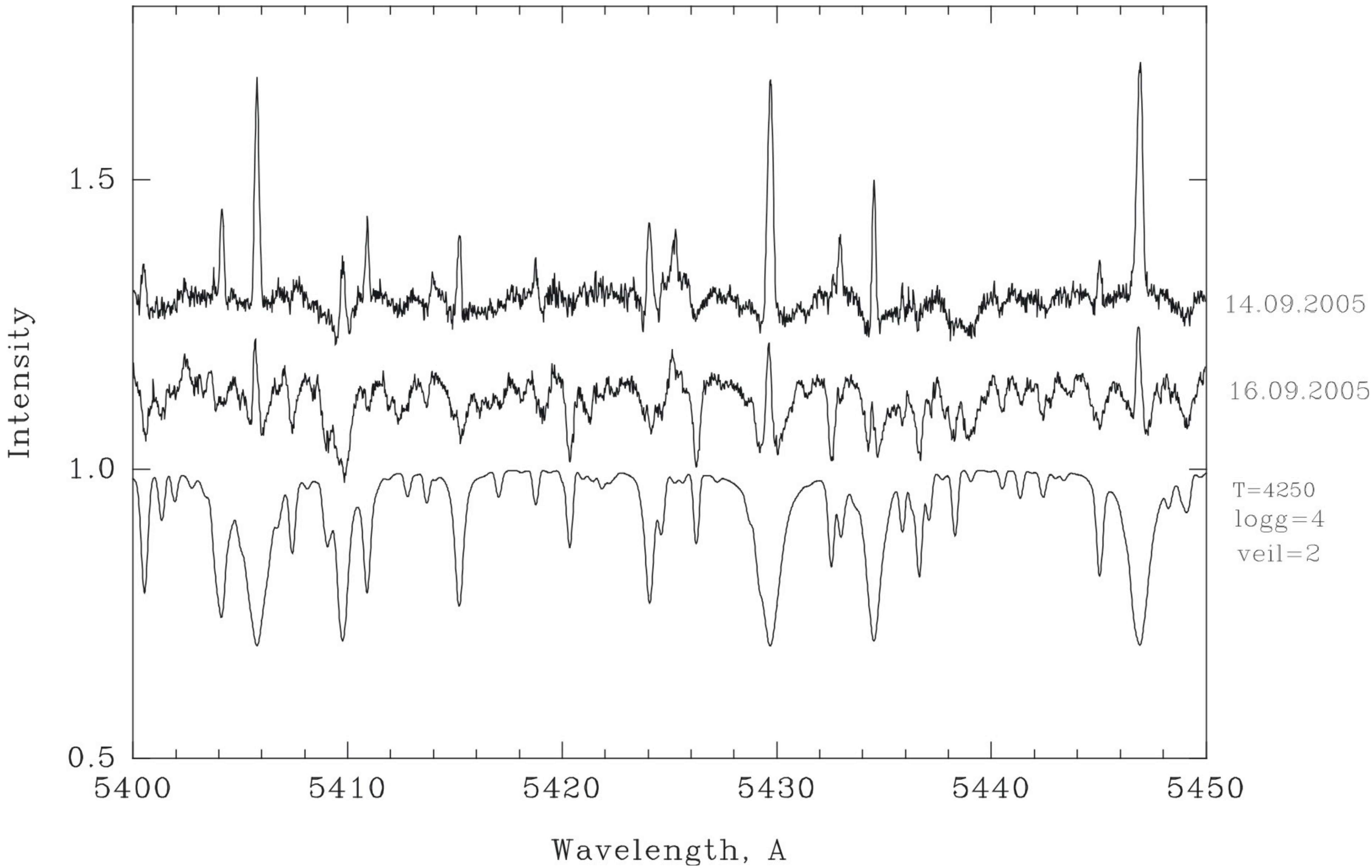
- The photospheric absorption lines often appear weak
- Canonical interpretation: dilution by the accretion continuum (e.g., Basri & Bathala 1990)
- Veiling factor $\mathbf{VF = f_{acc}/f_{ph}}$
- VF up to 10 observed
- Predicts strong correlation between VF and magnitude

Examples of Variable Veiling

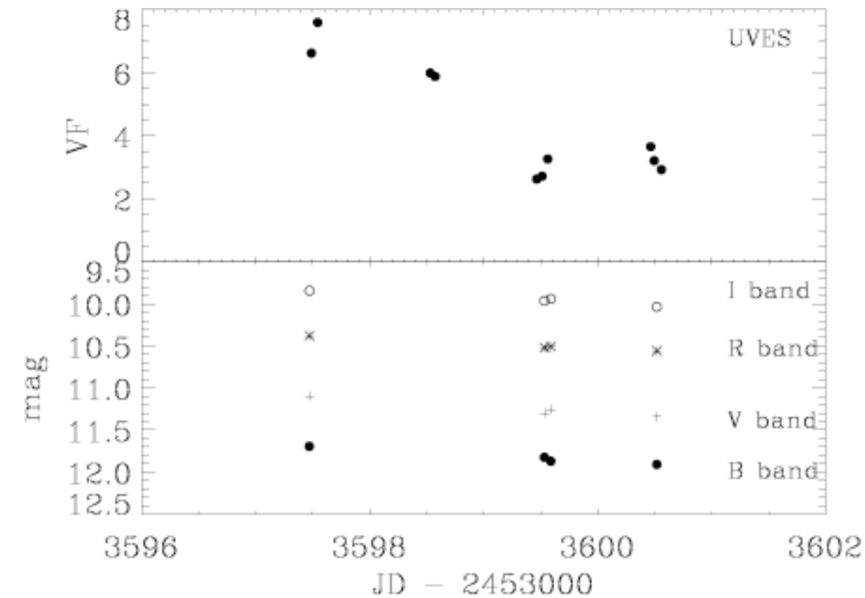


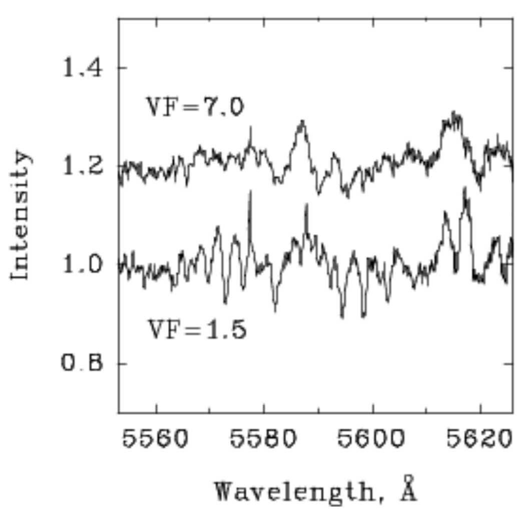
Gahm et al.
2008, A&A
482, L35

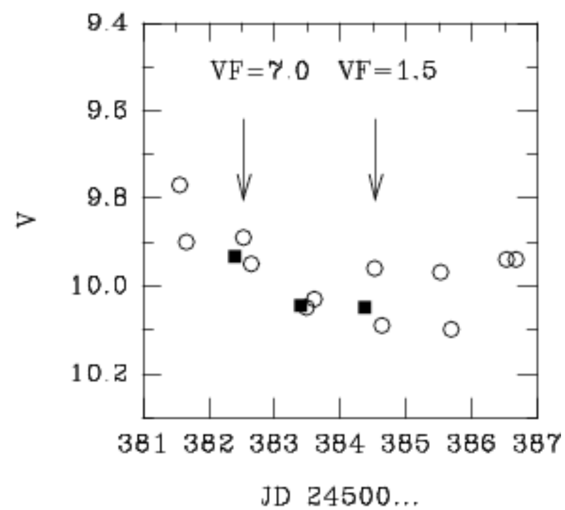
Variable Veiling in S CrA SE



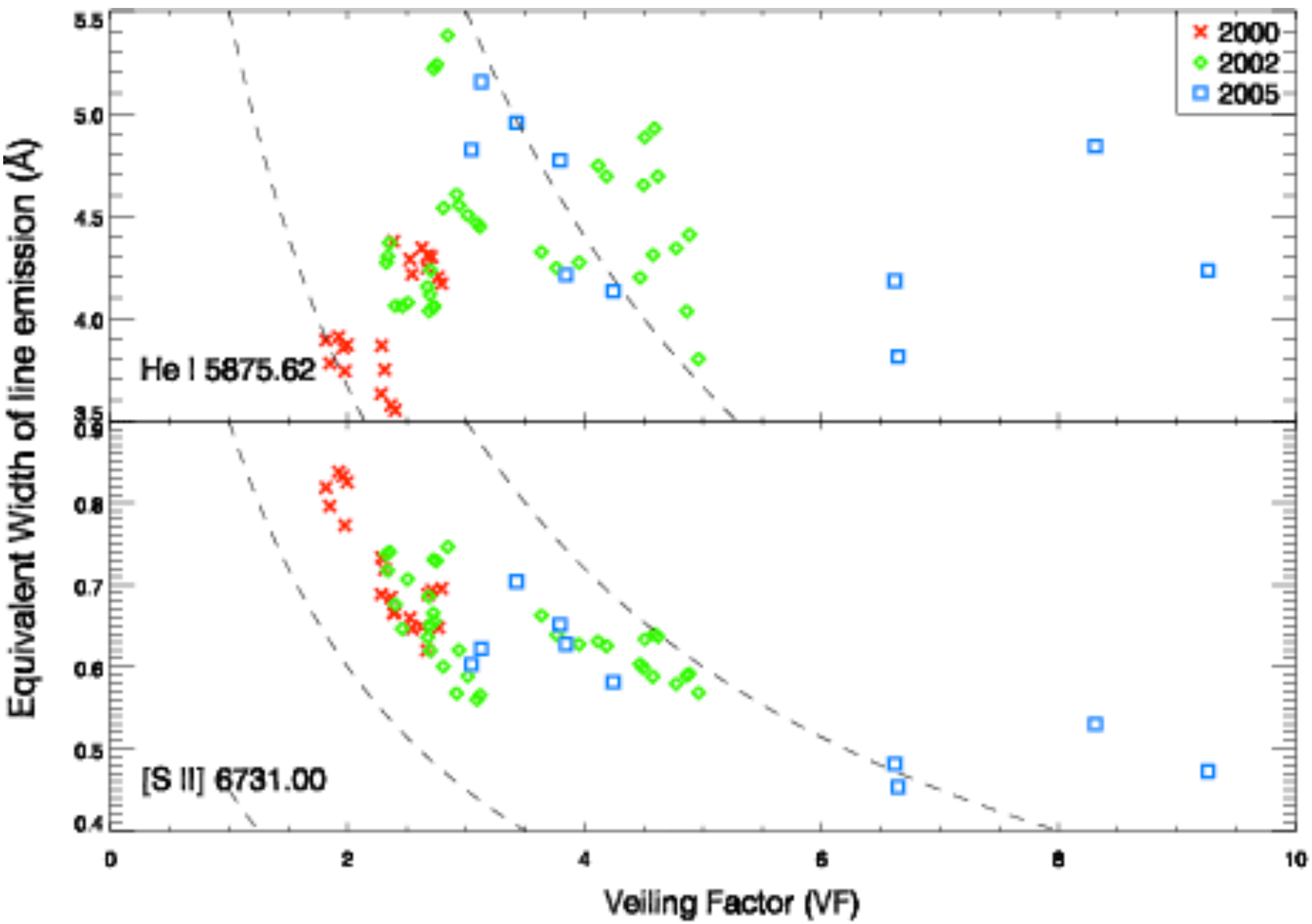
Correlations of Veiling with Brightness - not







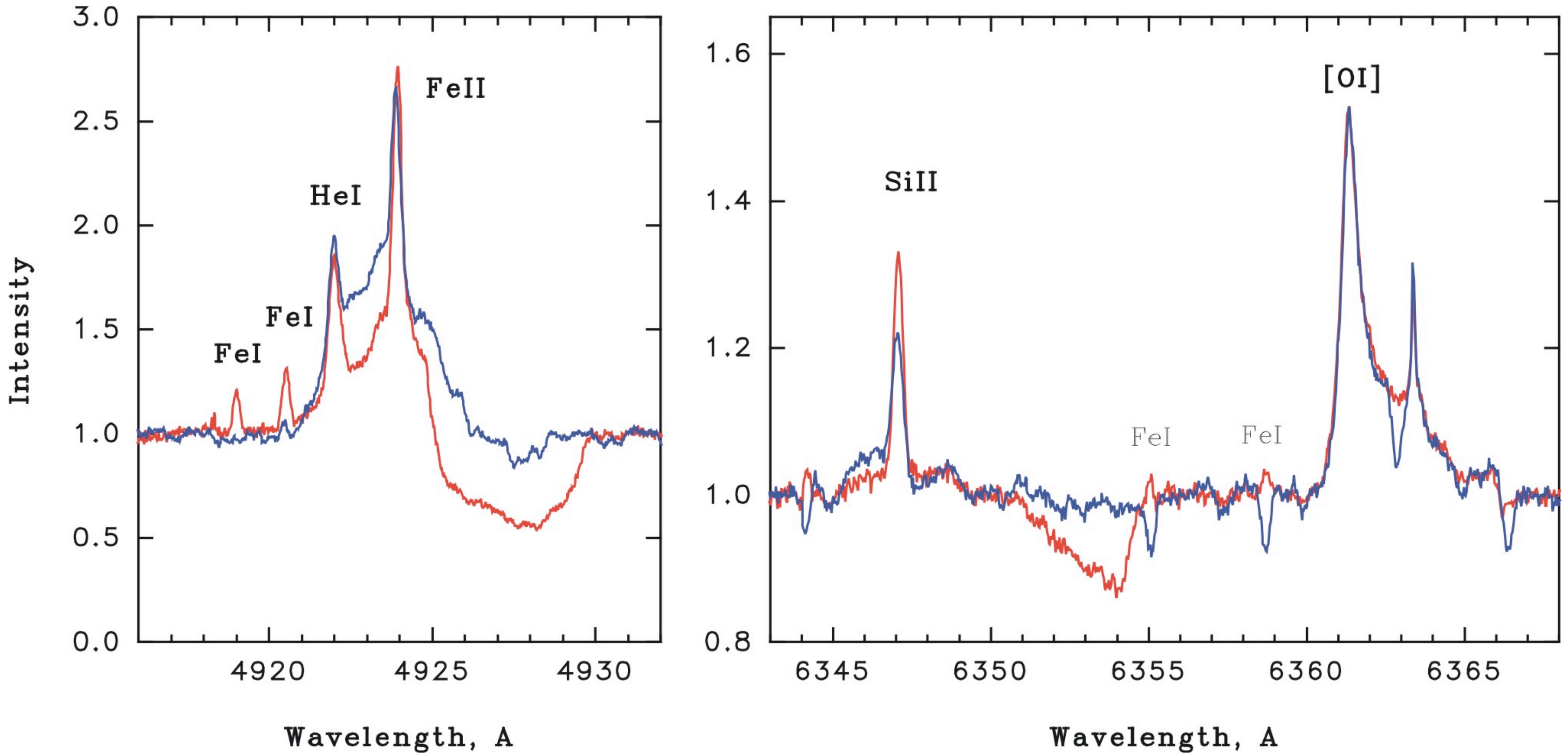
Gahm et al. 2008, A&A 482, L35



Dashed curves: constant emission flux, variable continuum.

Gahm et al. 2008, A&A 482, L35

Variable Veiling in S CrA SE



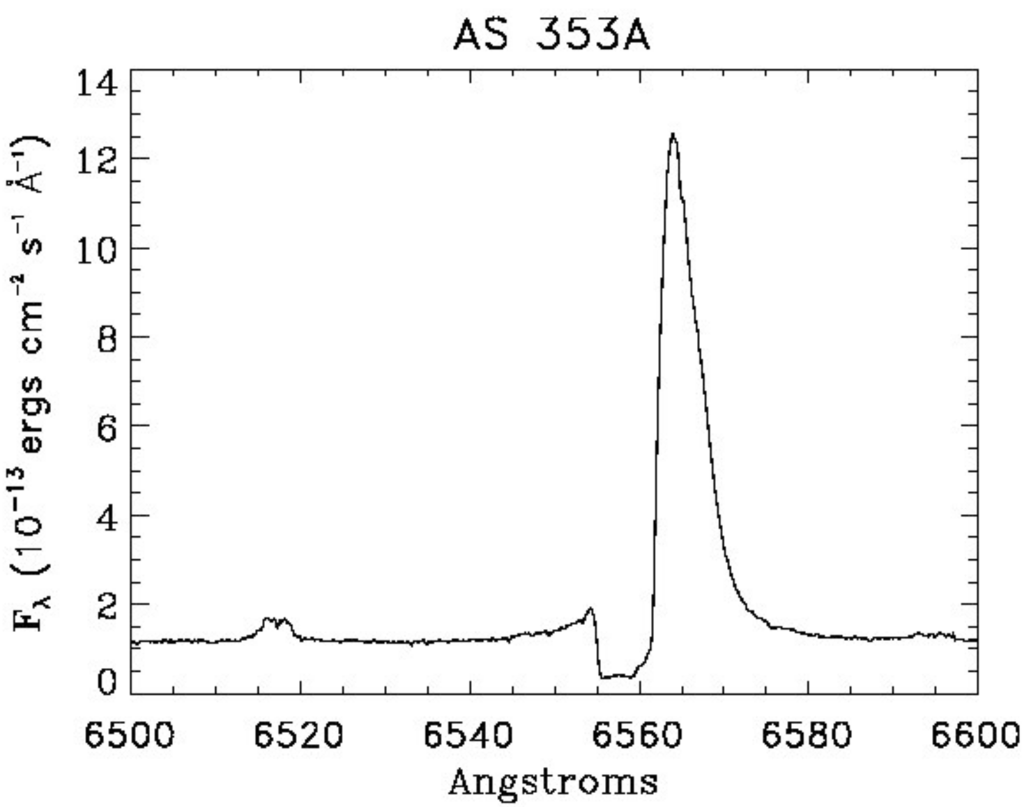
[O I] is circumstellar. That it remains constant indicates that the continuum does not change as the veiling increases

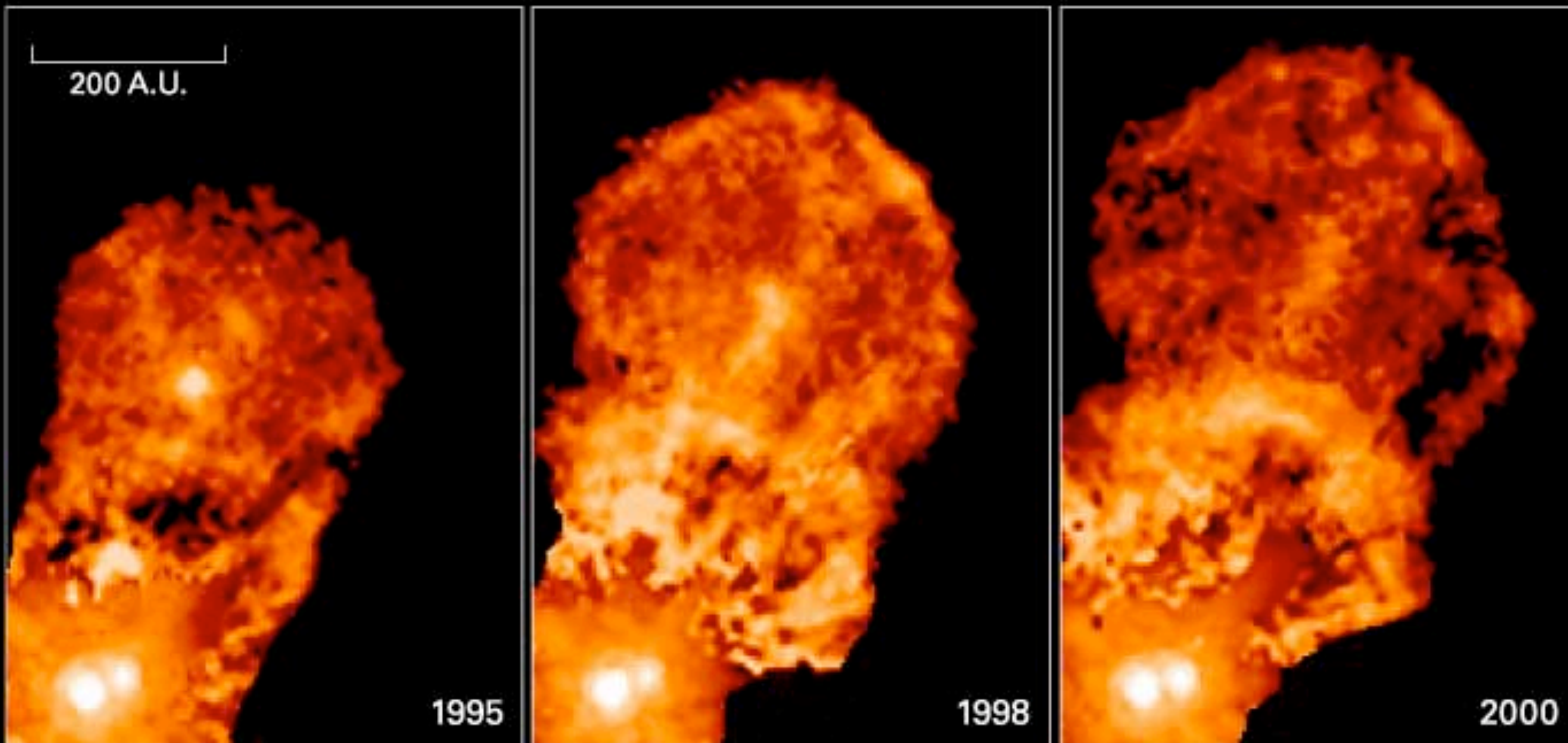
Explaining Veiling

- **VF<2**: enhanced accretion continuum
- **VF>2**: lines are diluted without an increase in the continuum
- Line filling-in is observed
- “chromospheric” emission RVs are in anti-phase with the absorption lines
- Electron-scattering?

Winds

- All T Tauri stars have winds
- Seen as P Cygni line profiles
- Wind velocity from extent of optically-thick trough
- In this case, $V_w \sim 380$ km/s





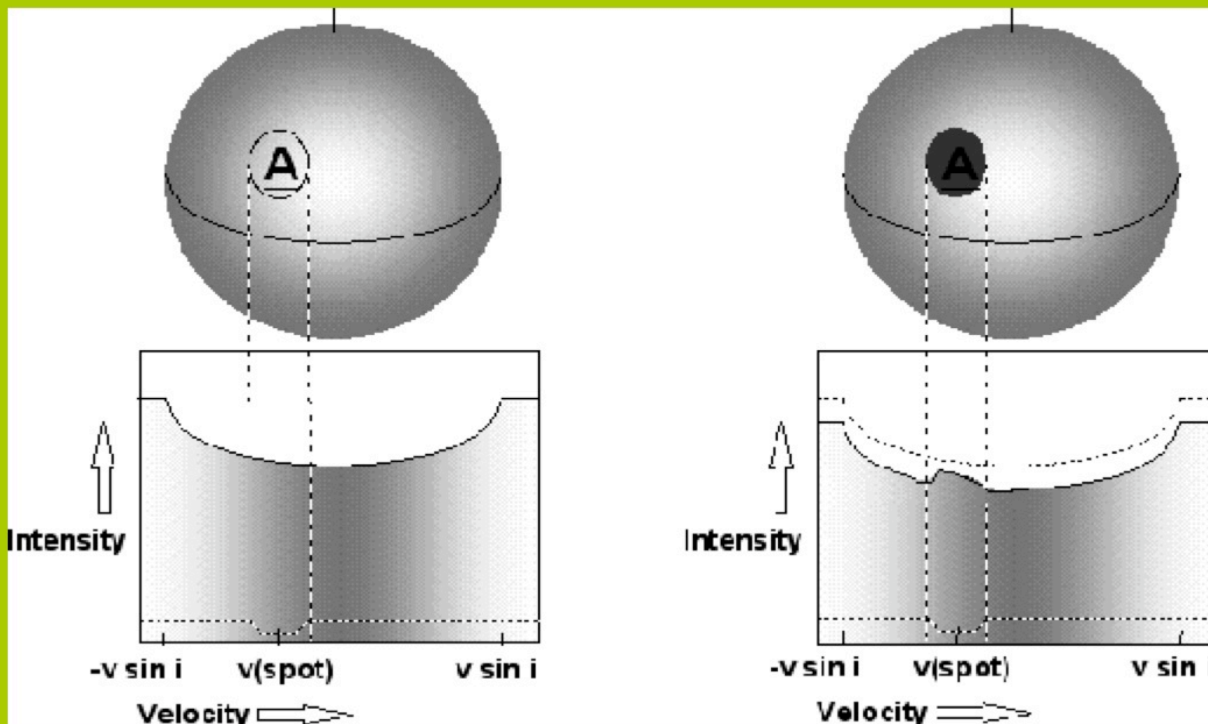
Hot Gas Bubble Ejected by Binary Star XZ Tauri

Hubble Space Telescope • WFPC2

NASA and J. Krist (STScI) • STScI-PRC00-32

Doppler Imaging

How does Doppler imaging work?

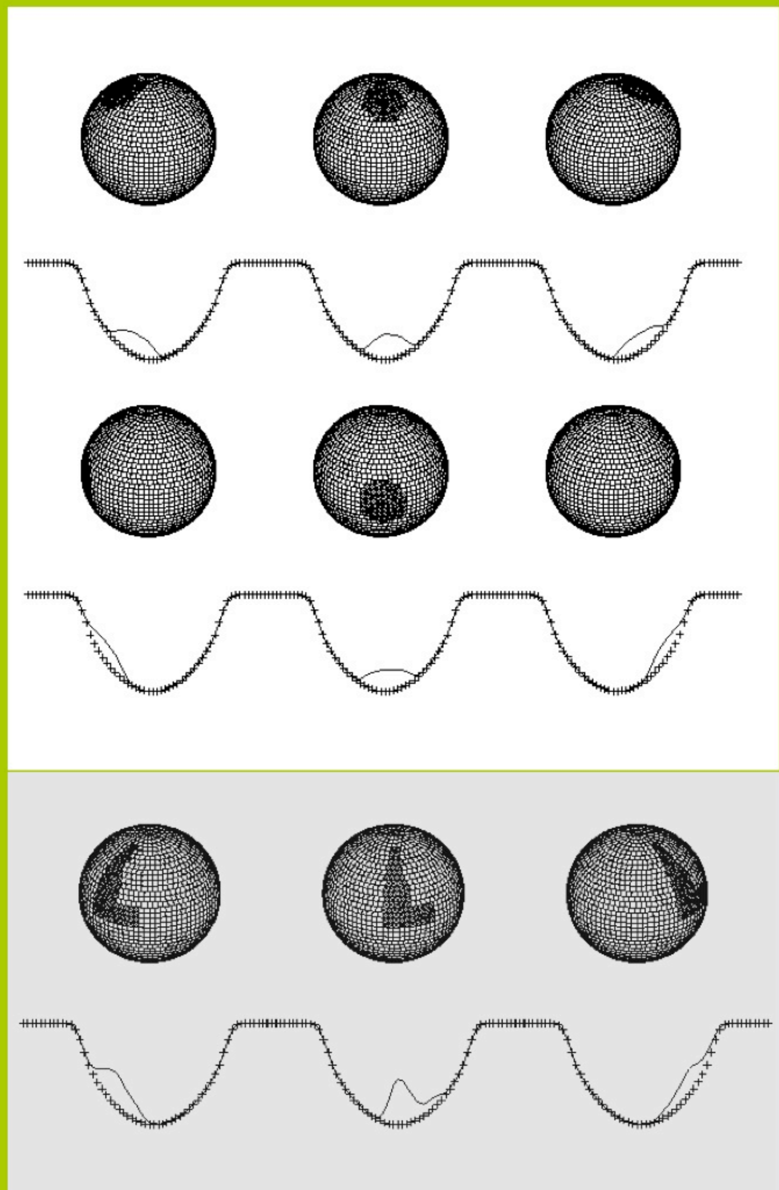


Collier Cameron 2002

Missing flux (in case of a dark spot) leaves a characteristic bump in the spectral line profile.

Doppler Imaging

AIP
K. G. Strassmeier
Stellar Coronae, MPIfR, December 2006



Line profile deformation due to spots at

high latitudes

low latitudes

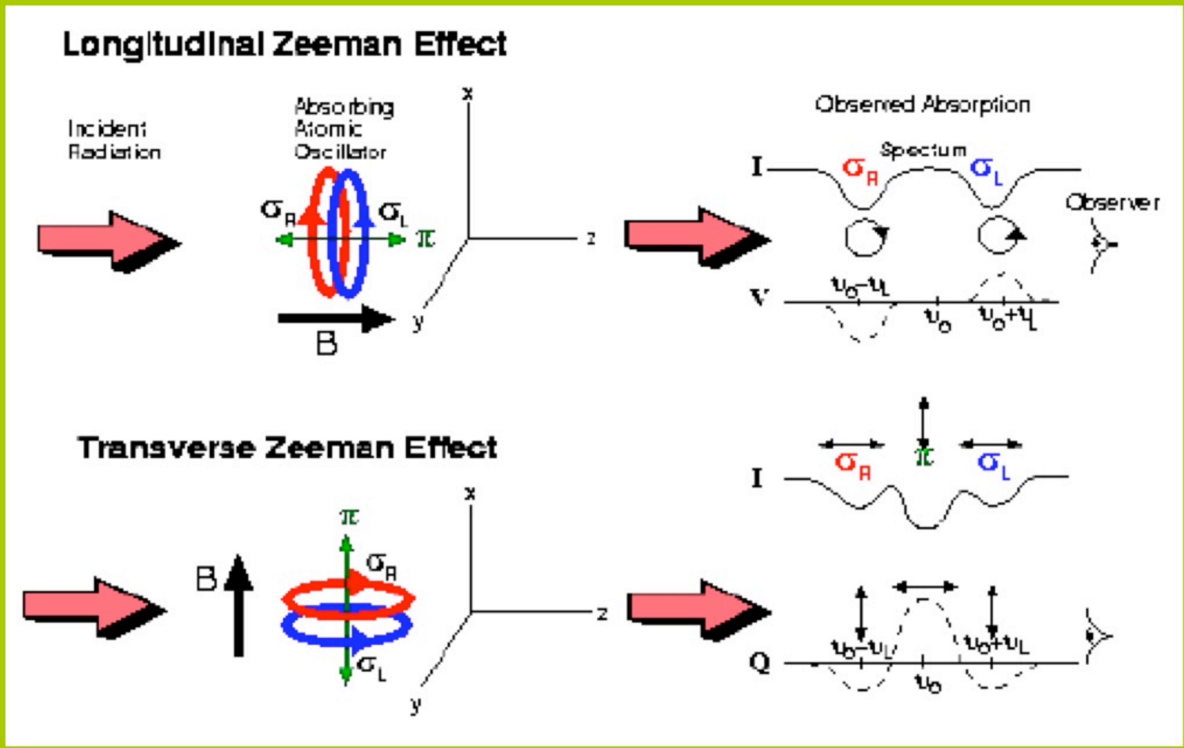
and of complex shape.

I USE IT

Zeeman Doppler Imaging

„The holy grail“

... full-Stokes Zeeman-Doppler imaging



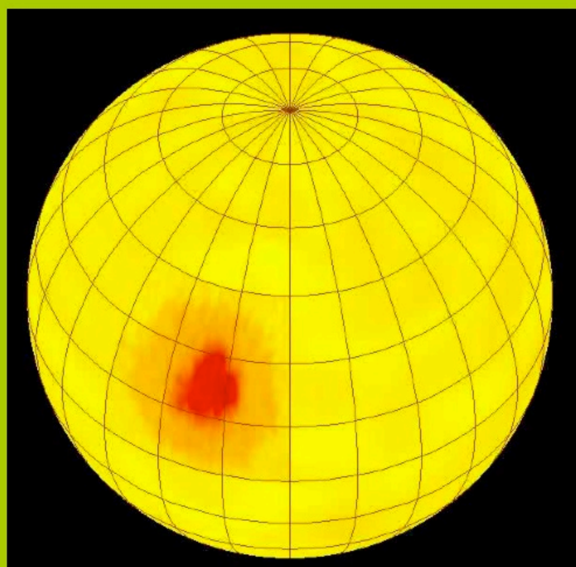
K. G. Strassmeier
Stellar Coronae, MPIfR, December 2006

Zeeman Doppler Imaging

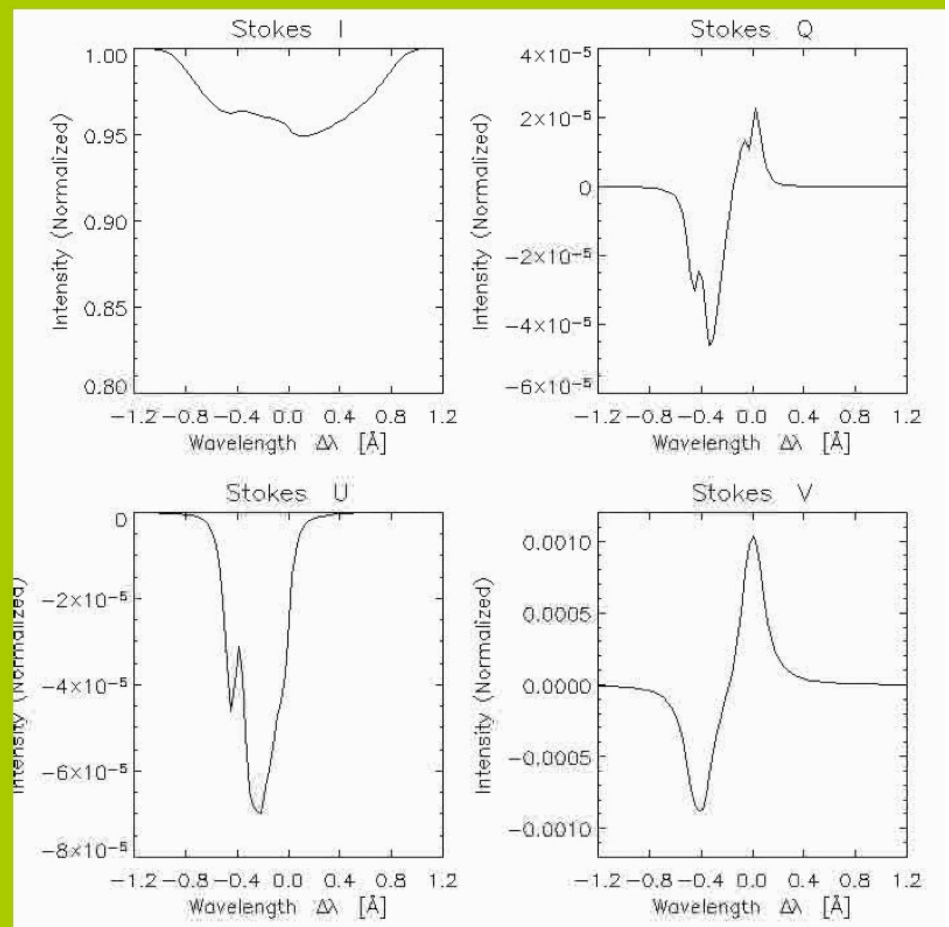
AIP

K. G. Strassmeier
Stellar Coronae, MPIfR, December 2006

4-Stokes simulation with two Sunspot vector-magnetograms



Kopf, Carroll & Strassmeier 2006



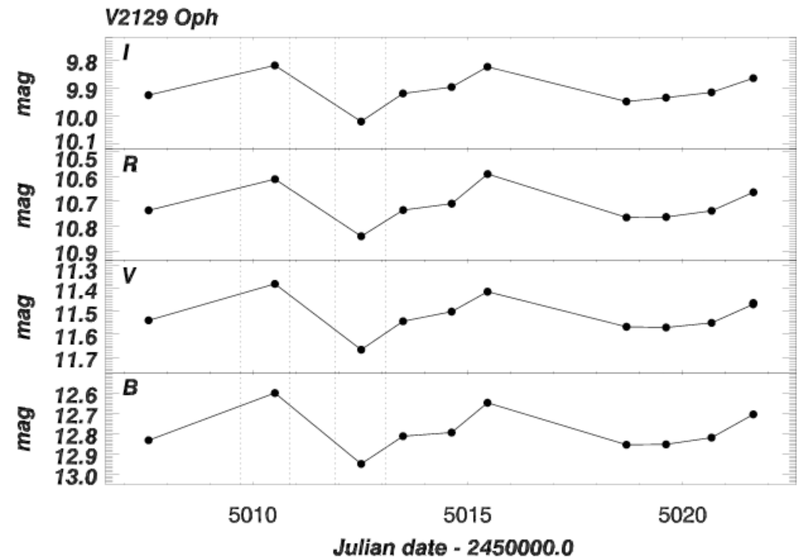

V2129 Oph
•Classical T Tauri star
•Member of ρ Oph complex
•K3.5V
•m-dot ~ 10^{-8} $M_{\odot}$/yr
•V=11.4
•A_V=0.6
•P_{rot} = 6.53^d
•V*sini* ~ 7 km/s
•*i* ~ 45-50^o

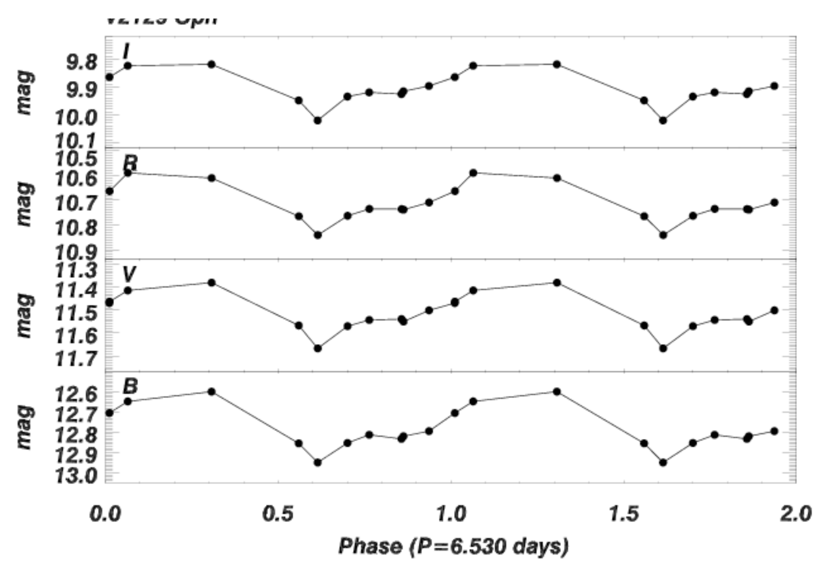
V2129 Oph

A coordinated campaign to study the relation between
- accretion,
- starspots,
- coronal structure, and
- the stellar magnetic field

C. Argiroffi , J.Bouvier, J.F. Donati, E. Flaccomio, S. Gregory, & others

Optical Light Curve





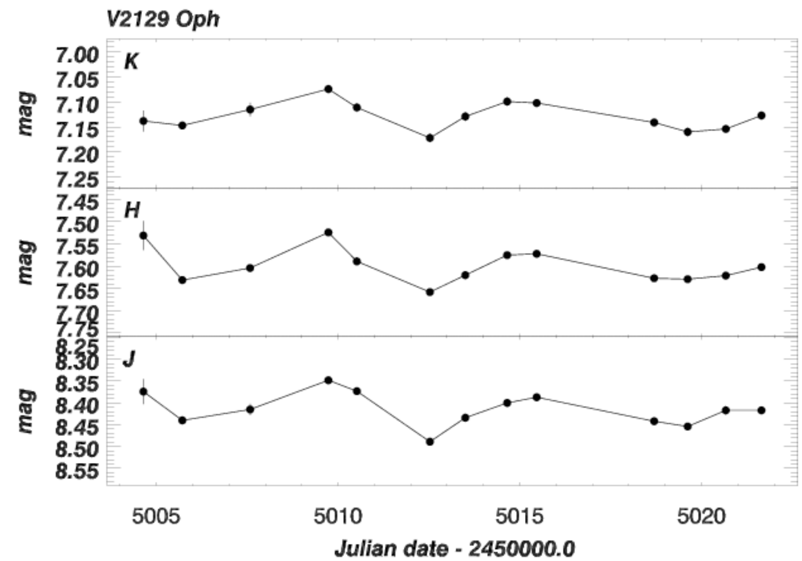
Folded on 6.53 day period

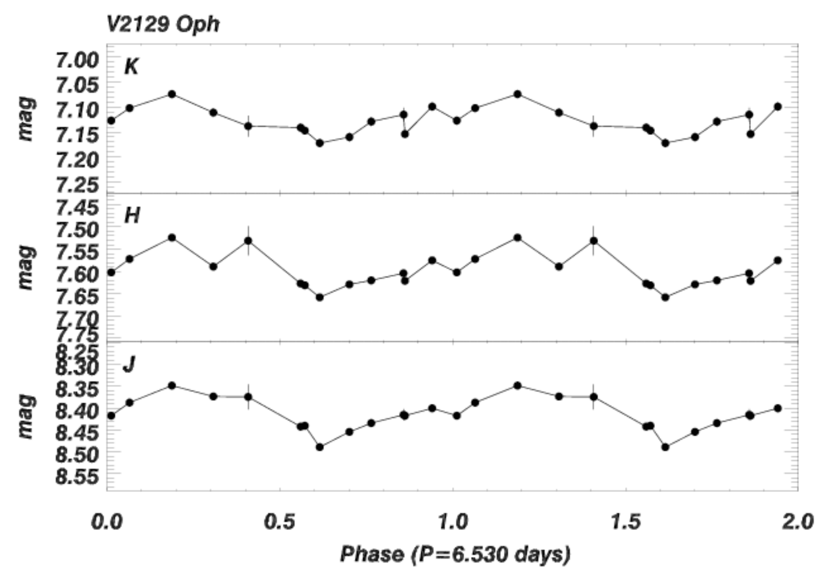
Minimum:
JD 2455012.34 +/- 0.21
(June 29.84 UT)
Xray ϕ=0 @ ϕ~0.2

n-IR Light Curve

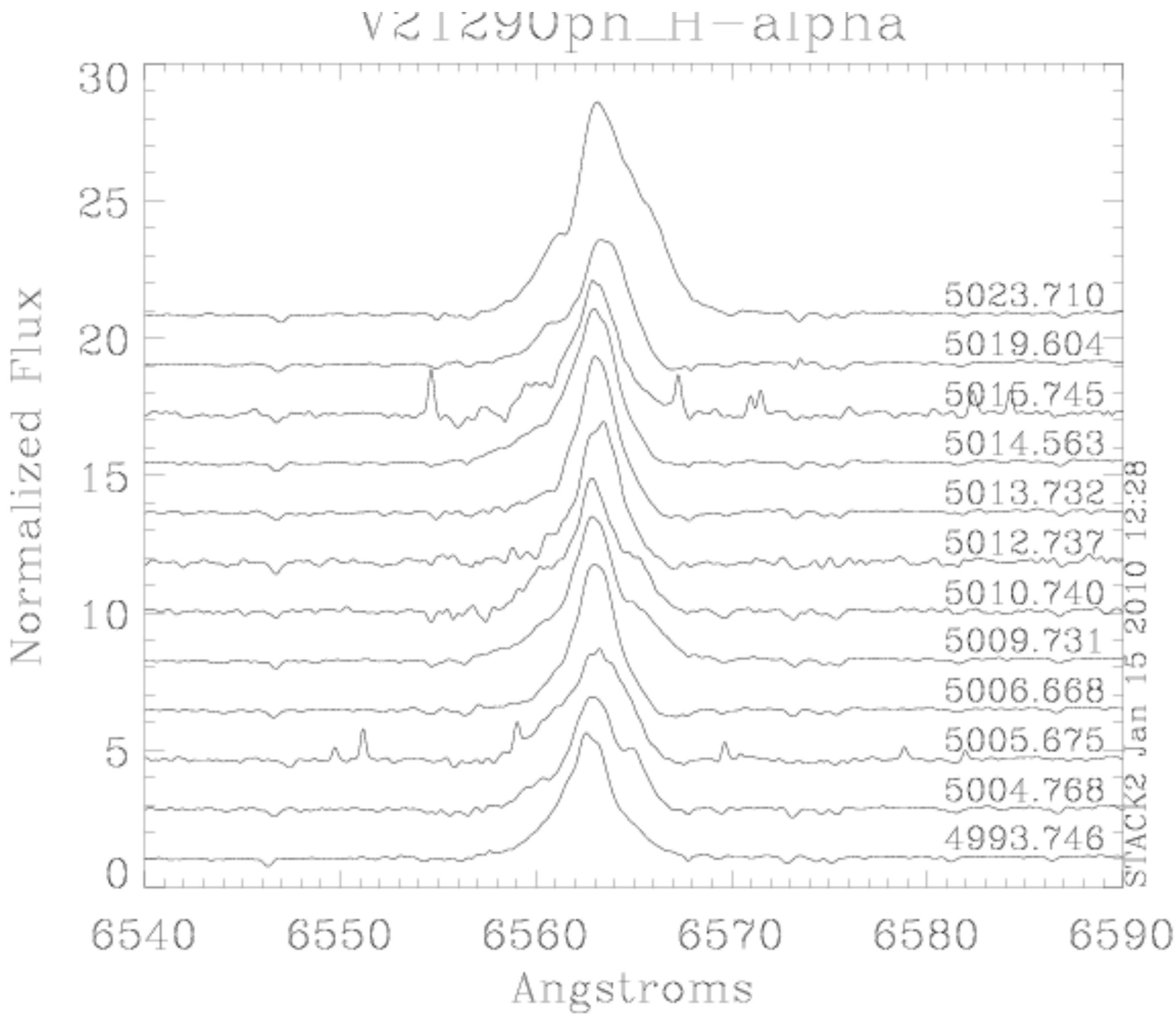
Folded on 6.53 day period

Spot solution:
T_{spot}= 3884.
f_{spot}= 0.1190

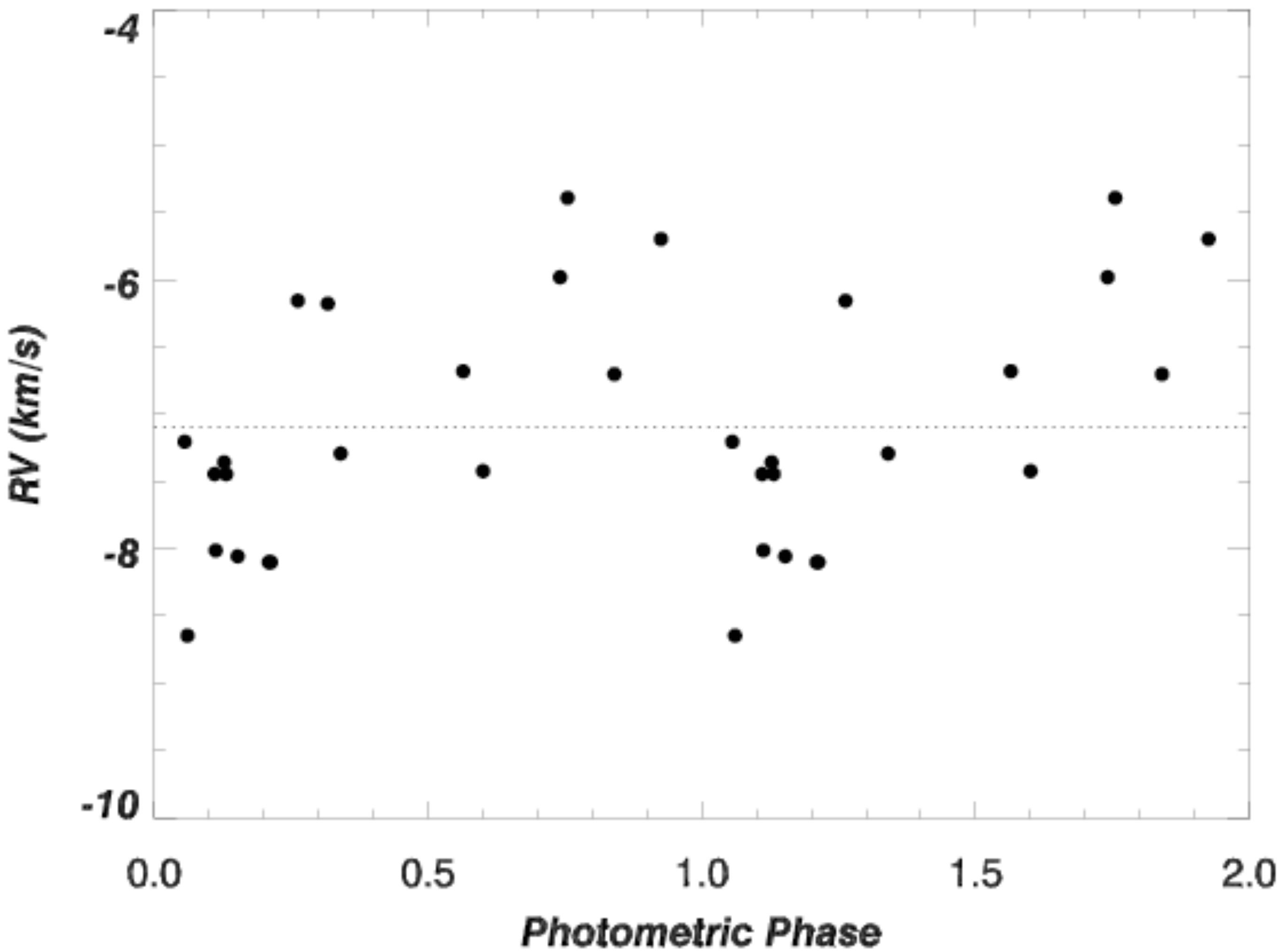




High Dispersion - Hα

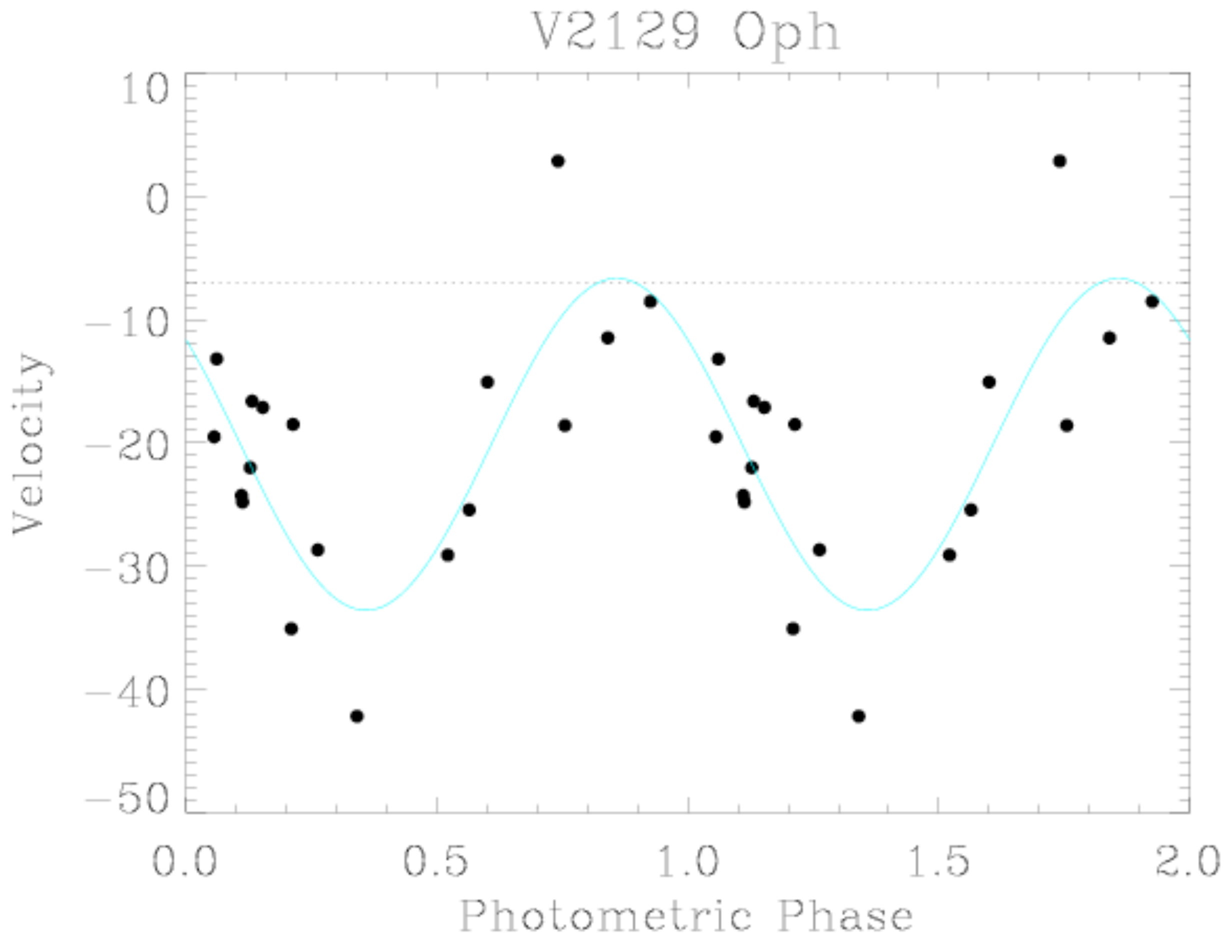


Li Absorption Radial Velocity

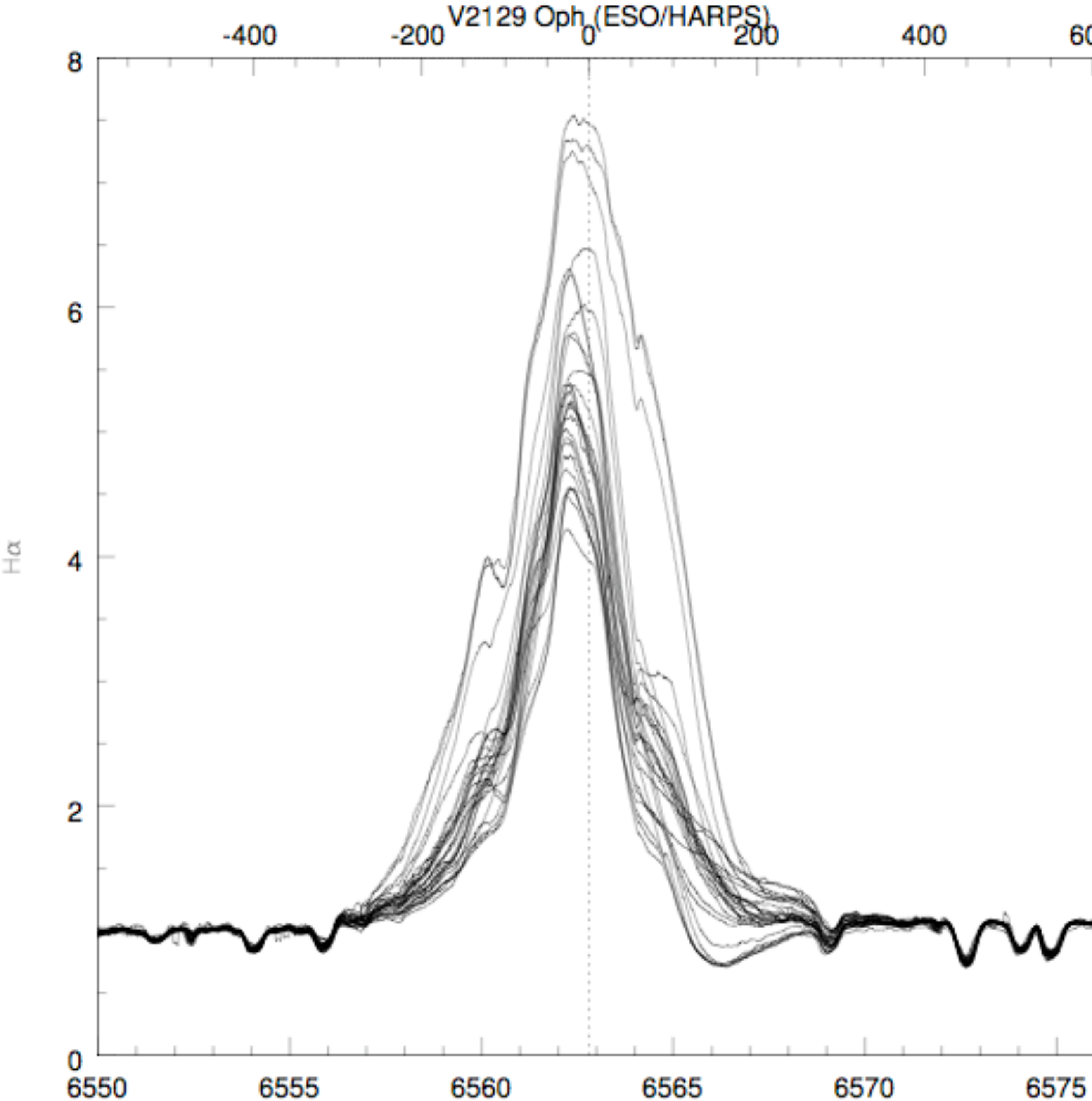


Mean: -7.2 km/s (agrees with literature)

Hα Radial Velocity



Mean: -13 km/s   Amplitude: 20 km/s

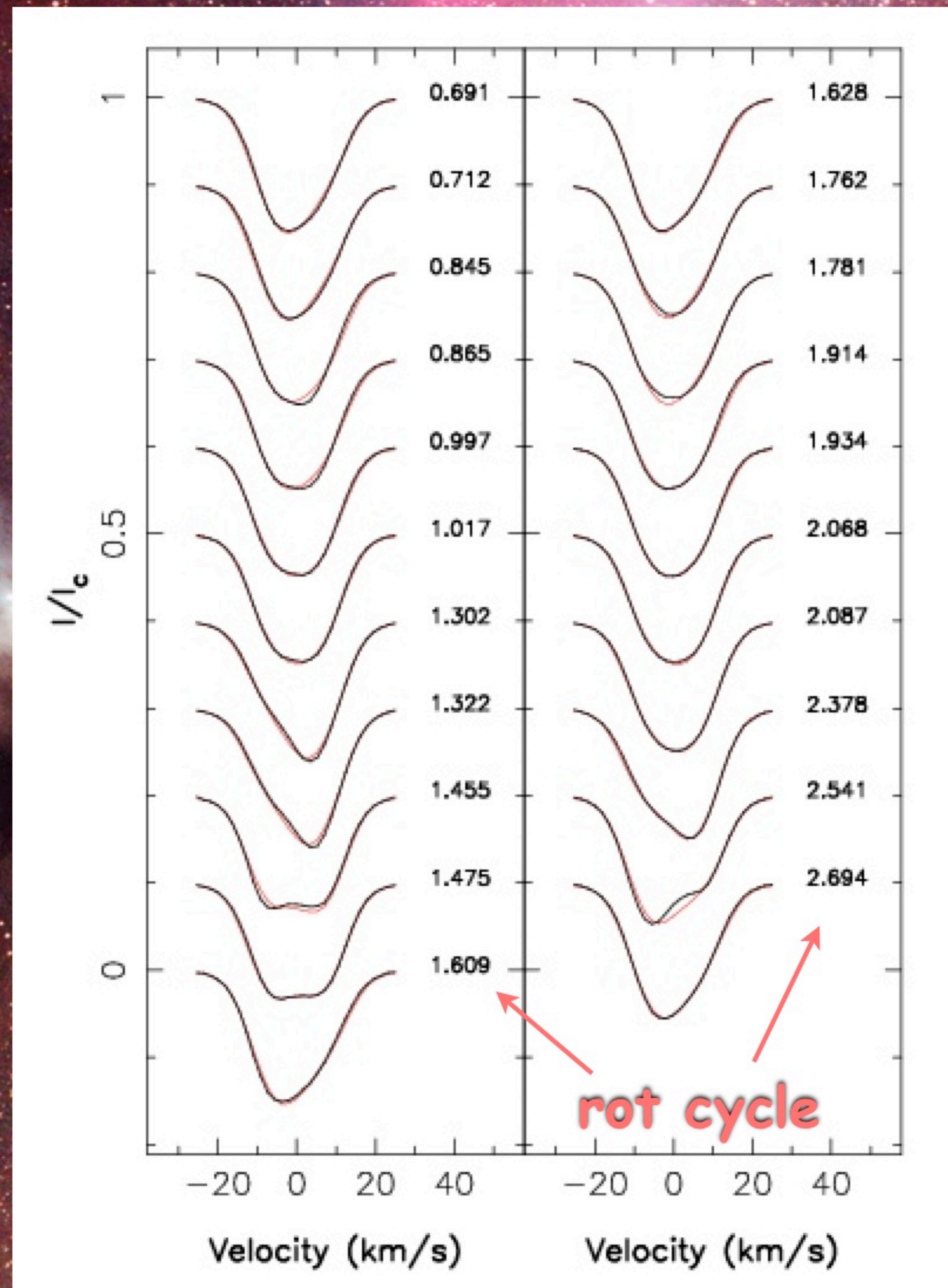


HARPS spectra

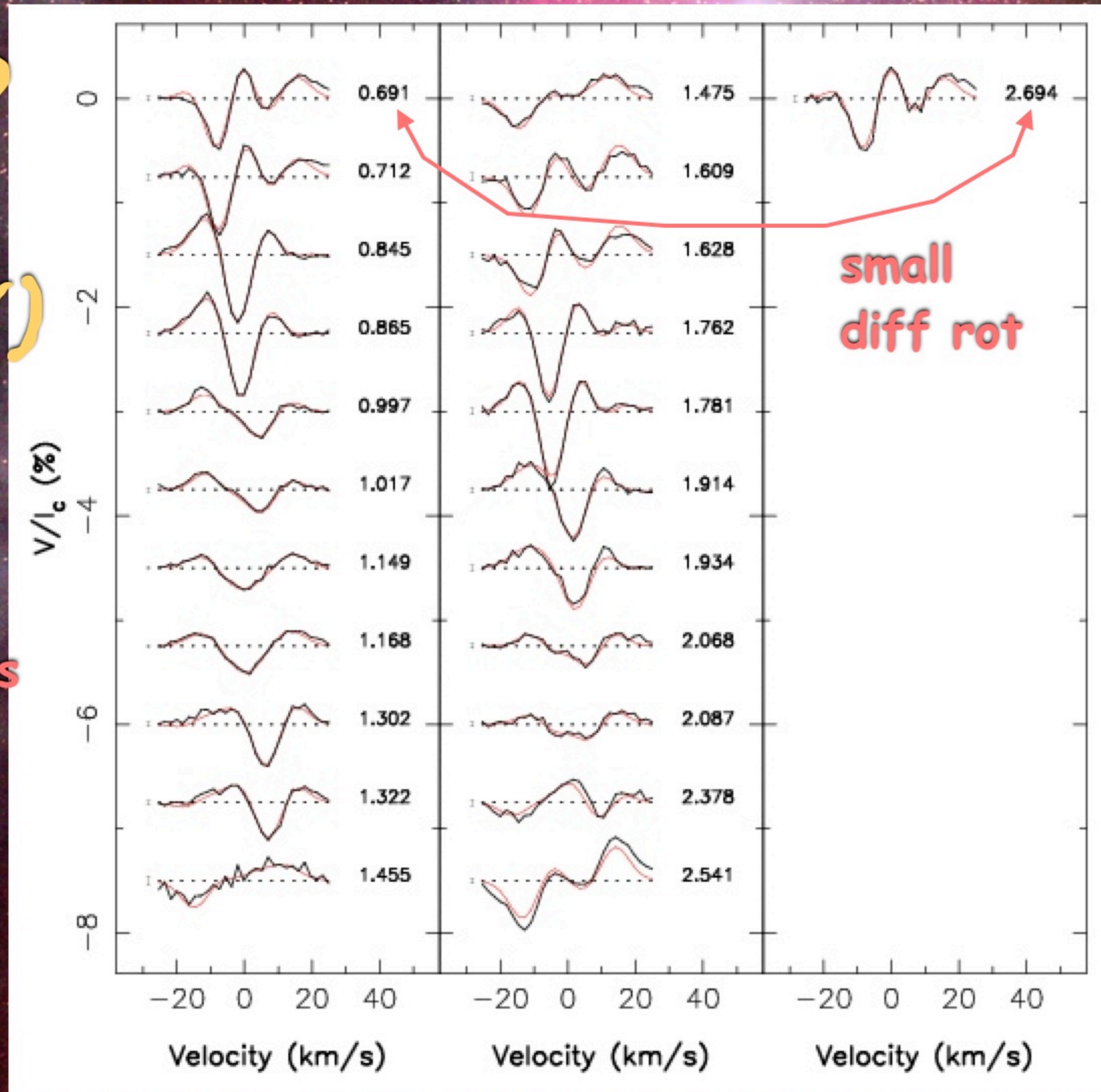
Note P Cygni and Inverse P Cygni profiles

phot LSD profiles (Stokes I)

veiling < 5%
vrad ~ -7.0 km/s

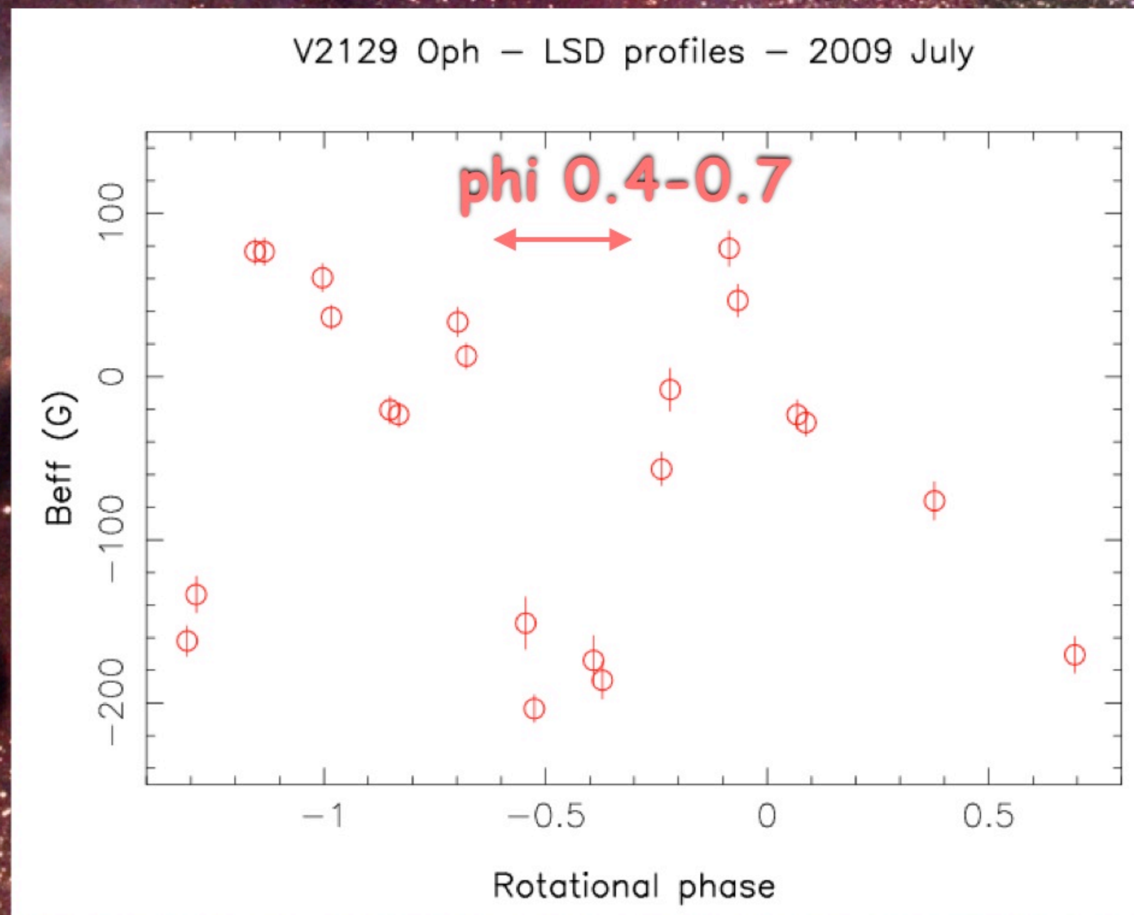


phot LSD profiles (Stokes V)



Zeeman signatures detected @ all phases

phot LSD profiles (Stokes V)



field strongest @ phase 0.4-0.7

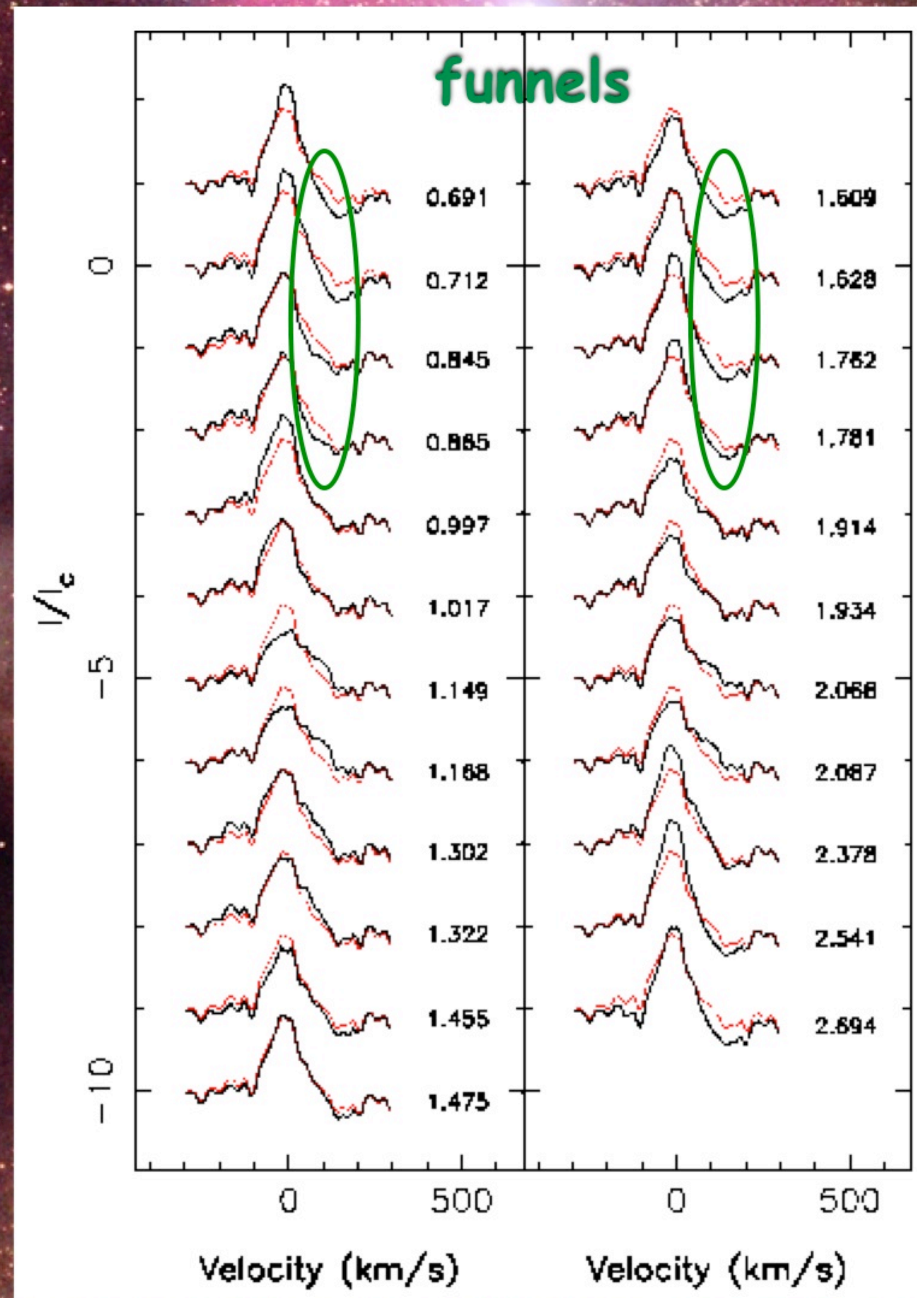
up to -200 G

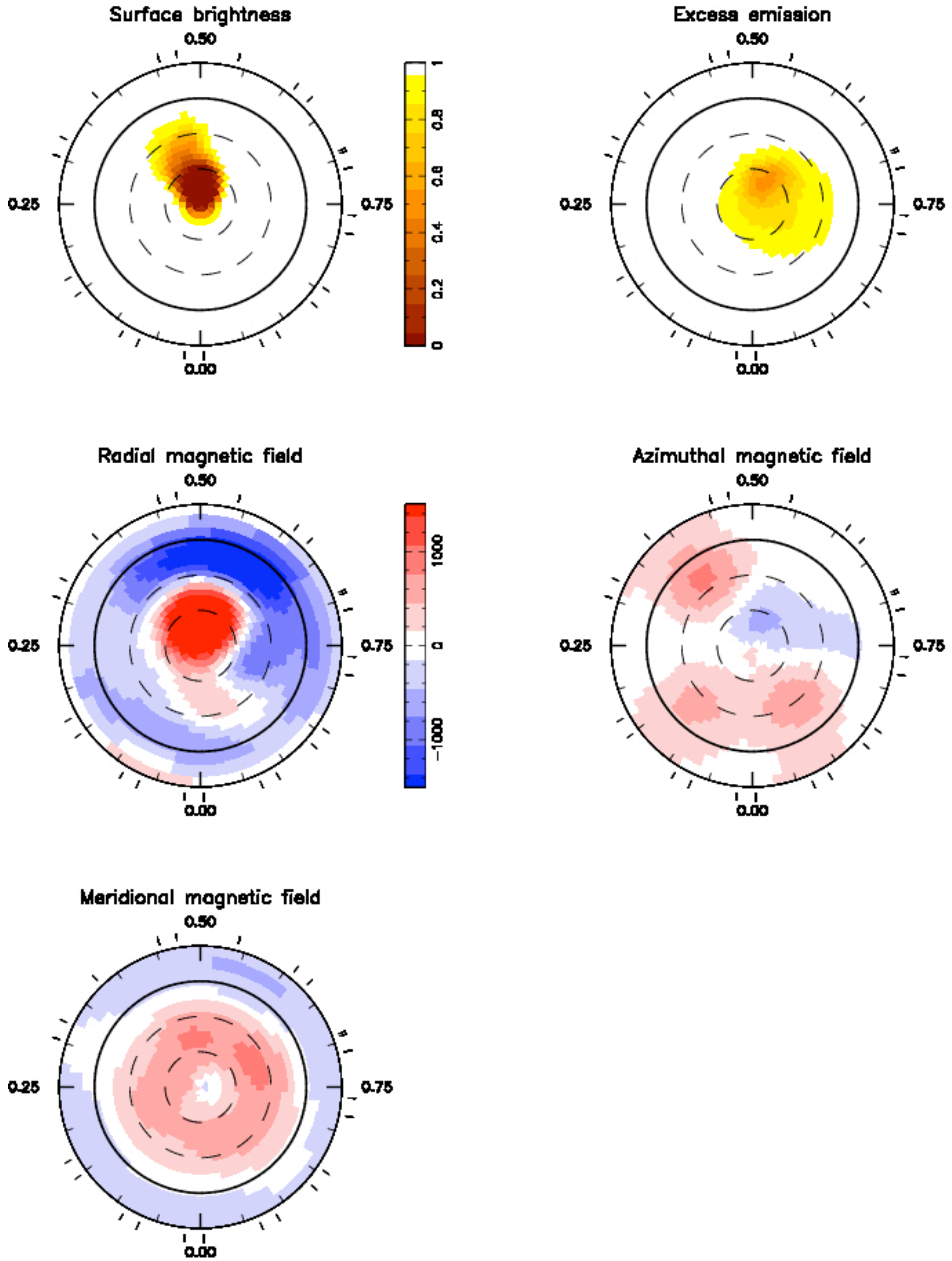
intrinsic variability

Hβ 486 nm

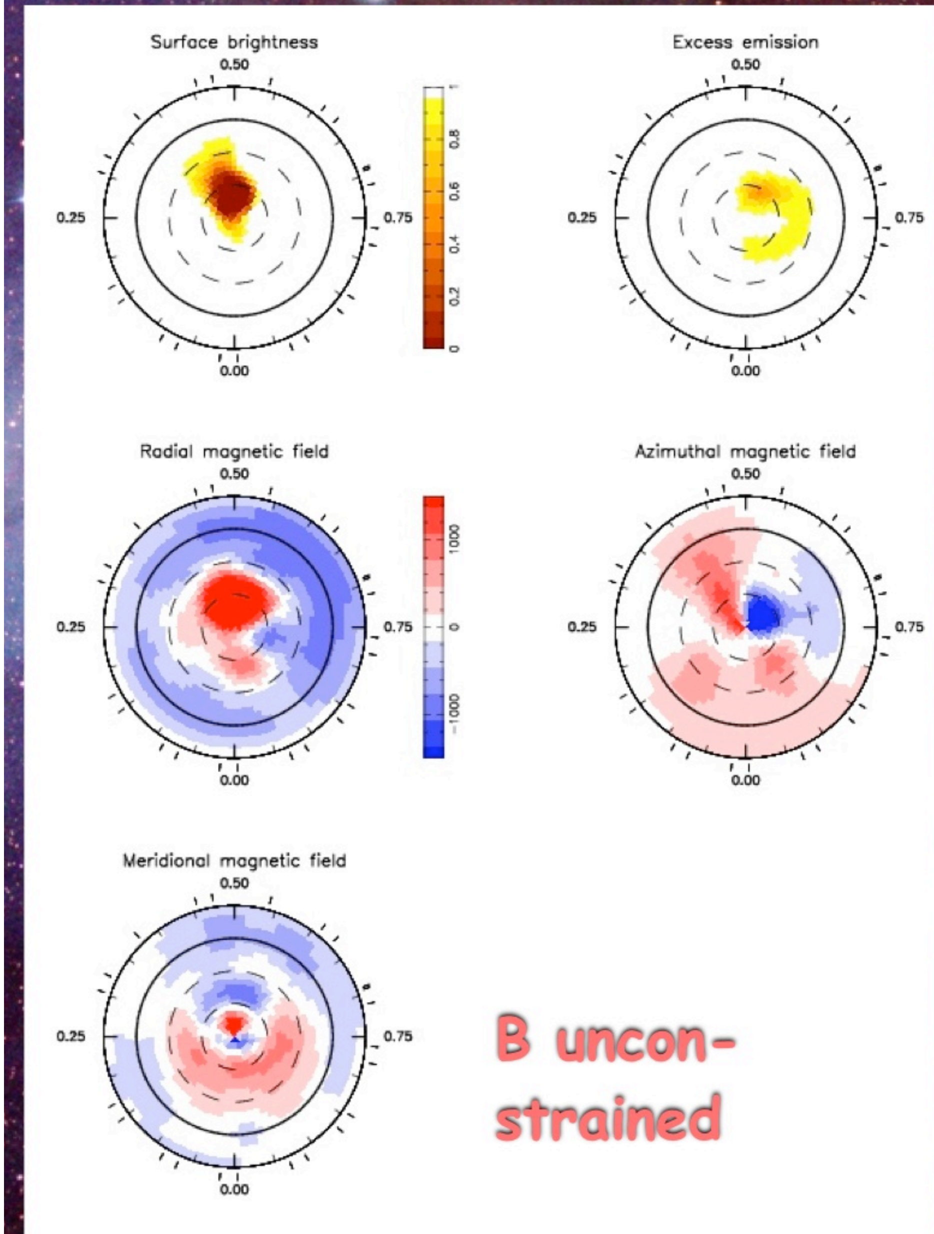
ew ~ 120 km/s or ~ 0.2 nm
fwhm ~ 115 km/s
centre ~ -16 km/s

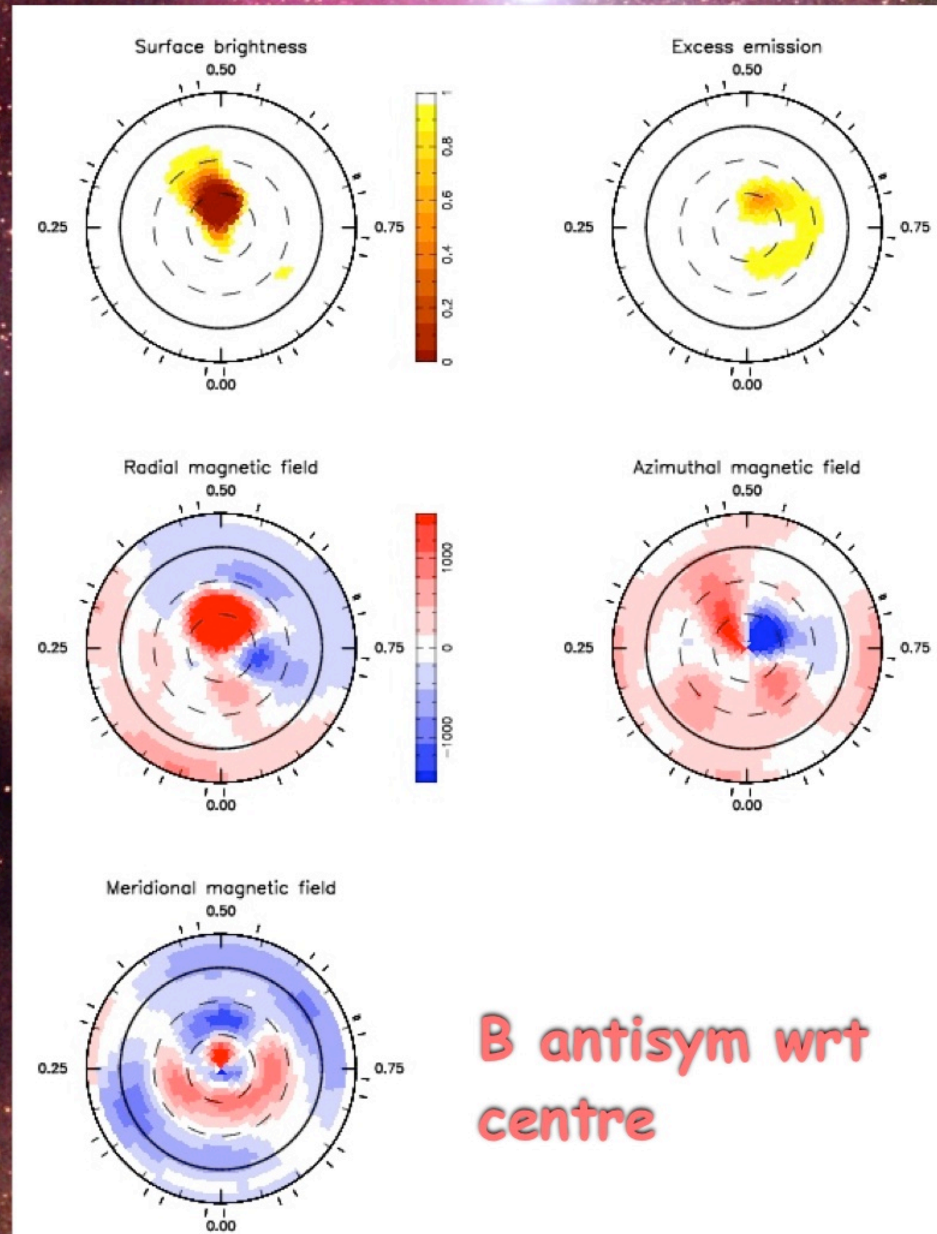
log Mdot ~ -9.6 Msun/yr
(Fang et al 2009)

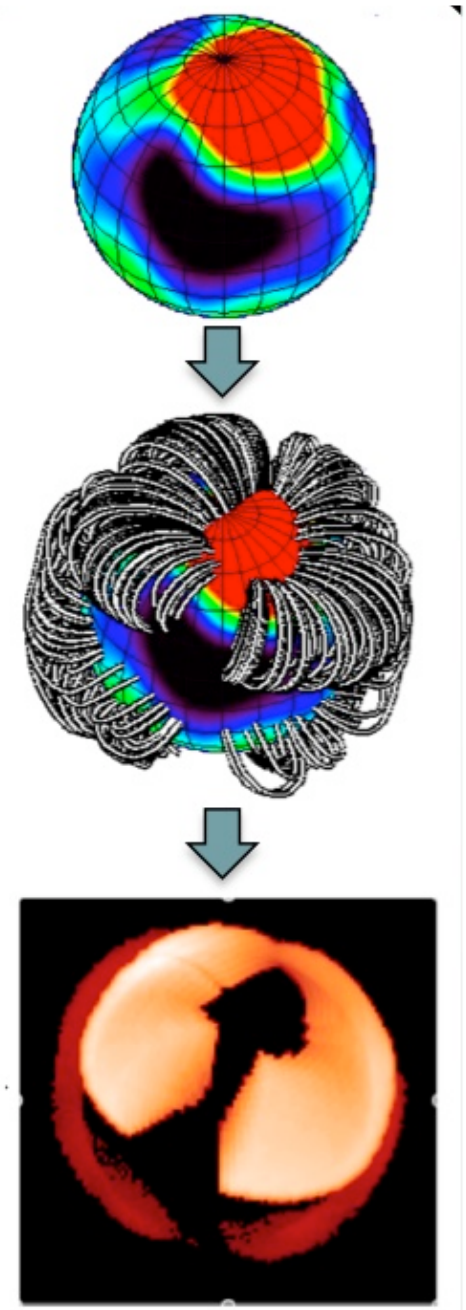



Surface brightness
0.50
0.25
0.75
0.00
1
0.8
0.6
0.4
0.2
0
Excess emission
0.50
0.25
0.75
0.00
Radial magnetic field
0.50
0.25
0.75
0.00
1000
0
−1000
Azimuthal magnetic field
0.50
0.25
0.75
0.00
Meridional magnetic field
0.50
0.25
0.75
0.00

reconstructed images





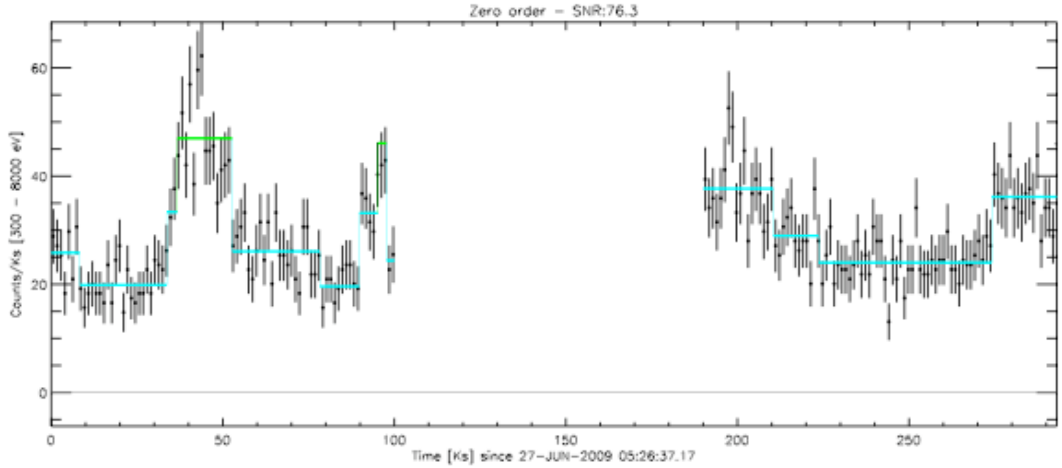


Magnetic Field Map

Potential Field Extrapolation

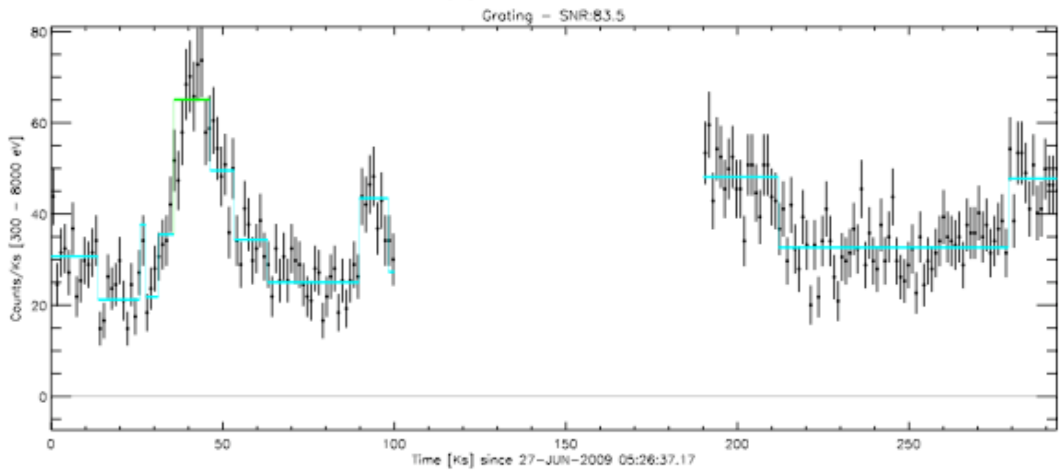
Simulated X-ray Corona

Lightcurve



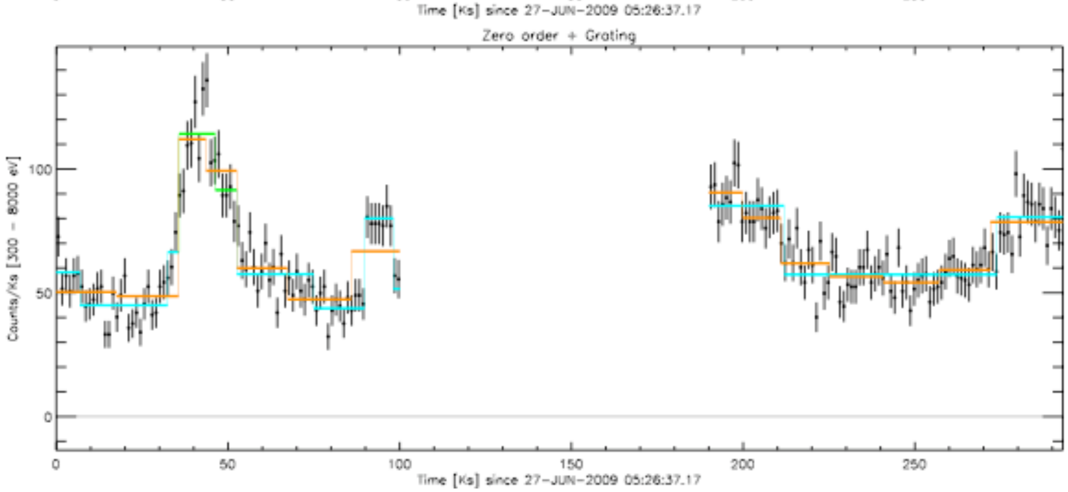
Zero Order

- Net counts: 5864
- Background: 0.4%



First Order

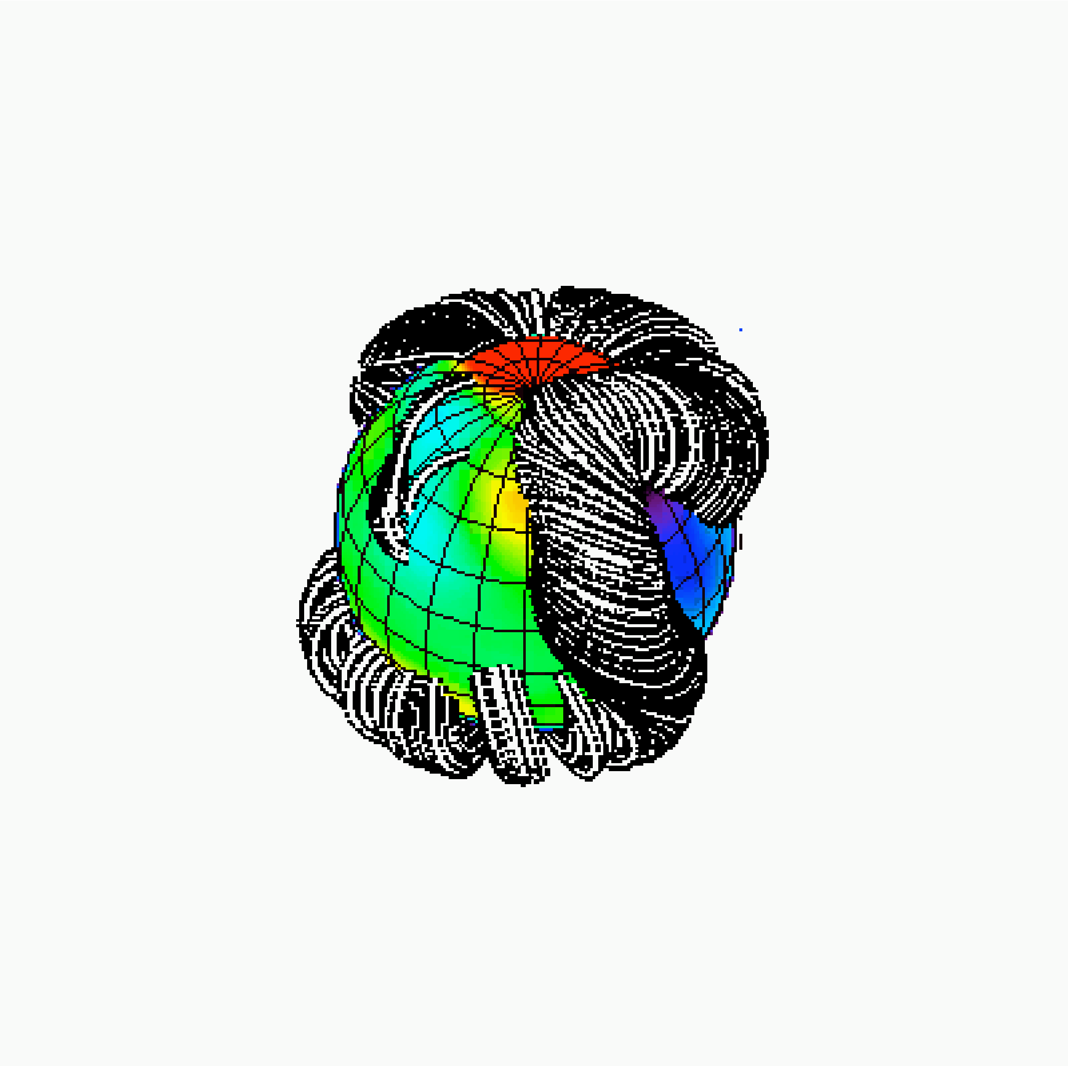
- Net counts: 7354
- Background: 2.7%



Order 0+1

- Net counts: 13217
- Background: 1.7%

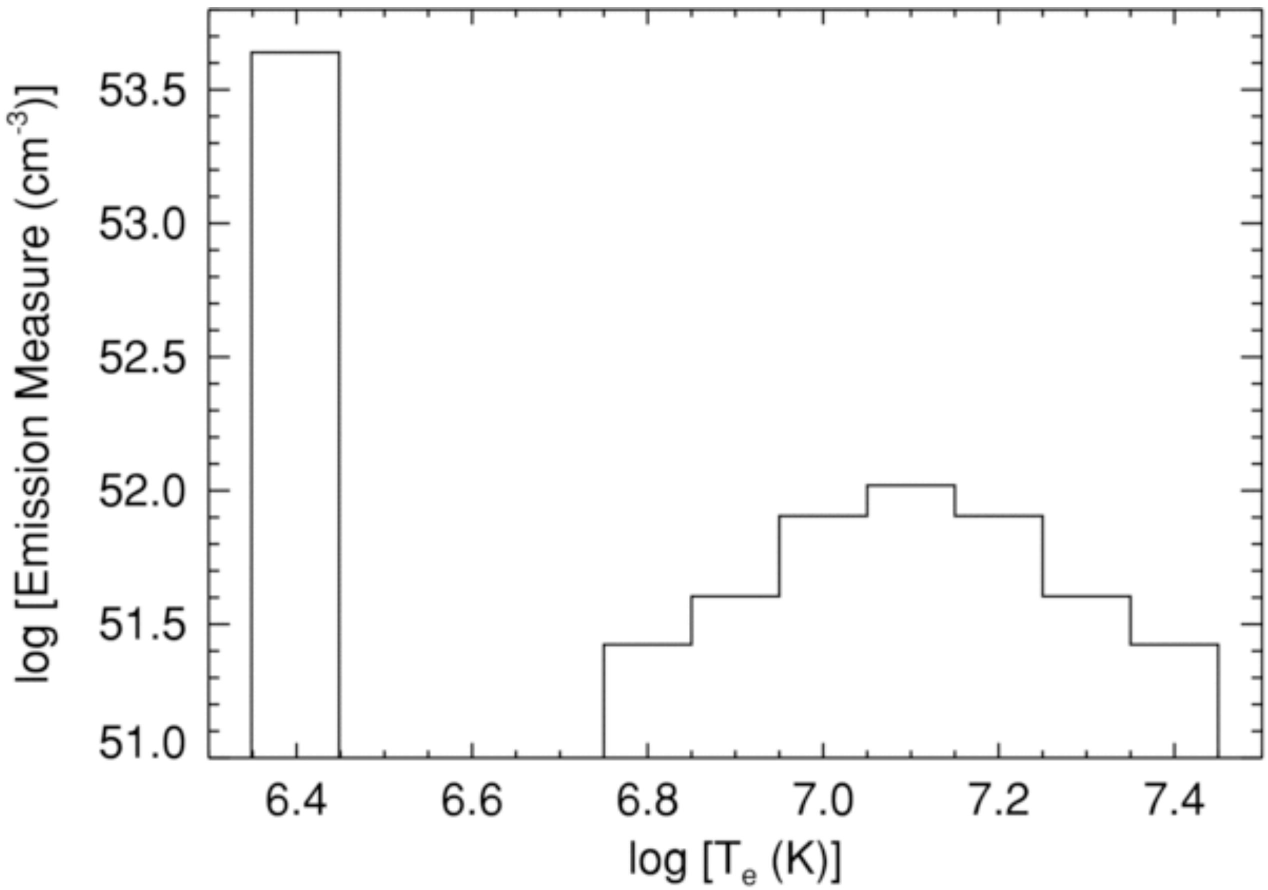
Extrapolated B Field



X-rays from T Tauri Stars

- In non-accreting systems, the emission is a scaled-up solar-like magnetic corona
- Accreting systems are more complicated

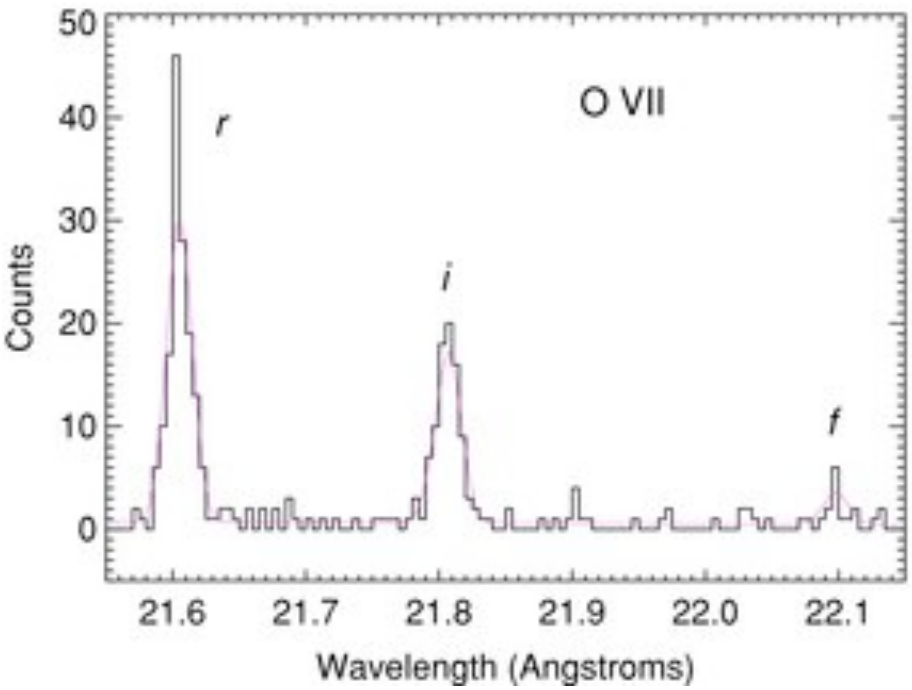
X-rays from the cTTS

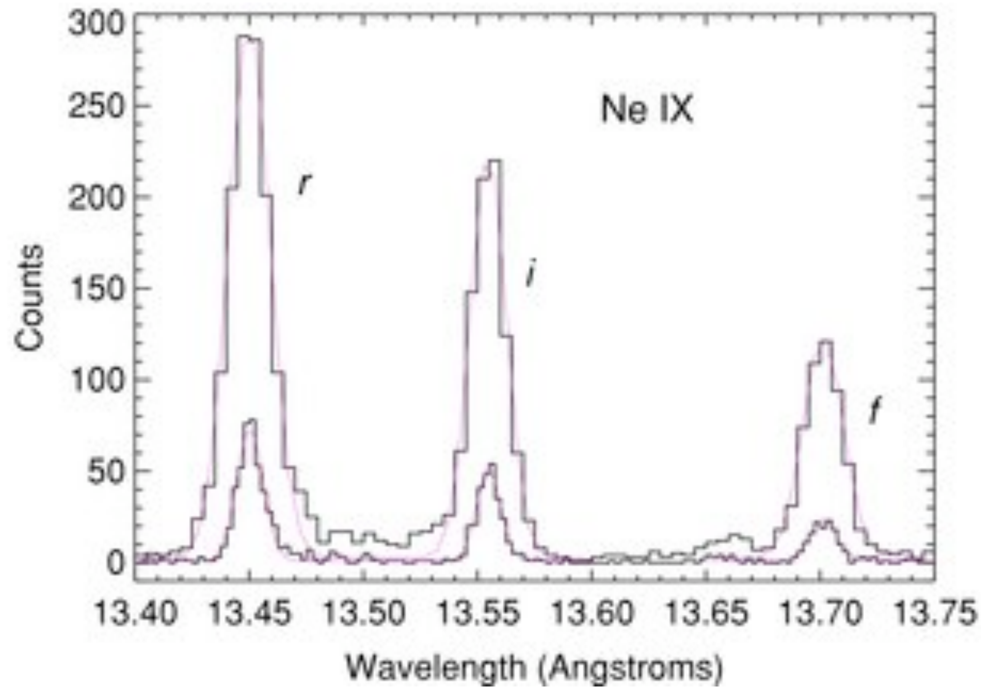


- Structured emission measure diagram

Brickhouse et al. 2010, ApJ, 710, 1835

X-rays from the cTTS

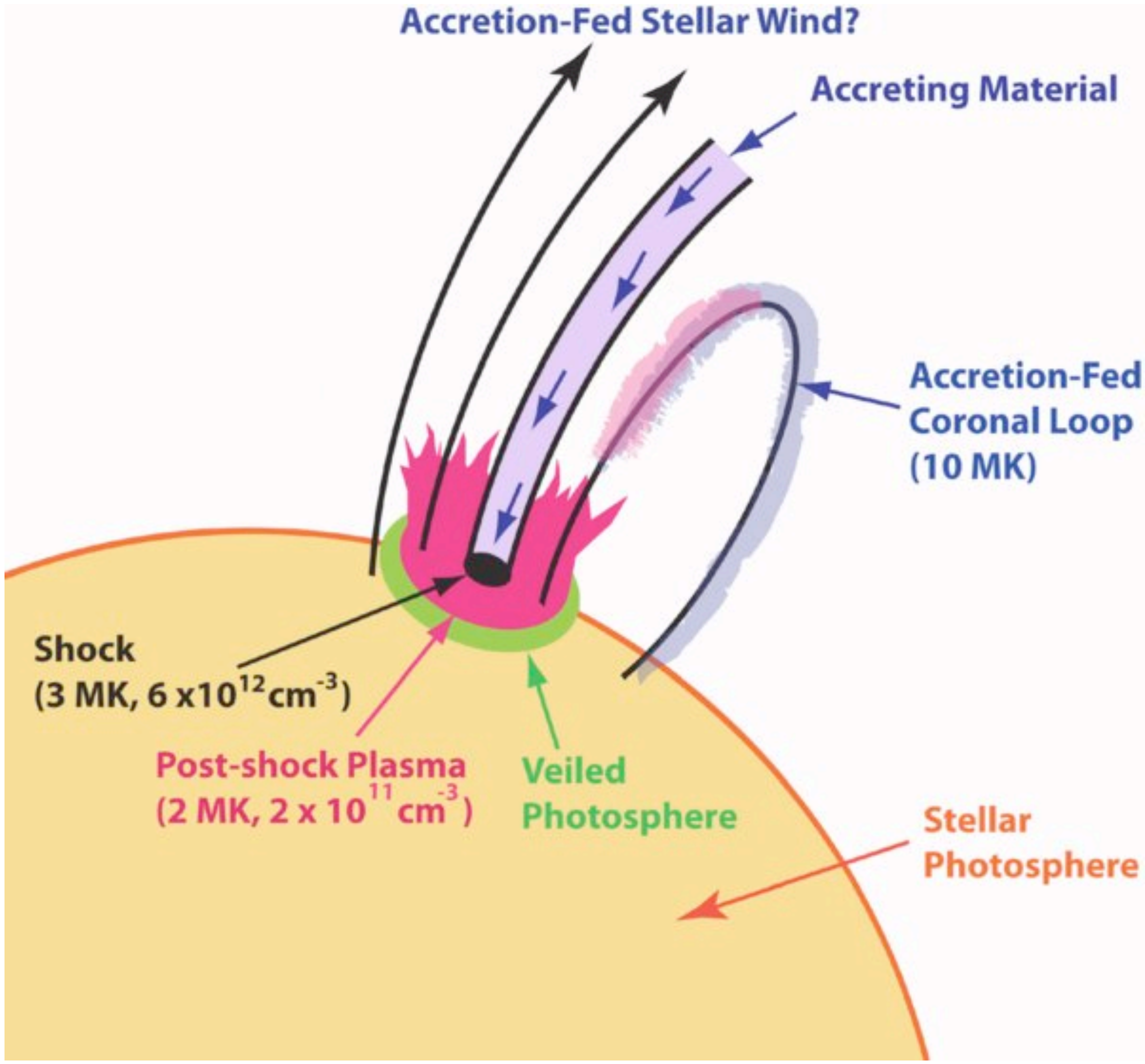




- High densities
  - $n_e = 3x10^{12}$ cm^{-3} (Ne IX)
  - $n_e = 6x10^{11}$ cm^{-3} (O VII)

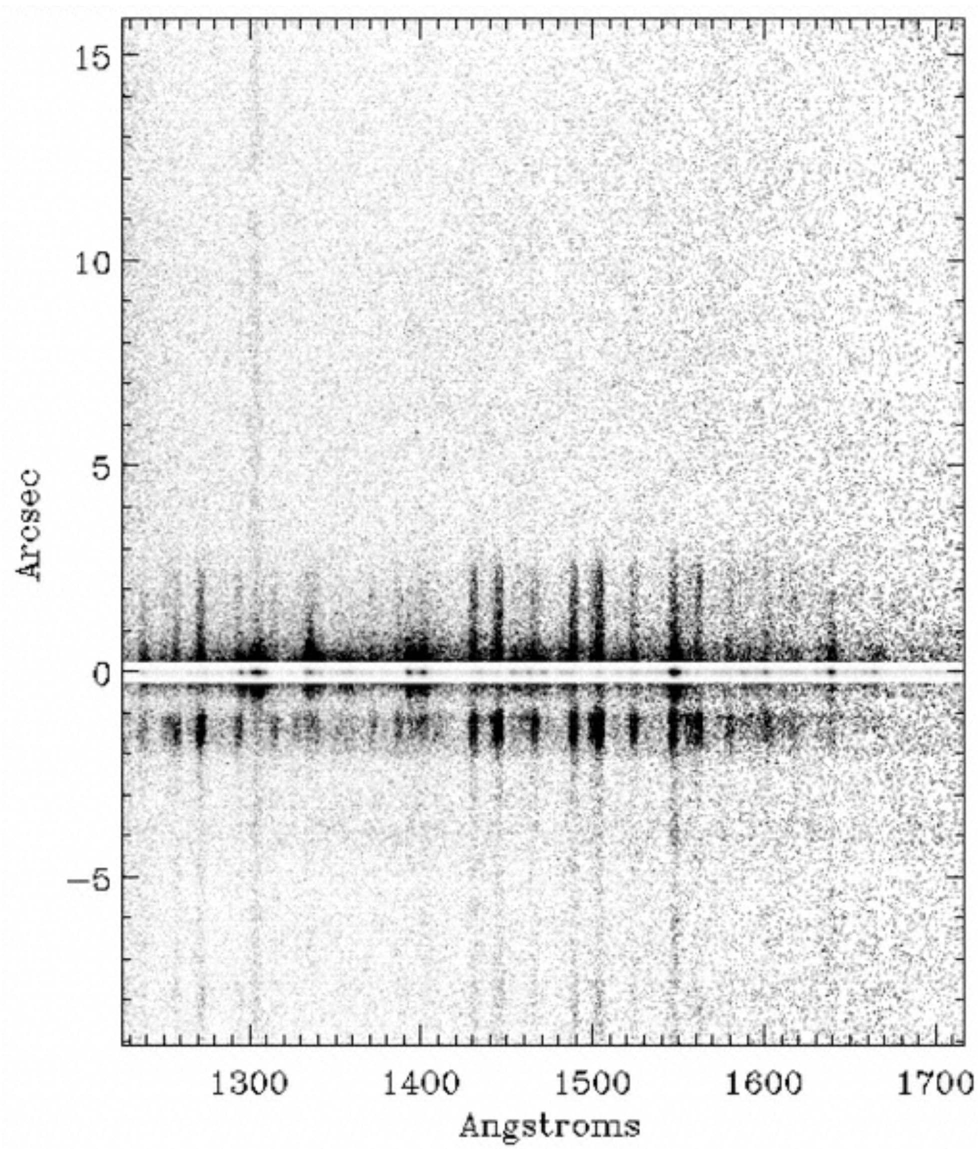
Brickhouse et al. 2010, ApJ, 710, 1835

Accretion Model



Brickhouse et al. 2010, ApJ, 710, 1835

Molecular Hydrogen



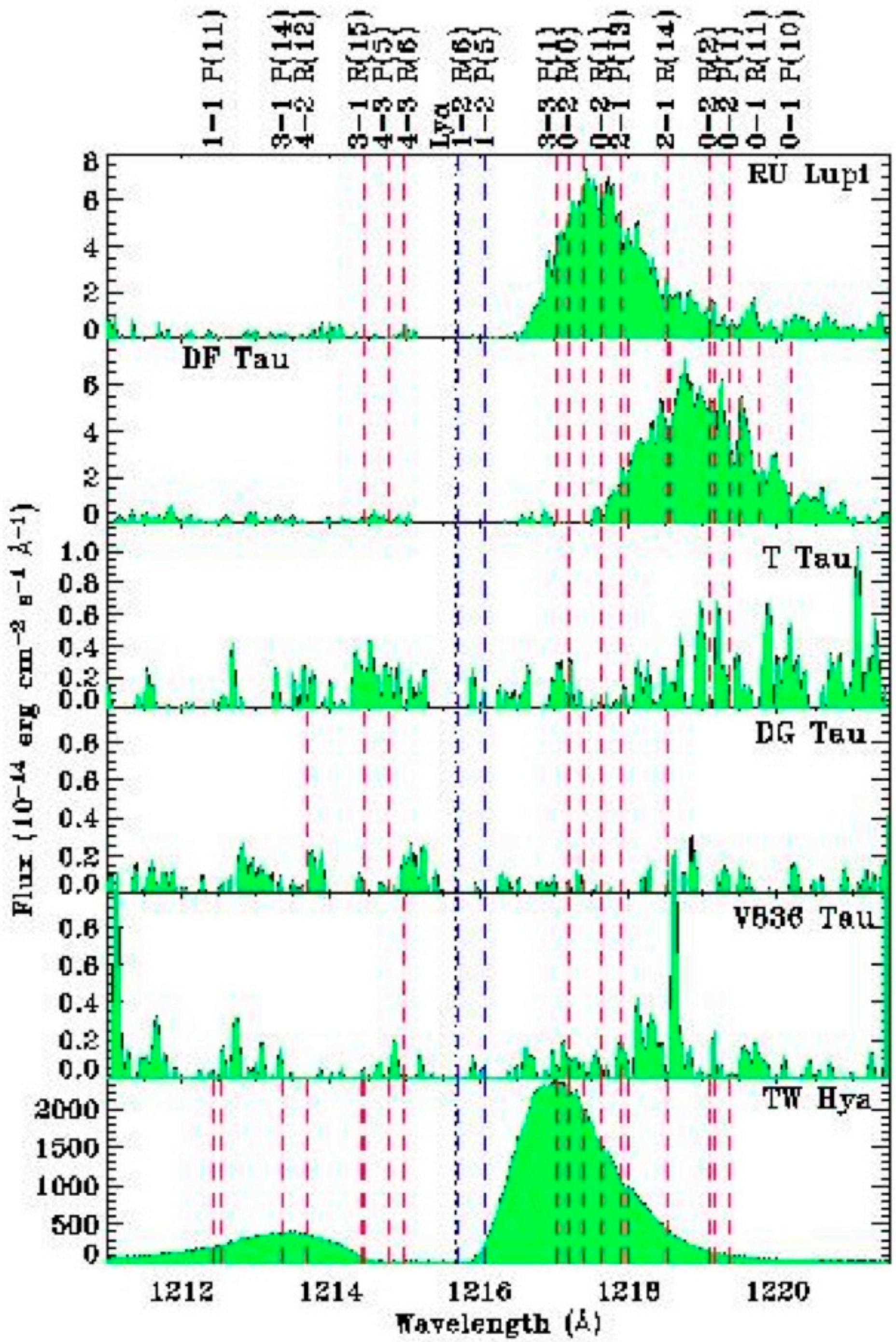
STIS long slit spectrum of T Tau, PA=345°

On-source flux reduced 100x

T Tau S is at -0.73 arcsec

Molecular Hydrogen

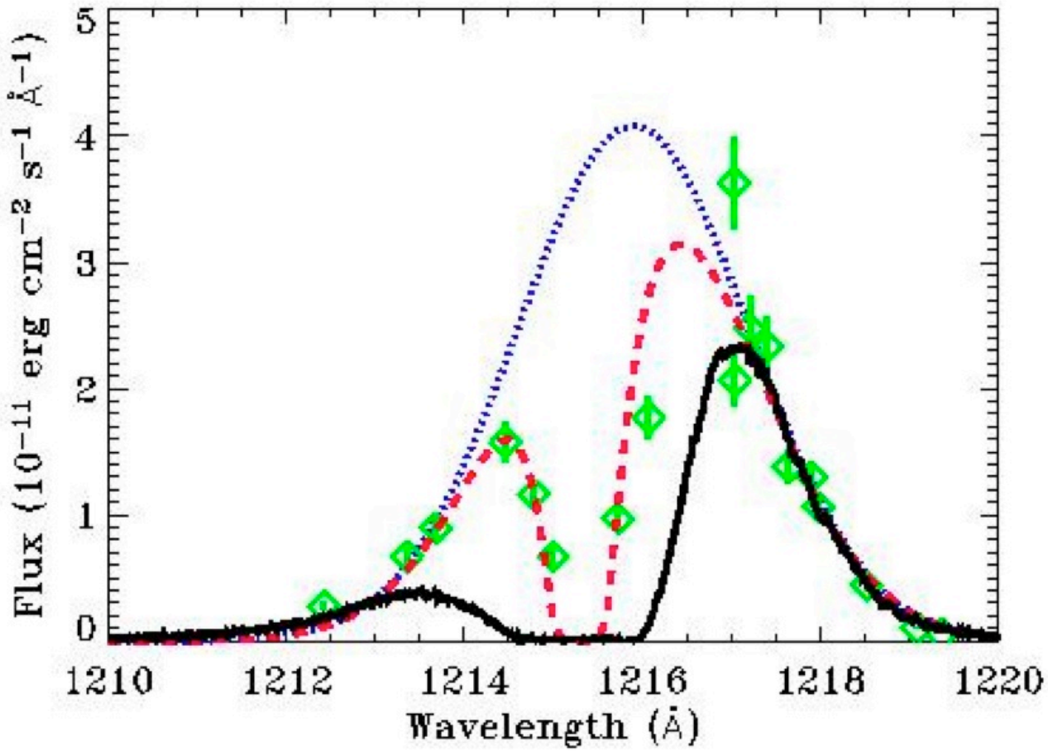
- **Off Source**:
  - 1-2 P(5), 1-2 R(6)
  - Pumped at 12 and 96 km/s redward of the center of Ly-α
  - In-situ fluorescence by narrow Ly-α in shock
  - Progressions: 1-n P(5),R(3); 1-n P(8),R(6)
- **On Source**:
  - At least 7 progressions seen
  - Pumped 1216.0 - 1219.2 Å
  - Levels lie 1-2 eV above ground ⇒ T~2000 - 3000K



Dashed lines: observed pumps

Herczeg et al. 2006, ApJS, 165, 256

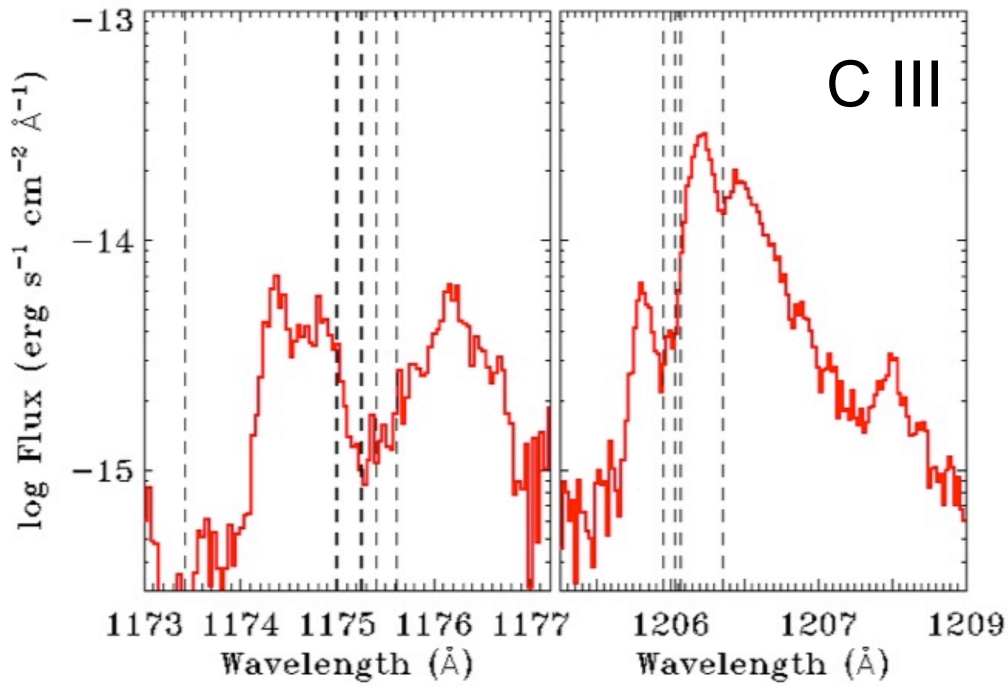
Lyman-α Reconstruction



TW Hya

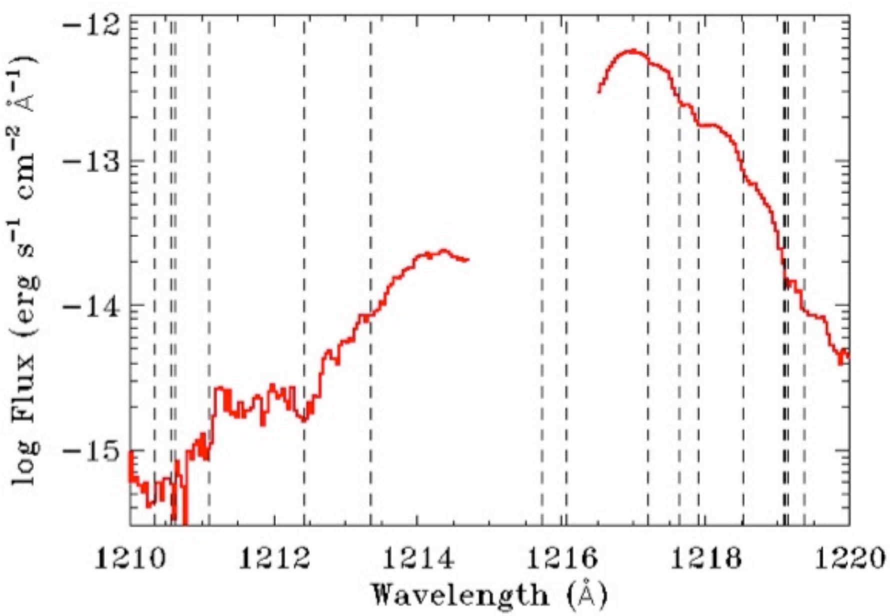
◇: I_λ prediction

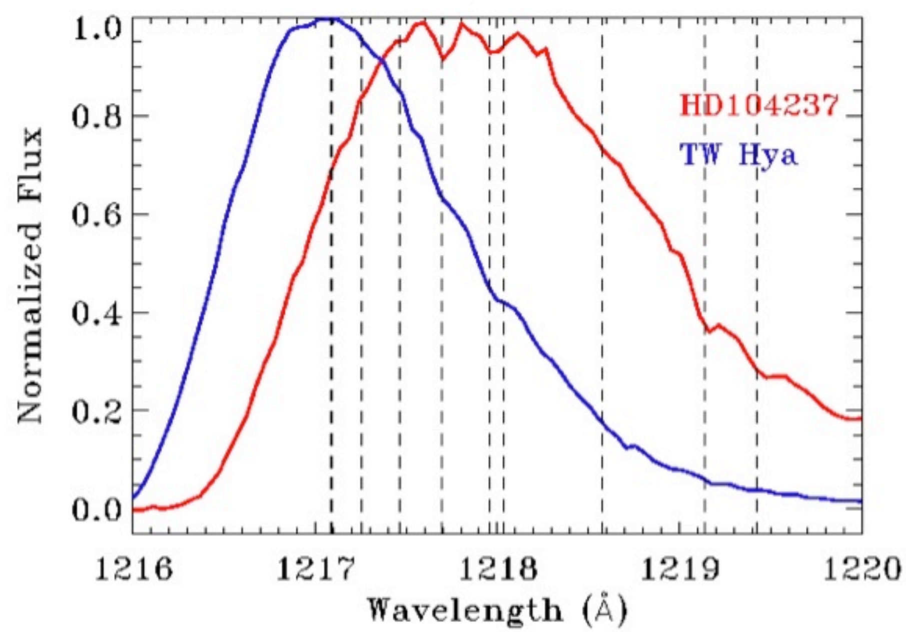
- Intrinsic Lyα flux=1.2 x 10^{-10} erg cm^{-2} s^{-1}
- Absorption of log N(H I)=18.7
  - Intrinsic self-reversal
  - Atomic layer in disk surface above layer of H_2
- H_2 emission produced interior to wind
- No evidence for depopulation of lower levels: LTE



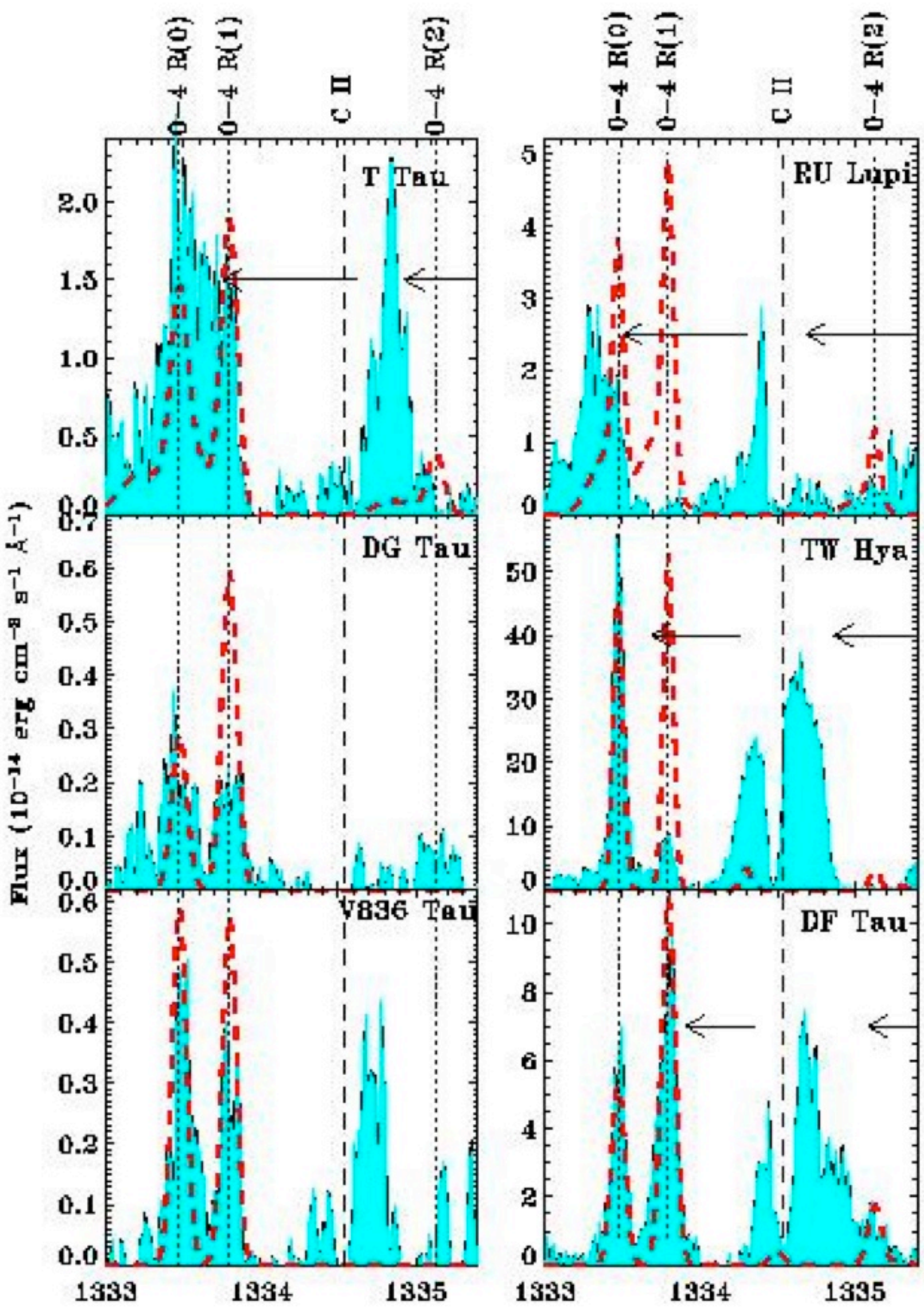
Pump Transitions

RECX 15 (left)
HD 104237 (below)
TW Hya (below)





On-source H_2 Location

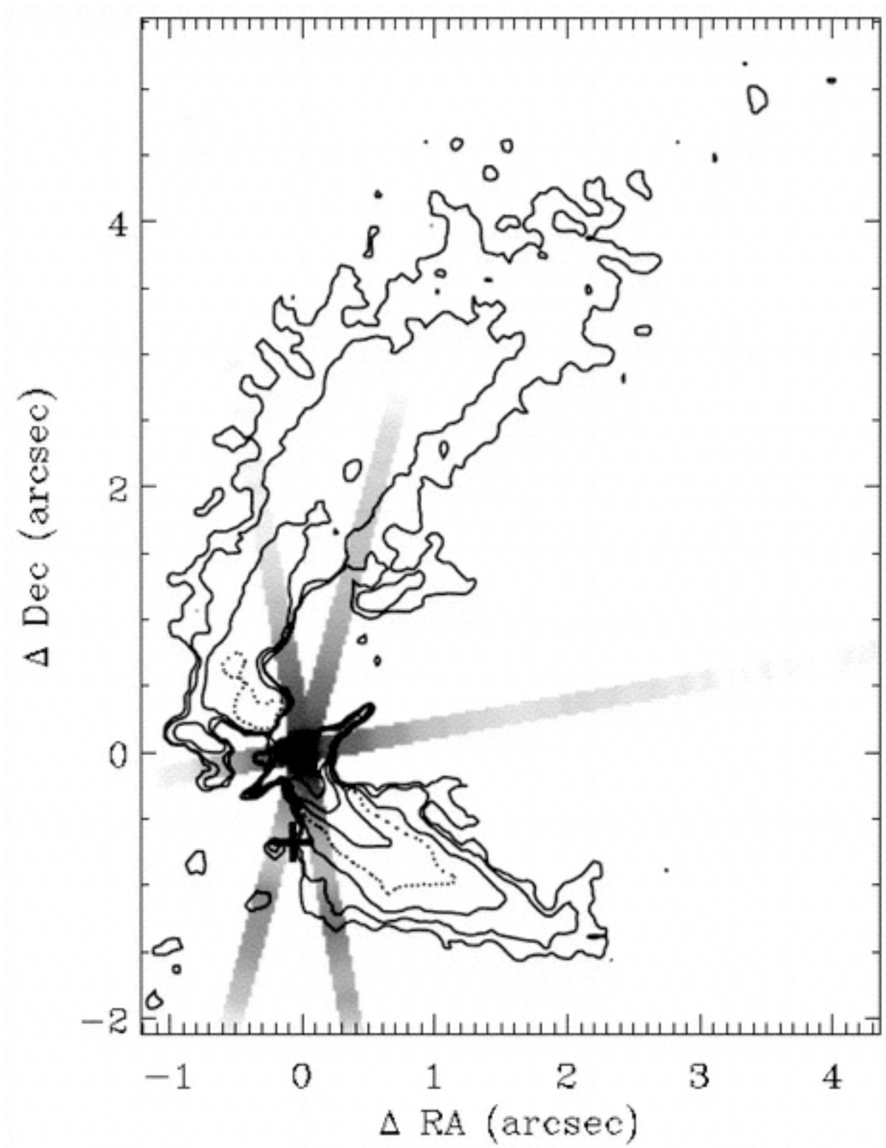


Close to star:
absorbed by wind

Dashed lines: predicted line strength

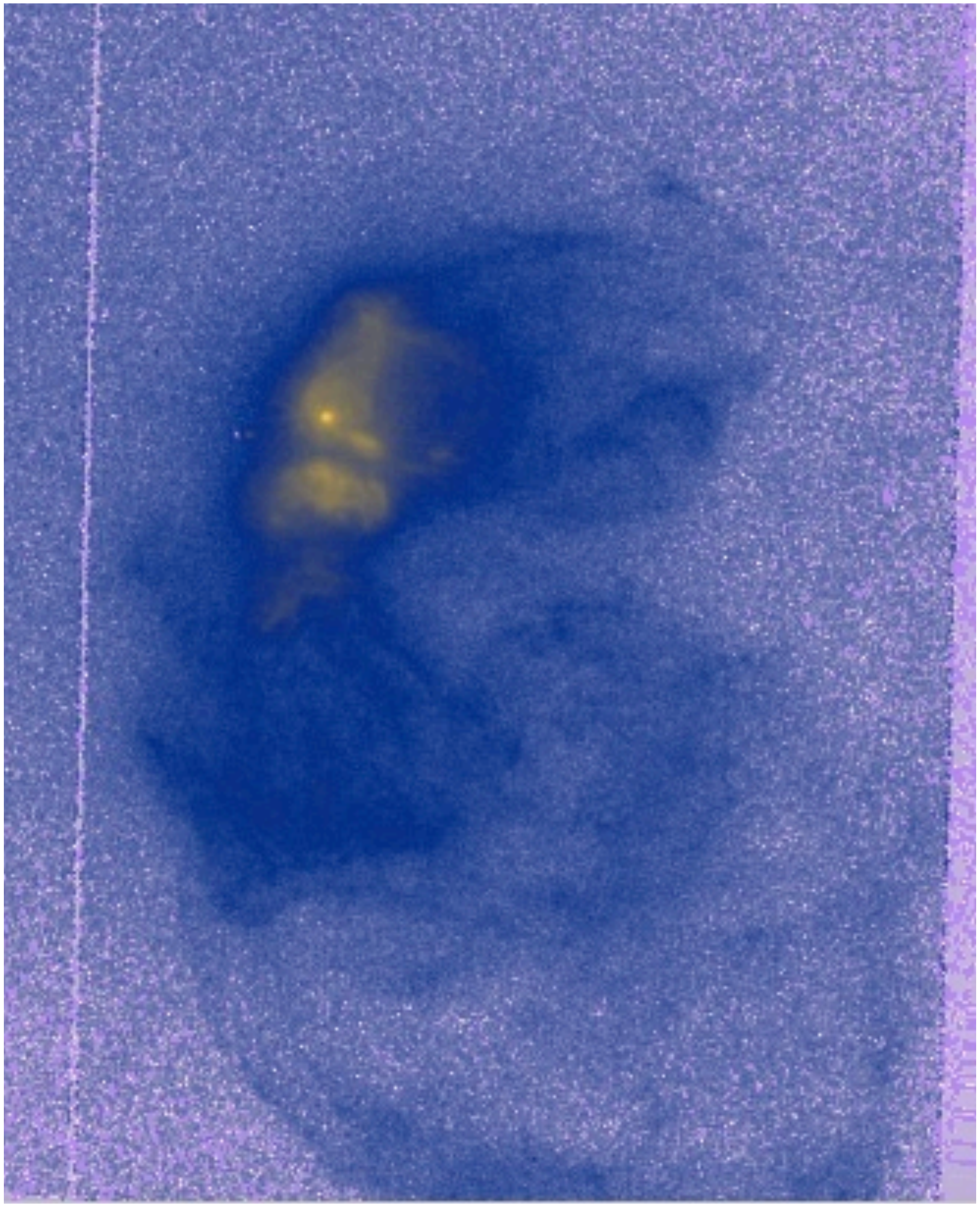
Line widths suggestive of Keplerian rotation, and origin in disk

Molecular Hydrogen



3 STIS long slit spectra, superposed on the optical reflected light contours

T Tau in H_2

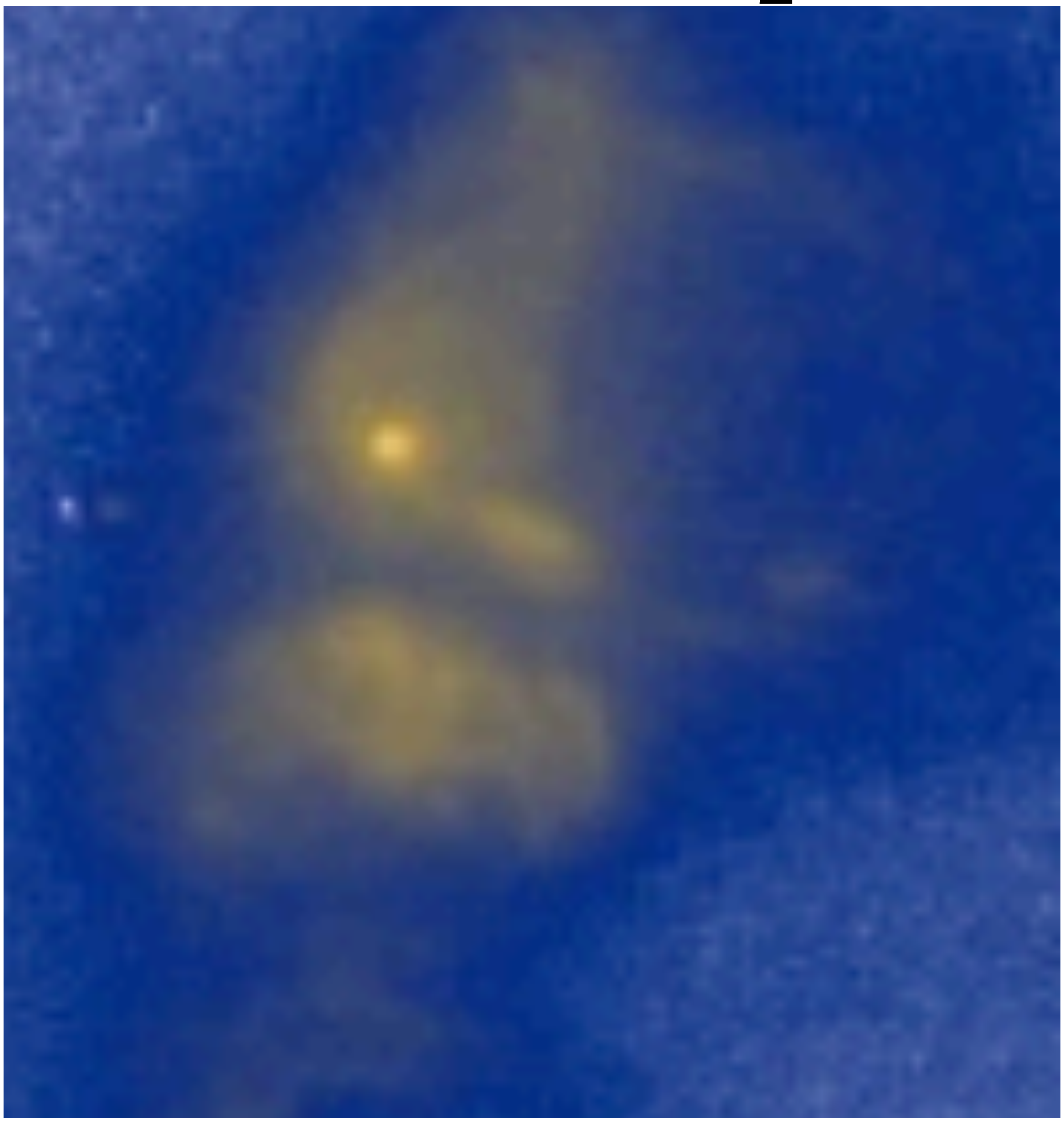


Difference image
ACS SB channel
F140LP - F165LP
Isolates complex of
H_2 Lyman band
lines.

Point is T Tau N.
Dark lane is the
edge-on disk of
T Tau S.
Outflow is from
T Tau S

Ref: Grady et al.

T Tau in H_2



Class 3 Stars

- From a spectroscopic viewpoint, they are fairly normal
- Little or no accretion
- No H_2 seen
- Narrow chromospheric lines
- $F_X/F_{bol} \sim 10^{-3}$

Comparison of 2 wTTS

- **RECX-1** (red dashed line) shows no evidence of accretion.

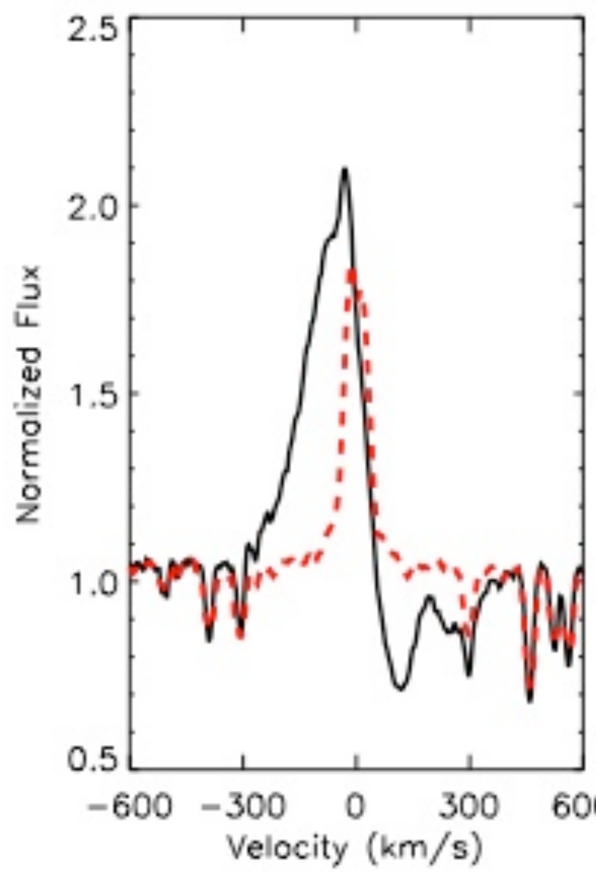
  $W_\lambda(H\alpha)$=1.3Å

- **RECX-11** (solid black line) is a wTTS.

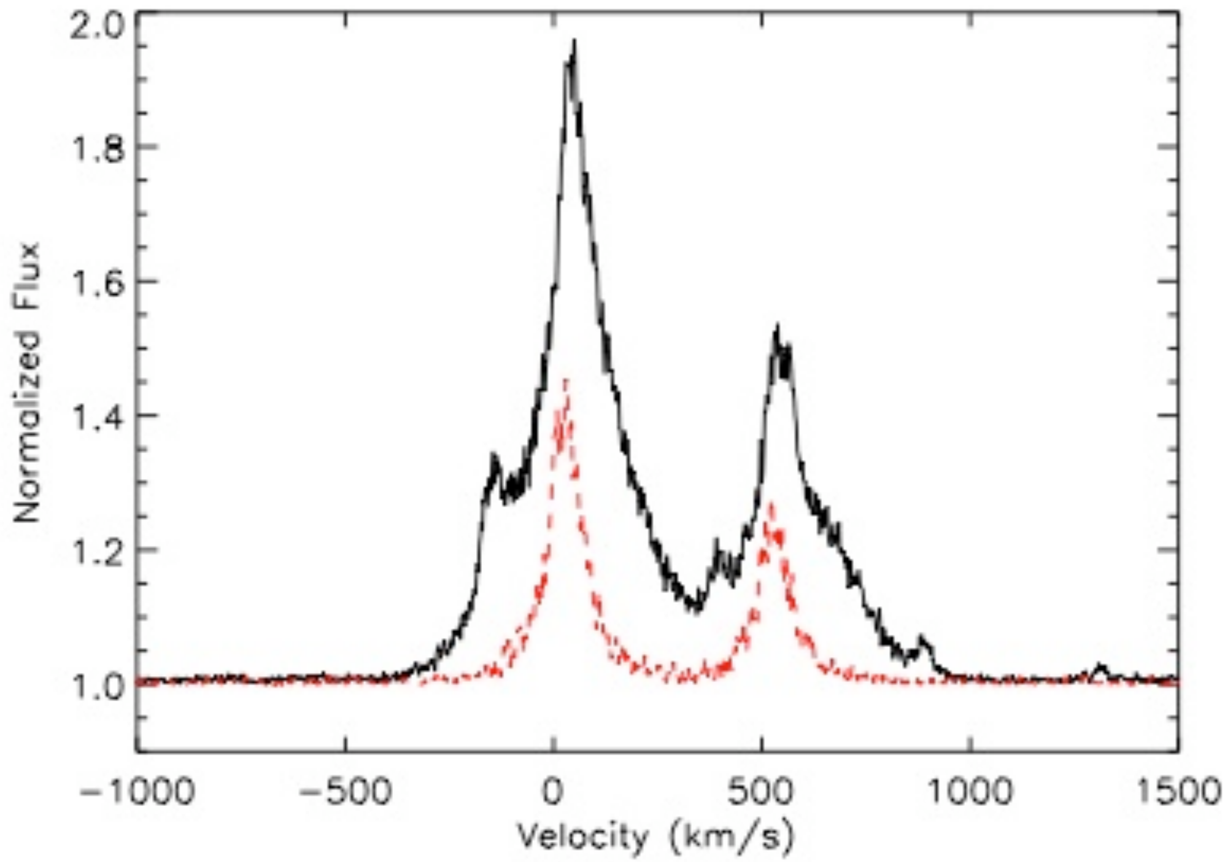
  $W_\lambda(H\alpha)$=4Å.

  Note the IPC absorption

- Both stars are K5-6 members of the η Cha SFR



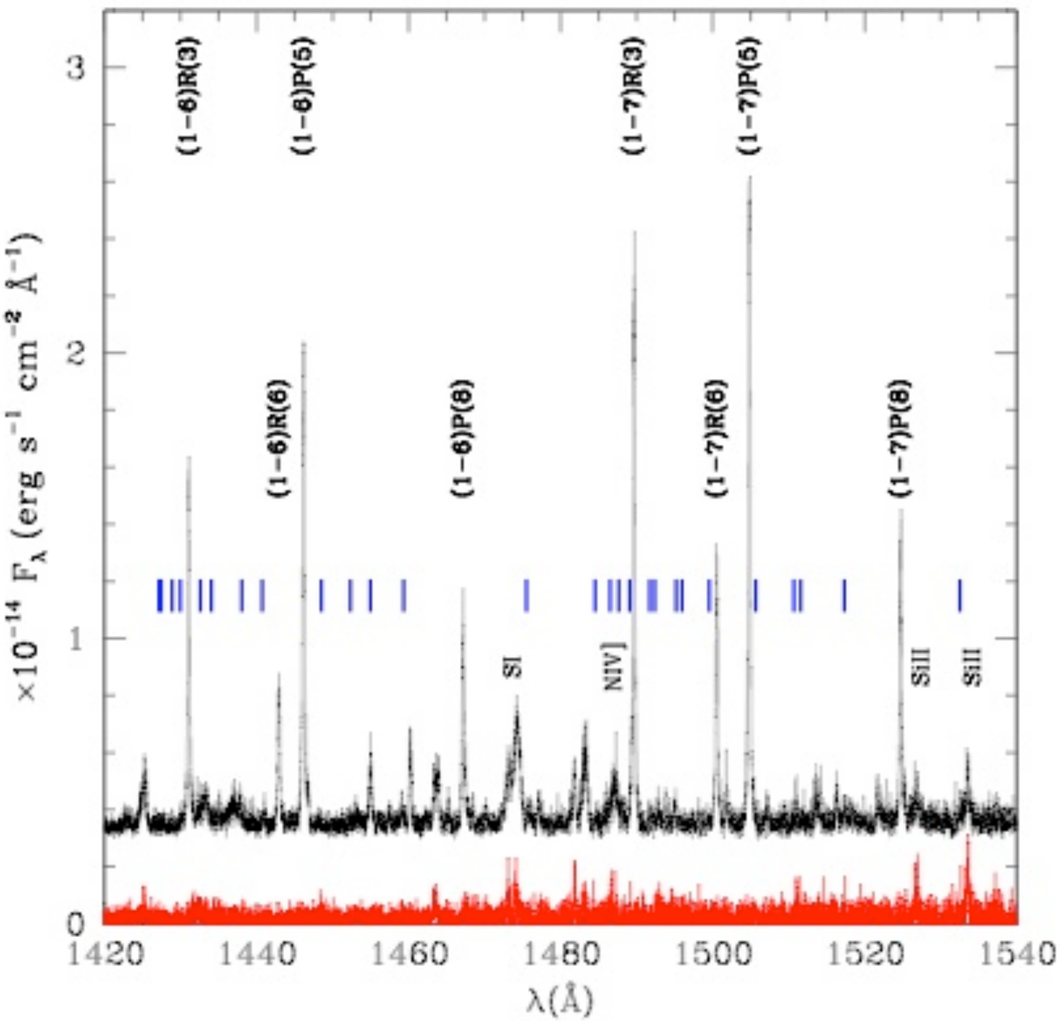
Comparison of 2 wTTS



C IV 1540.

RECX-11 lines are broadened in the accretion shock.

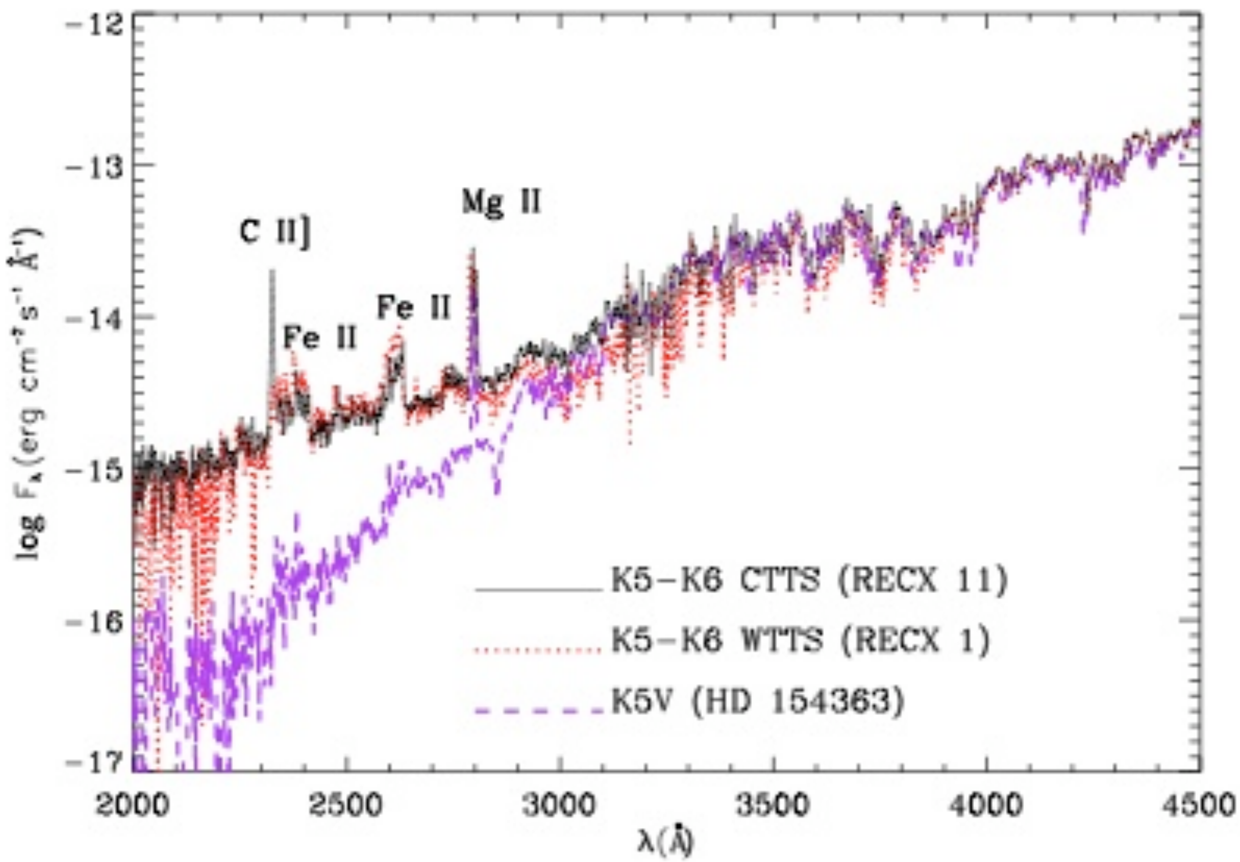
Comparison of 2 wTTS



H_2.

Not seen in RECX-1. Circumstellar region clear of gas.

Comparison of 2 wTTS

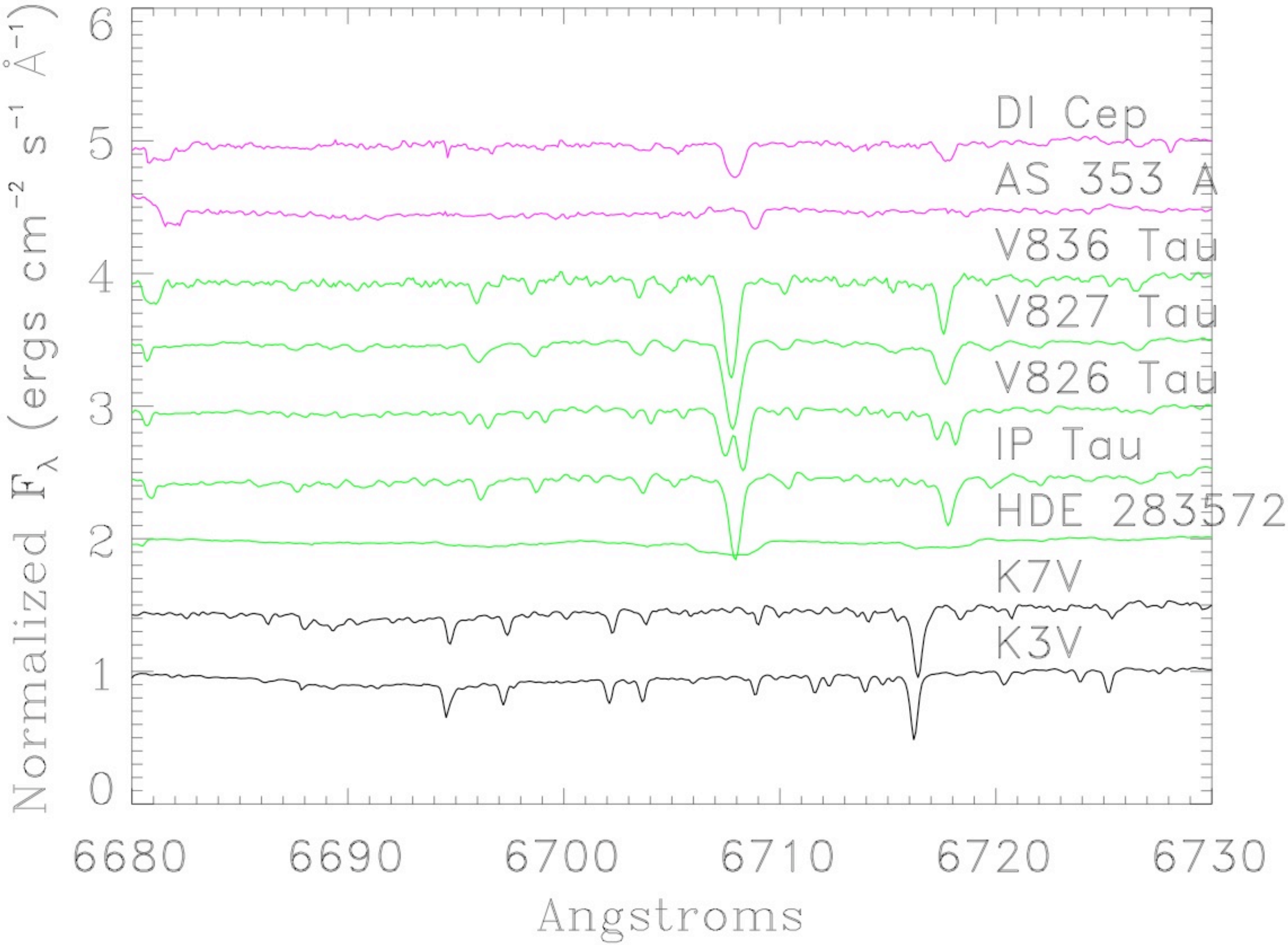


NUV Continuum.

Caution: this is not a reliable indicator of accretion.

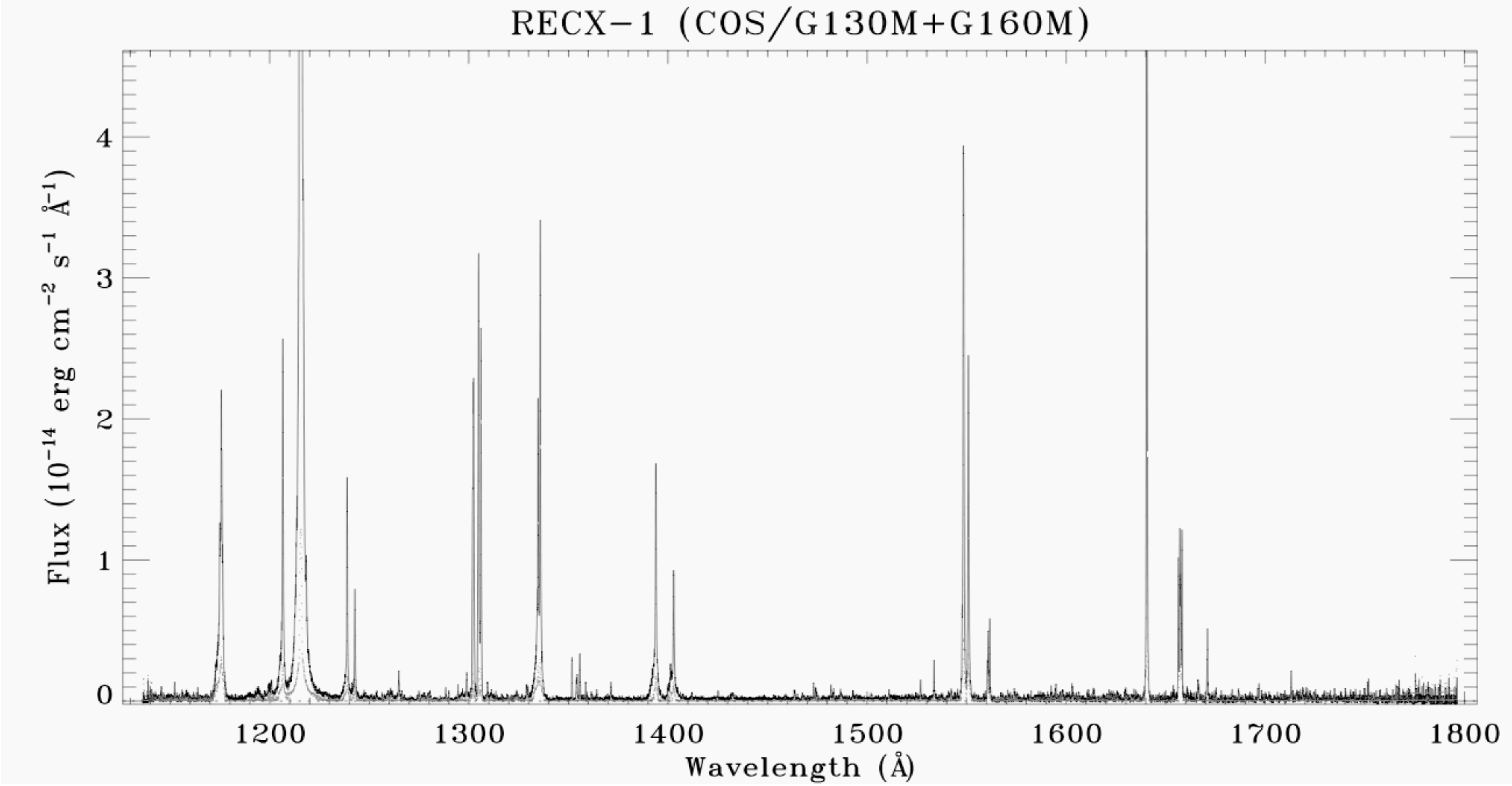
Lithium

- The main photospheric “anomaly” is the strong Li I absorption line at 6707 Å
- The line strength is consistent with $\log(N_{Li}) \sim 3.4$
- This line persists even in strongly veiled systems
- Li is an age indicator because it fuses at temperatures that exist at the base of the convective zone.

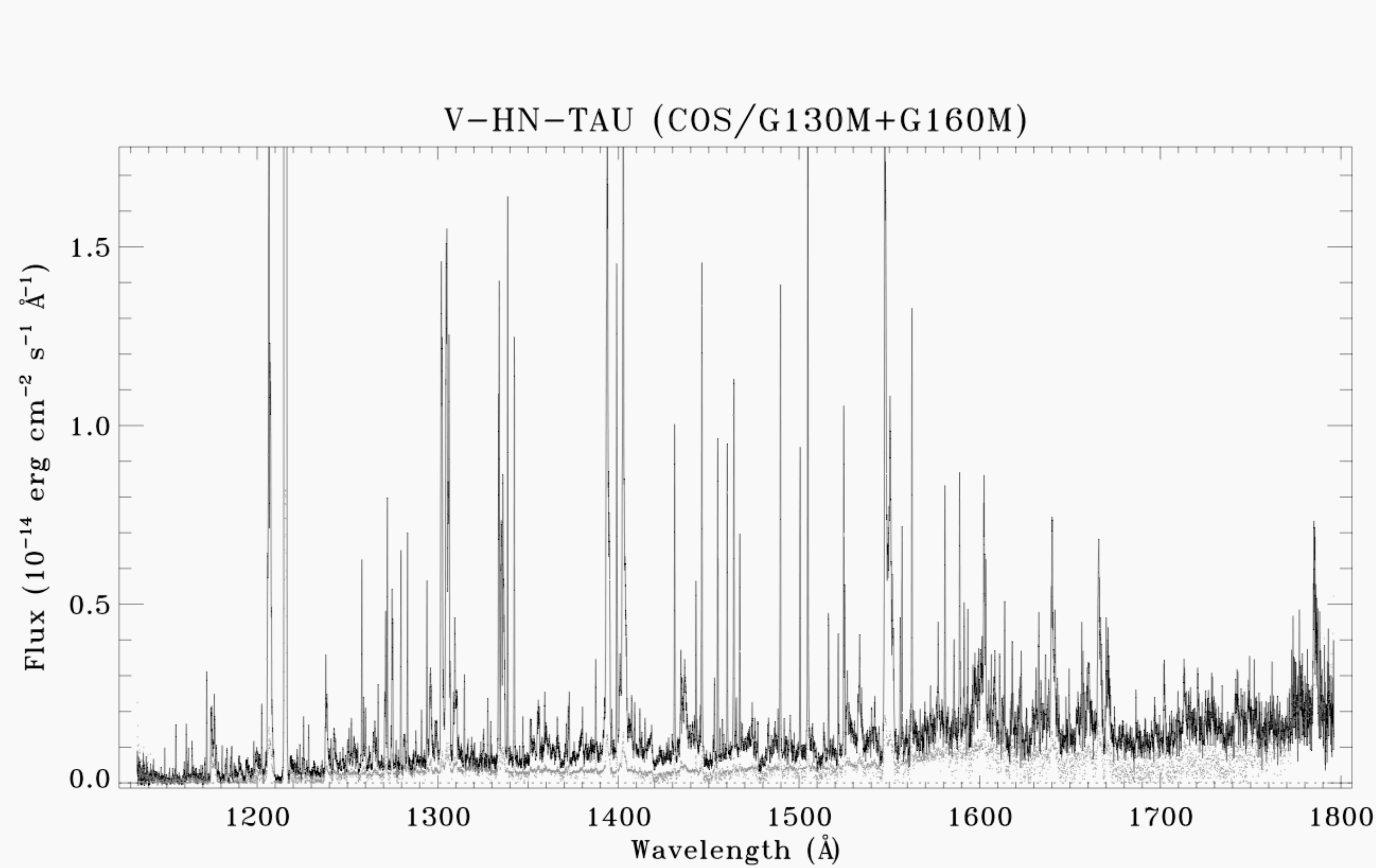


Normalized F_λ (ergs cm^{-2} s^{-1} Å^{-1})
DI Cep
AS 353 A
V836 Tau
V827 Tau
V826 Tau
IP Tau
HDE 283572
K7V
K3V
0
1
2
3
4
5
6
6680
6690
6700
6710
6720
6730
Angstroms

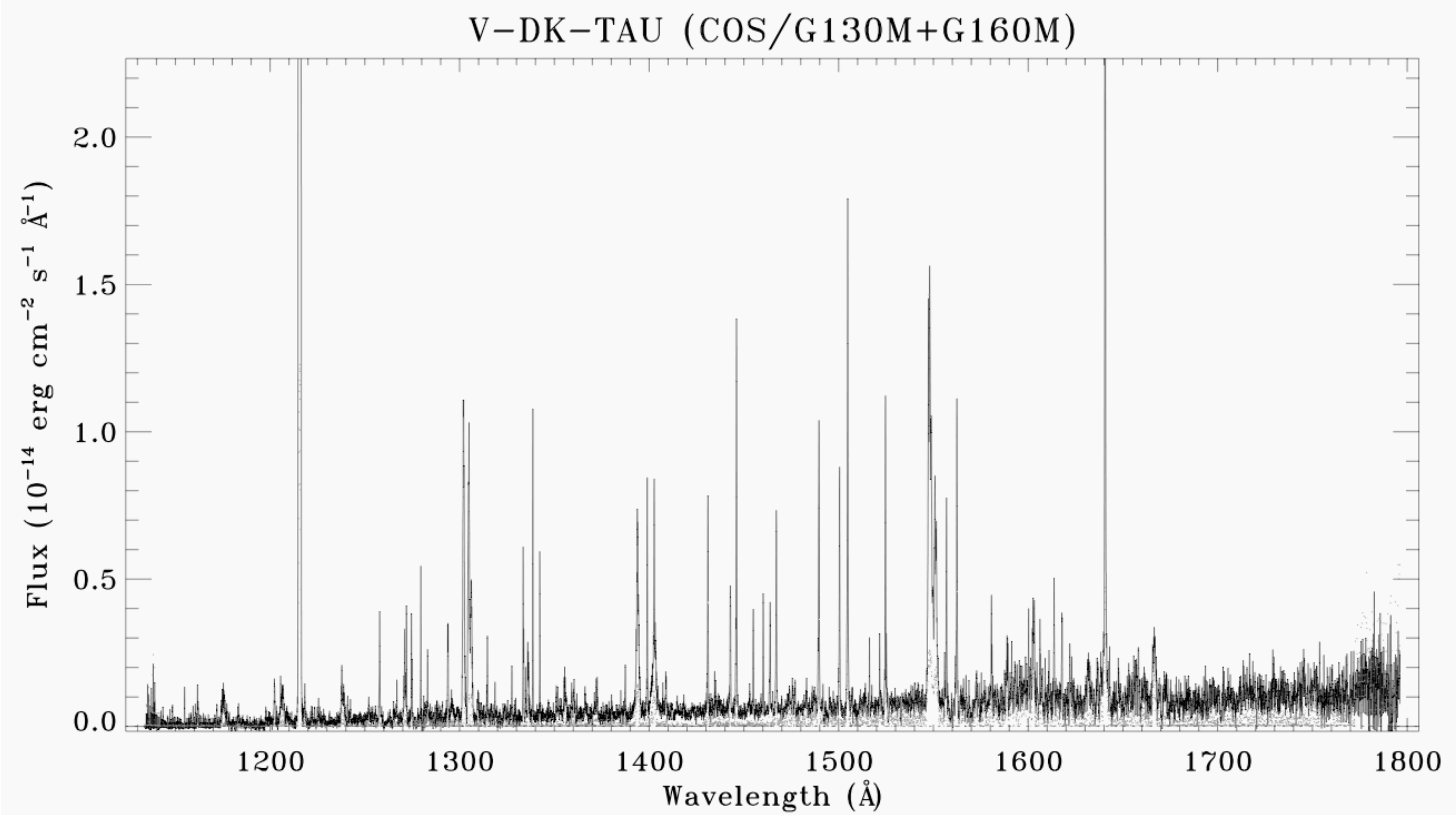
COS spectra



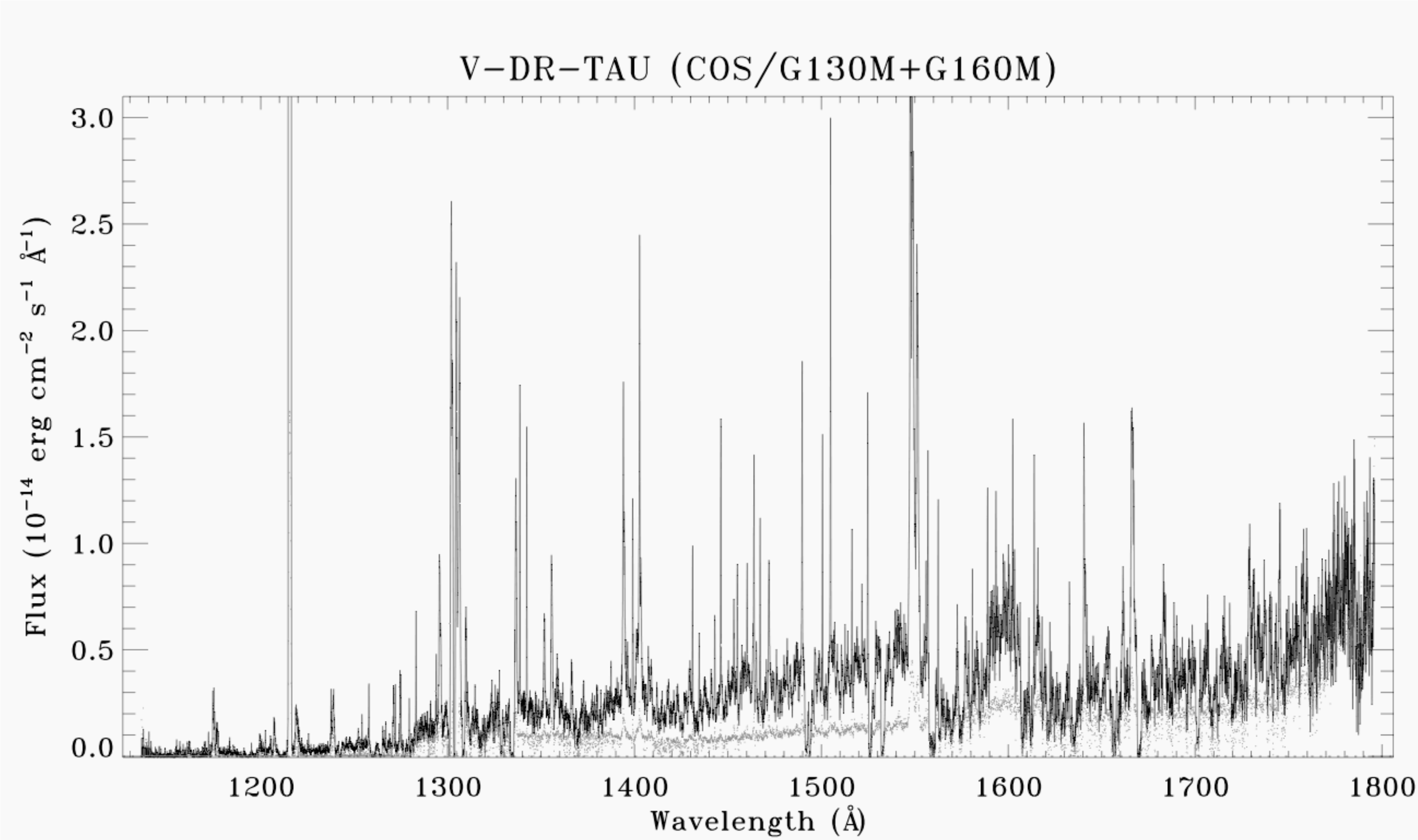
Naked T Tauri star: narrow chromospheric and TR lines



Classical T Tauri star: narrow H_2 and broad TR lines
m_{dot}=-8.9

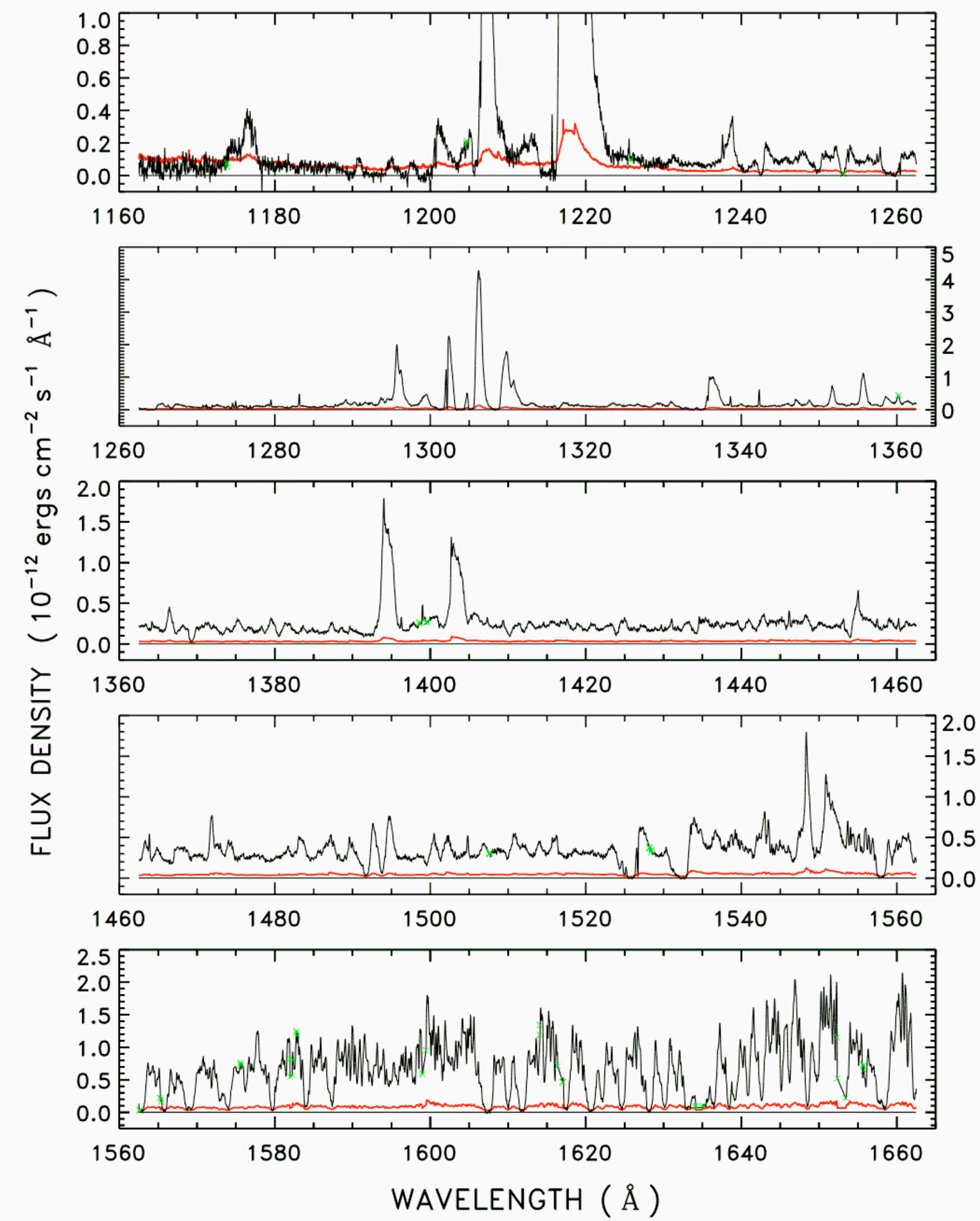


Classical T Tauri star: narrow H_2 and broad TR lines.
m_{dot}=-7.4



Classical T Tauri star: narrow H_2 and broad TR lines

m_{dot}=-6.5



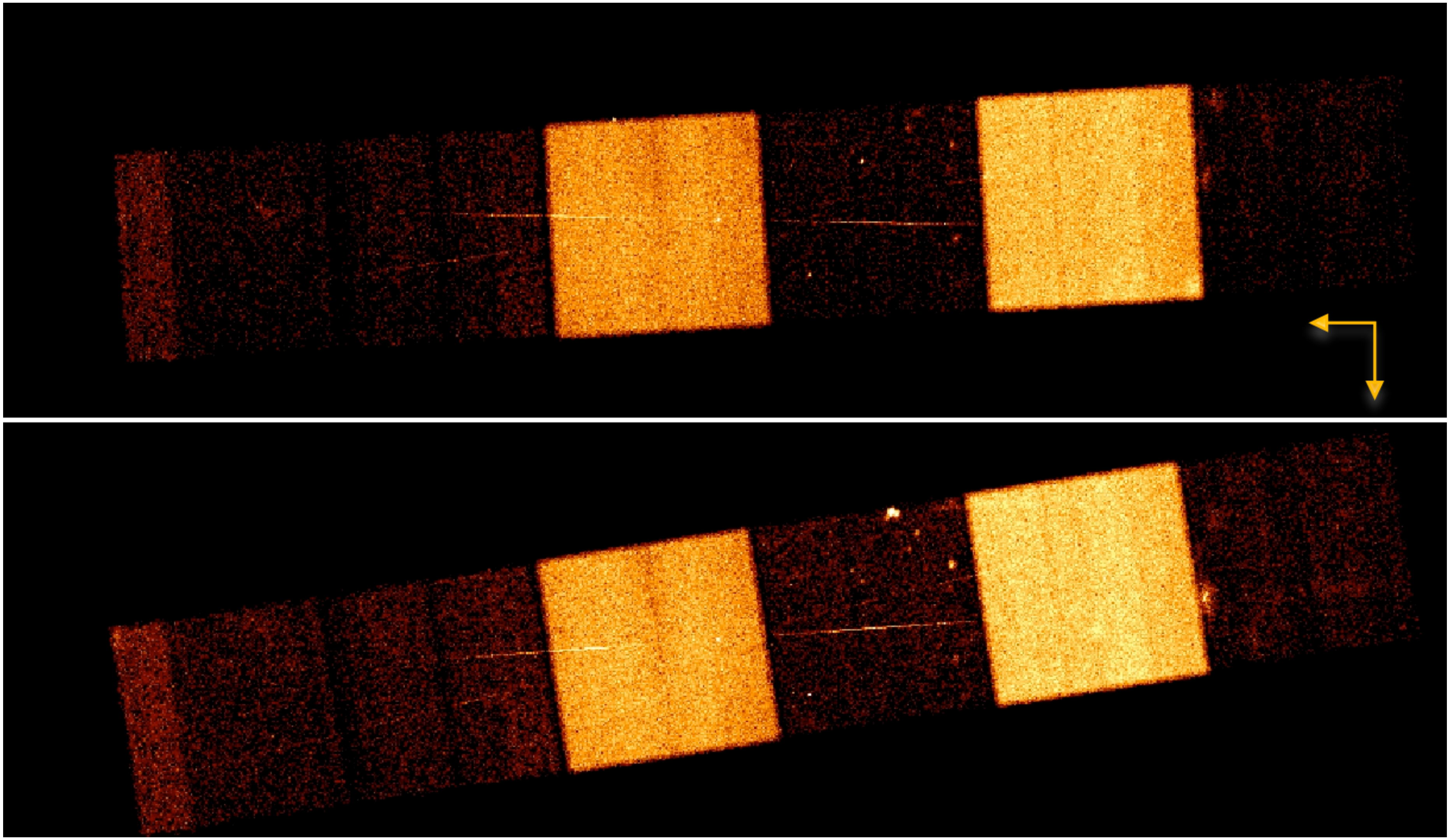
Herbig Ae star:

- Photospheric continuum,
- Wind absorption
- Accretion-driven emission
- m_{dot}=-7.4

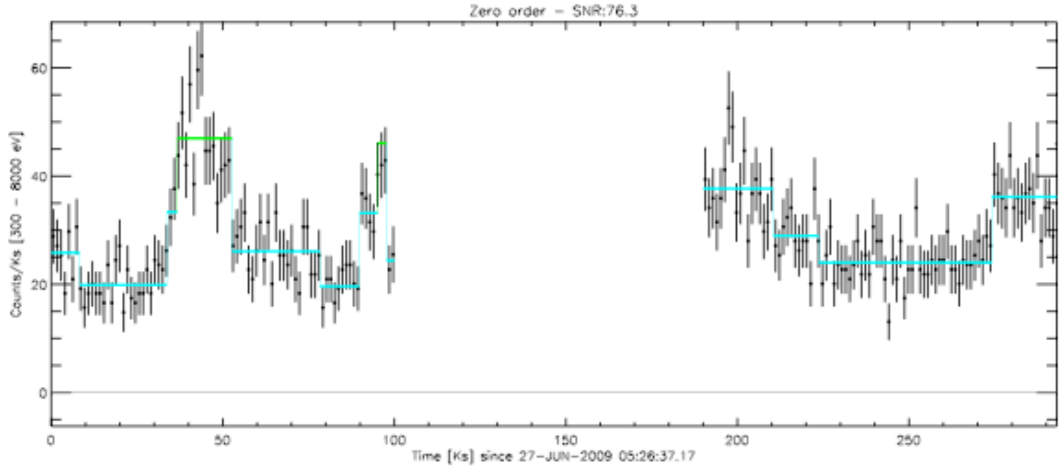

The End

The HETG data

2 x 100 ksec

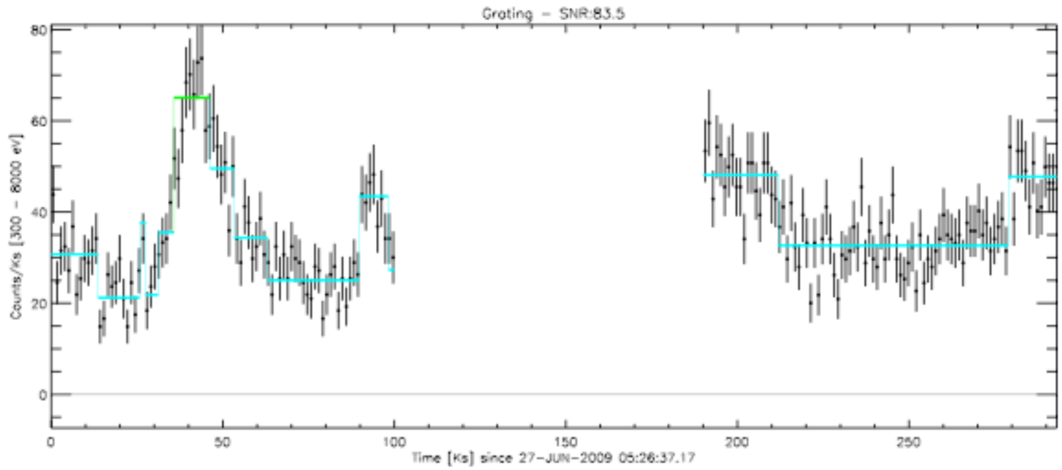


Lightcurve (II)



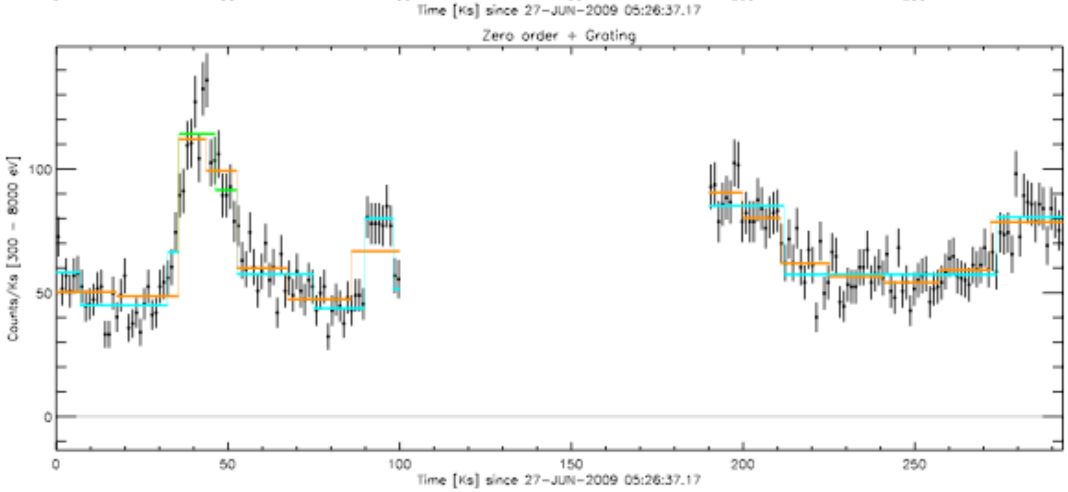
Zero Order

•Net counts: 5864
•Background: 0.4%



First Order

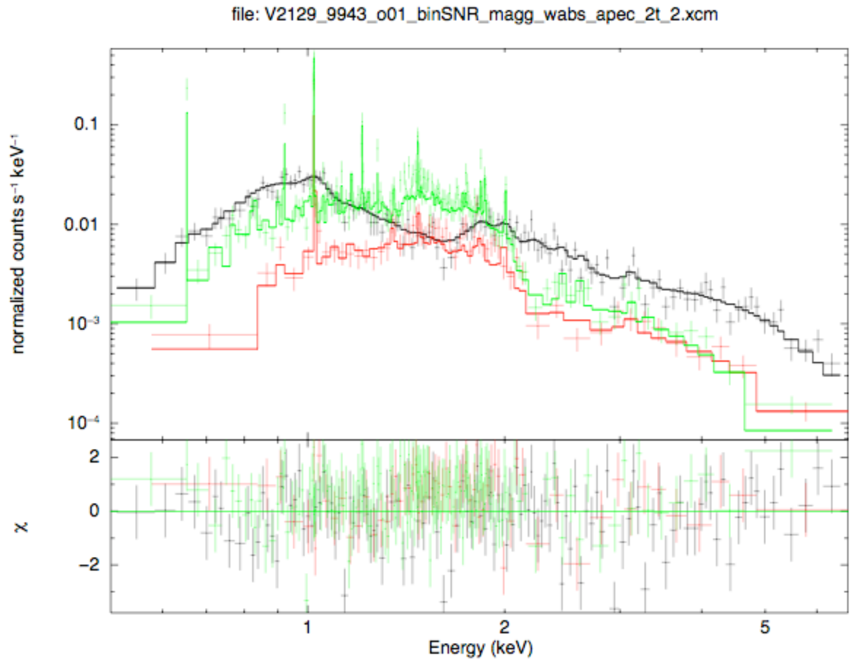
•Net counts: 7354
•Background: 2.7%

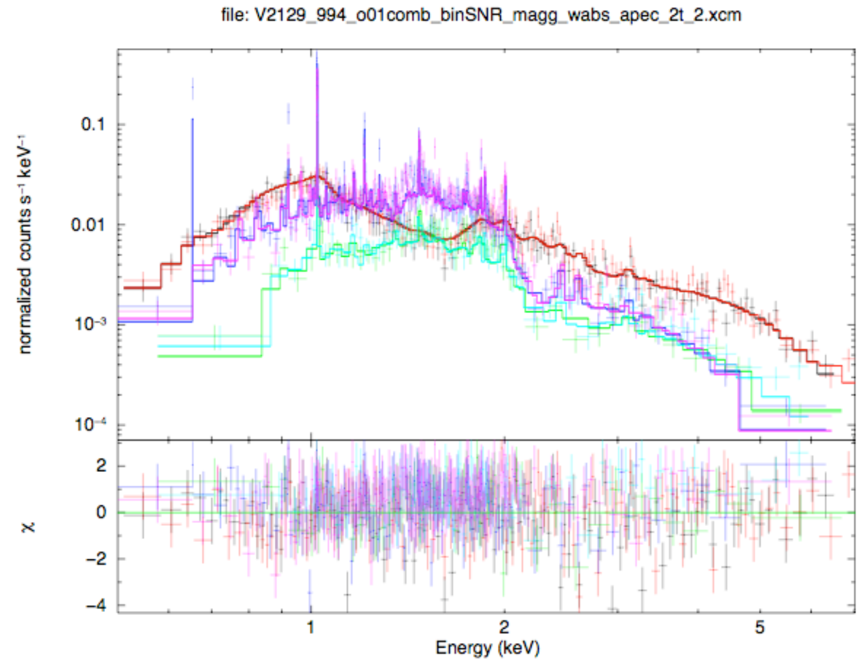


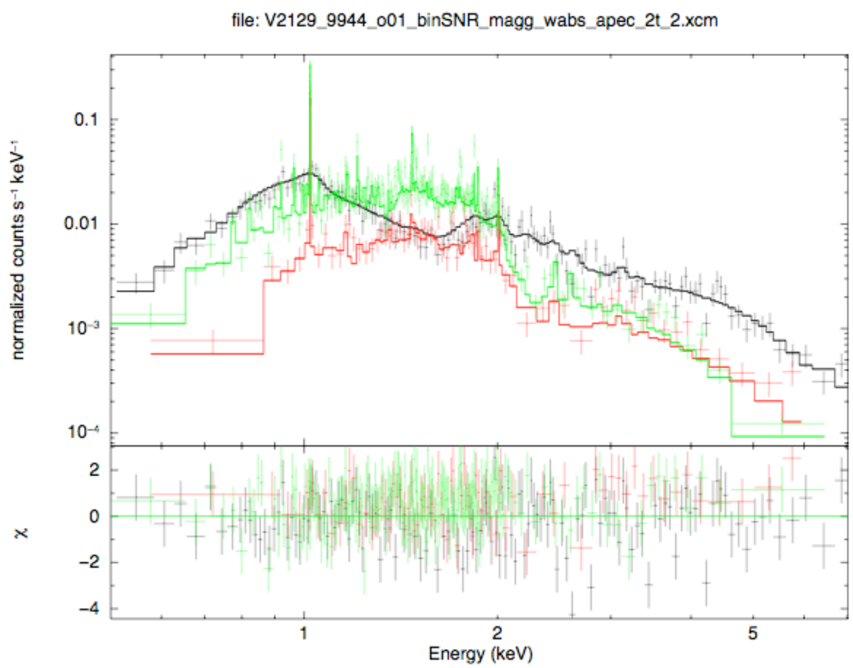
Order 0+1

•Net counts: 13217
•Background: 1.7%

Low resolution spectra

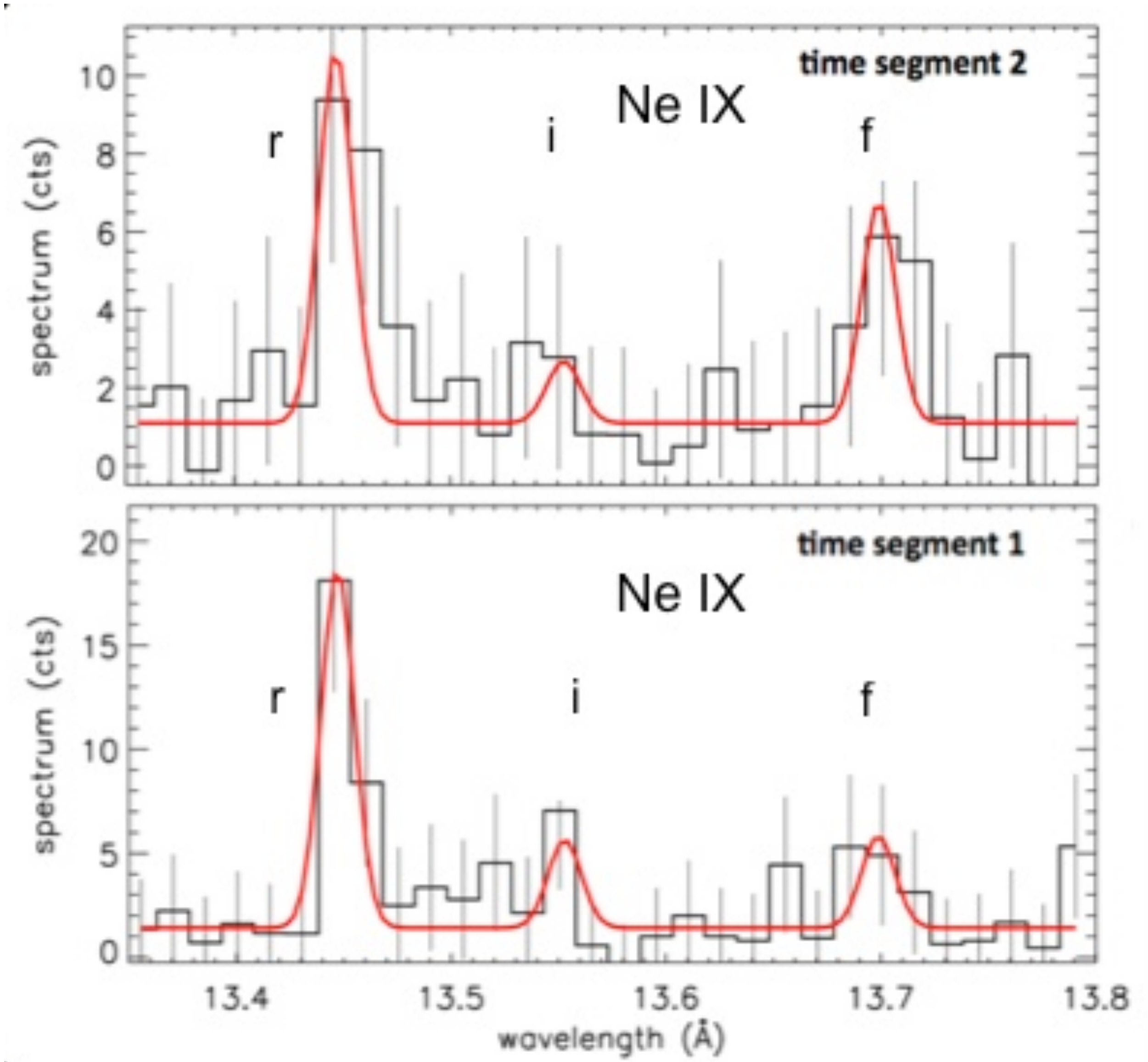


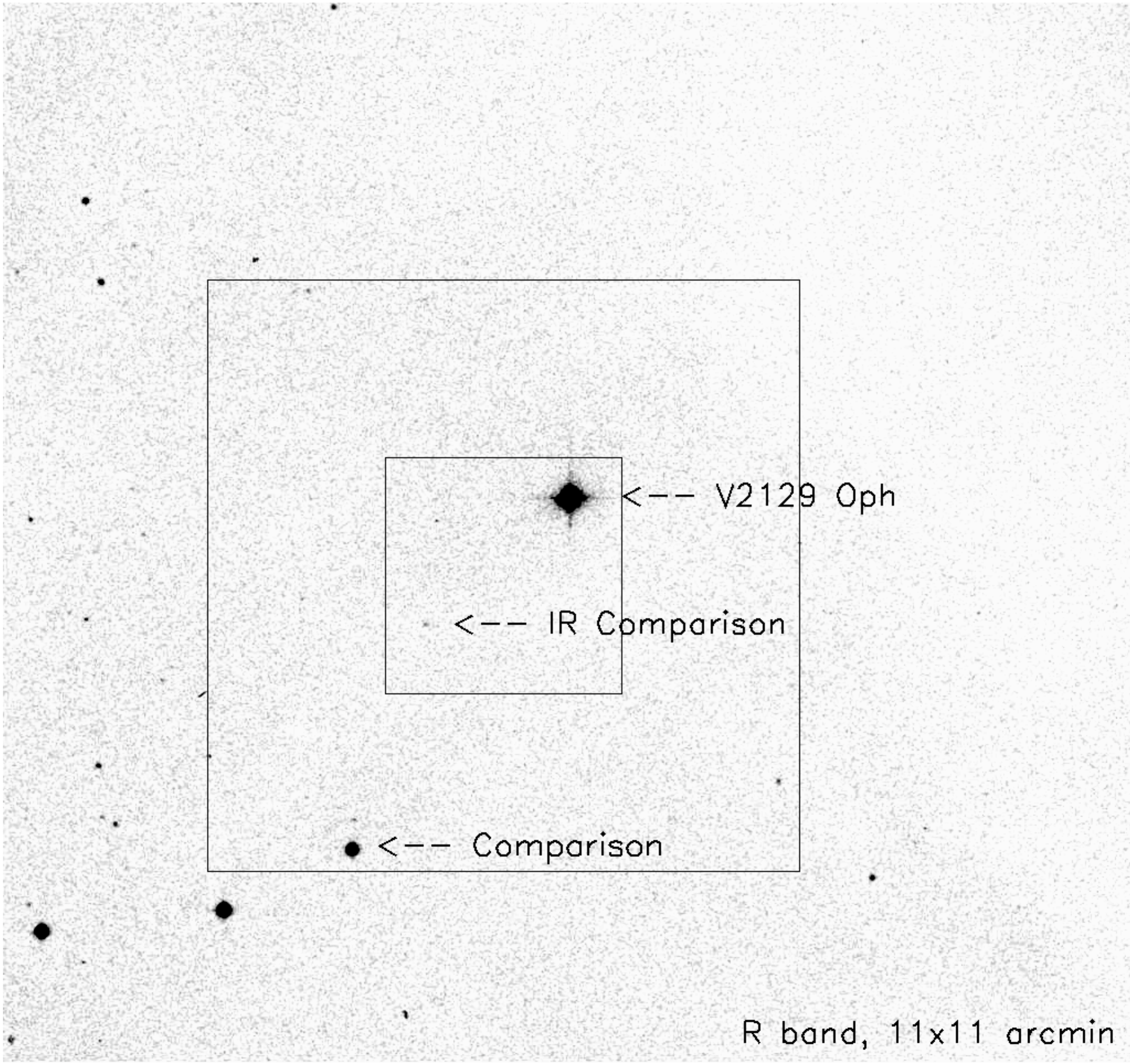




	1st seg	2nd seg	1st+2nd seg
nH [1e22 cm-2]	0.16	0.16	0.15
kT1 [keV]	0.65	0.77	0.73
norm1 [1e-14/(4π d[cm]^2) EM]	6.7e-4	5.9e-4	6.1e-4
kT2 [keV]	2.5	2.4	2.5
norm2 [1e-14/(4π d[cm]^2) EM]	1.1e-3	1.2e-3	1.1e-3
Absorbed Flux [erg/s/cm2]	1.4e-12	1.5e-12	1.5e-12
Unabsorbed Flux [erg/s/cm2]	2.2e-12	2.3e-12	2.2e-12

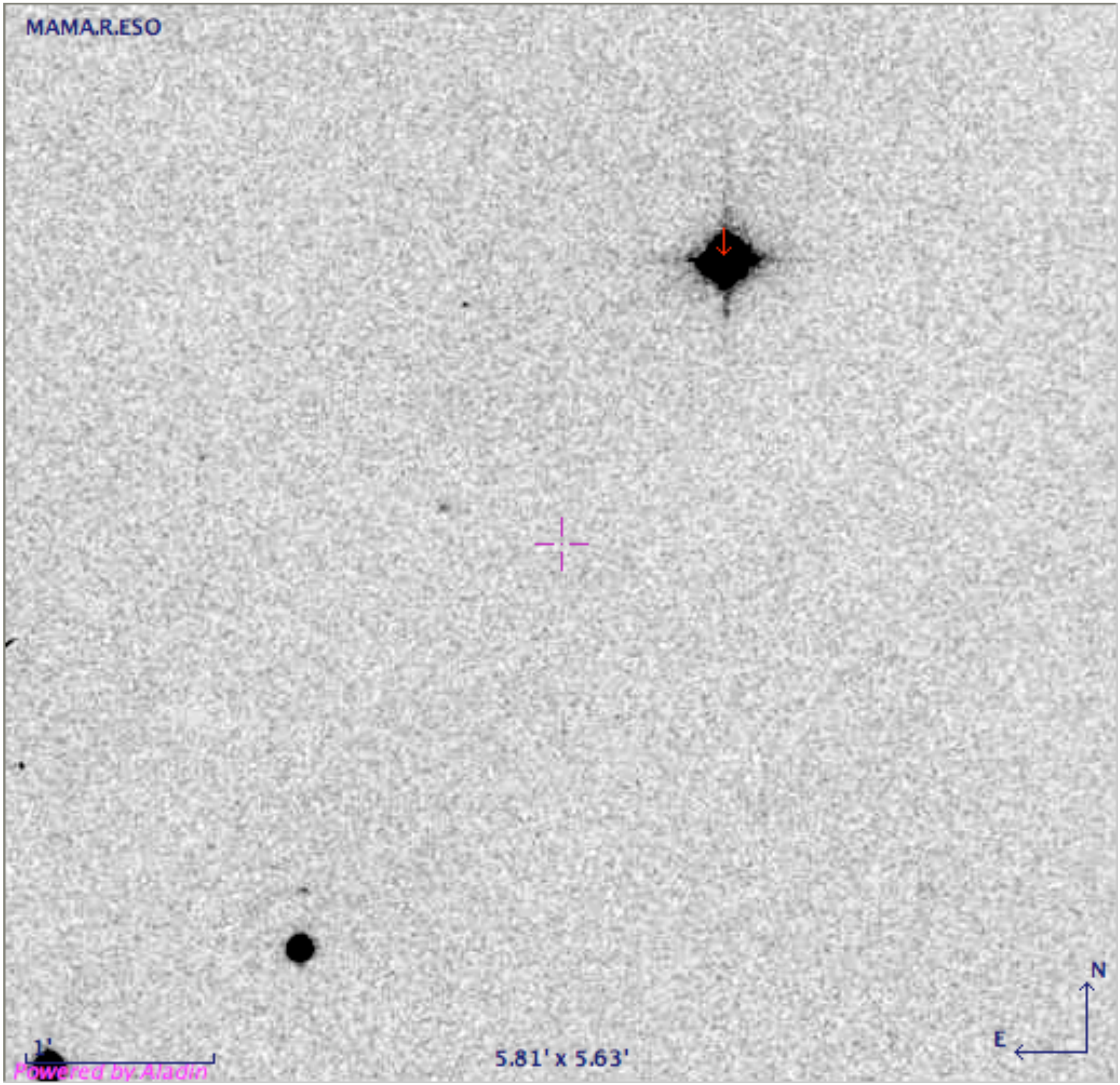
High resolution spectra





<-- V2129 Oph
<-- IR Comparison
<-- Comparison
R band, 11x11 arcmin

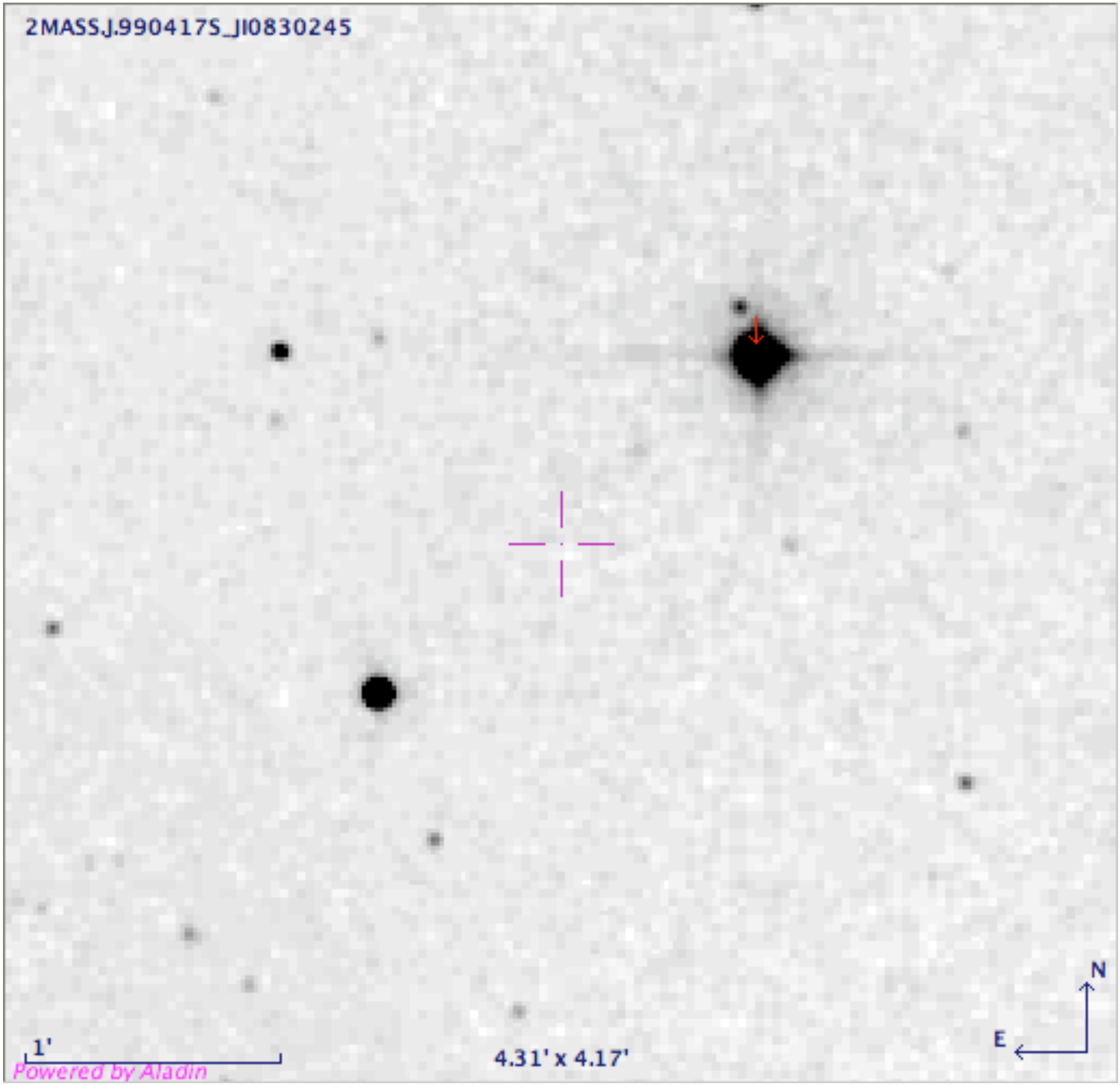
R band



Comps:
VSSG 14 *
V2059 Oph

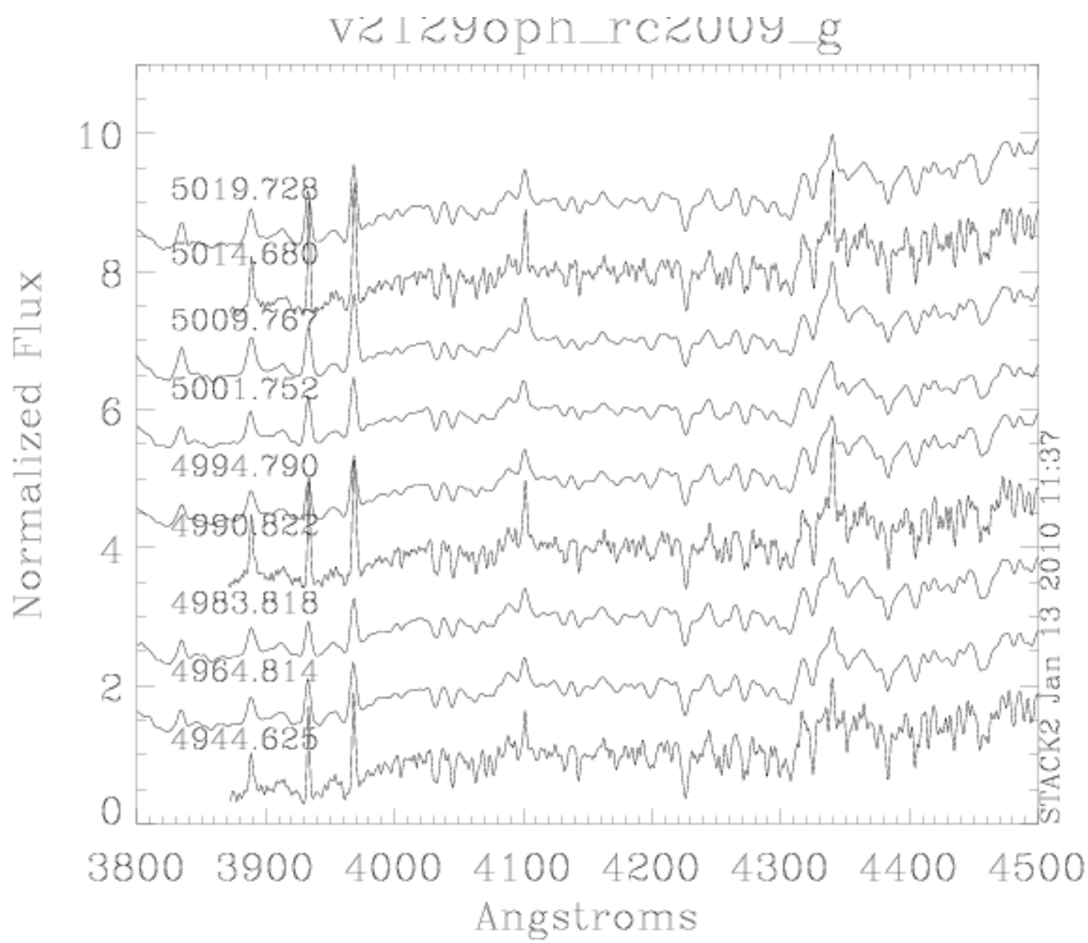
Both likely variable; used VSSG 14

J band

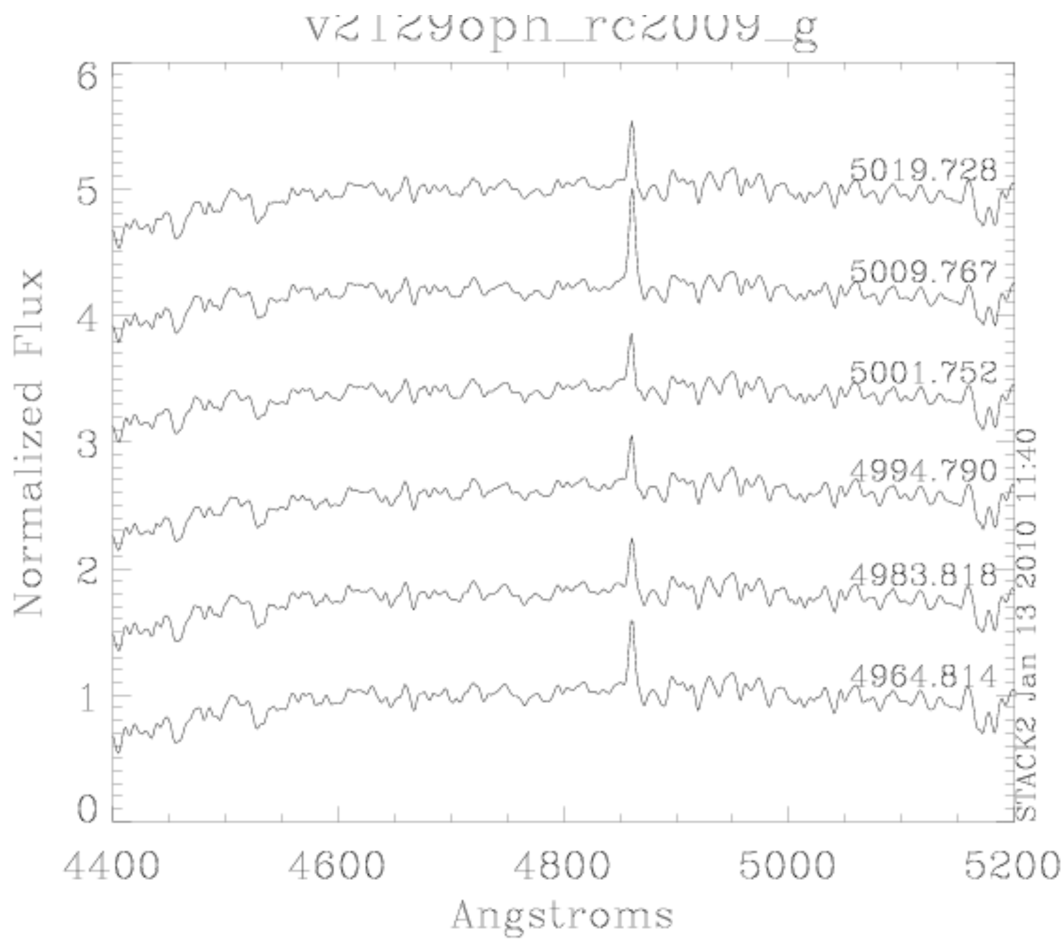


Comp:
VSSG 13
Background
K5III

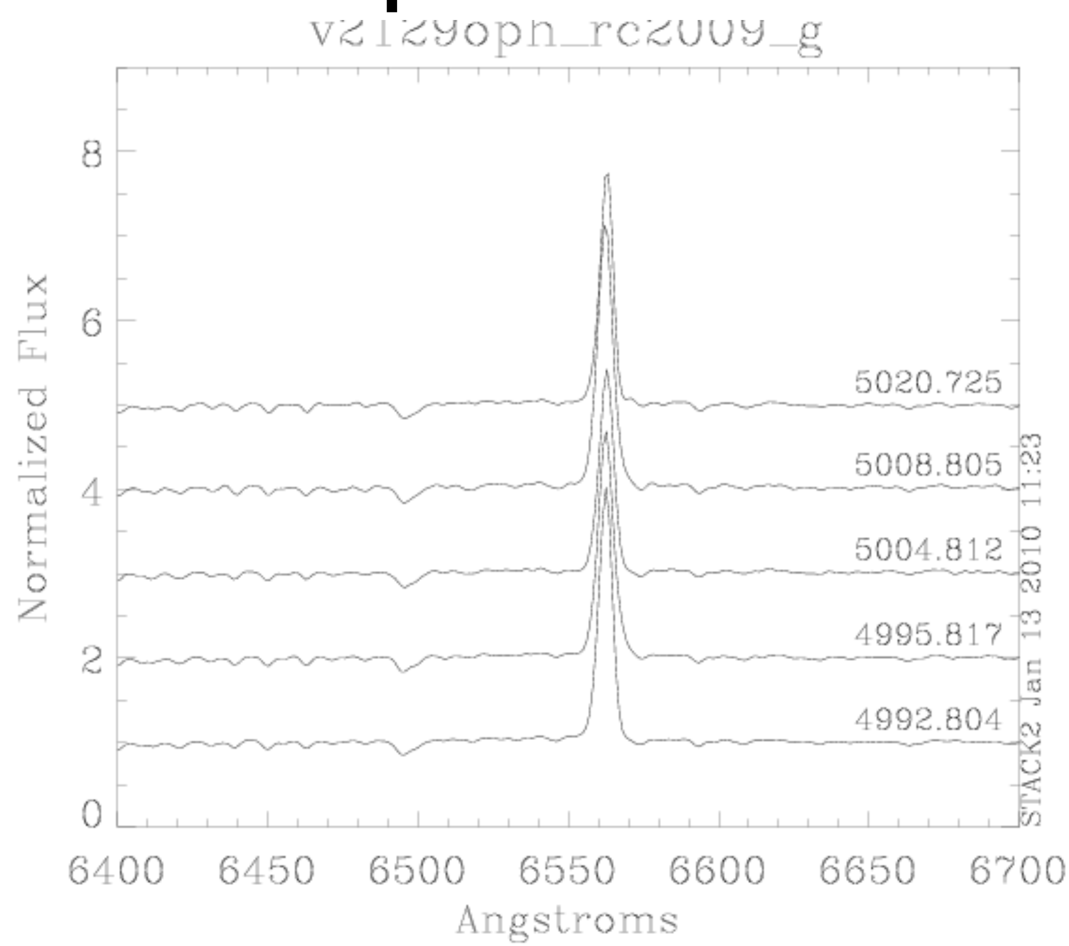
Low Dispersion - blue

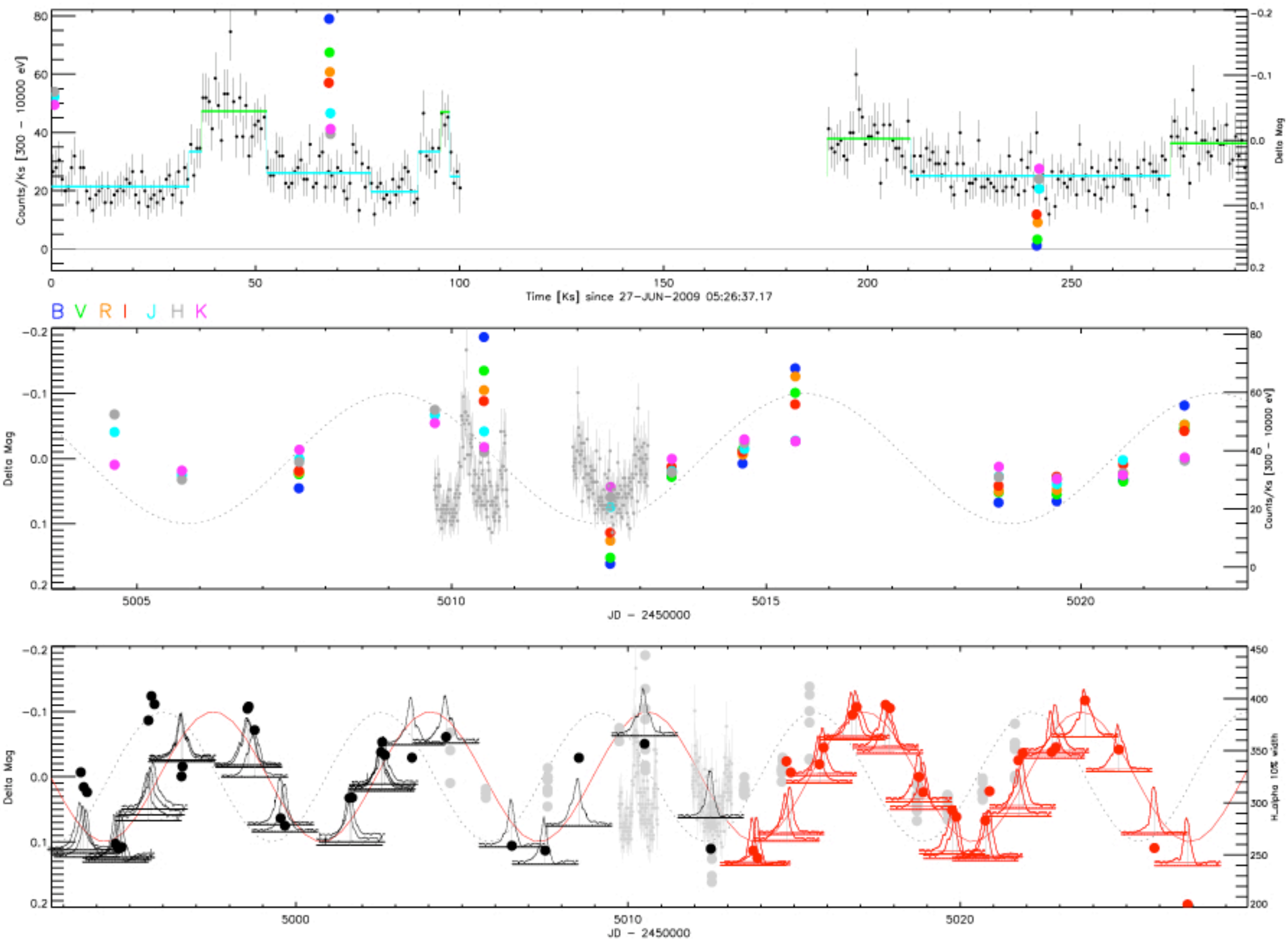


Low Dispersion - blue

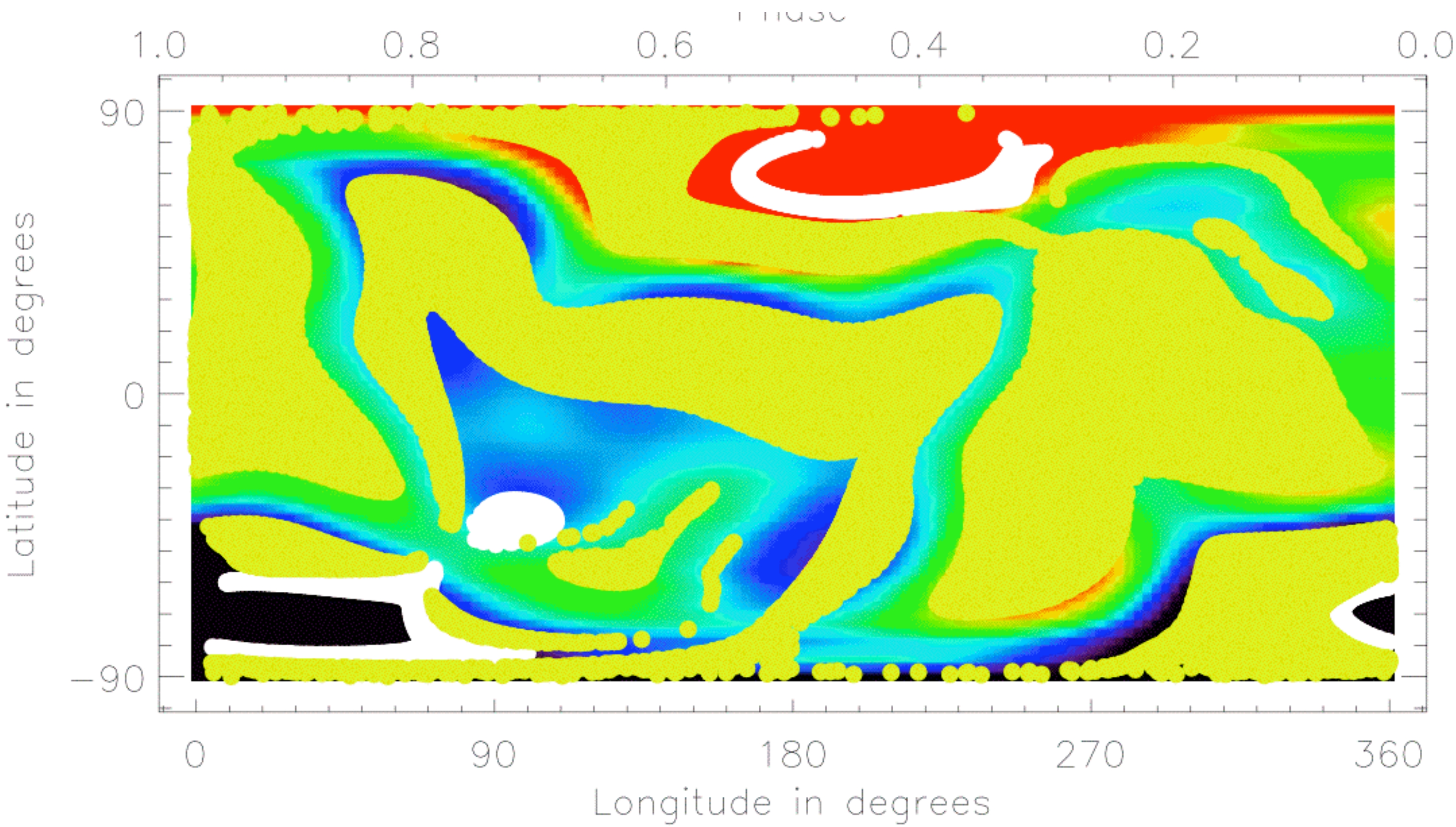


Low Dispersion - red





Counts/Ks [300 - 10000 eV]
Time [Ks] since 27-JUN-2009 05:26:37.17
Delta Mag
B V R I J H K
JD - 2450000
Counts/Ks [300 - 10000 eV]
Delta Mag
JD - 2450000
H_alpha 10% width



Magnetic Footprints