X-ray Emission from Massive Stars

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Swarthmore College

with Emma Wollman ('09) & Erin Martell ('09)

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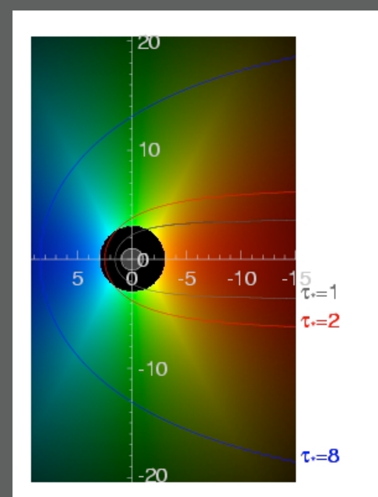
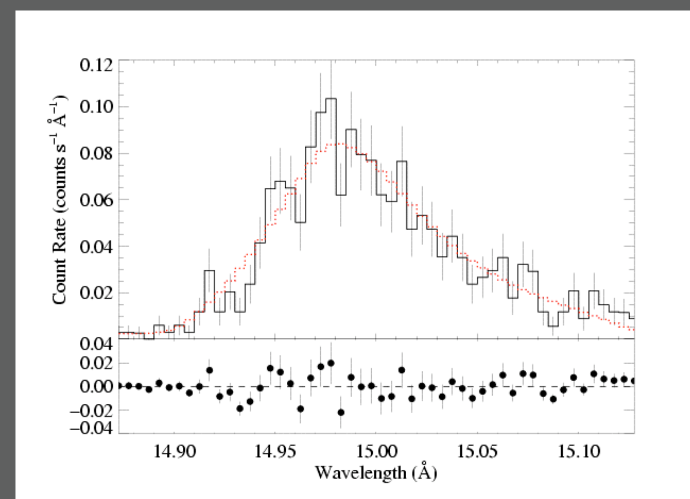
Marc Gagne (West Chester)





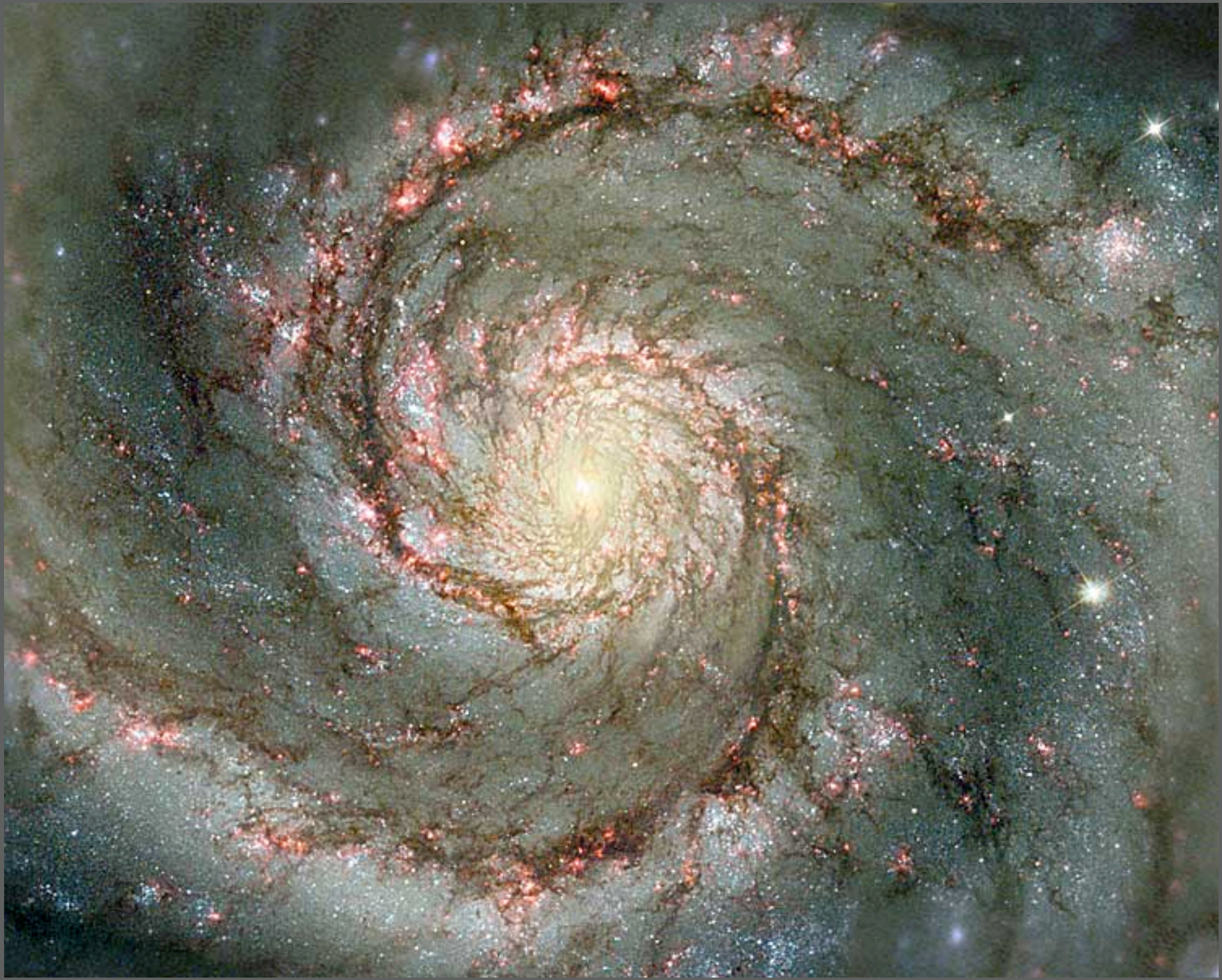
Outline

Background

- Massive star X-rays vs. solar-type X-rays
- Radiation-driven stellar winds
- The wind-shock paradigm

X-ray spectroscopy of massive stars: Data

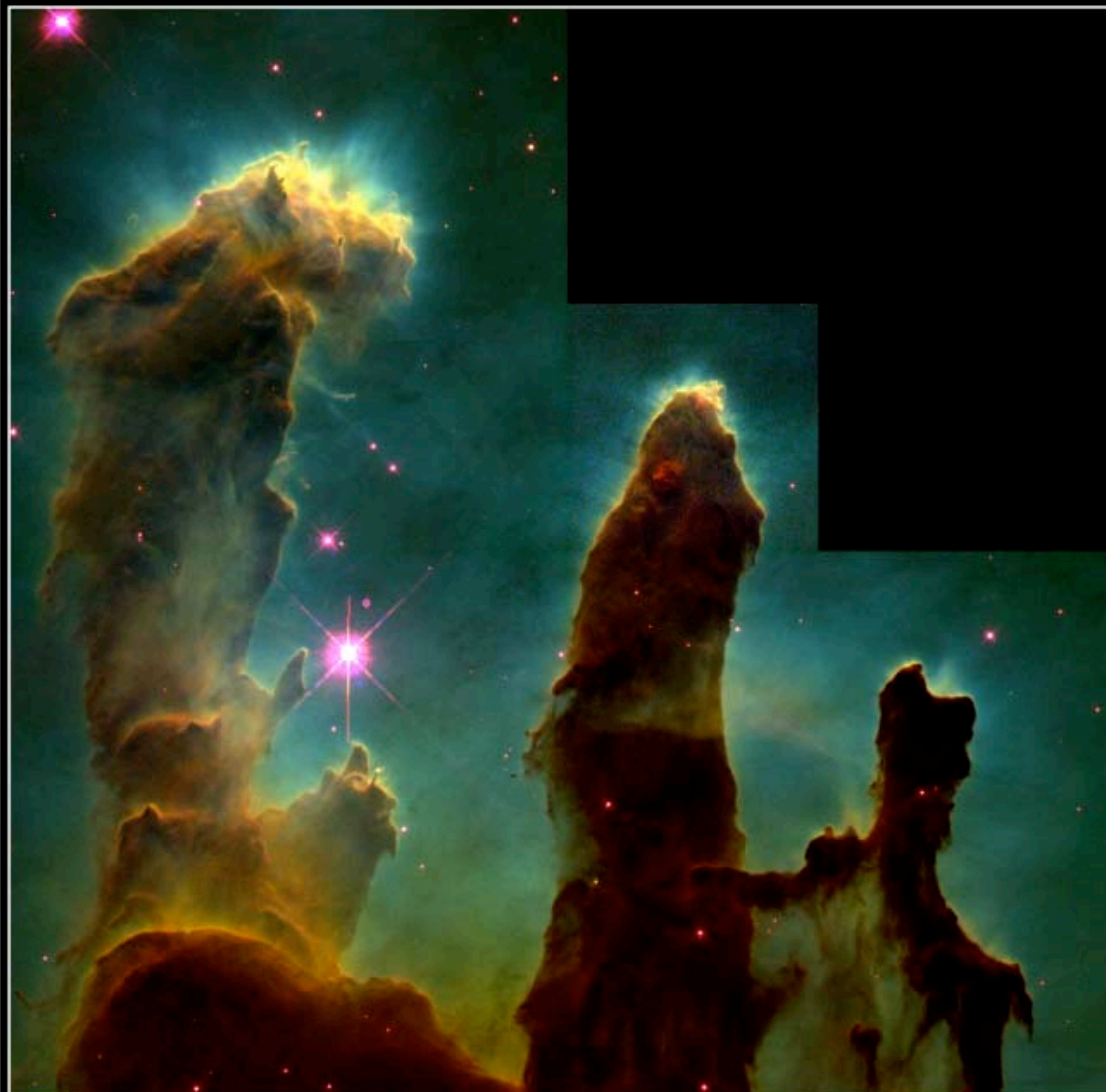
- Kinematics of the shock-heated wind
- Are mass-loss rates lower than we thought?


Whirlpool Galaxy, HST

Keyhole Nebula

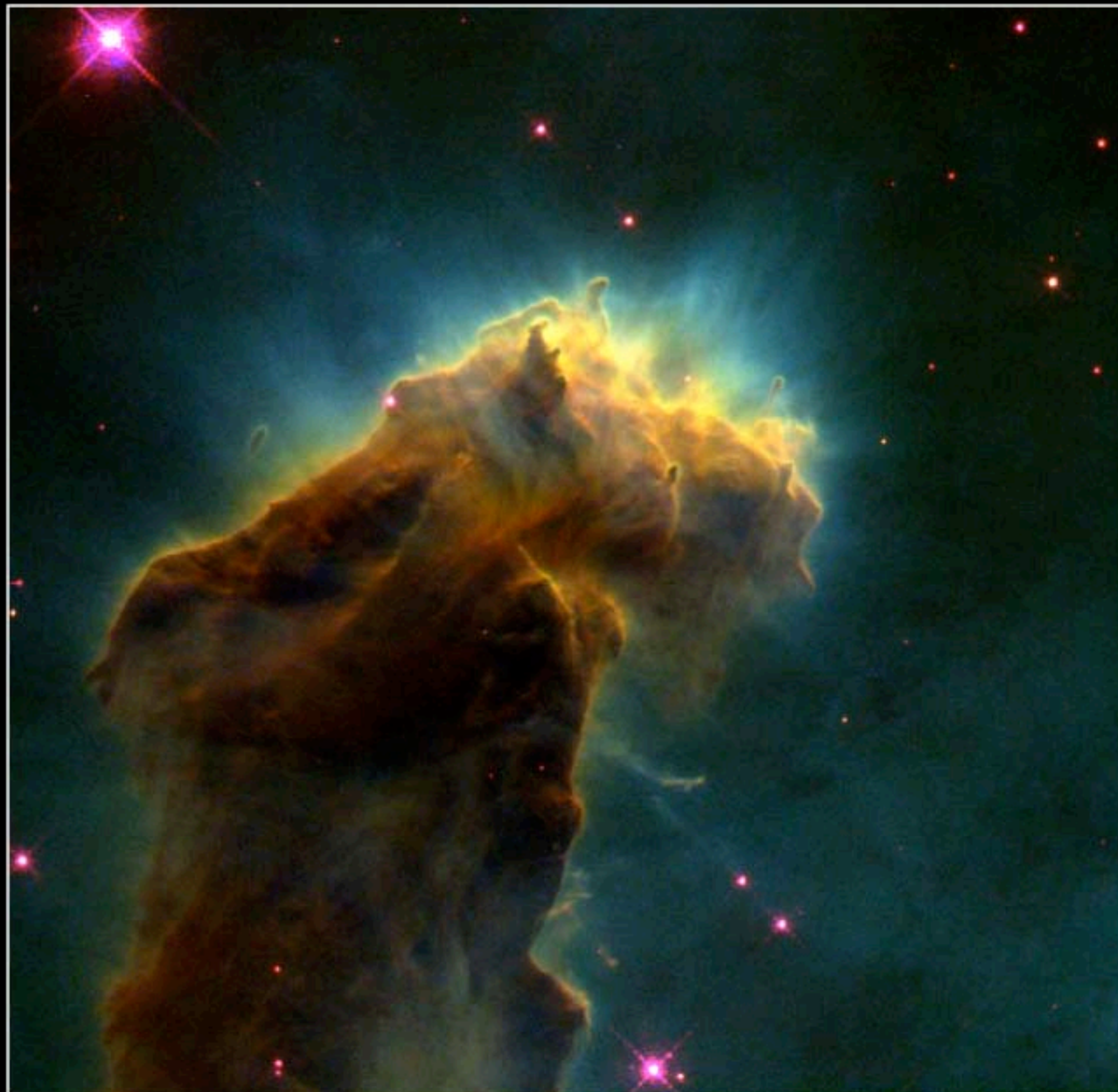
Hubble Heritage

NASA and The Hubble Heritage Team (STScI) • Hubble Space Telescope WFPC2 • STScI-PRC00-06



Gaseous Pillars · M16 HST · WFPC2

PRC95-44a · ST ScI OPO · November 2, 1995
J. Hester and P. Scowen (AZ State Univ.), NASA



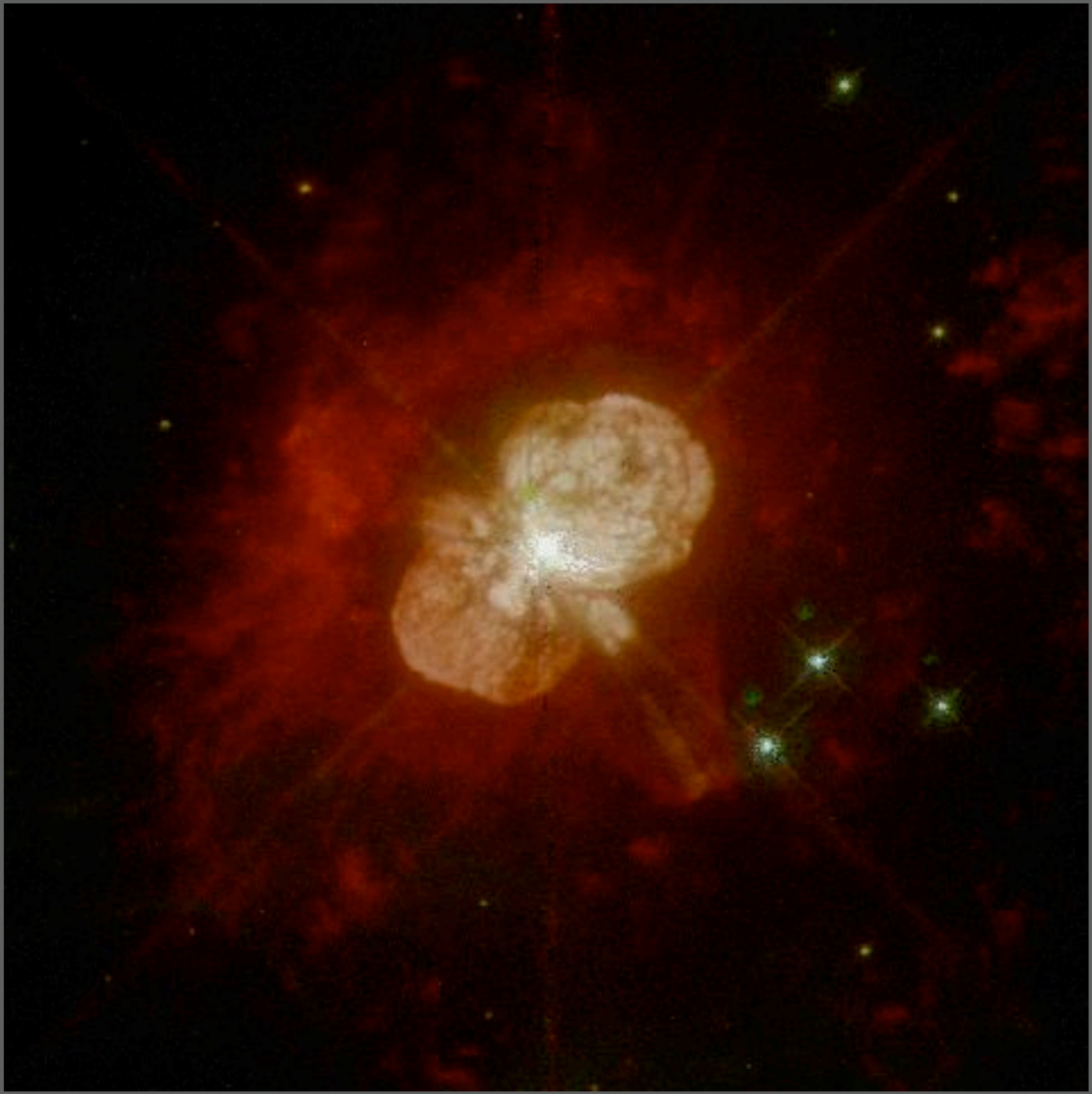
Star-Birth Clouds · M16 HST · WFPC2

PRC95-44b · ST ScI OPO · November 2, 1995
J. Hester and P. Scowen (AZ State Univ.), NASA

1000 yr old supernova remnant

Crab Nebula, WIYN

explosive mass loss



eta Carina, HST

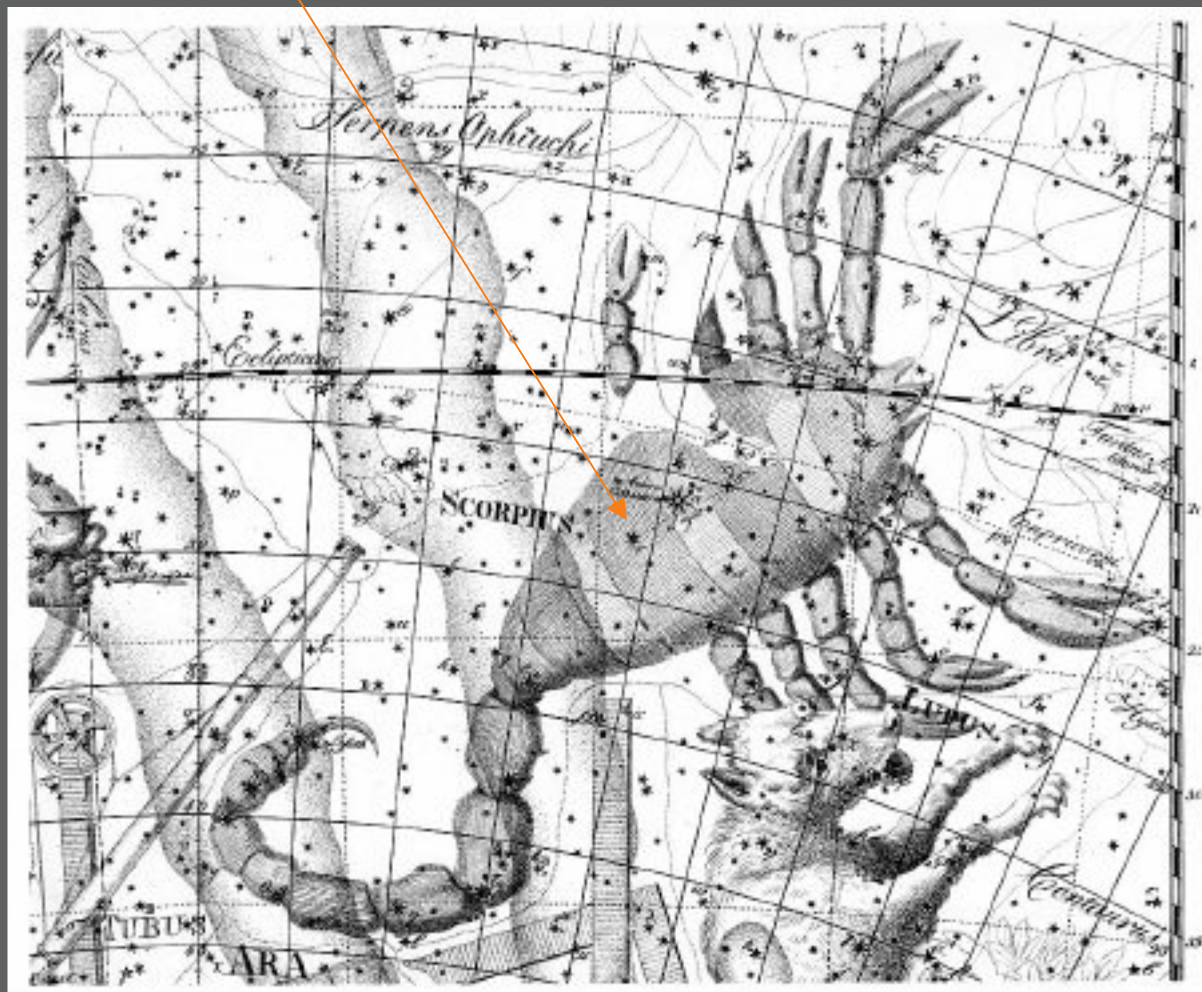
wind-blown bubble: steady mass-loss

NGC 6888 Crescent Nebula - Tony Hallas

No spatial information from imaging?

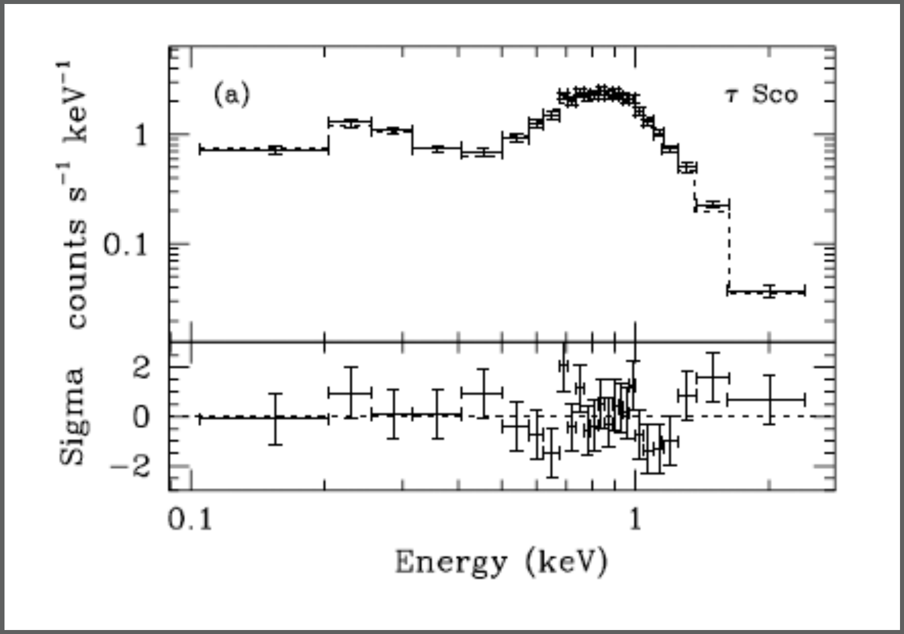
…use **spectroscopy**

τ Scorpii: 20 M_{sun}

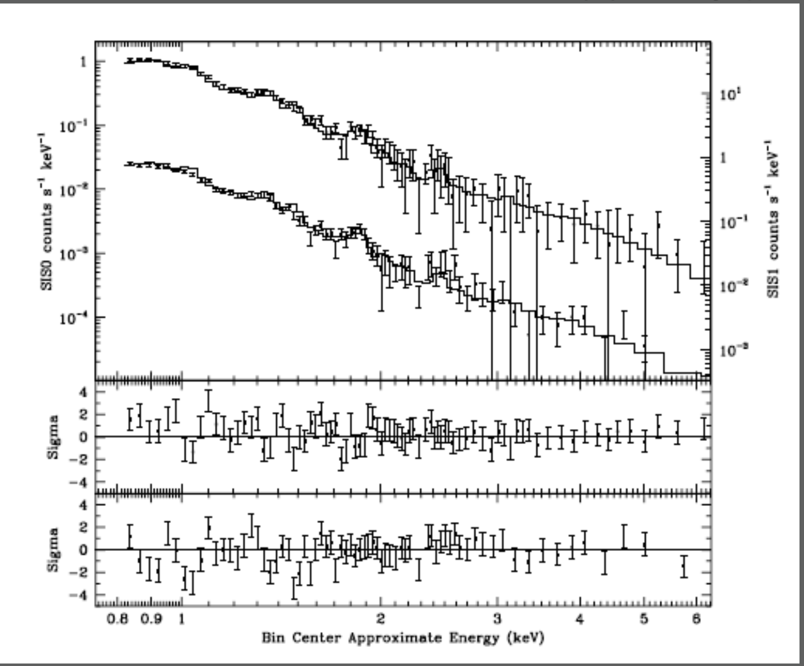


Johann Bode, Uranographia

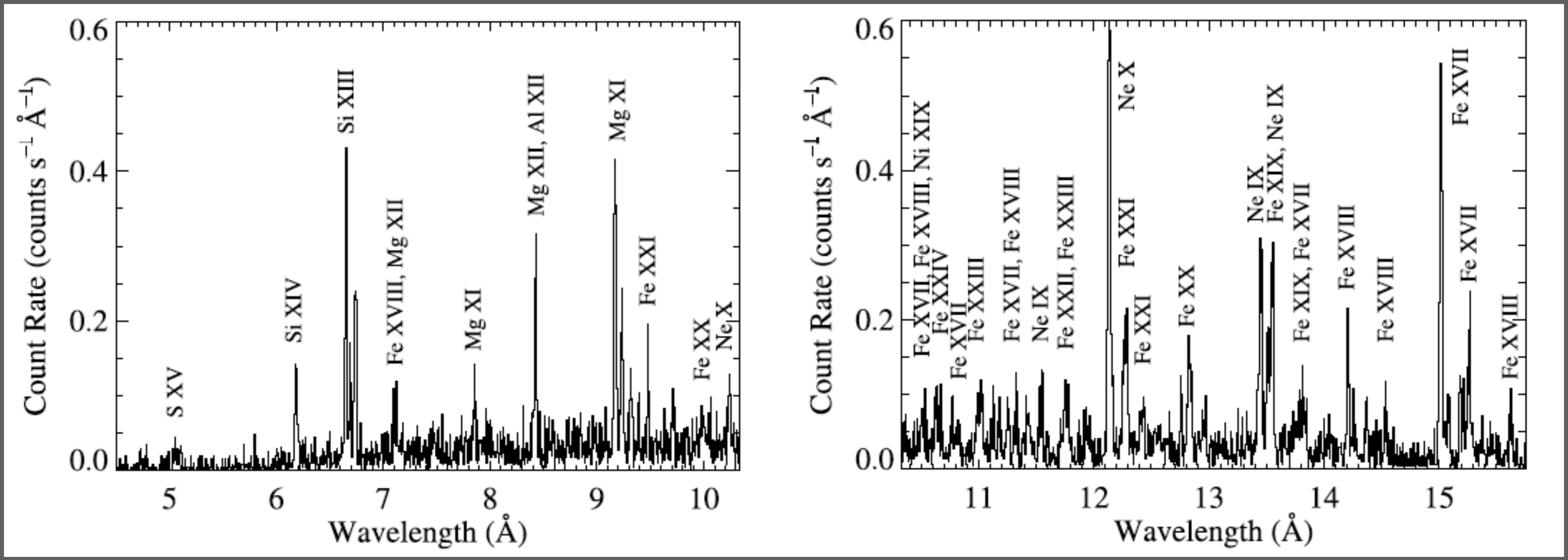
1991 *ROSAT*



1994 *ASCA*



2000 *Chandra*

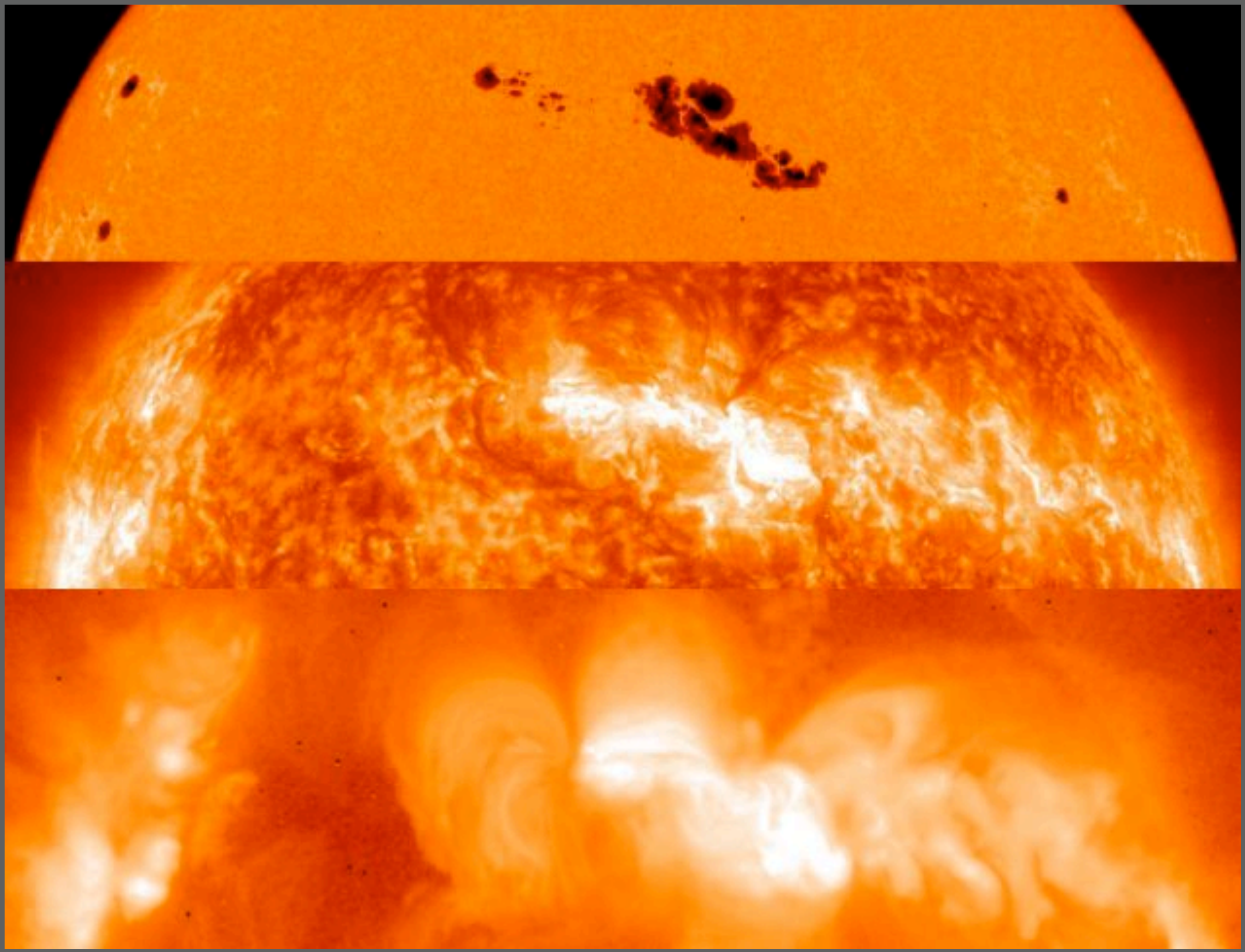


Massive star X-rays

vs.

Solar-type X-rays

The Sun at different wavelengths

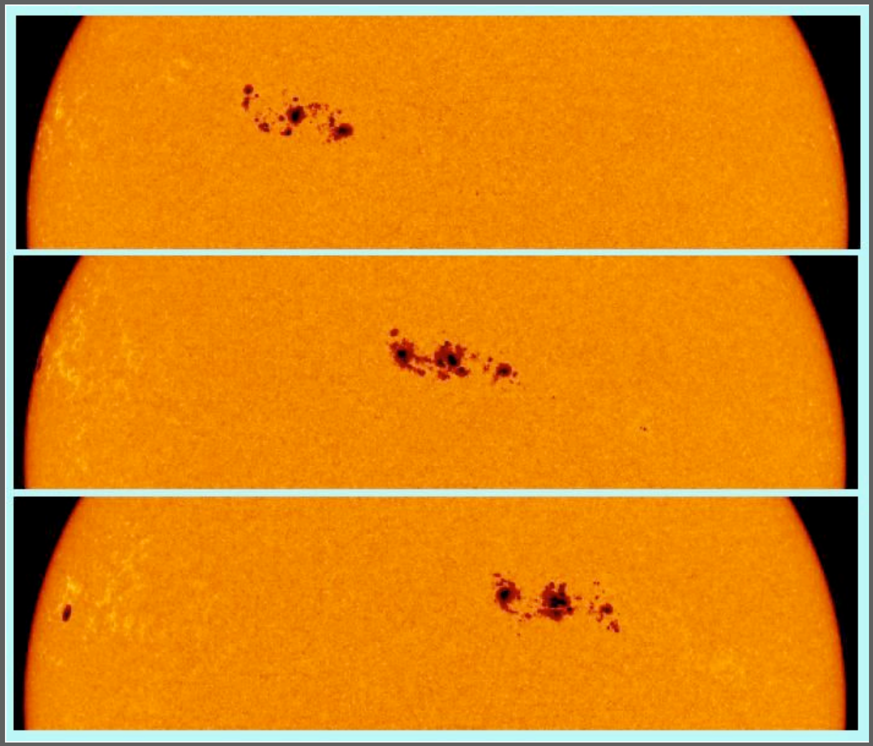


Optical
5800 K

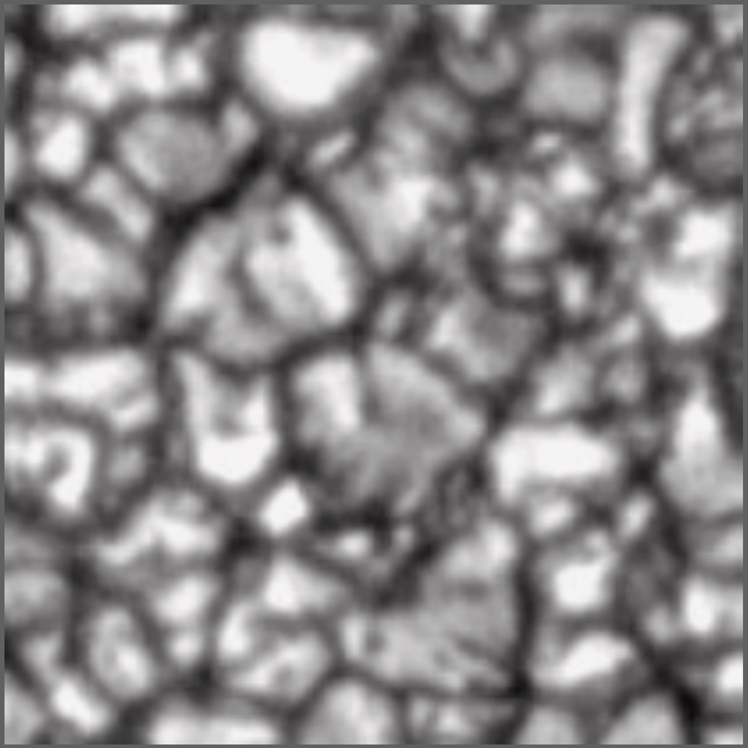
SOHO
EUV
few 10^5 K

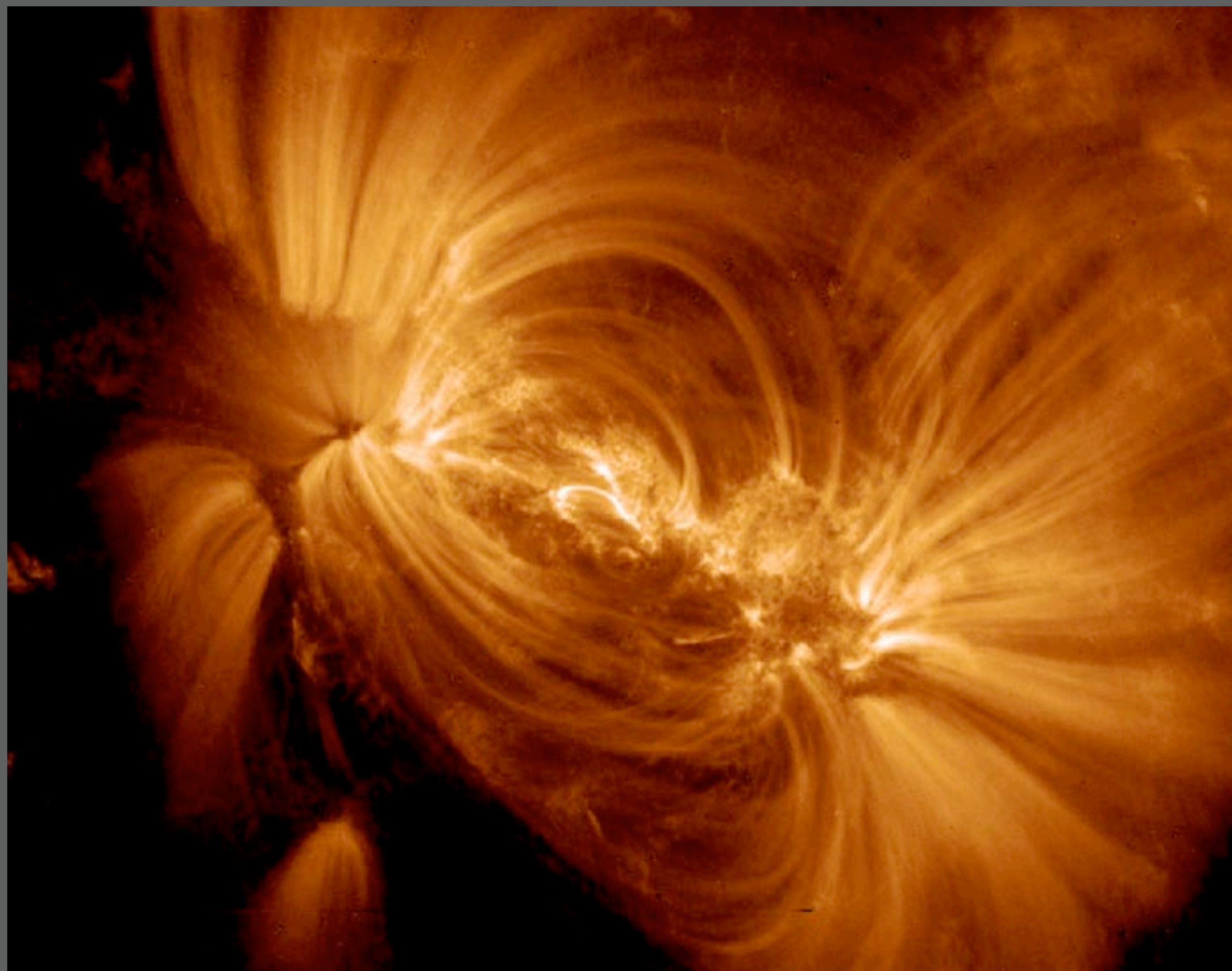
YOKOH
x-ray
few 10^6 K

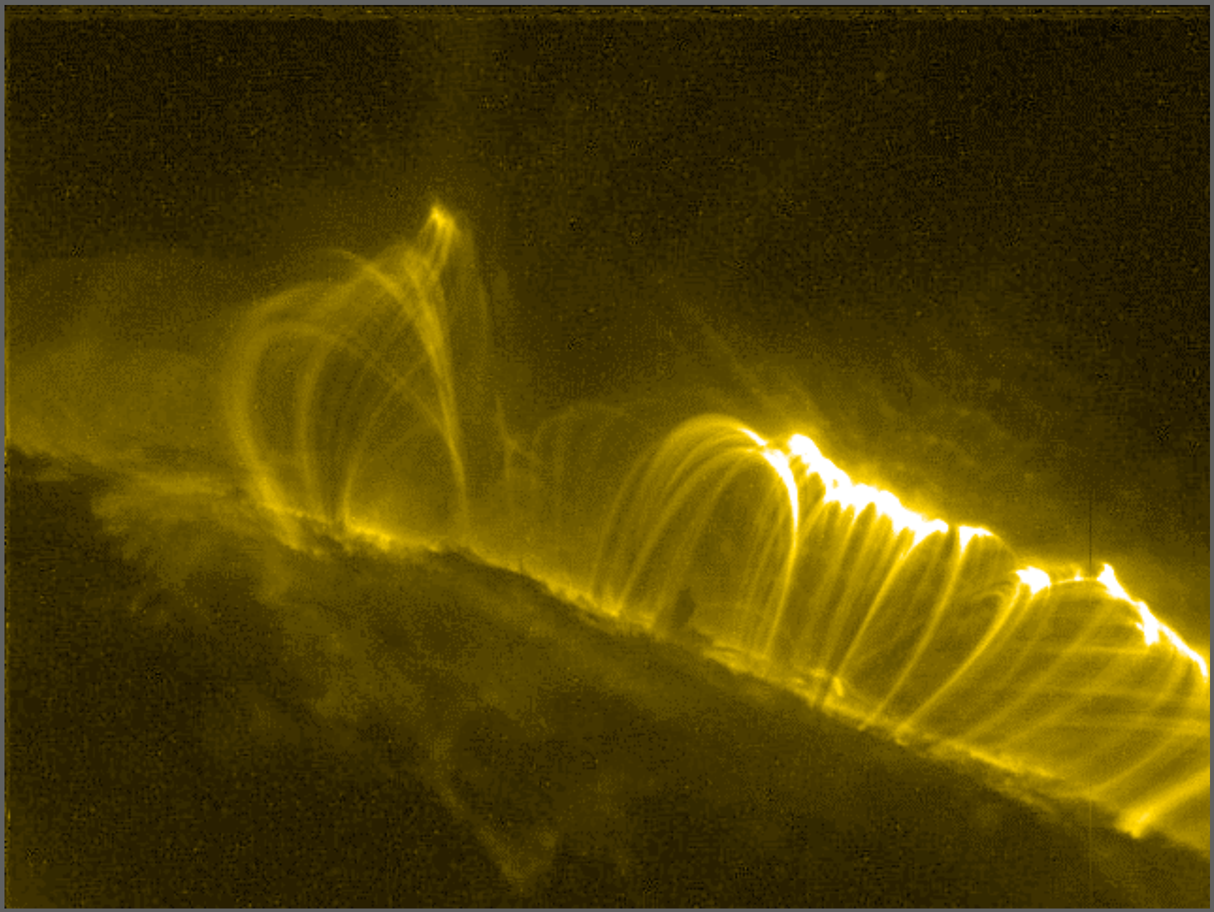
rotation

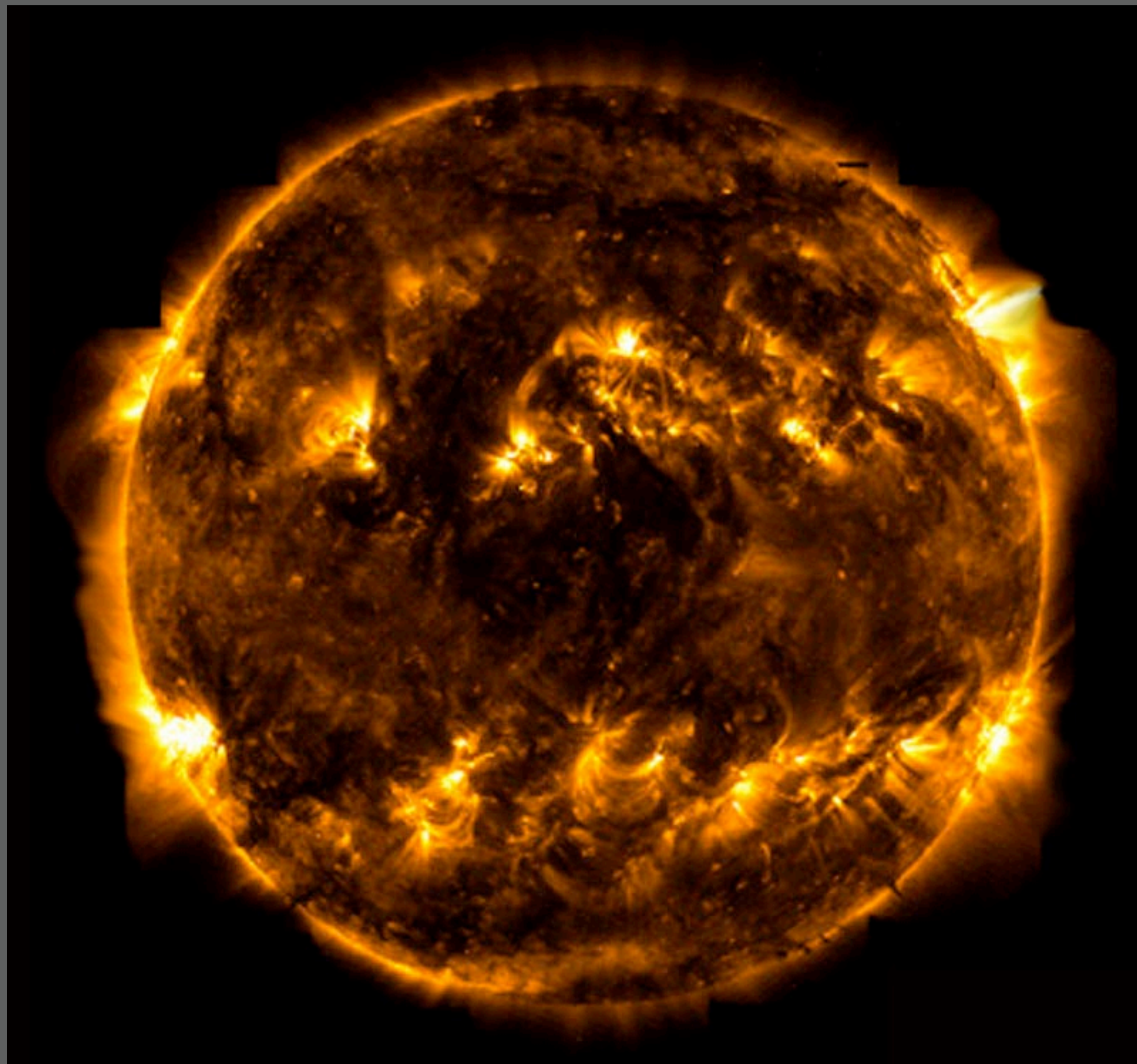


convection





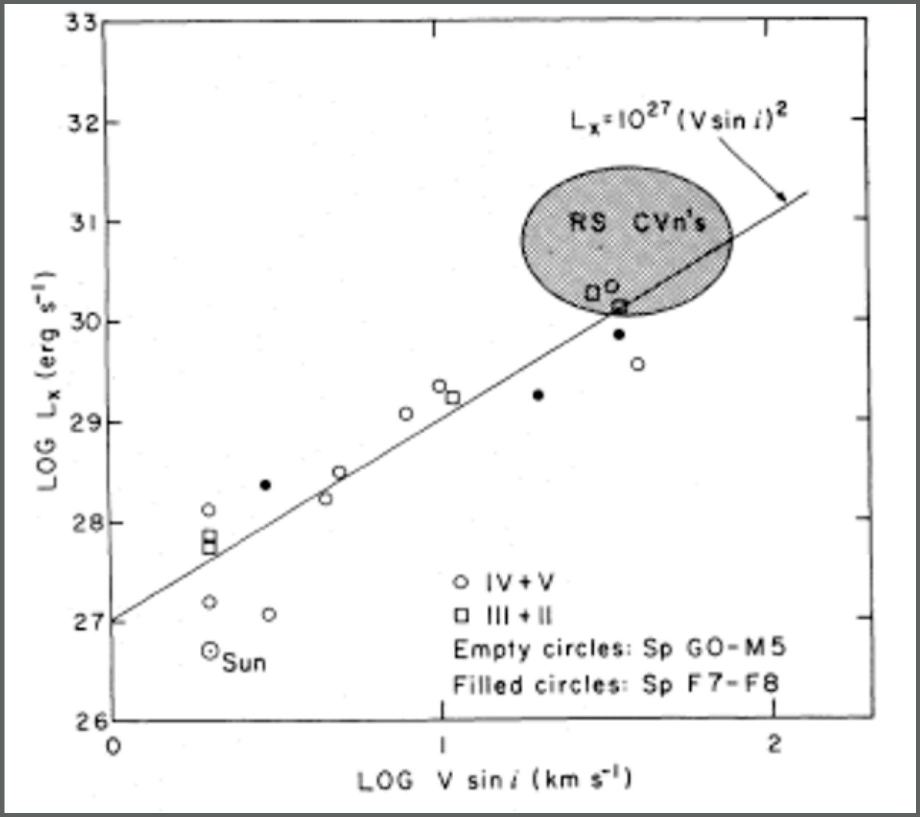




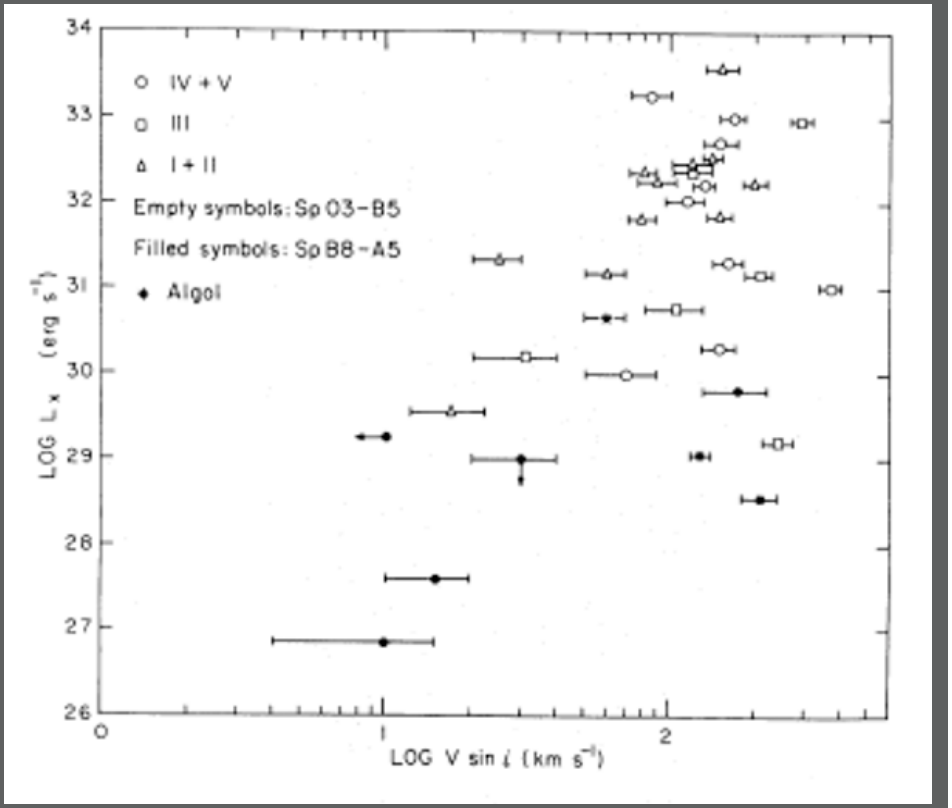
TRACE

Stellar rotation vs. X-ray luminosity

low-mass stars



high-mass stars



THE ASTROPHYSICAL JOURNAL, 234:L51–54, 1979 November 15

DISCOVERY OF AN X-RAY STAR ASSOCIATION IN VI CYGNI (CYG OB2)

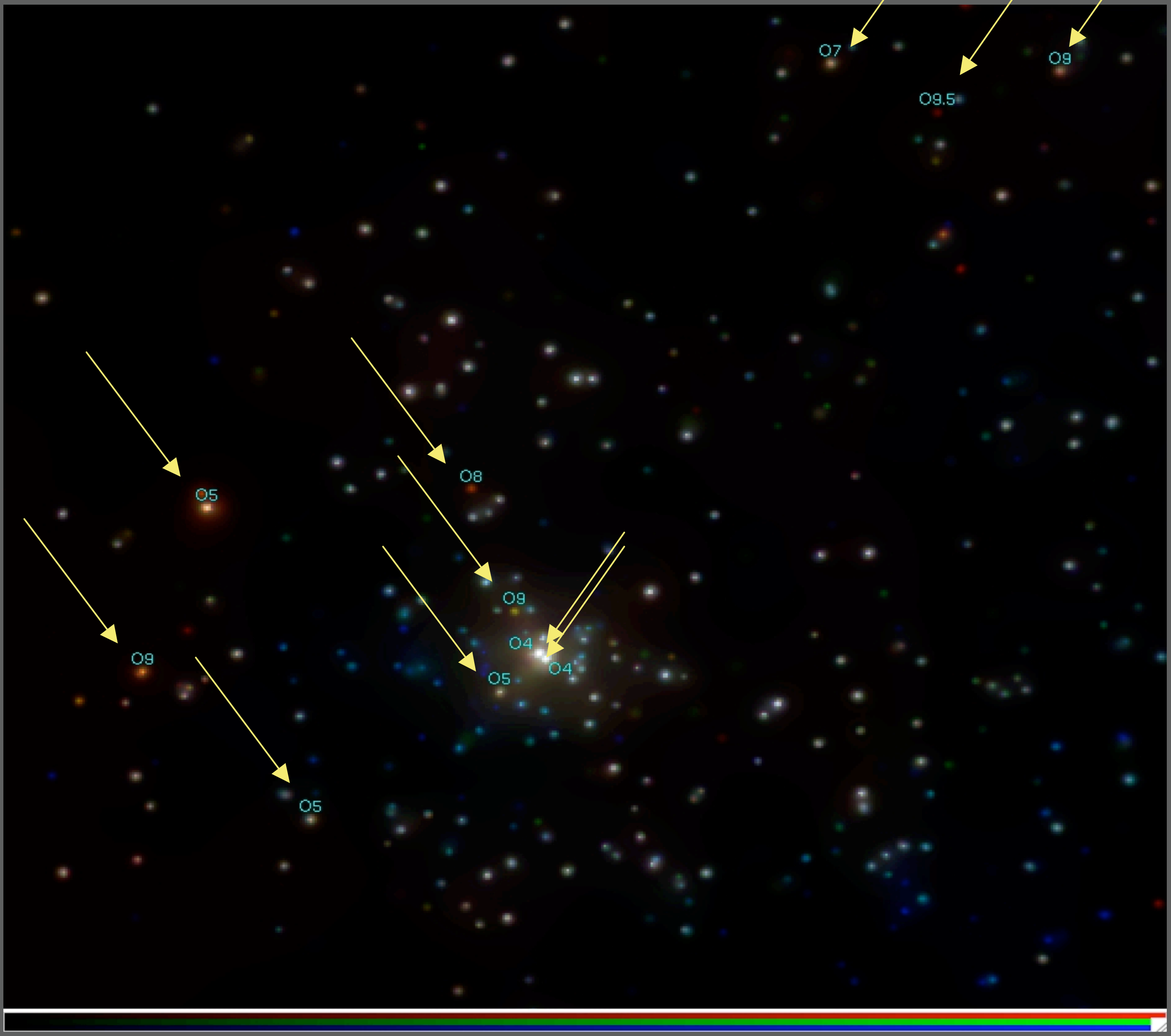
F. R. HARNDEN, JR., G. BRANDUARDI, M. ELVIS,[1] P. GORENSTEIN, J. GRINDLAY,
J. P. PYE,[1] R. ROSNER, K. TOPKA, AND G. S. VAIANA[2]
Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts
Received 1979 June 26; accepted 1979 July 26

ABSTRACT

A group of six X-ray sources located within 0°.4 of Cygnus X-3 has been discovered with the *Einstein* Observatory. These sources have been positively identified and five of them correspond to stars in the heavily obscured OB association VI Cygni. The optical counterparts include four of the most luminous O stars within the field of view and a B5 supergiant. These sources are found to have typical X-ray luminosities L_x (0.2–4.0 keV) $\sim 5 \times 10^{33}$ ergs s^{-1}, with temperatures $T \sim 10^{6.8}$ K and hydrogen column densities $N_H \sim 10^{22}$ cm^{-2}, and therefore comprise a new class of low-luminosity galactic X-ray sources associated with early-type stars.

Chandra X-rays: soft medium hard

M17 - massive star cluster



4 arcmin

THE ASTROPHYSICAL JOURNAL, **220**:573–581, 1978 March 1

THE STRUCTURE OF THE WINDS AND CORONAE OF O STARS DERIVED FROM Hα LINE-PROFILE ANALYSES

JOSEPH P. CASSINELLI AND GORDON L. OLSON
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AND

ROBERTO STALIO
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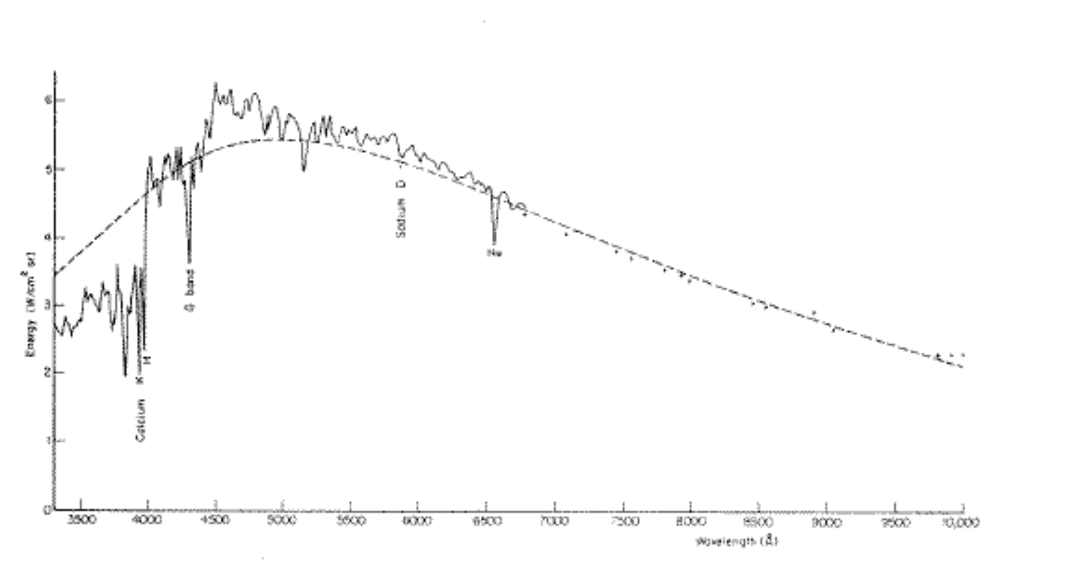
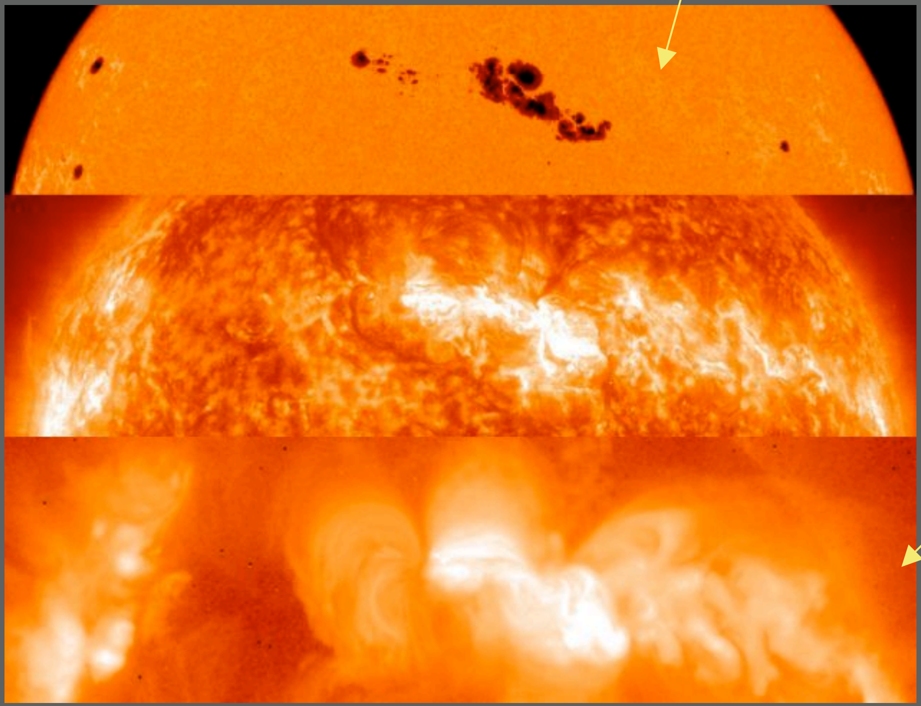
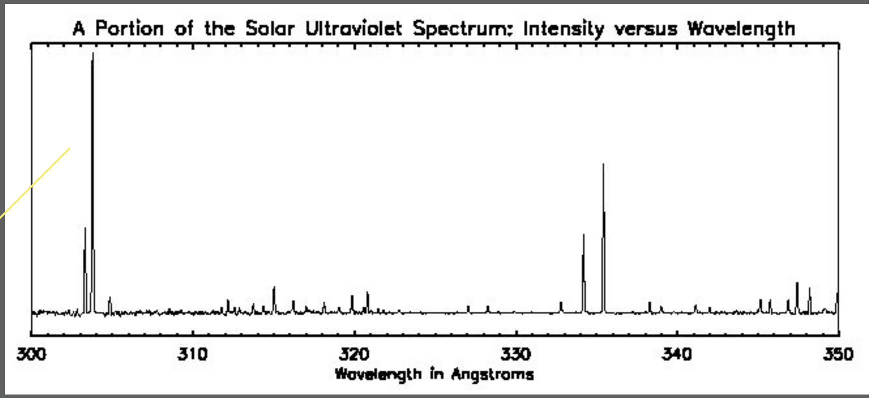
Received 1977 July 20; accepted 1977 September 2

Spectroscopic aside



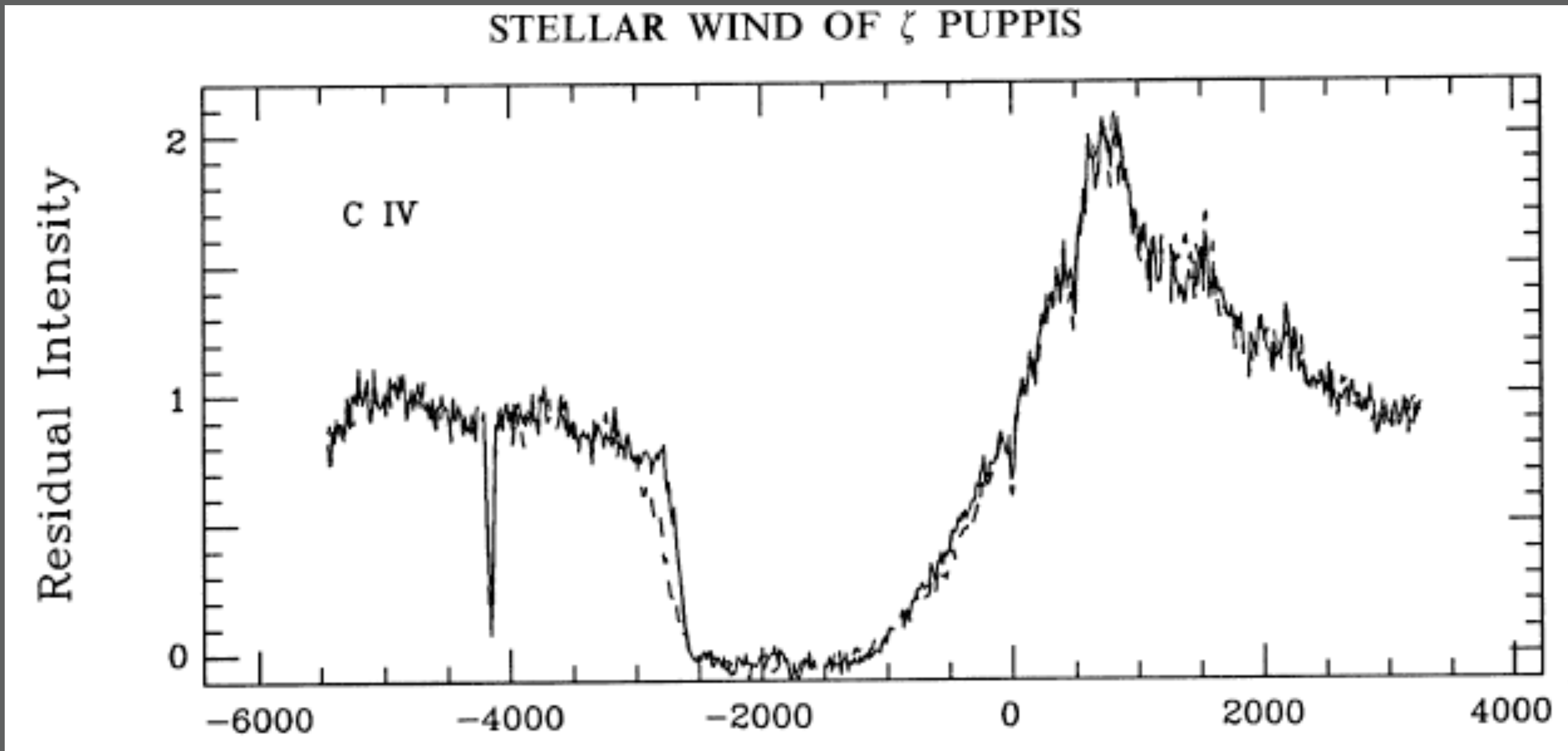
Energy (W/cm² sr)
Calcium K H
G band
Sodium D
Hα
3500 4000 4500 5000 5500 6000 6500 7000 7500 8000 8500 9000 9500 10,000
Wavelength (Å)





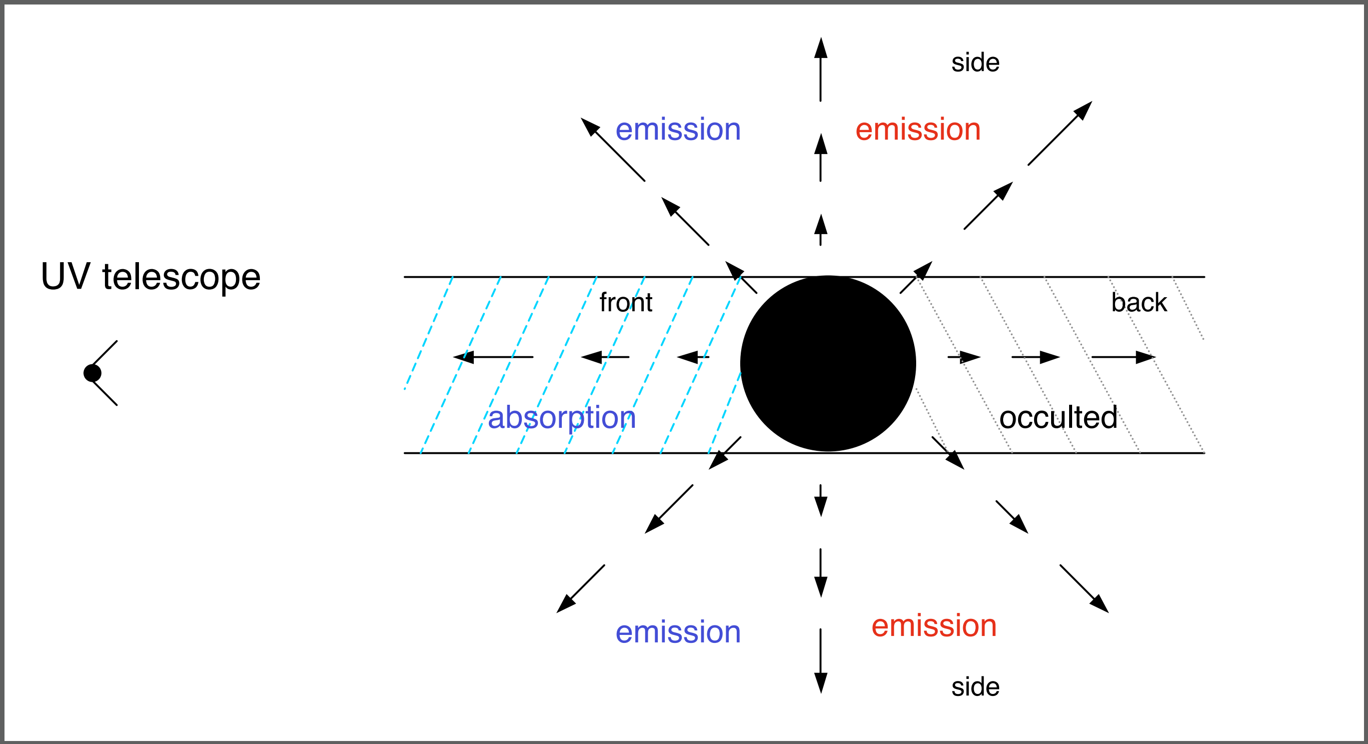
A Portion of the Solar Ultraviolet Spectrum: Intensity versus Wavelength
300 310 320 330 340 350
Wavelength in Angstroms

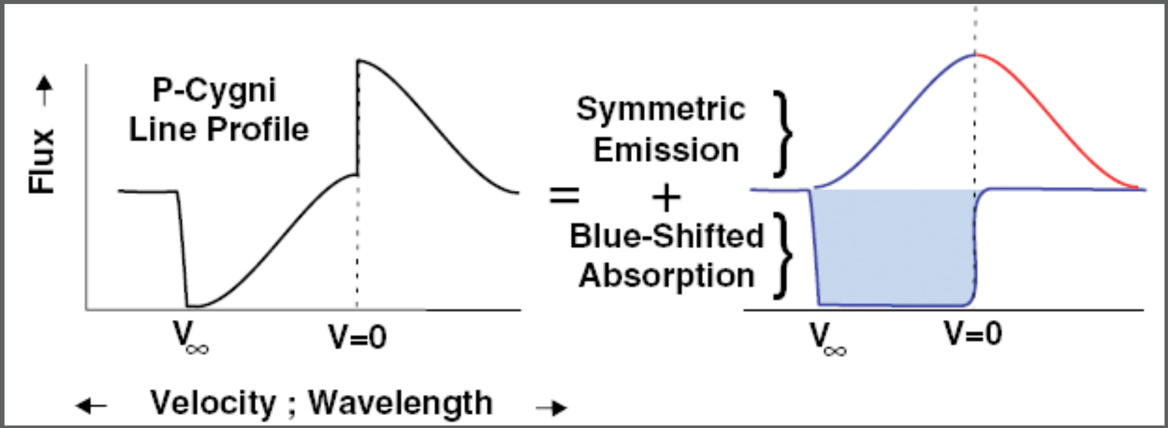
Radiation-driven stellar winds

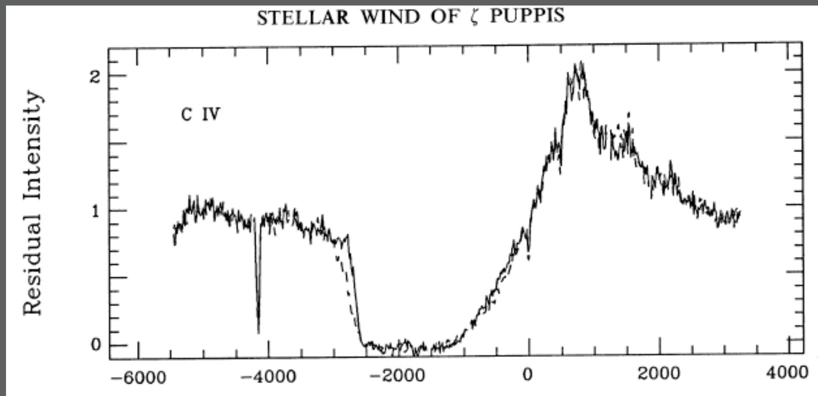


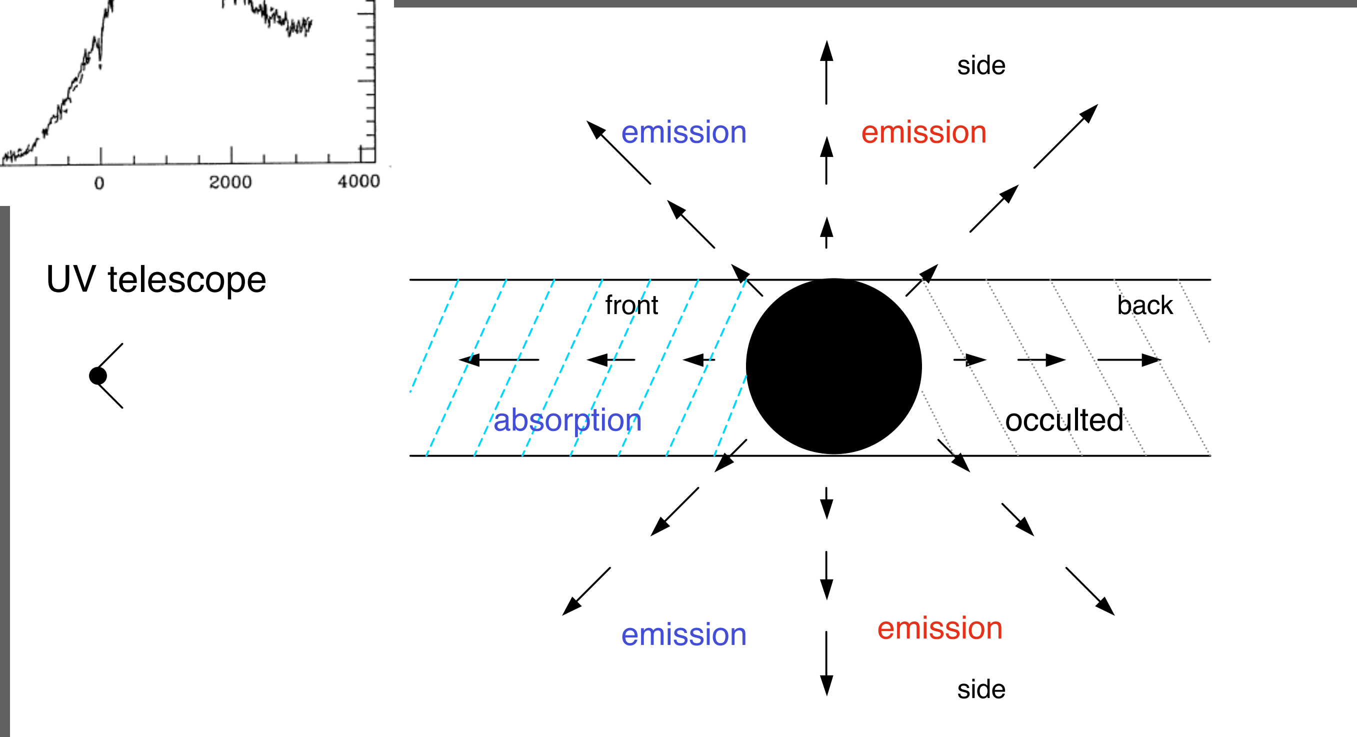
Velocity (km/s)

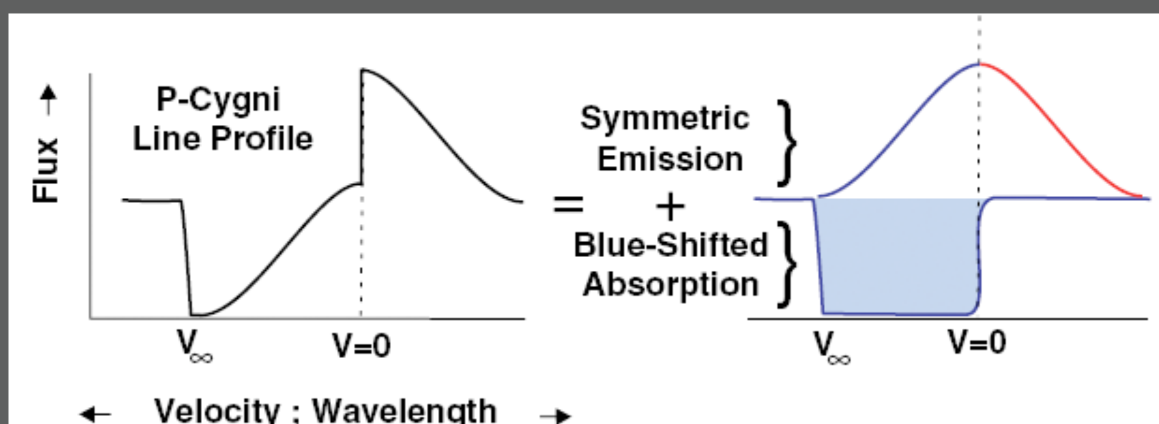
Prinja et al. 1992, ApJ, 390, 266


UV telescope
side
emission
emission
front
back
absorption
occulted
emission
emission
side

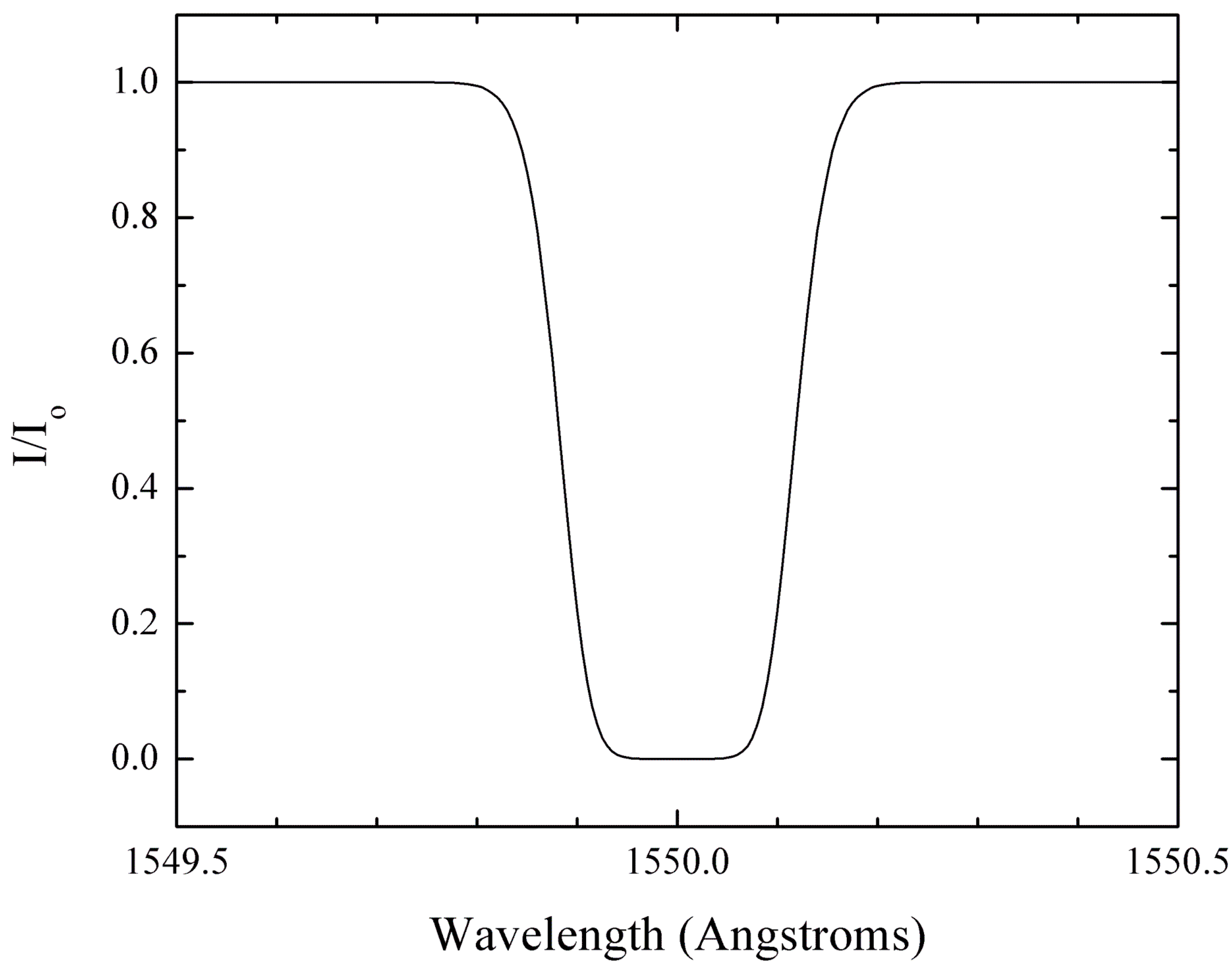

Flux
P-Cygni
Line Profile
V∞
V=0
=
Symmetric
Emission
+
Blue-Shifted
Absorption
V∞
V=0
Velocity ; Wavelength


STELLAR WIND OF ζ PUPPIS
Residual Intensity
C IV
2
1
0
−6000
−4000
−2000
0
2000
4000


UV telescope
side
emission
emission
front
back
absorption
occulted
emission
emission
side

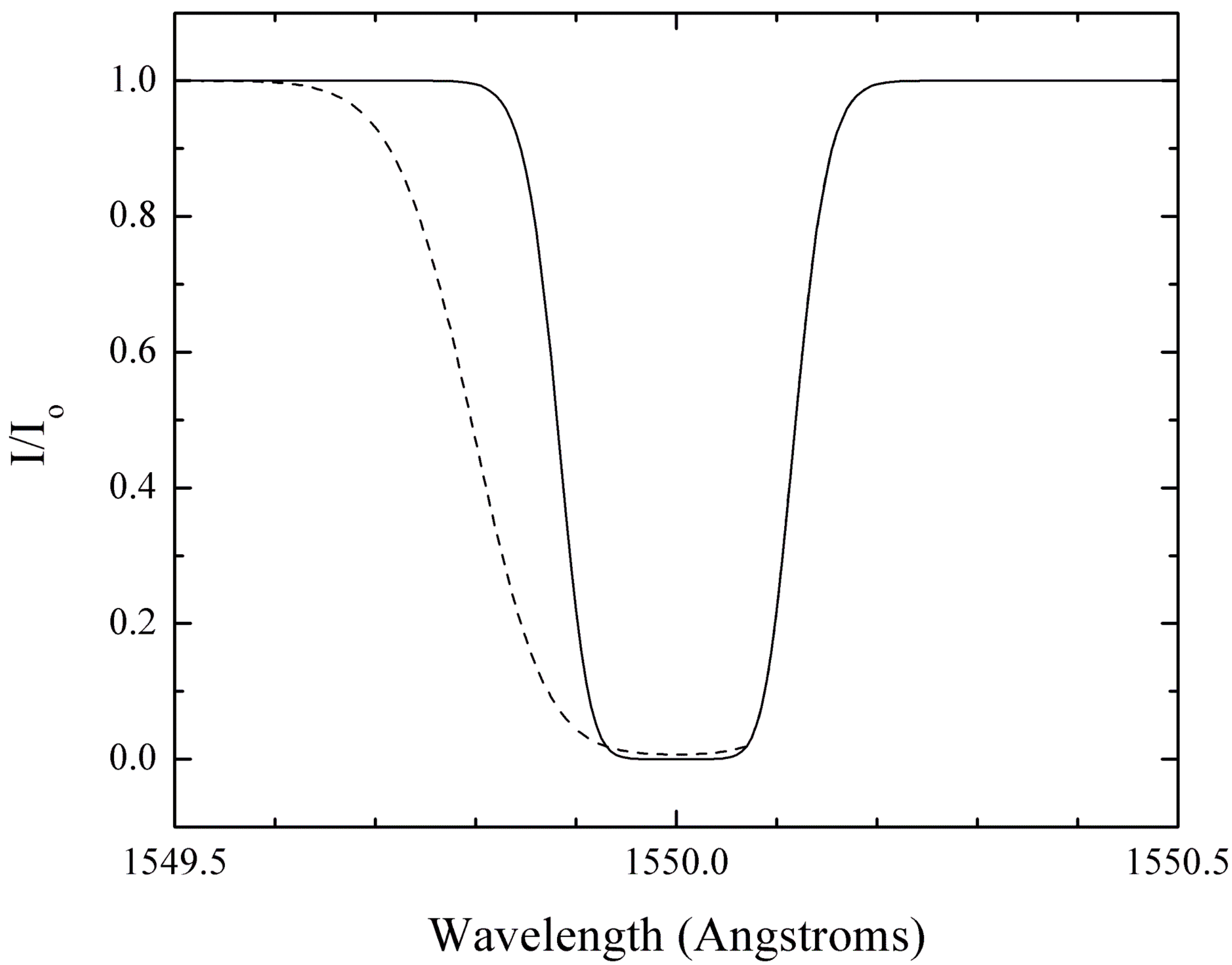

P-Cygni
Line Profile
Flux
V∞
V=0
Velocity ; Wavelength
=
Symmetric
Emission
+
Blue-Shifted
Absorption
V∞
V=0

The *momentum* in starlight drives massive stellar winds



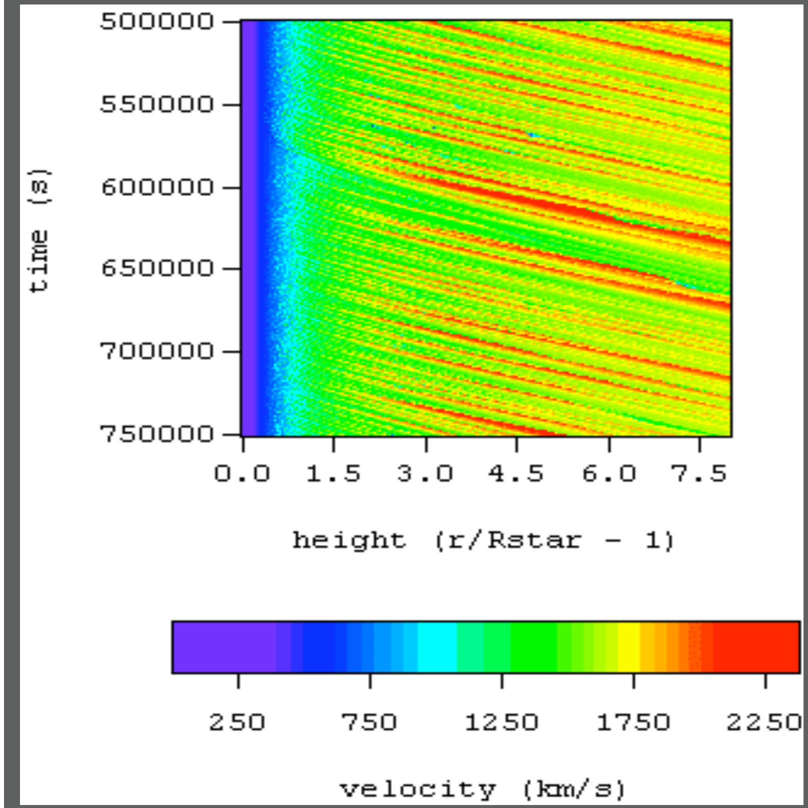
1.0
0.8
0.6
0.4
0.2
0.0
I/I$_o$
1549.5
1550.0
1550.5
Wavelength (Angstroms)

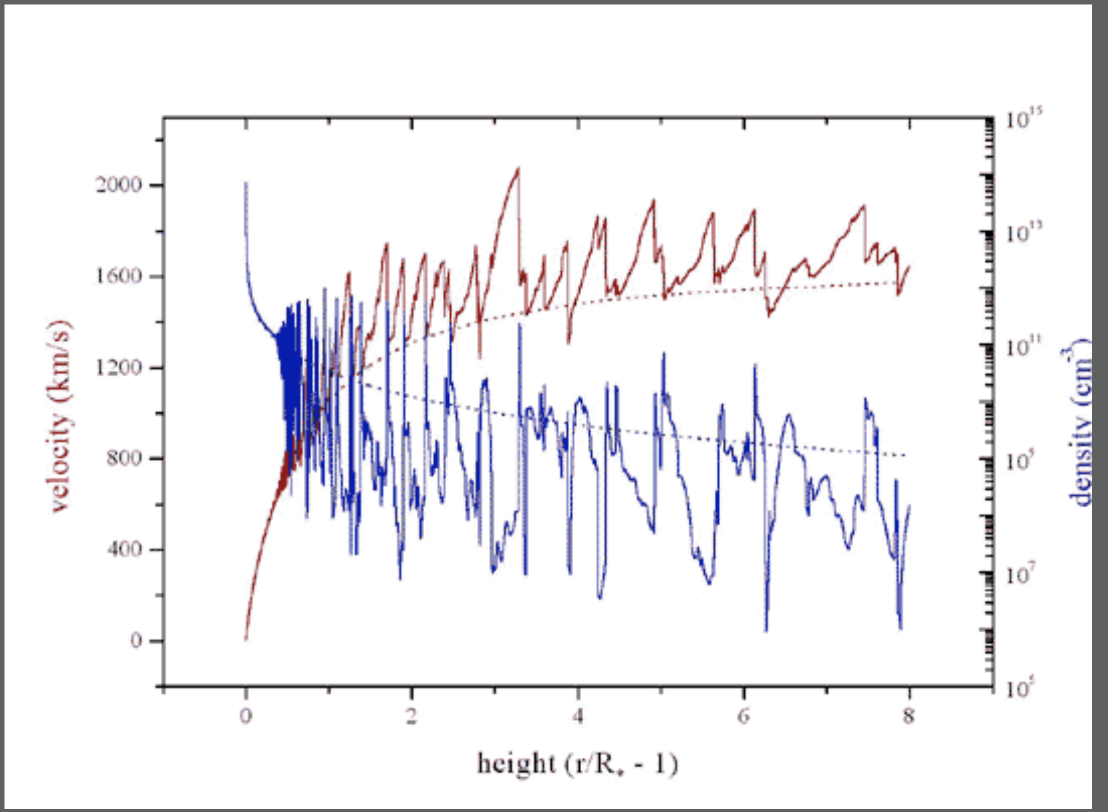
Doppler desaturation



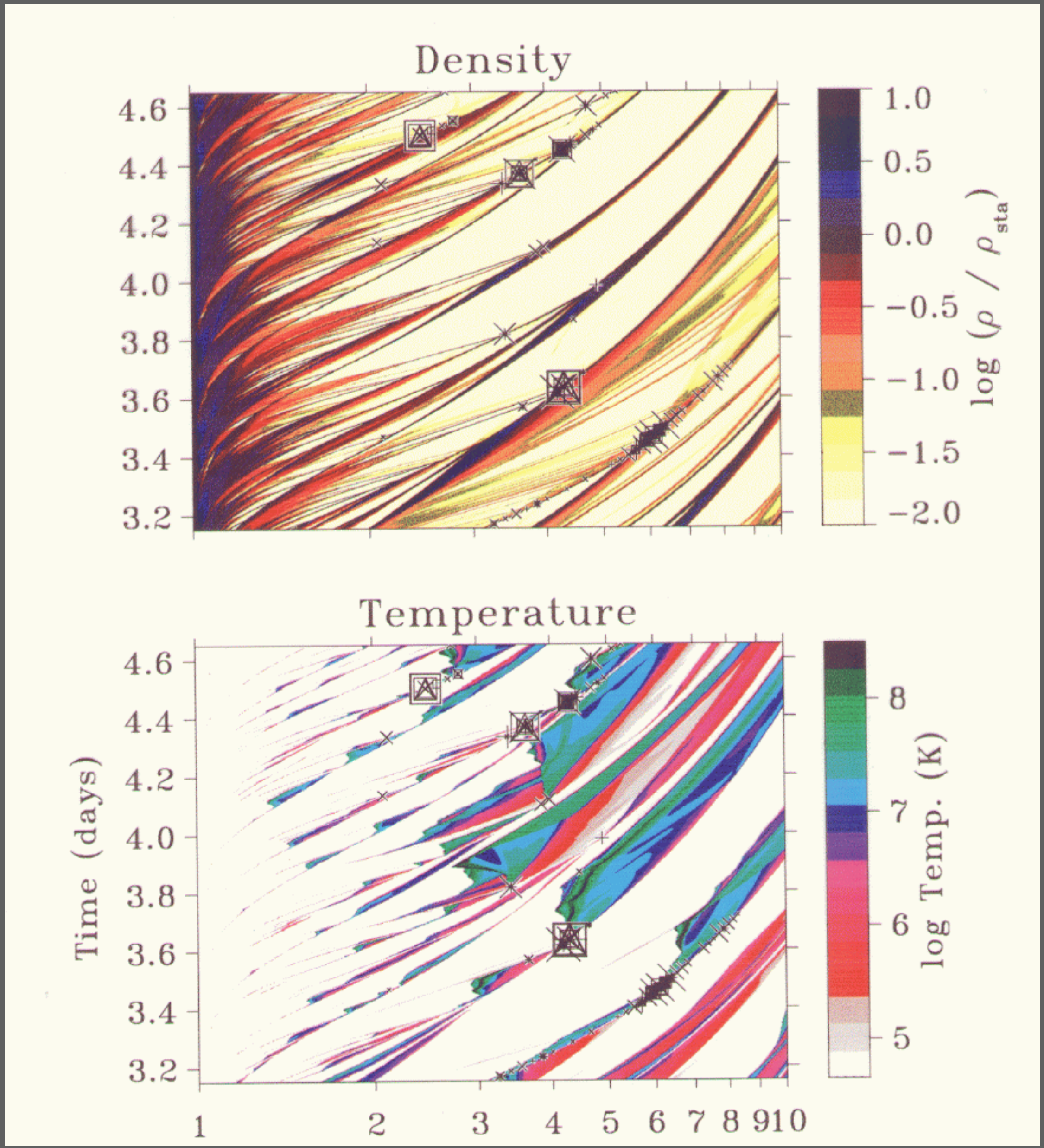
The wind-shock paradigm

1-D rad-hydro simulation of an O star wind



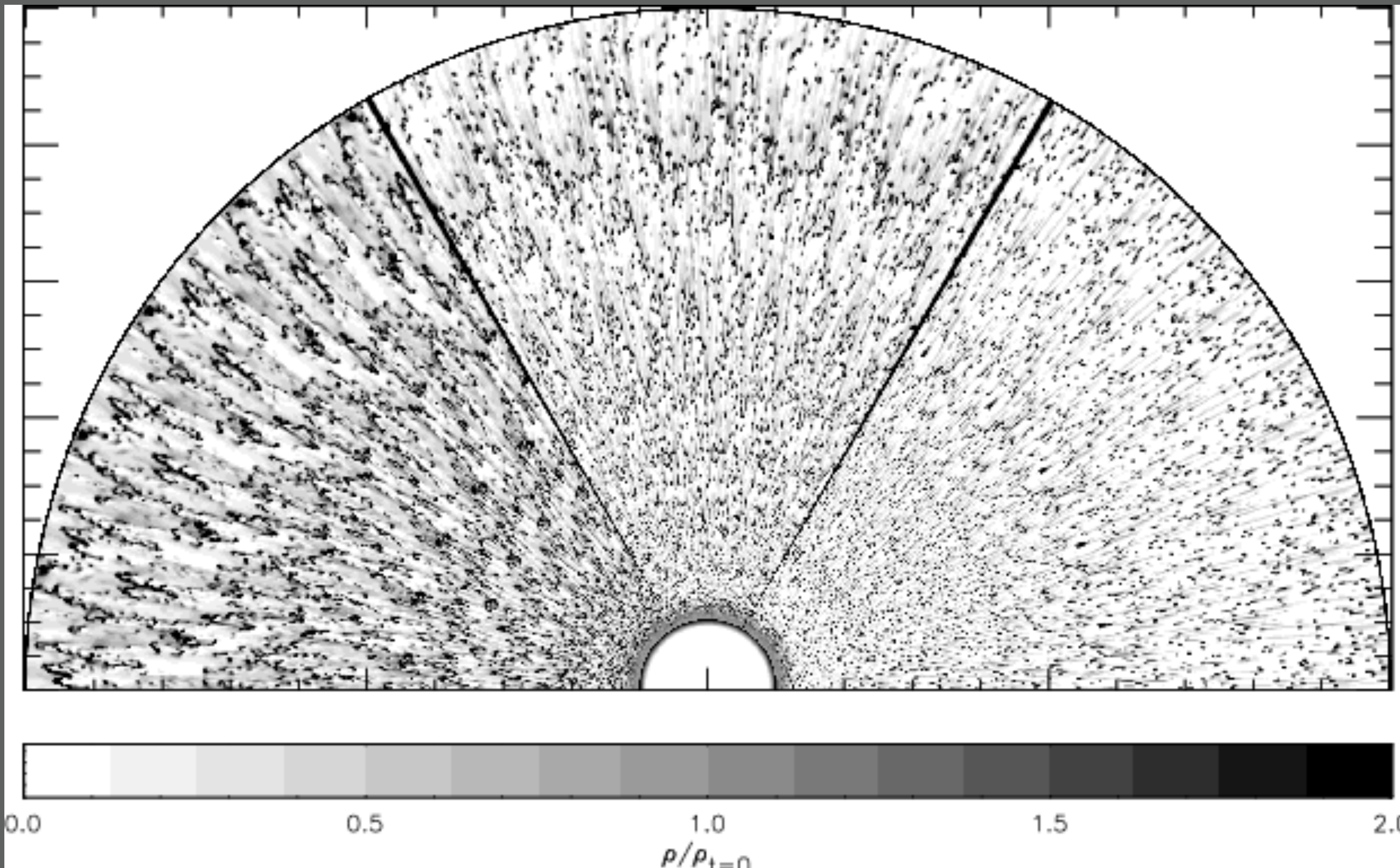


Shell-shell collisions induced by turbulence at the base of the wind flow



Feldmeier, et al. 1997

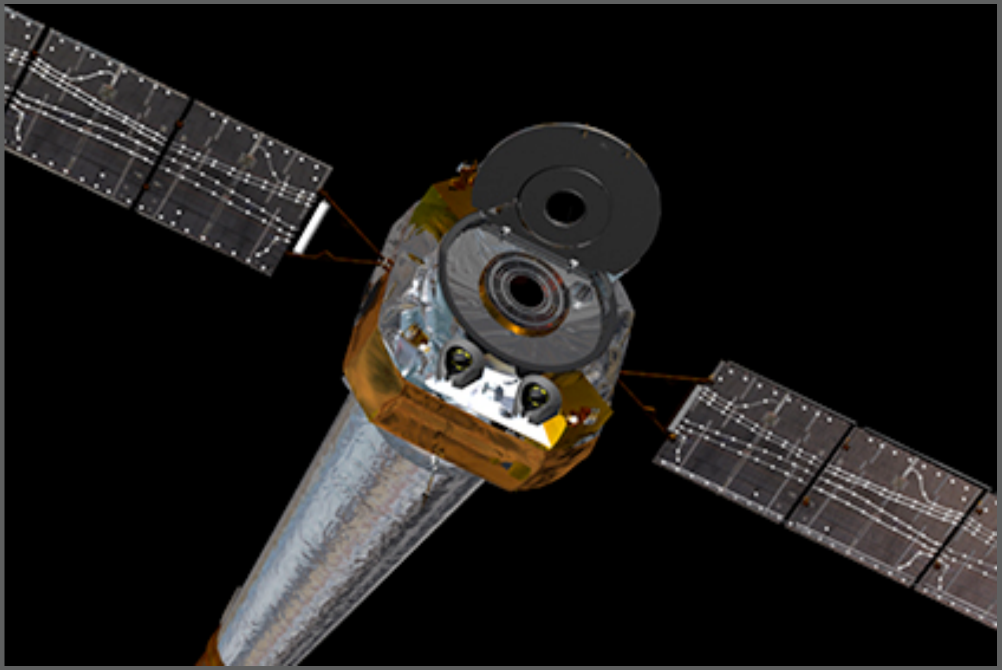
The clumping in 2-D simulations (density shown below) is on quite *small scales*



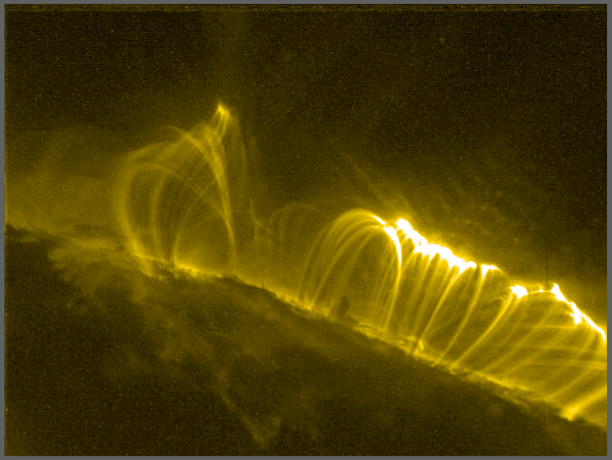
Dessart & Owocki 2003, *A&A*, 406, L1

The Data

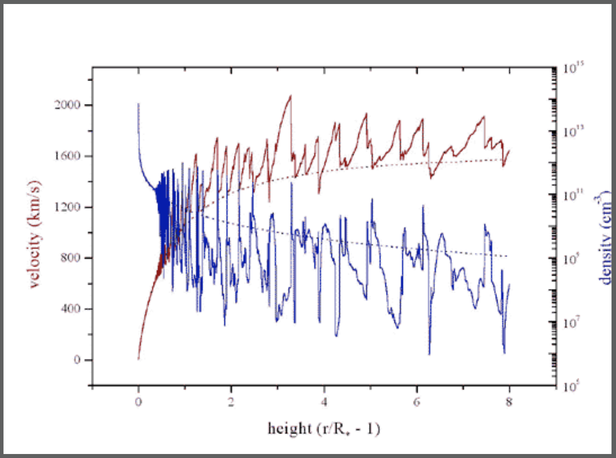
Chandra launched in 1999 - *50 X* better spectral resolution



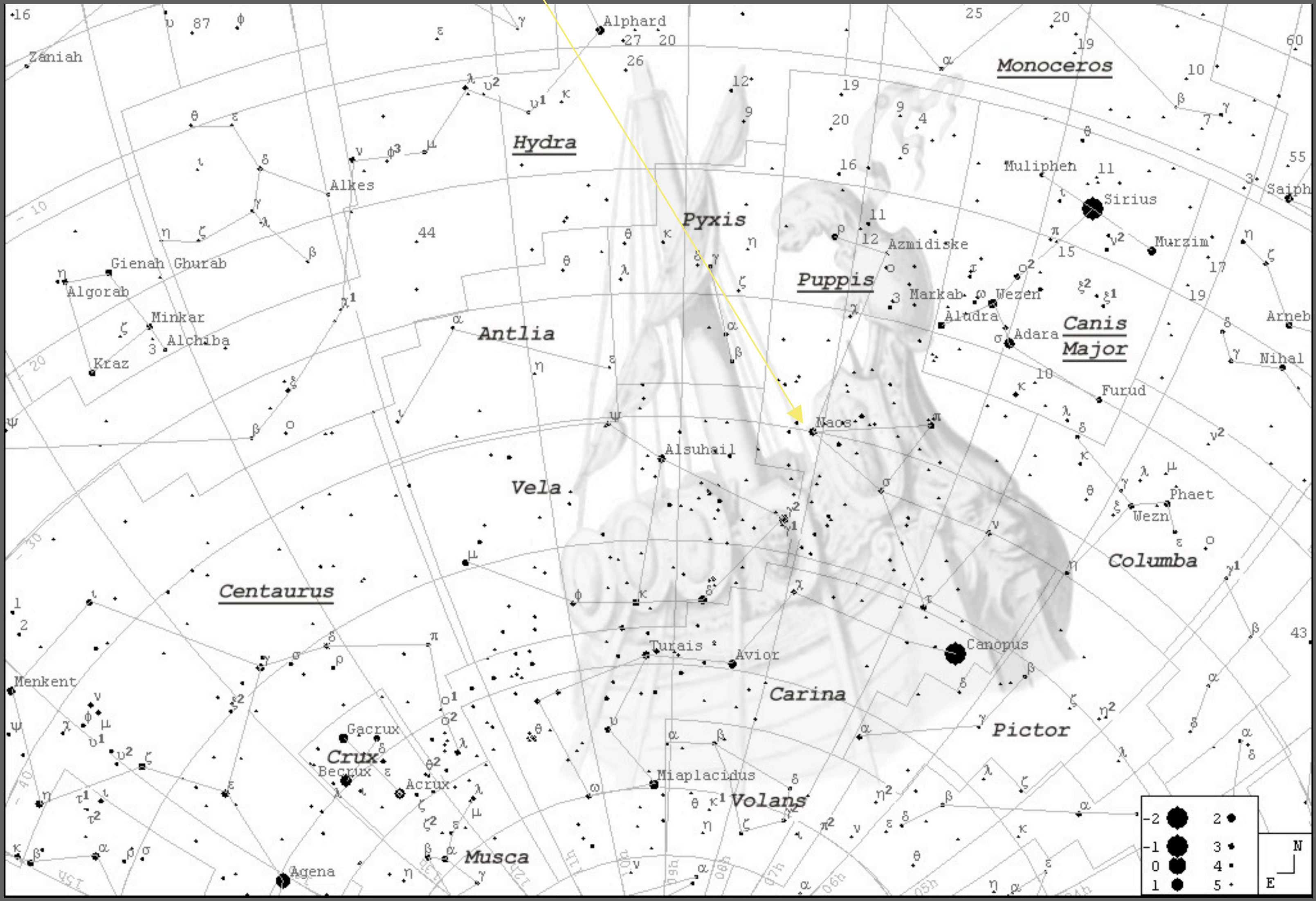
stationary? - narrow emission lines



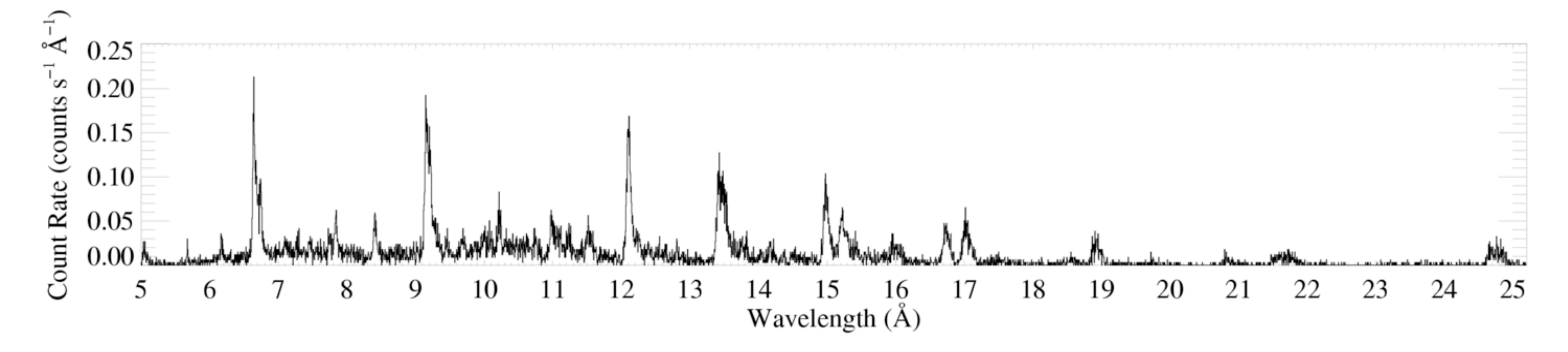
fast? - Doppler broadened lines



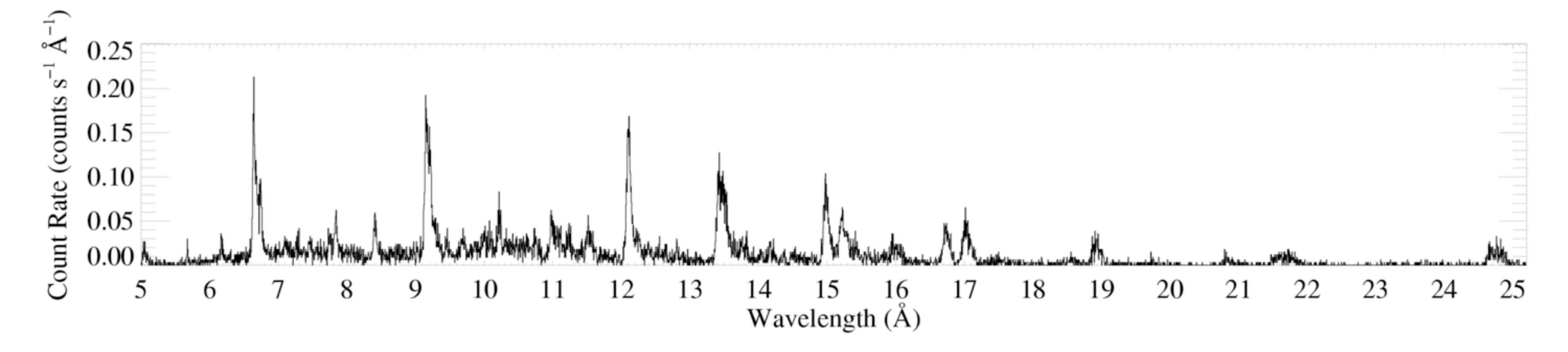
ζ Puppis: 50 M_{sun}, 10^6 L_{sun}

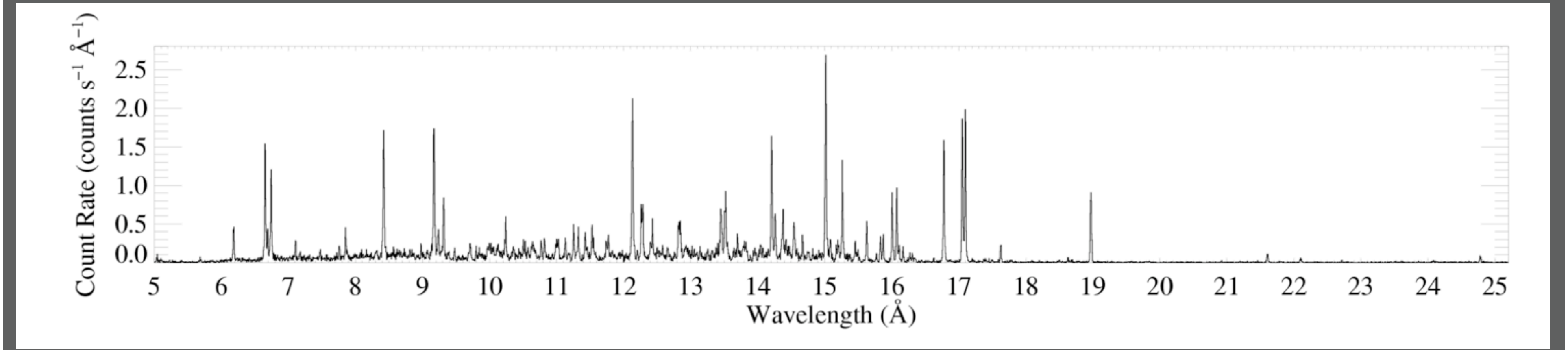


ζ Pup


Count Rate (counts s^{-1} Å^{-1})
0.25
0.20
0.15
0.10
0.05
0.00
5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25
Wavelength (Å)

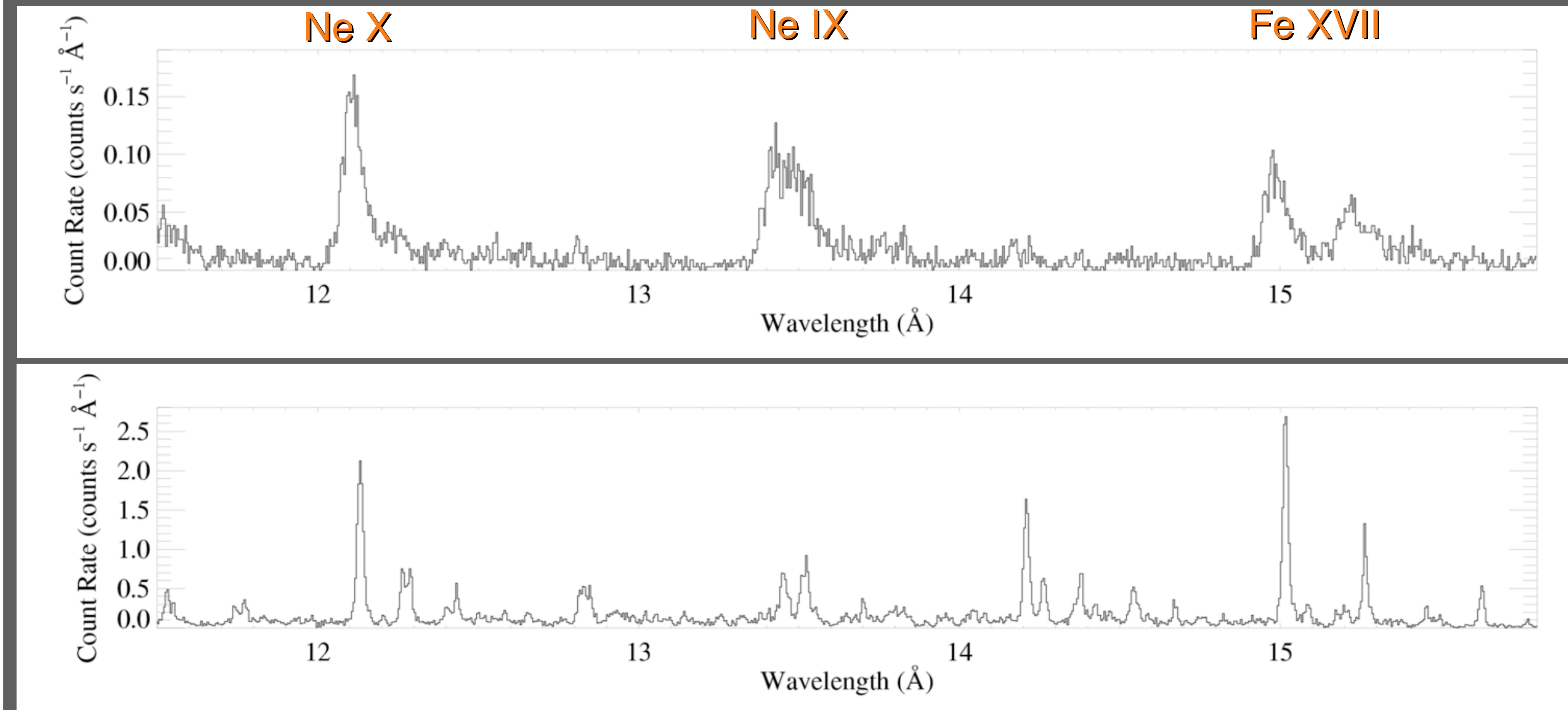
ζ Pup





Low-mass star (Capella) for comparison

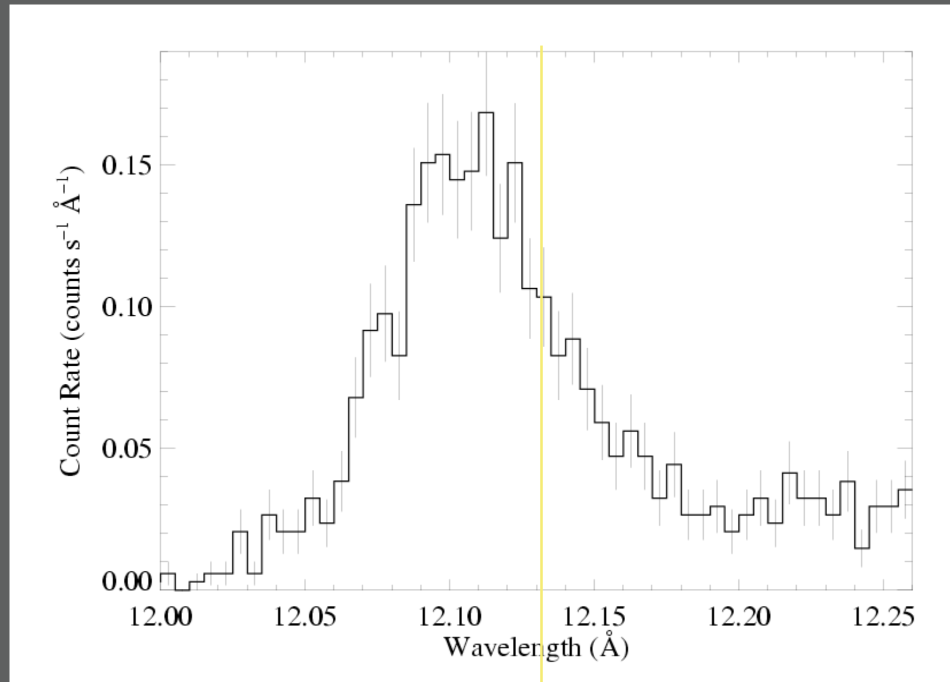
ζ Pup

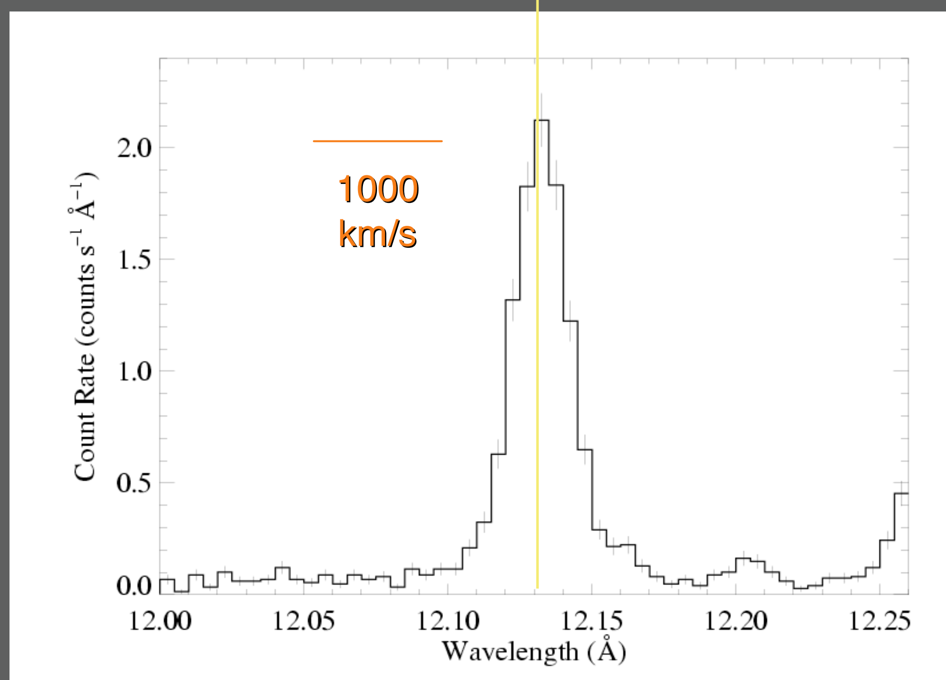


Capella

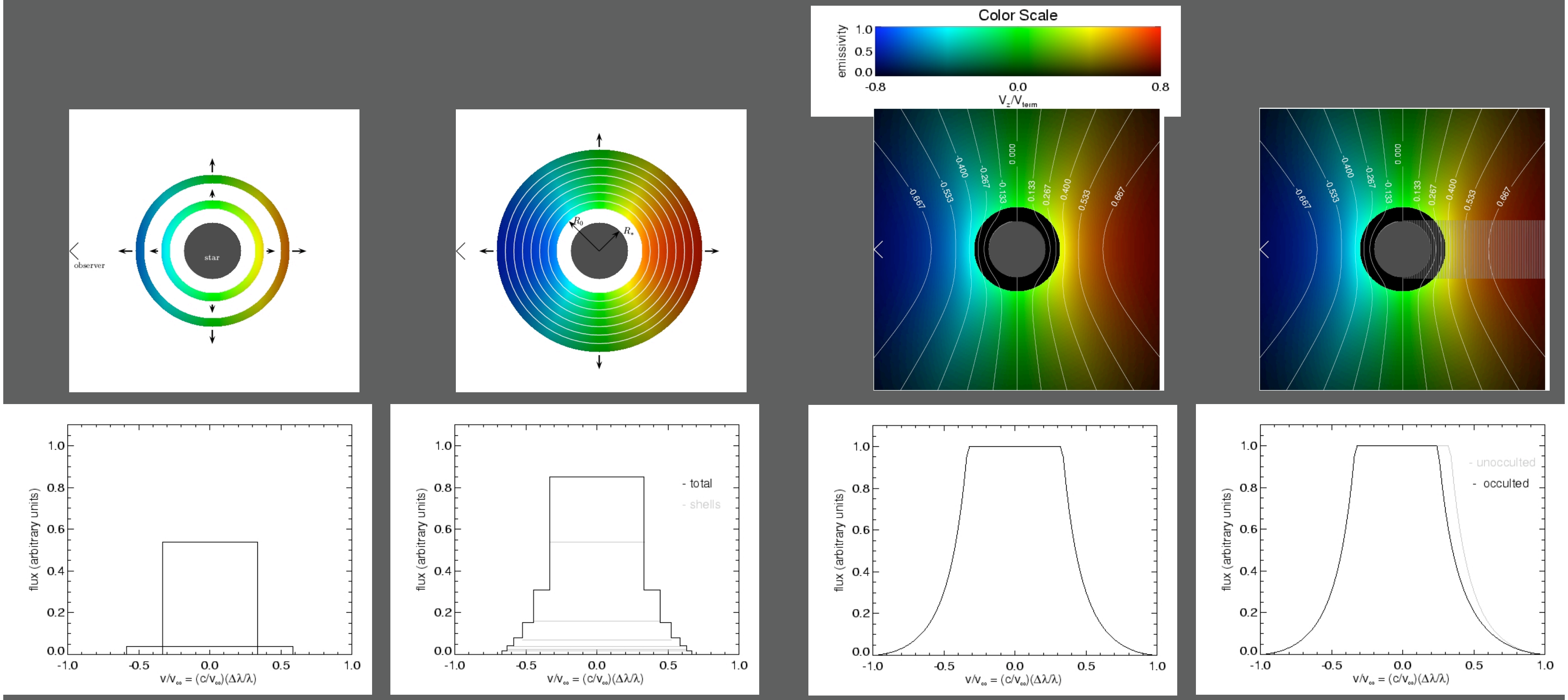
ζ Pup

Ne X: Lyman-α



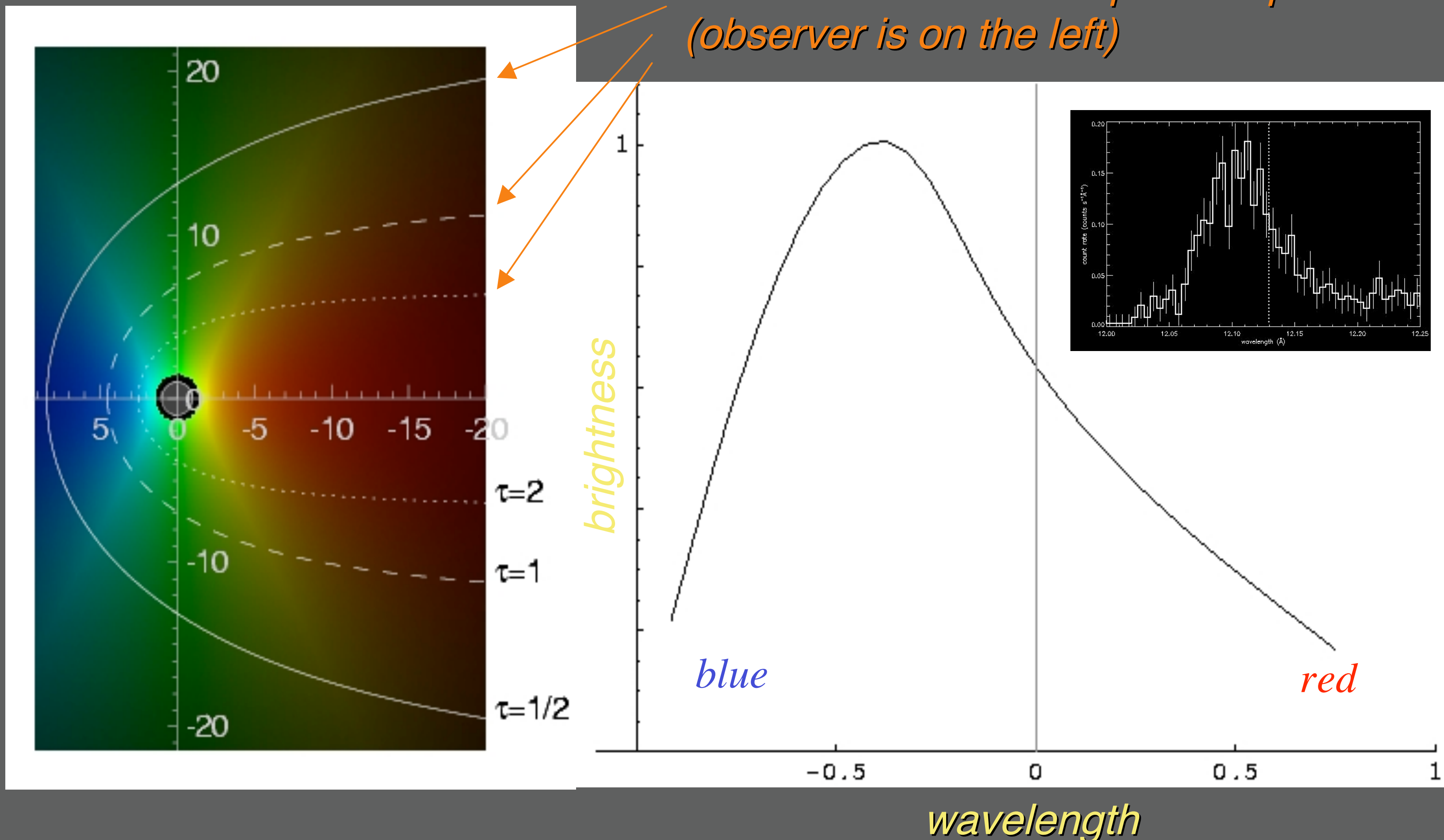


Capella



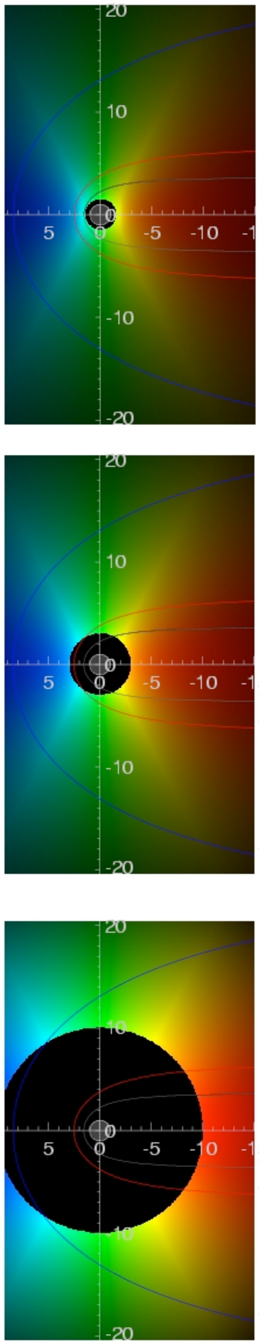
observer
star
R_0
R_*
Color Scale
emissivity
1.0
0.5
0.0
-0.8
0.0
0.8
V_z/V_{term}
-0.667
-0.533
-0.400
-0.267
-0.133
0.000
0.133
0.267
0.400
0.533
0.667
flux (arbitrary units)
$v/v_\infty = (c/v_\infty)(\Delta\lambda/\lambda)$
- total
- shells
- unocculted
- occulted

Contours of constant optical depth (observer is on the left)

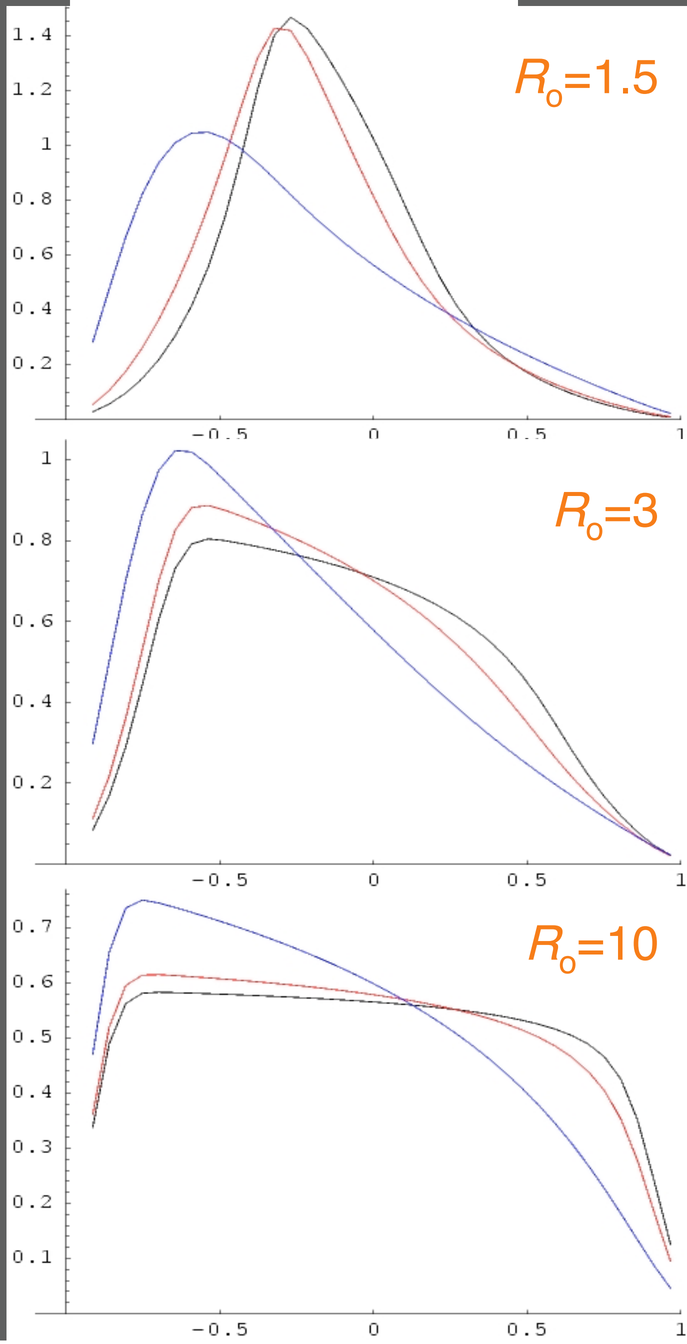


The basic wind-profile model

τ=1 contours



τ_*=1,2,8



key parameters: $\mathbf{R_o}$ & τ_*

$j \sim \rho^2$ for $r/R_* > R_o$,

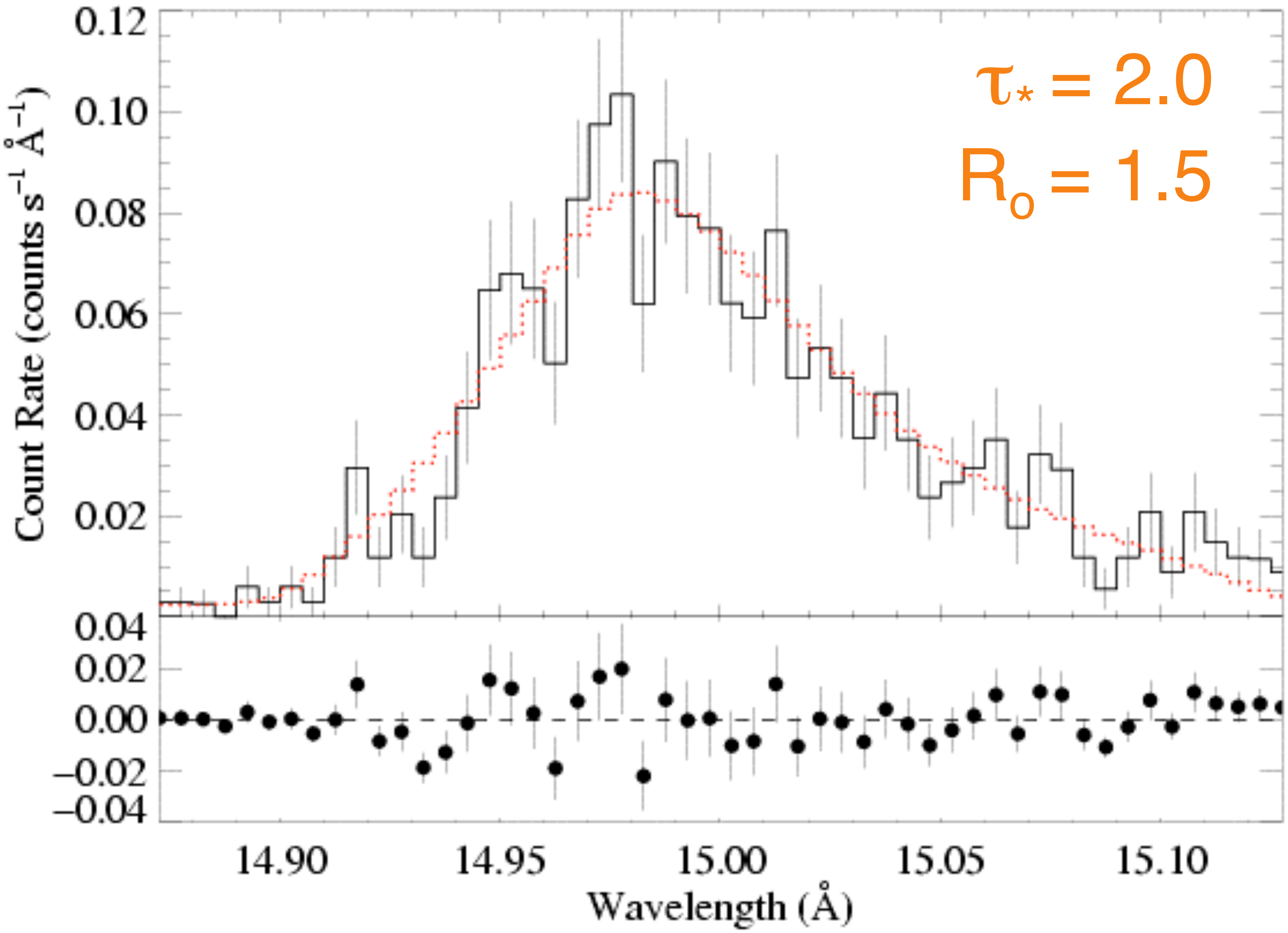
$= 0$ otherwise

$$\tau = \tau_* \int_z^\infty \frac{R_* dz'}{r'^2 (1 - R_*/r')^\beta}$$

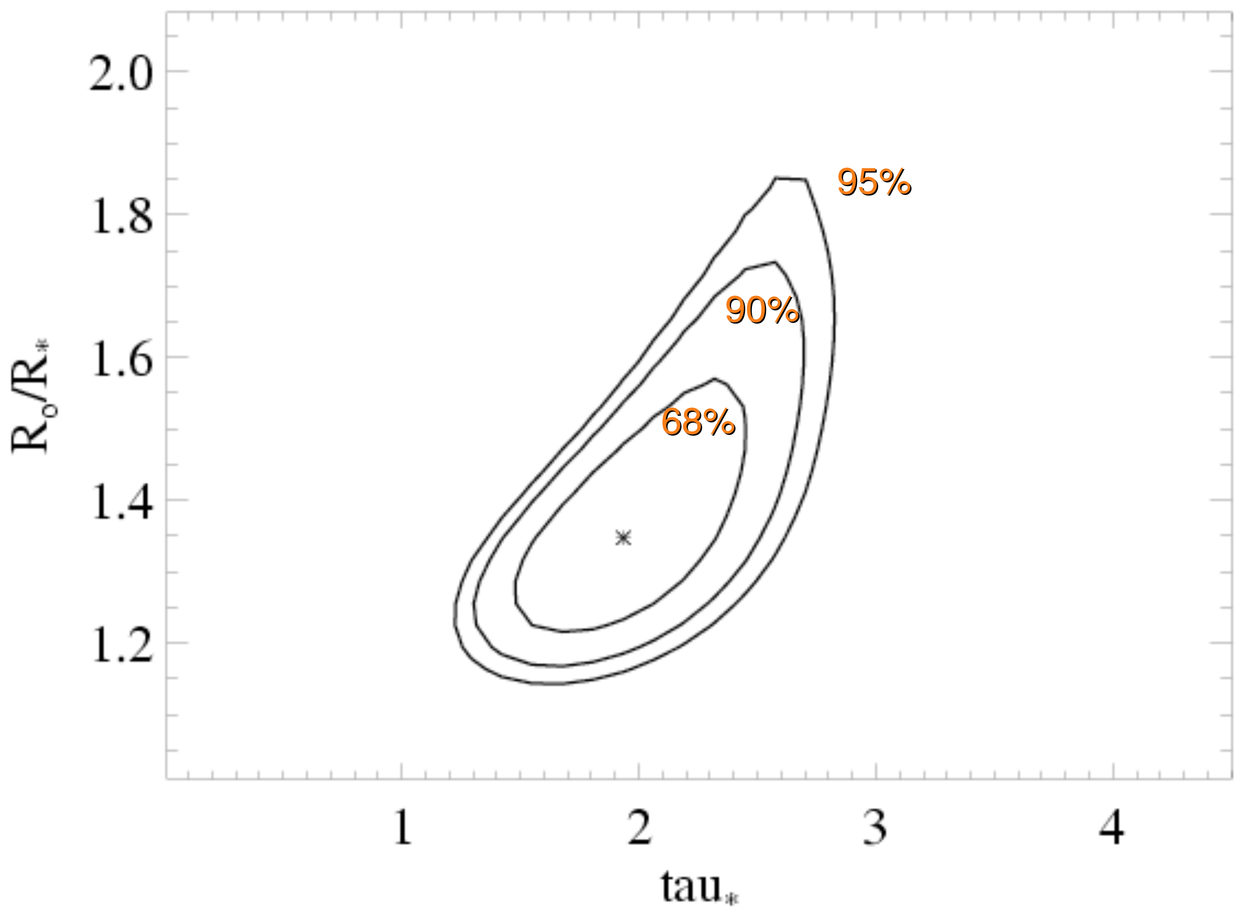
$$\tau_* \equiv \frac{\kappa \dot{M}}{4\pi R_* v_\infty}$$

Fitting this model to data

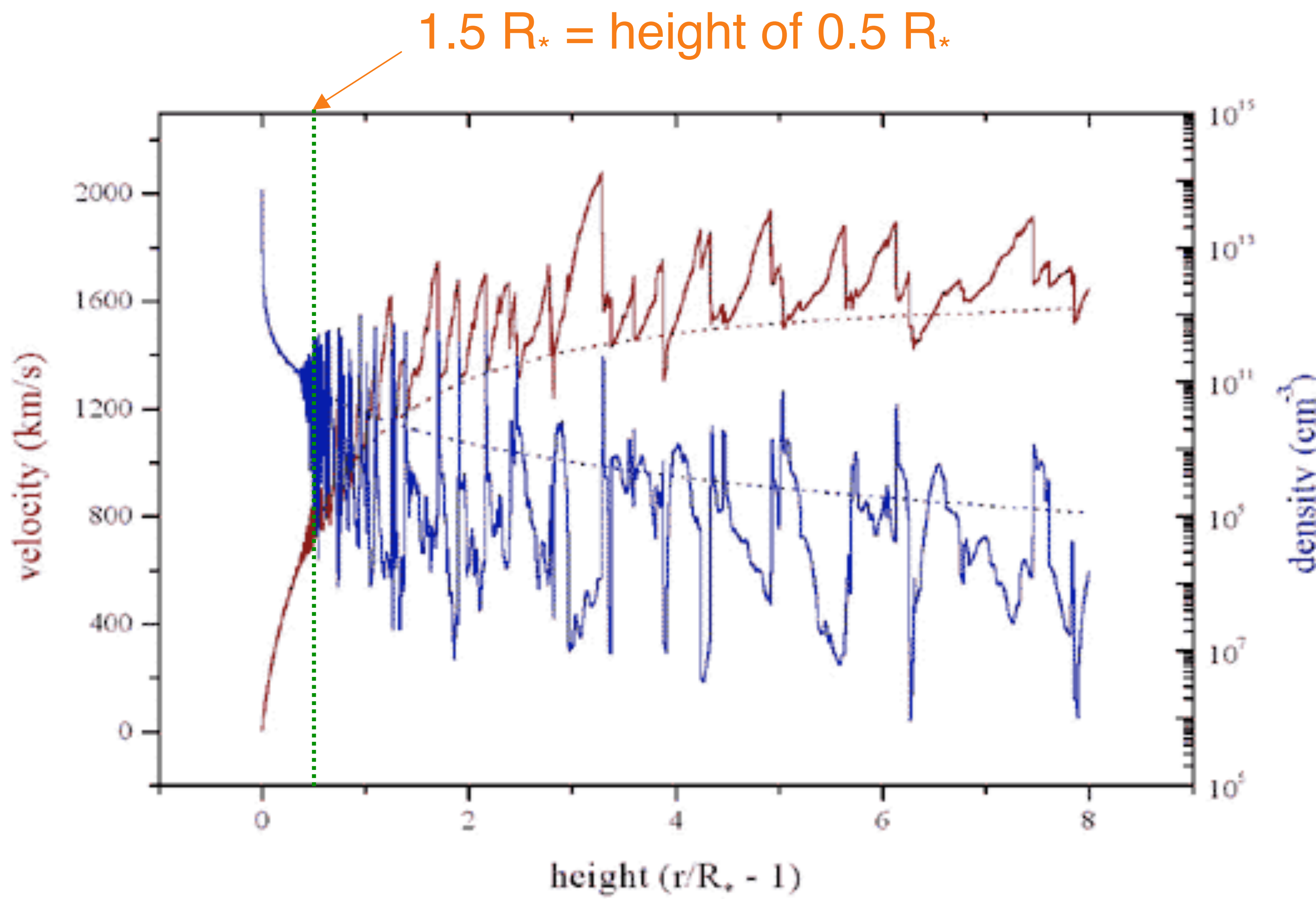
ζ Pup: Fe XVII line at 15.014 Å

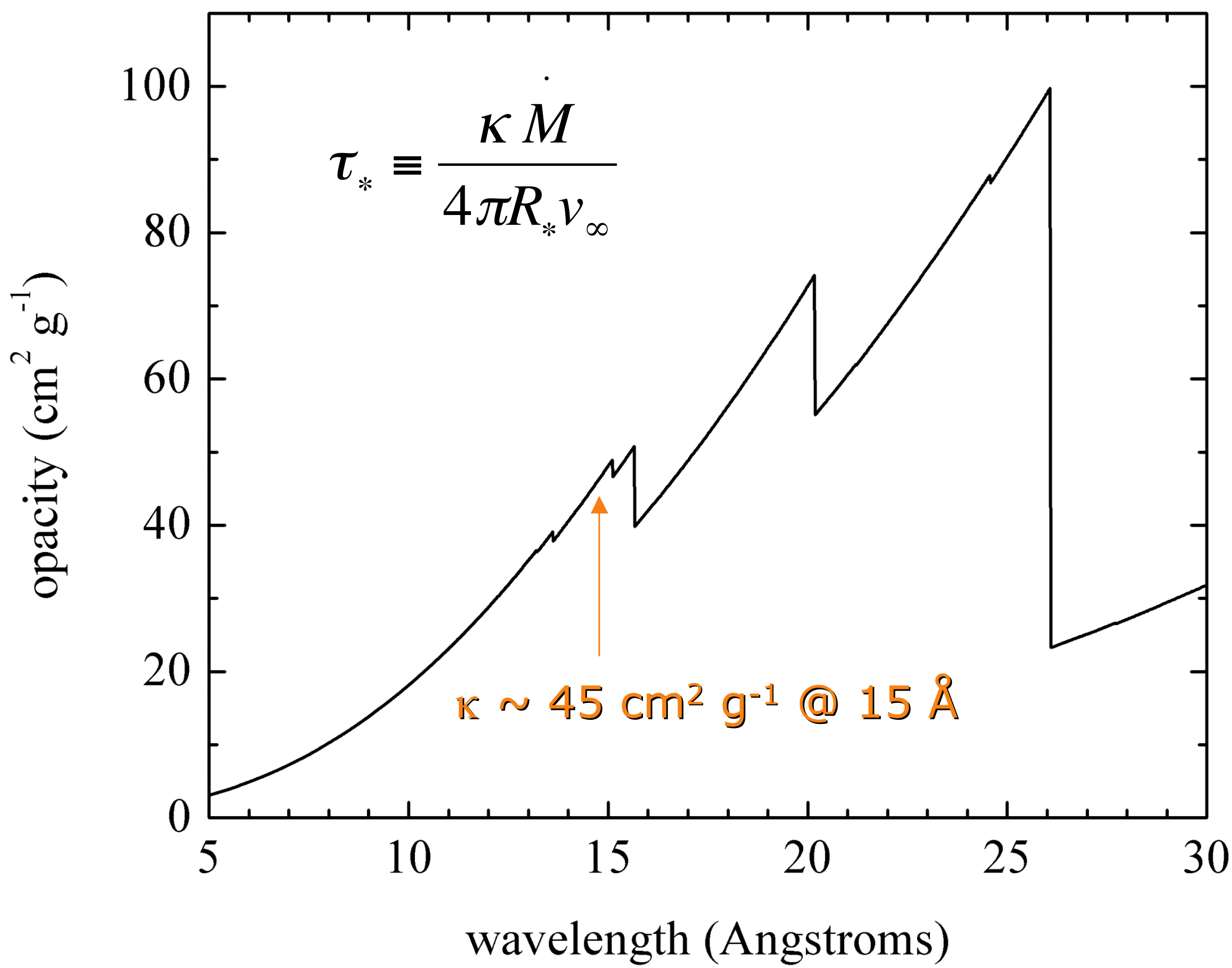


Confidence limits on fit parameters



Onset of instability-induced shock structure: $R_o \sim 1.5$





$\tau_* \equiv \frac{\kappa \dot{M}}{4\pi R_* v_\infty}$
κ ~ 45 cm² g⁻¹ @ 15 Å
opacity ($cm^2\ g^{-1}$)
wavelength (Angstroms)
0
20
40
60
80
100
5
10
15
20
25
30

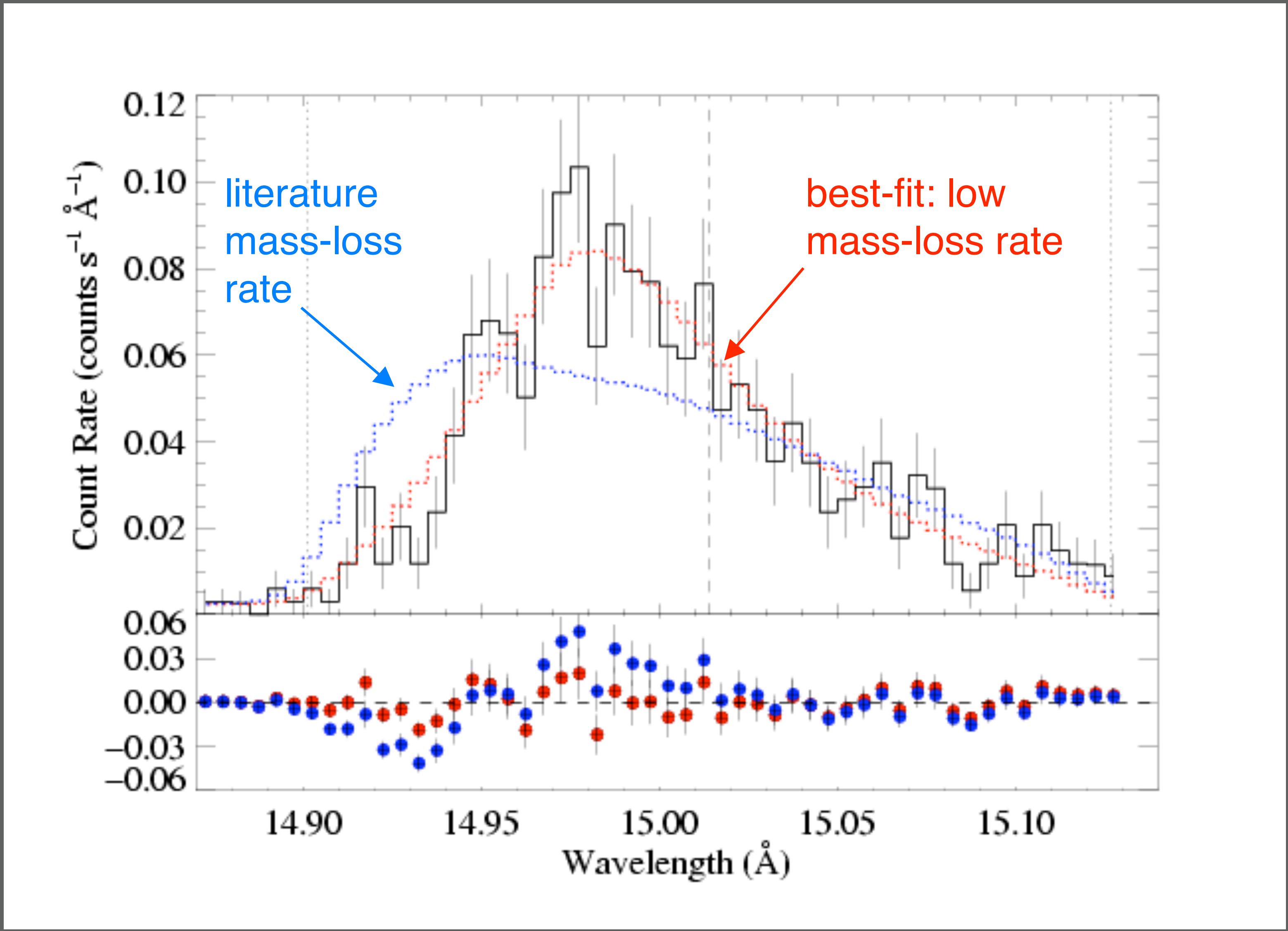
$$\tau_* \equiv \frac{\kappa \dot{M}}{4\pi R_* v_\infty}$$

for $\tau_* = 2$

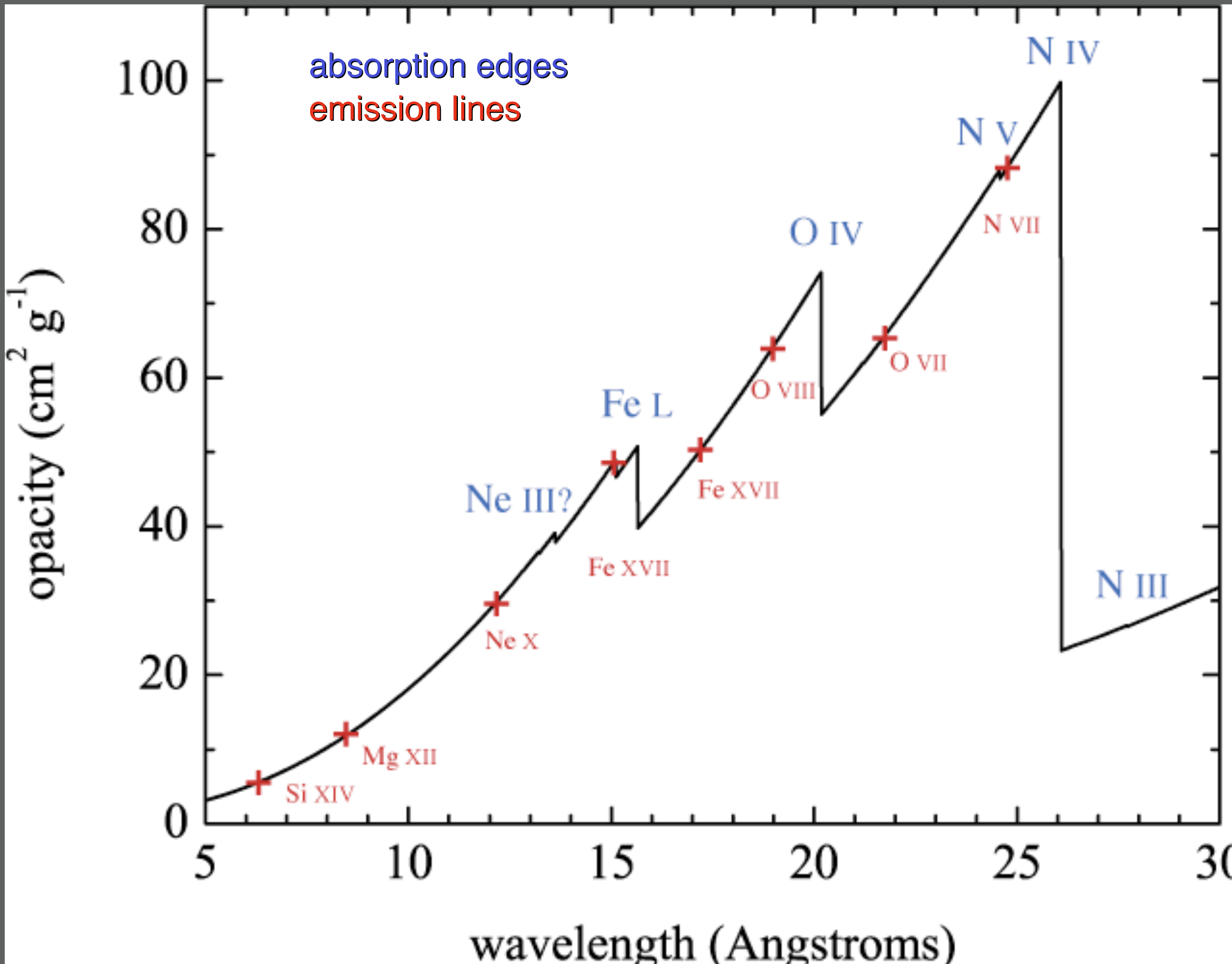
$\dot{M} = 3.0 \times 10^{-6}\ M_{sun}/yr$

A **factor of 3** reduction in mass-loss rate over the literature value of $8.8 \times 10^{-6}\ M_{sun}/yr$

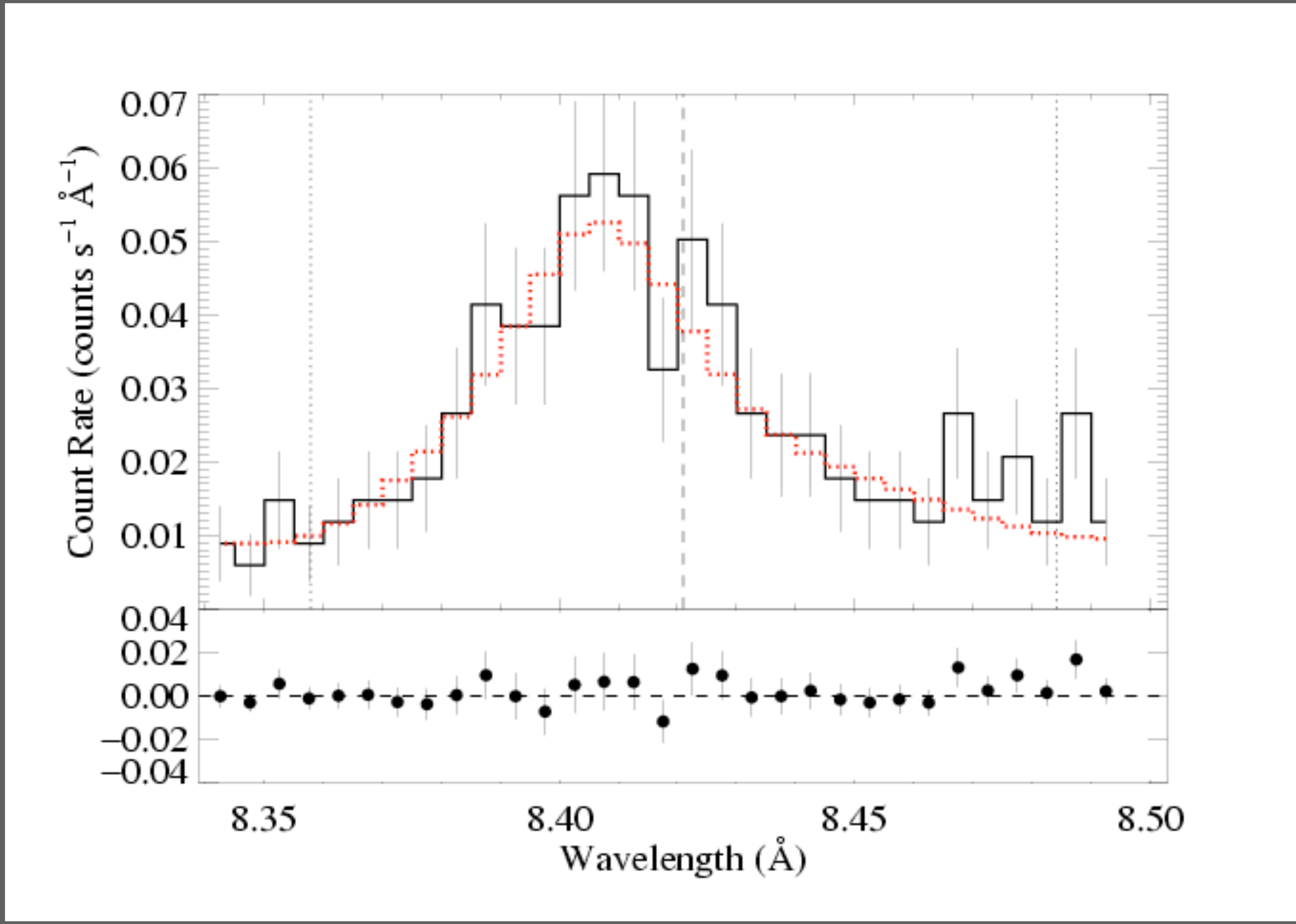
ζ Pup: Fe XVII line at 15.014 Å - again



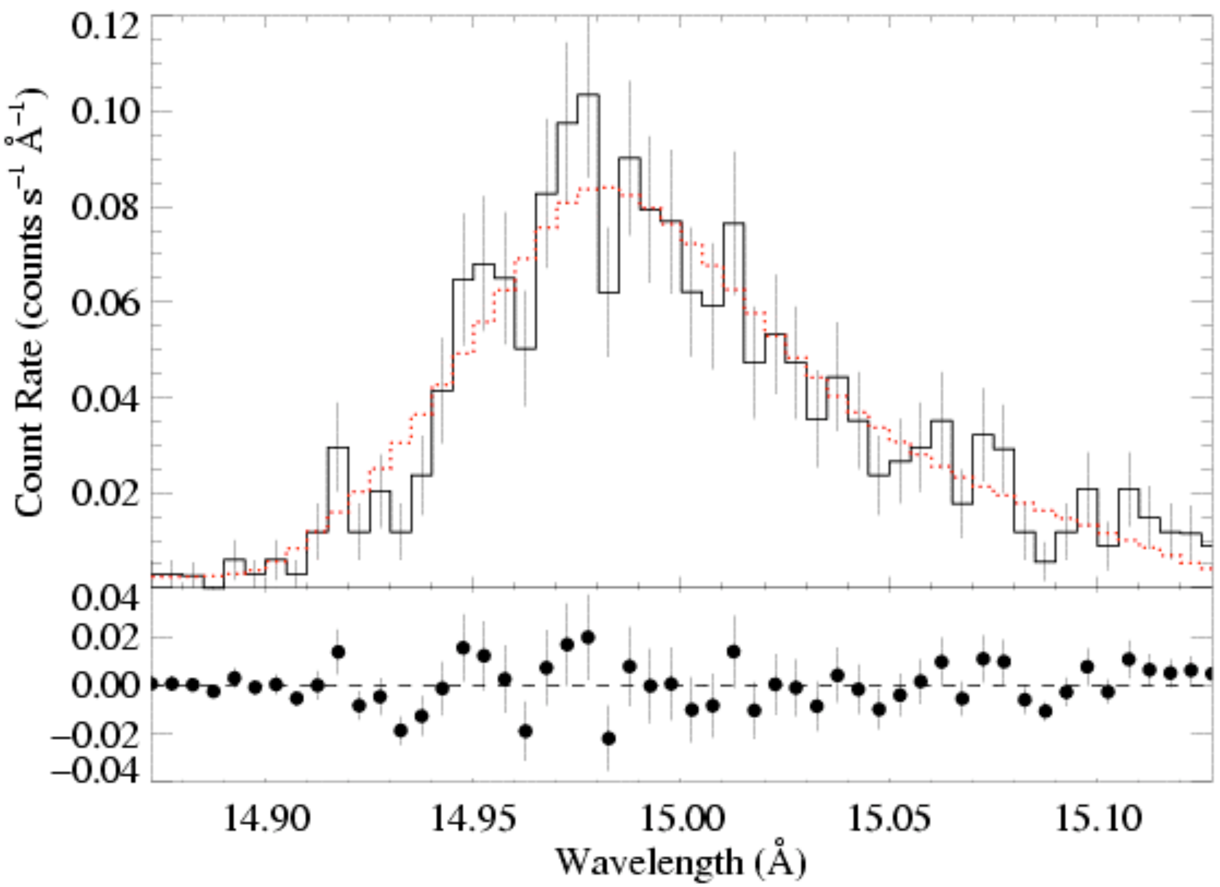
Different lines, different opacities



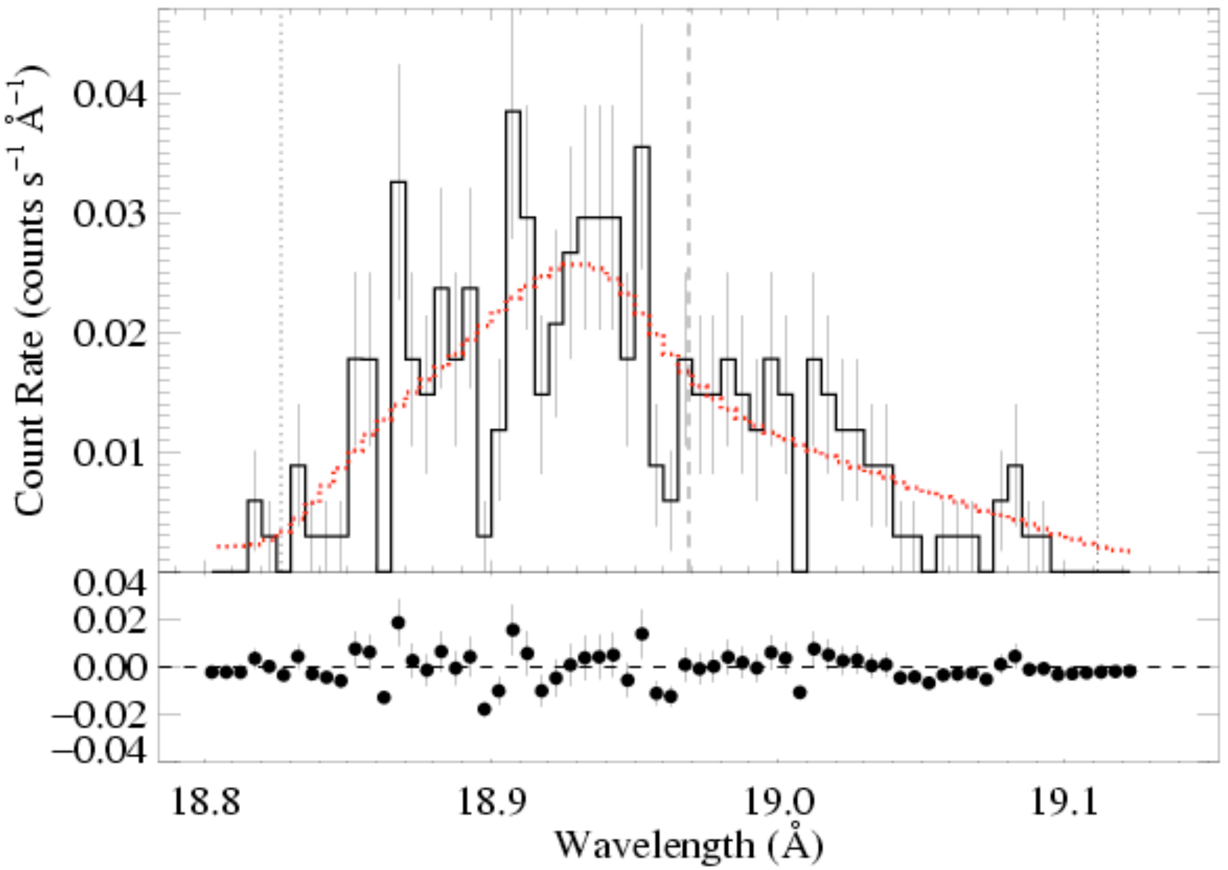
Mg XII Lyman-α: $\tau_{*}=1$



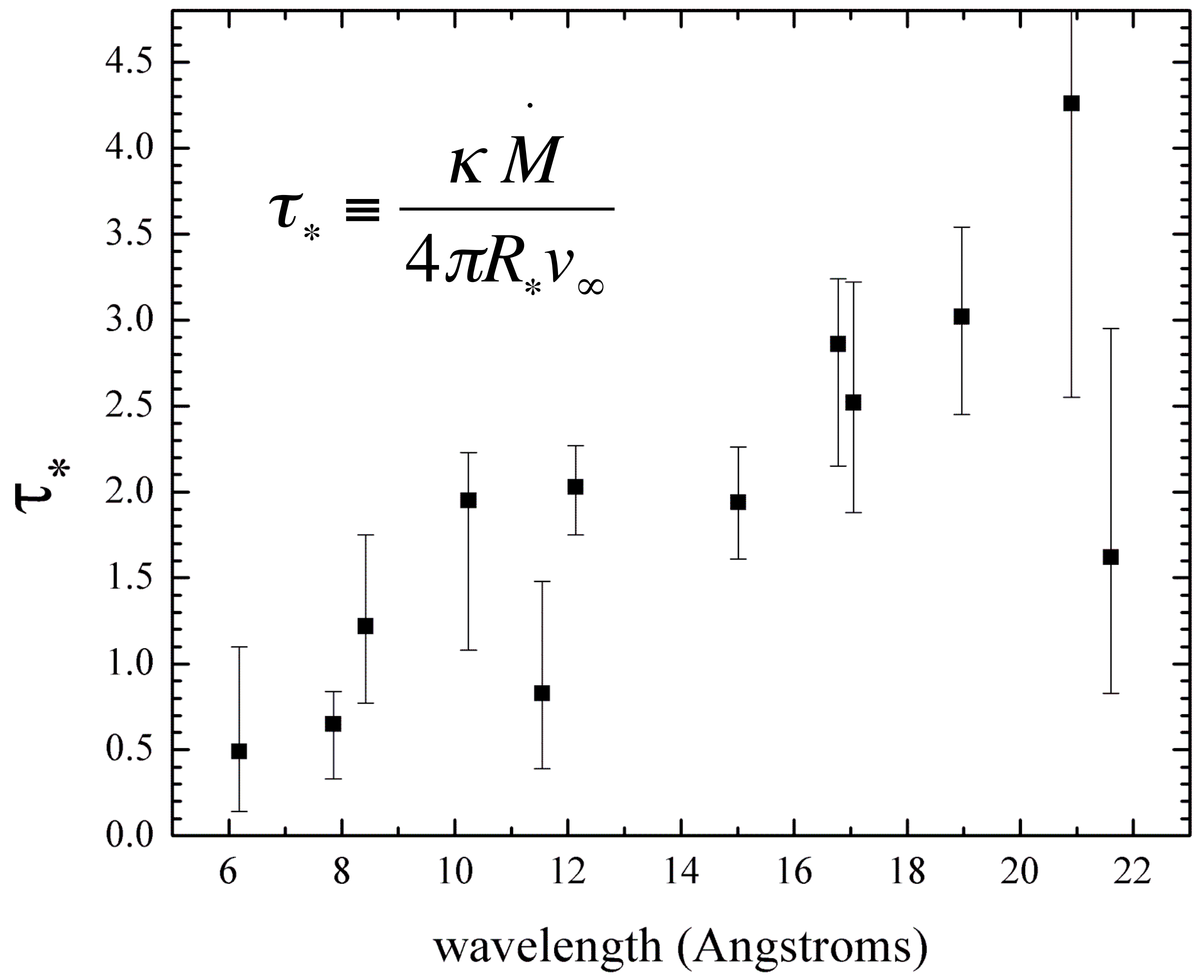
Fe XVII : τ_*=2


Count Rate (counts s^{-1} Å^{-1})
0.12
0.10
0.08
0.06
0.04
0.02
0.04
0.02
0.00
−0.02
−0.04
14.90
14.95
15.00
15.05
15.10
Wavelength (Å)

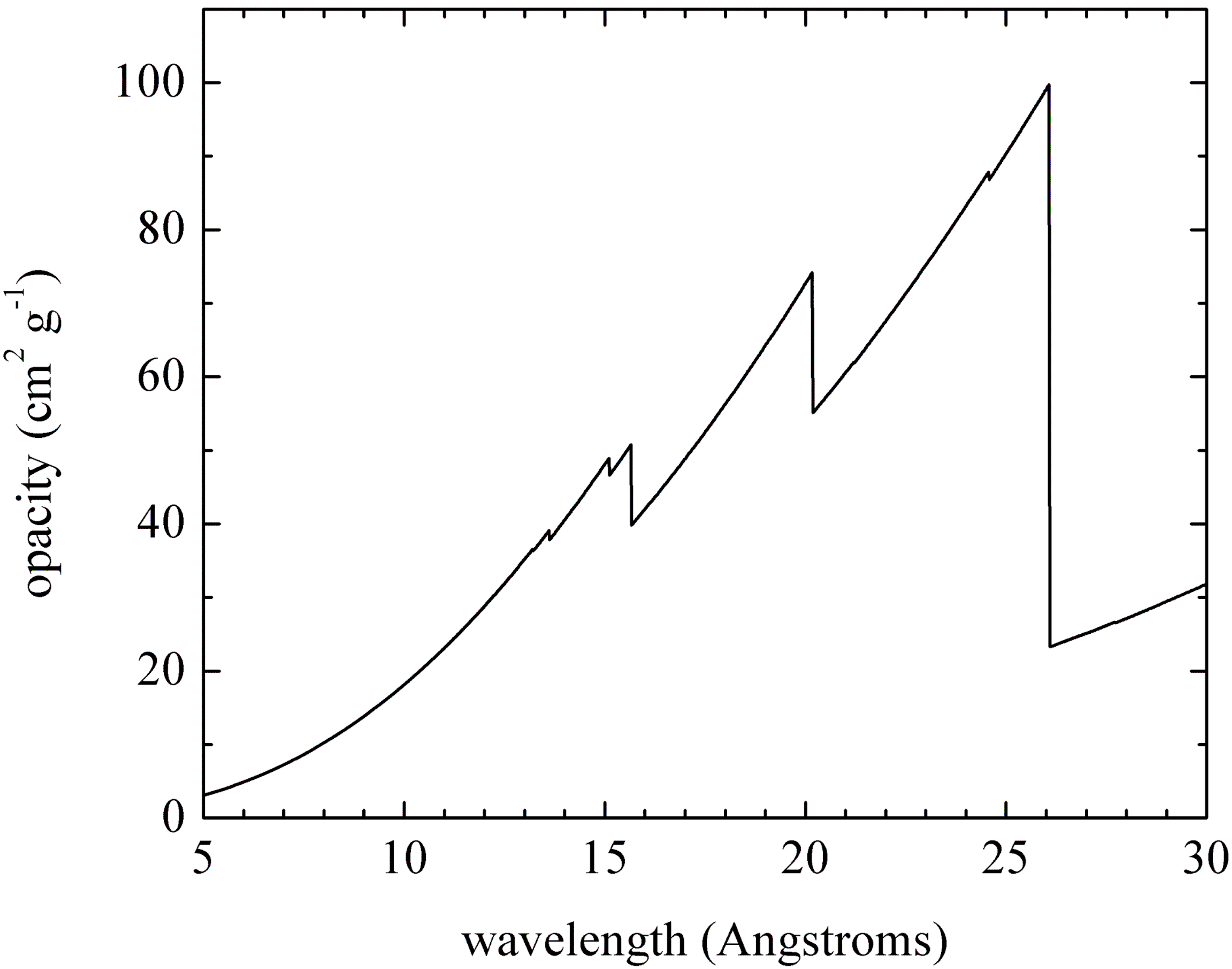
O VIII Lyman-α: τ_*=3



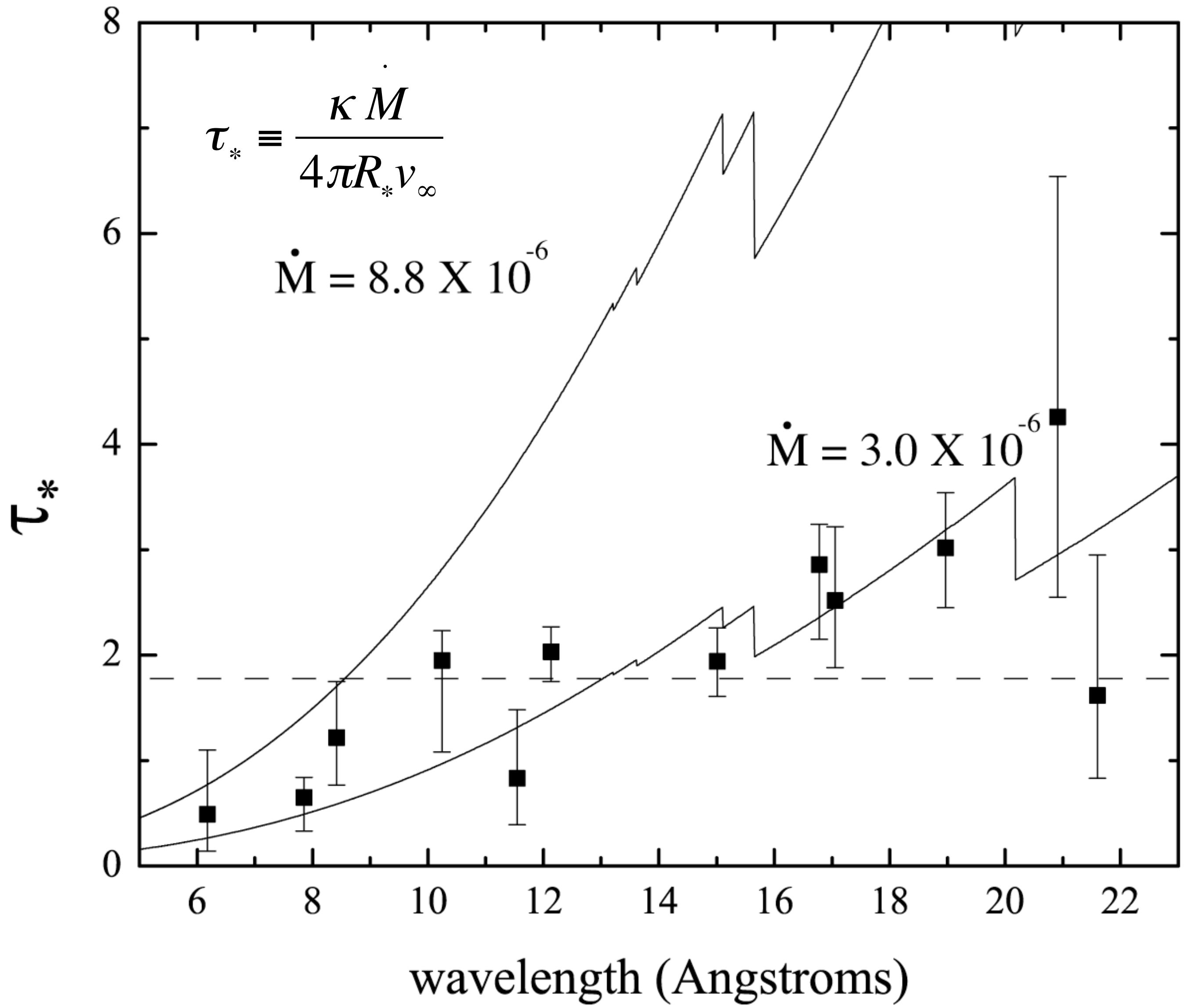
Empirical τ_* trend for ζ Pup



opacity, κ

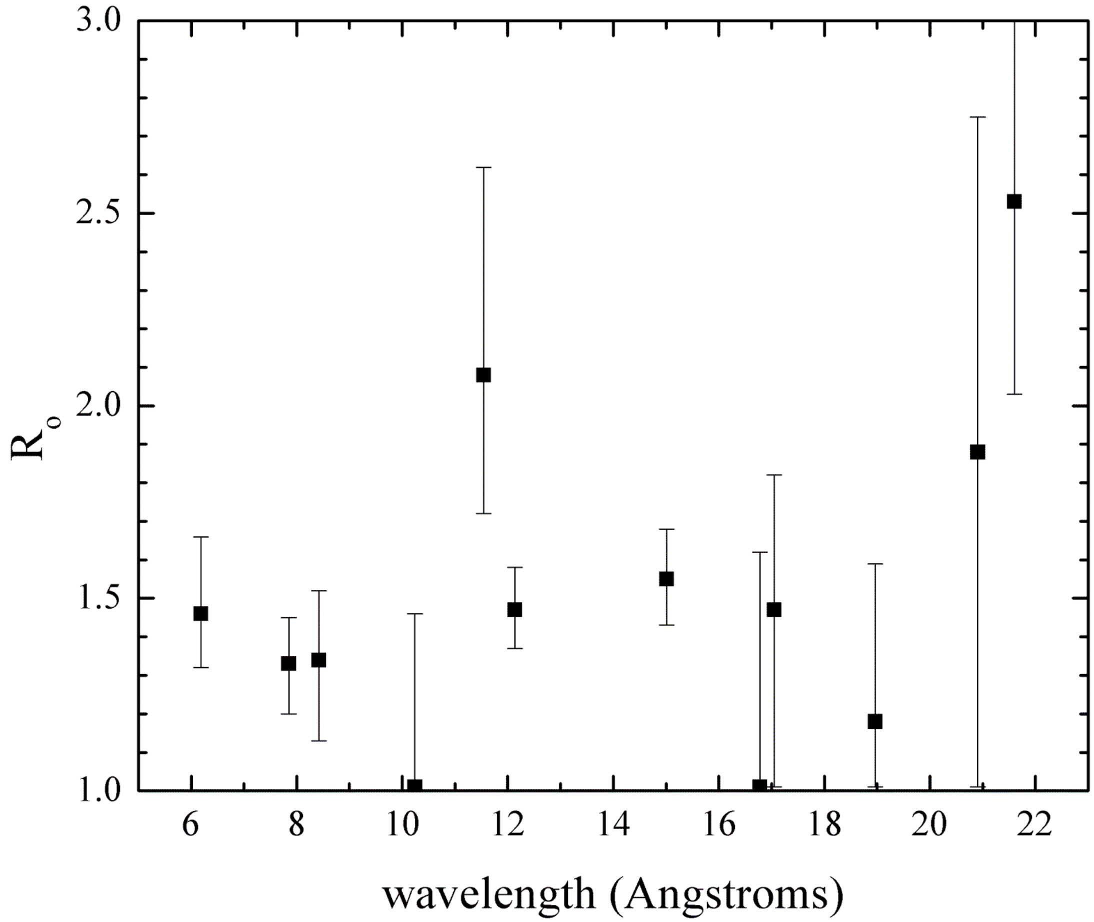


opacity (cm² g⁻¹)
0
20
40
60
80
100
5
10
15
20
25
30
wavelength (Angstroms)

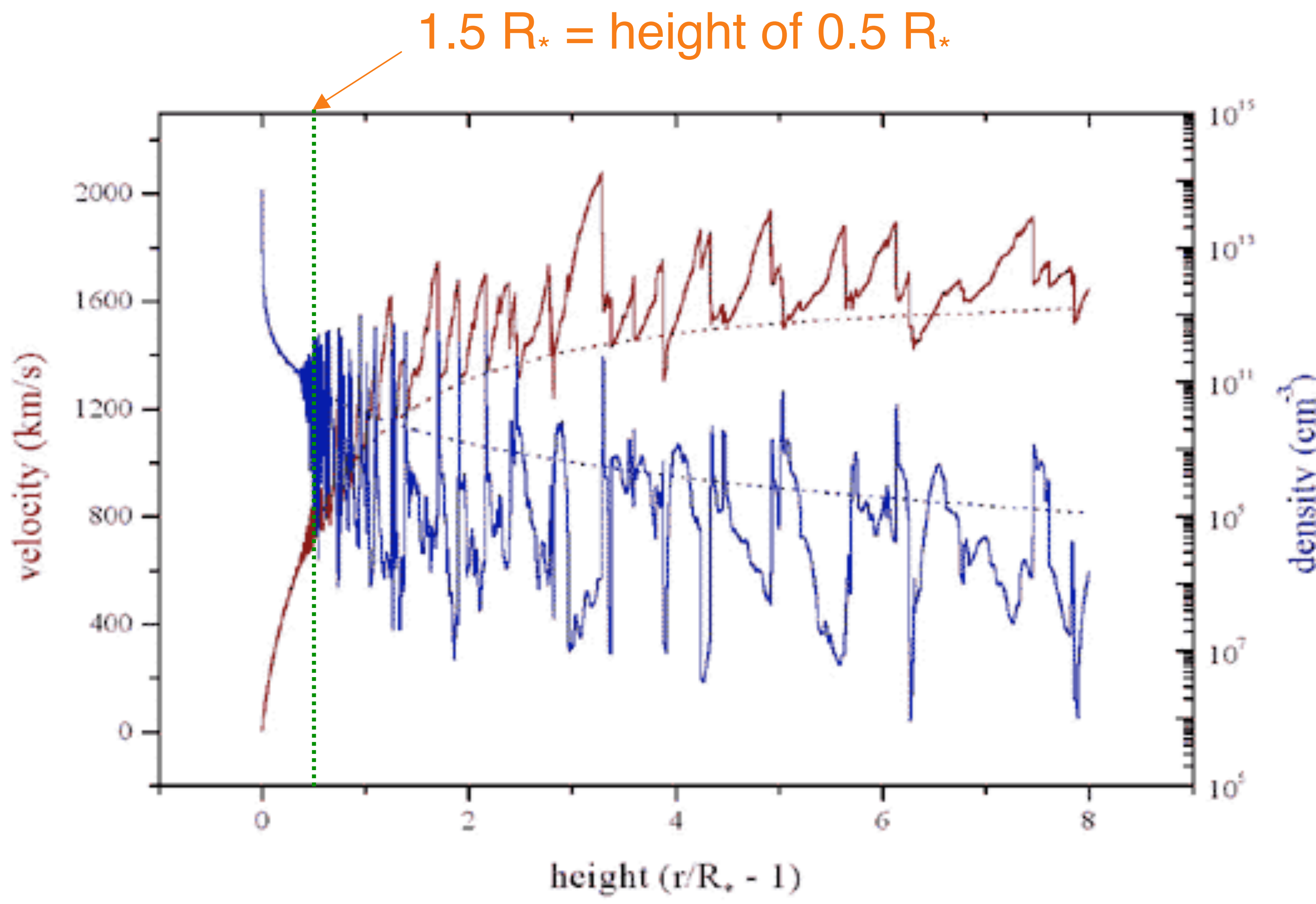


$\tau_* \equiv \frac{\kappa \dot{M}}{4\pi R_* v_\infty}$
$\dot{M}$ = 8.8 X 10^{-6}
$\dot{M}$ = 3.0 X 10^{-6}
τ_*
0
2
4
6
8
6
8
10
12
14
16
18
20
22
wavelength (Angstroms)

R_o values for each line are consistent

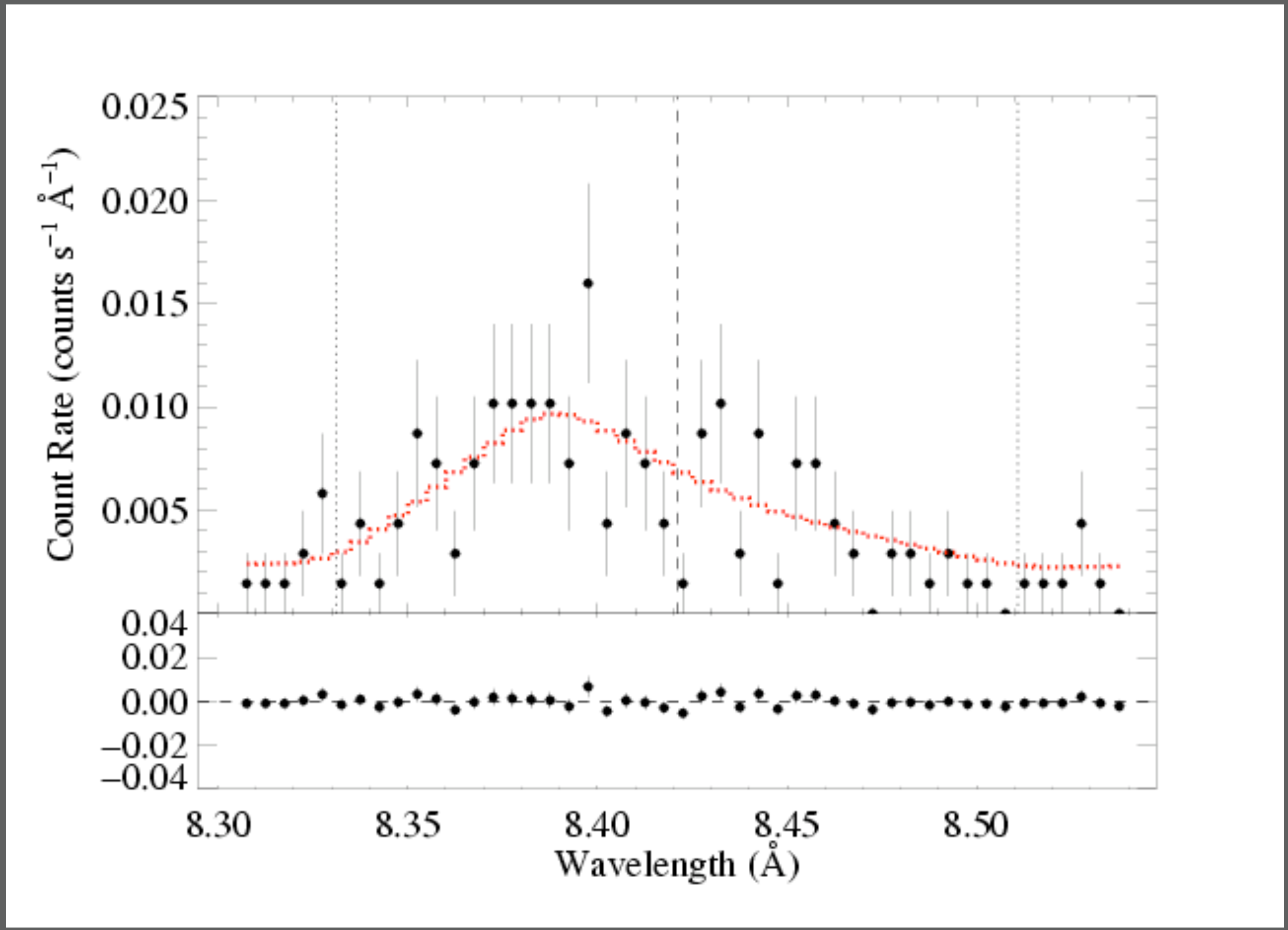


Onset of instability-induced shock structure: $R_o \sim 1.5$

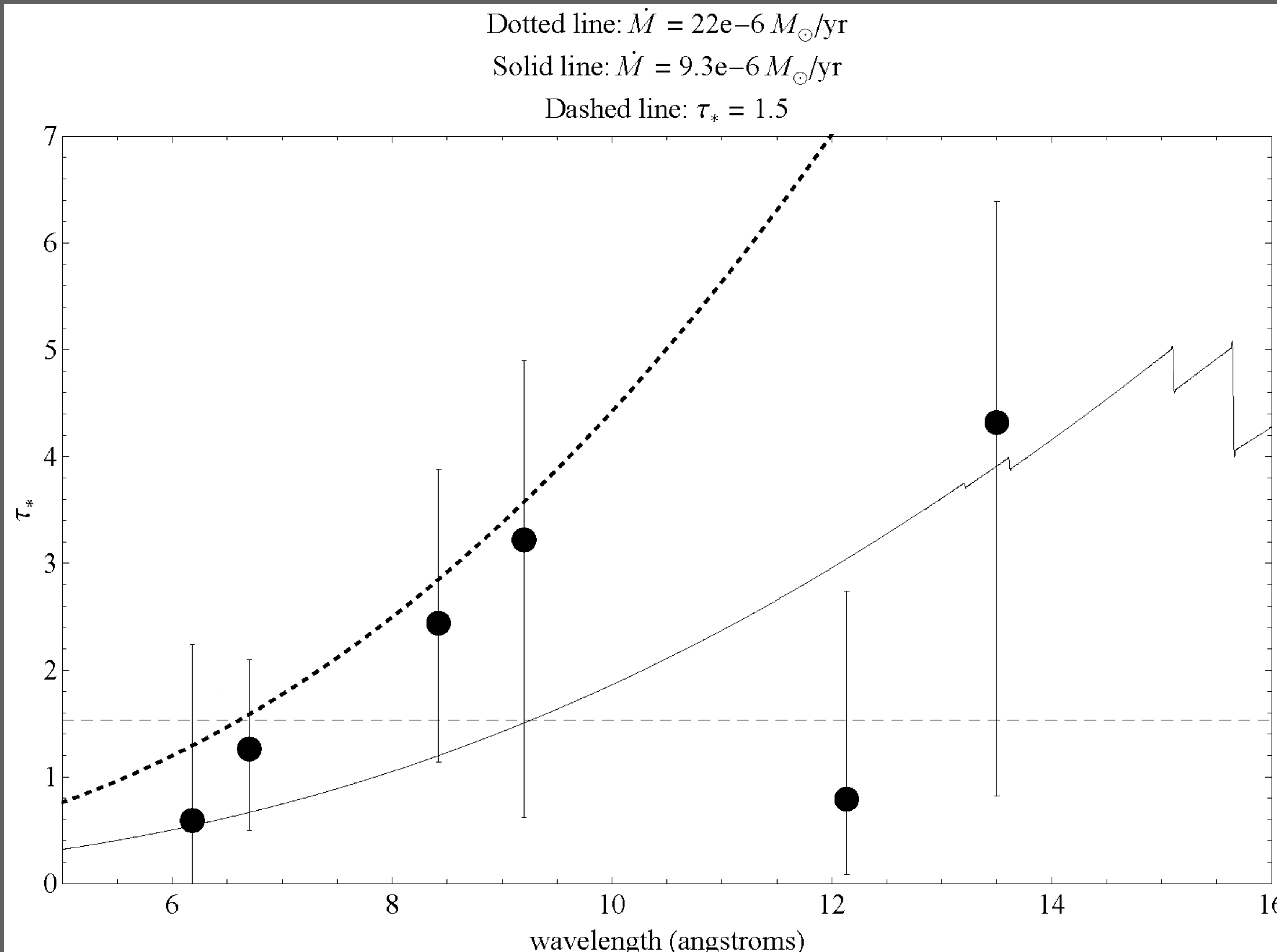


What about other stars?

HD93129: O2.5 - most massive (100 M_{sun})



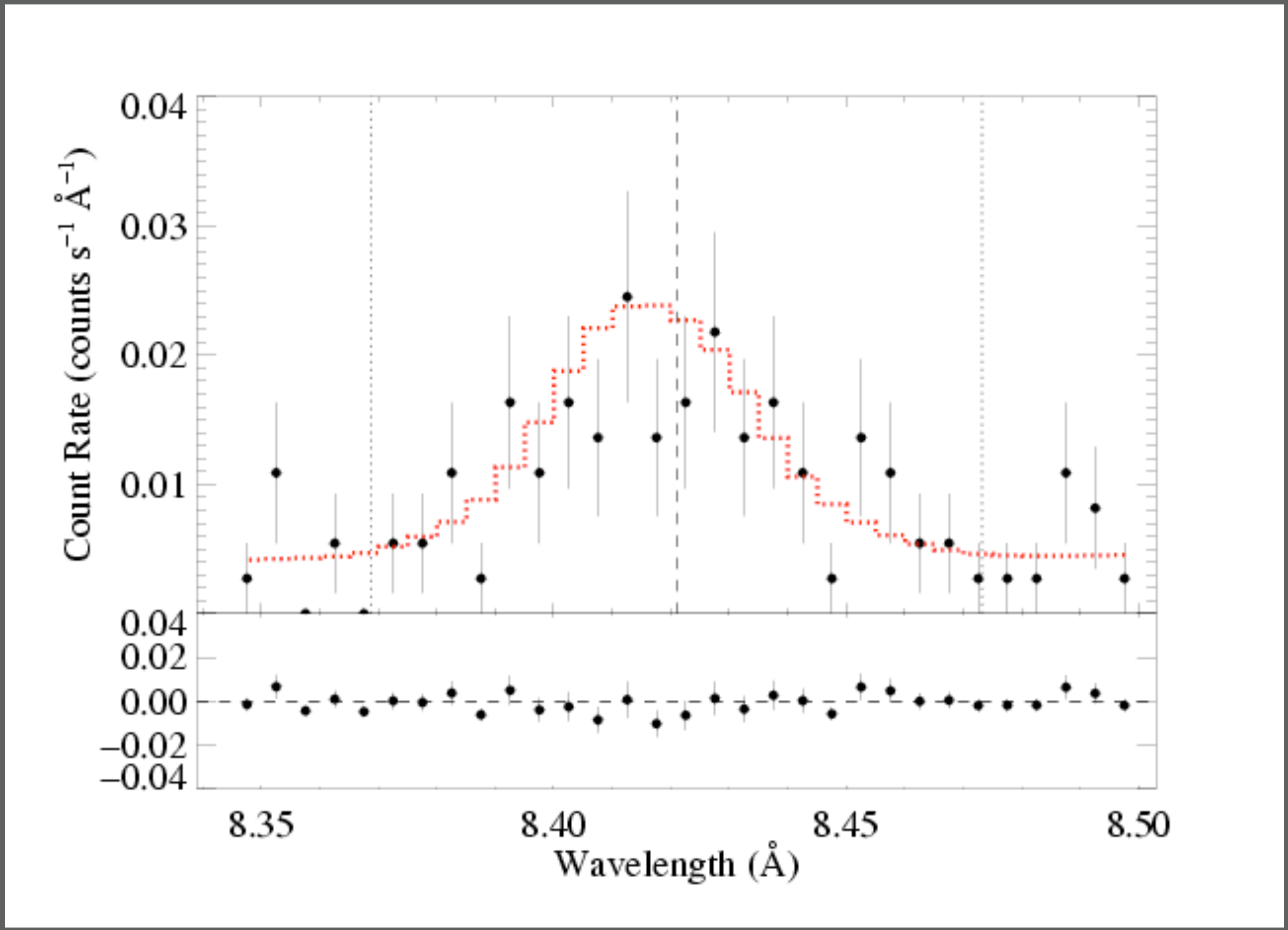
Mg XII Lyman-α: $\tau_* = 2.5$



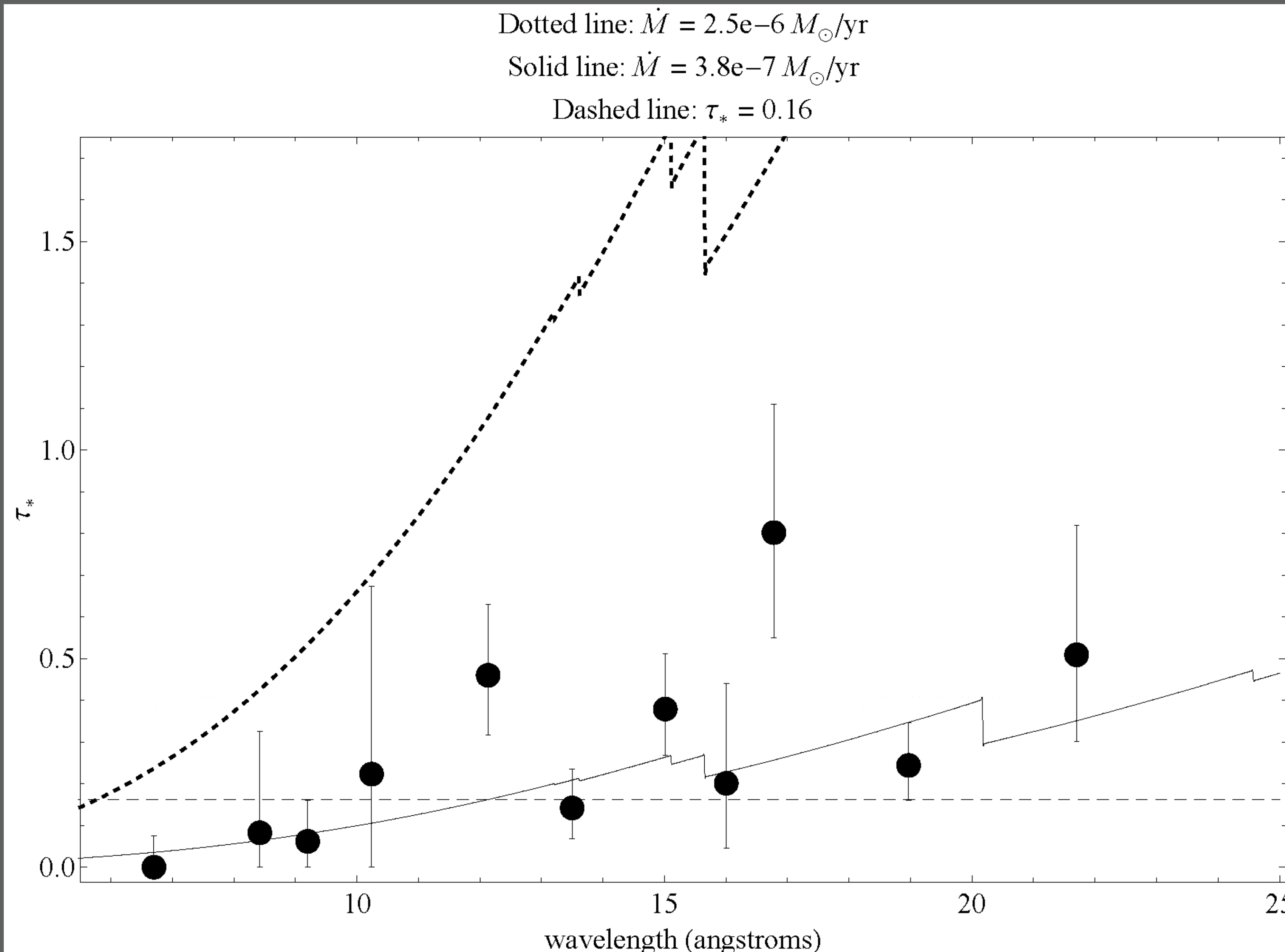
Dotted line: $\dot{M}$ = 22e−6 $M_\odot$/yr
Solid line: $\dot{M}$ = 9.3e−6 $M_\odot$/yr
Dashed line: τ_* = 1.5
τ_*
0
1
2
3
4
5
6
7
6
8
10
12
14
16
wavelength (angstroms)

ζ Ori: O9.5

ζ Ori: O9.5 - less massive



Mg XII Lyman-α: $\tau_* = 0.1$



Dotted line: $\dot{M}$ = 2.5e−6 $M_\odot$/yr
Solid line: $\dot{M}$ = 3.8e−7 $M_\odot$/yr
Dashed line: τ_* = 0.16
1.5
1.0
0.5
0.0
τ_*
10
15
20
25
wavelength (angstroms)

Wind shock scenario: consistent with X-ray line profiles…

…but mass-loss rates must be revised downward!

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Astronomy & Astrophysics

Lower mass loss rates in O-type stars: Spectral signatures of dense clumps in the wind of two Galactic O4 stars*

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THE DISCORDANCE OF MASS-LOSS ESTIMATES FOR GALACTIC O-TYPE STARS

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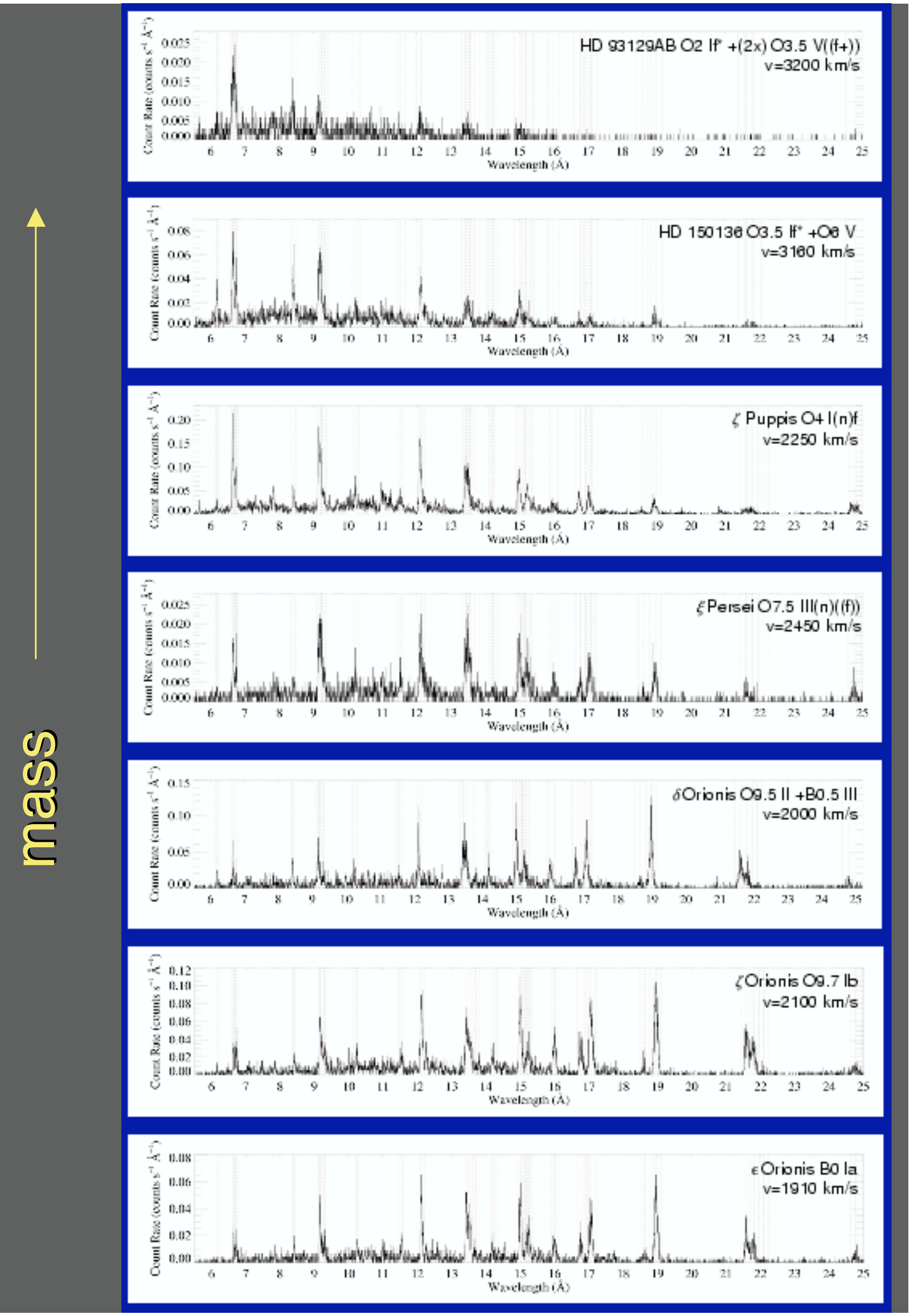
Received 2005 June 10; accepted 2005 October 4

What about the overall trends in massive star X-ray spectra?

Observed trend: higher mass stars have harder X-ray emission



Is this a temperature/ionization trend?

Multiwavelength Systematics of OB Spectra

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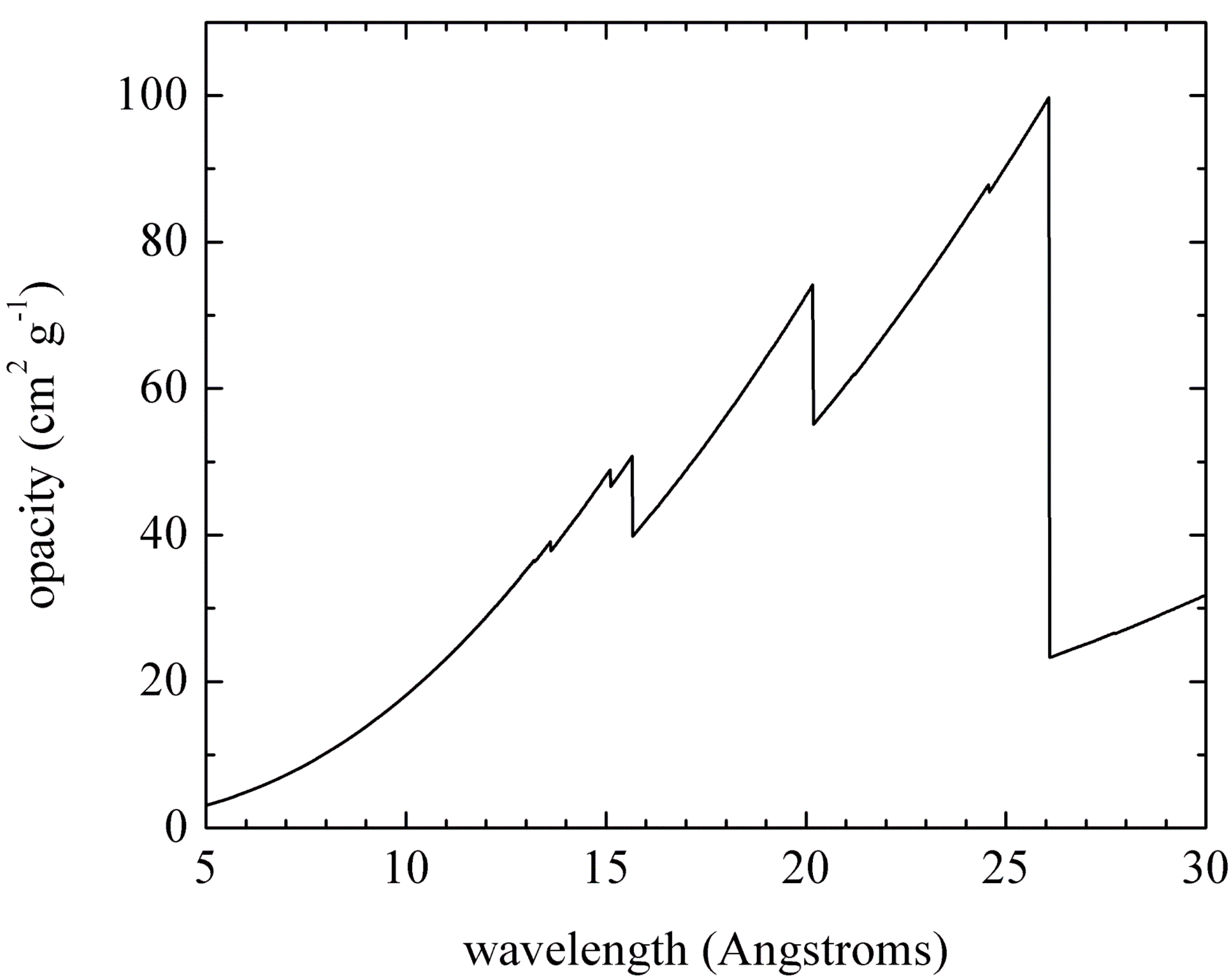
27 Oct 2006

4. X-Ray Systematics

The spectroscopic capabilities of the *Chandra* (and *XMM-Newton*) X-ray observatories permit for the first time the extension of morphological techniques as described above in the optical and UV domains, to the X-ray line spectra of the OB stars. A *Chandra* program (PI W. Waldron) to fill gaps in the archival HR Diagram coverage has been conducted. Although such coverage to date remains sparse, it is now sufficient to support a preliminary investigation of the X-ray spectral systematics in relation to the optical spectral types of the stars. To that end, supergiant/(giant) and main-sequence/(giant) X-ray spectral sequences from *Chandra* HETGS data are displayed in Figures 9 and 10, respectively. It should be emphasized that these stars have been selected as normal representatives of their spectral types; e.g., the magnetic stars discussed in the previous section also have peculiar X-ray spectra and must be omitted from the search for fundamental morphological trends.

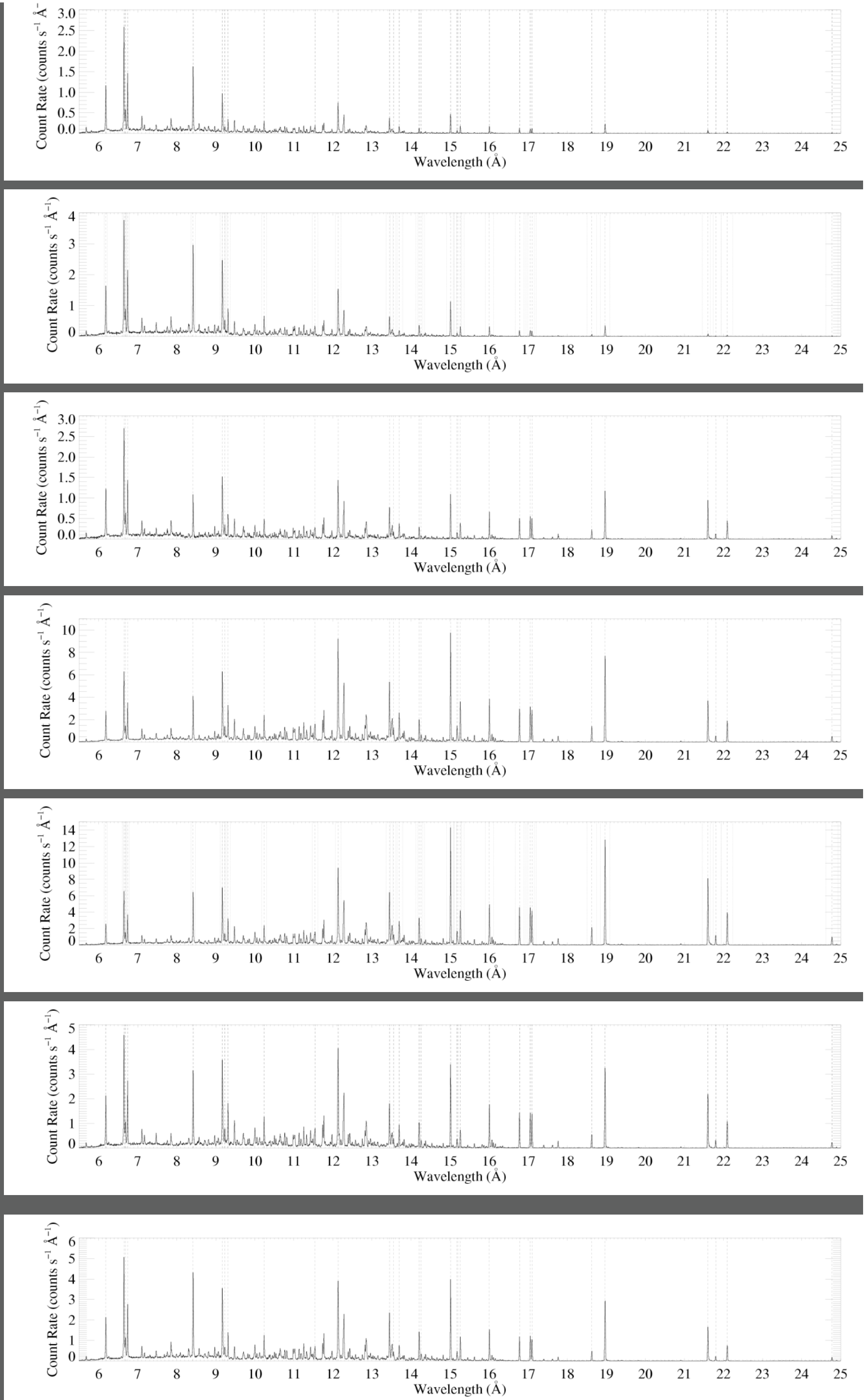
The existence of such trends is readily apparent in the figures. First, the strongest lines migrate toward longer wavelengths with advancing spectral type, which is an ionization effect. Second, the ratios of the close pairs of He- and H-like ionic lines from Si, Mg, Ne, and O display correlations with the spectral types. For instance, the

Recall the wind opacity

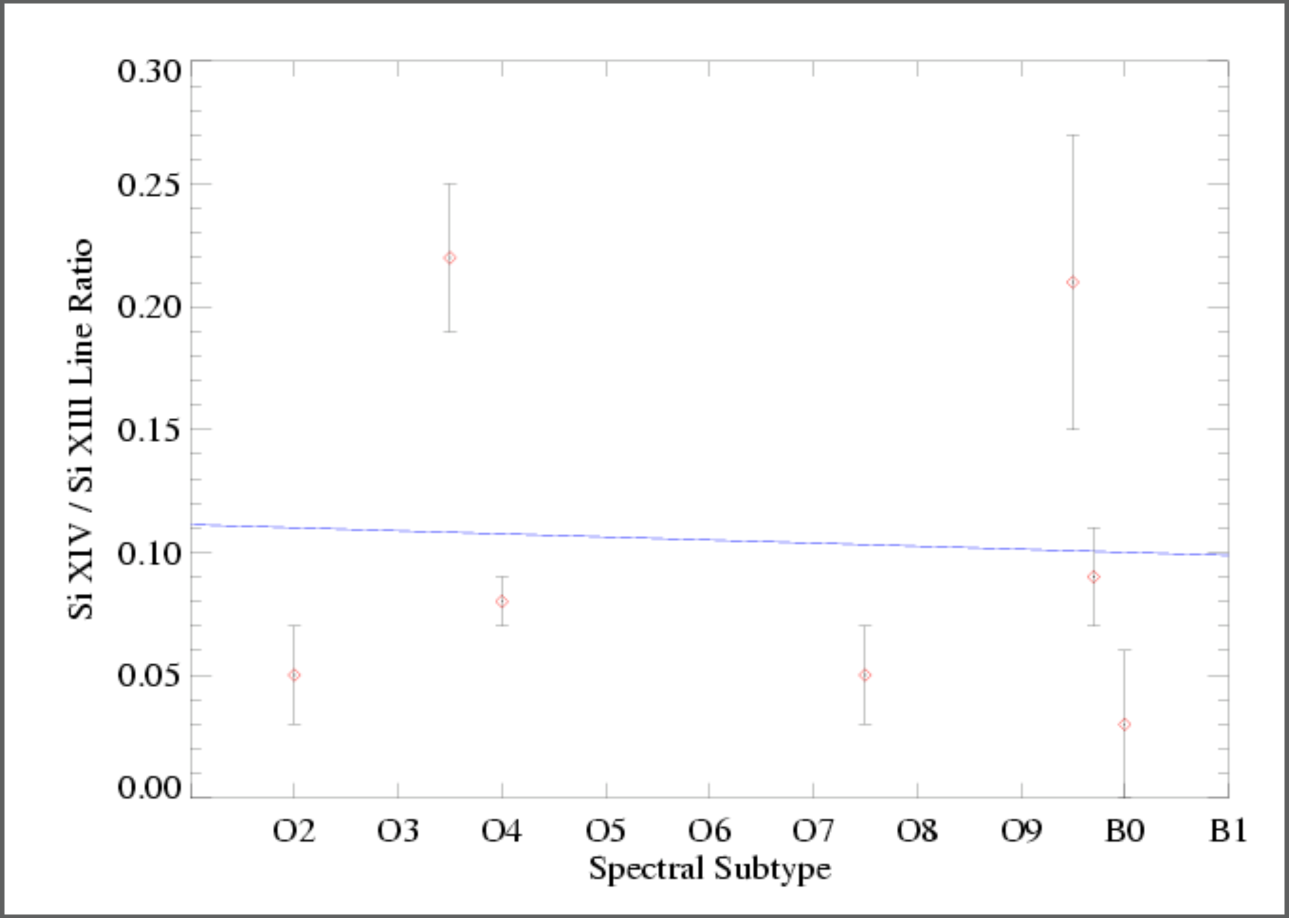


Single emission model but different wind absorption

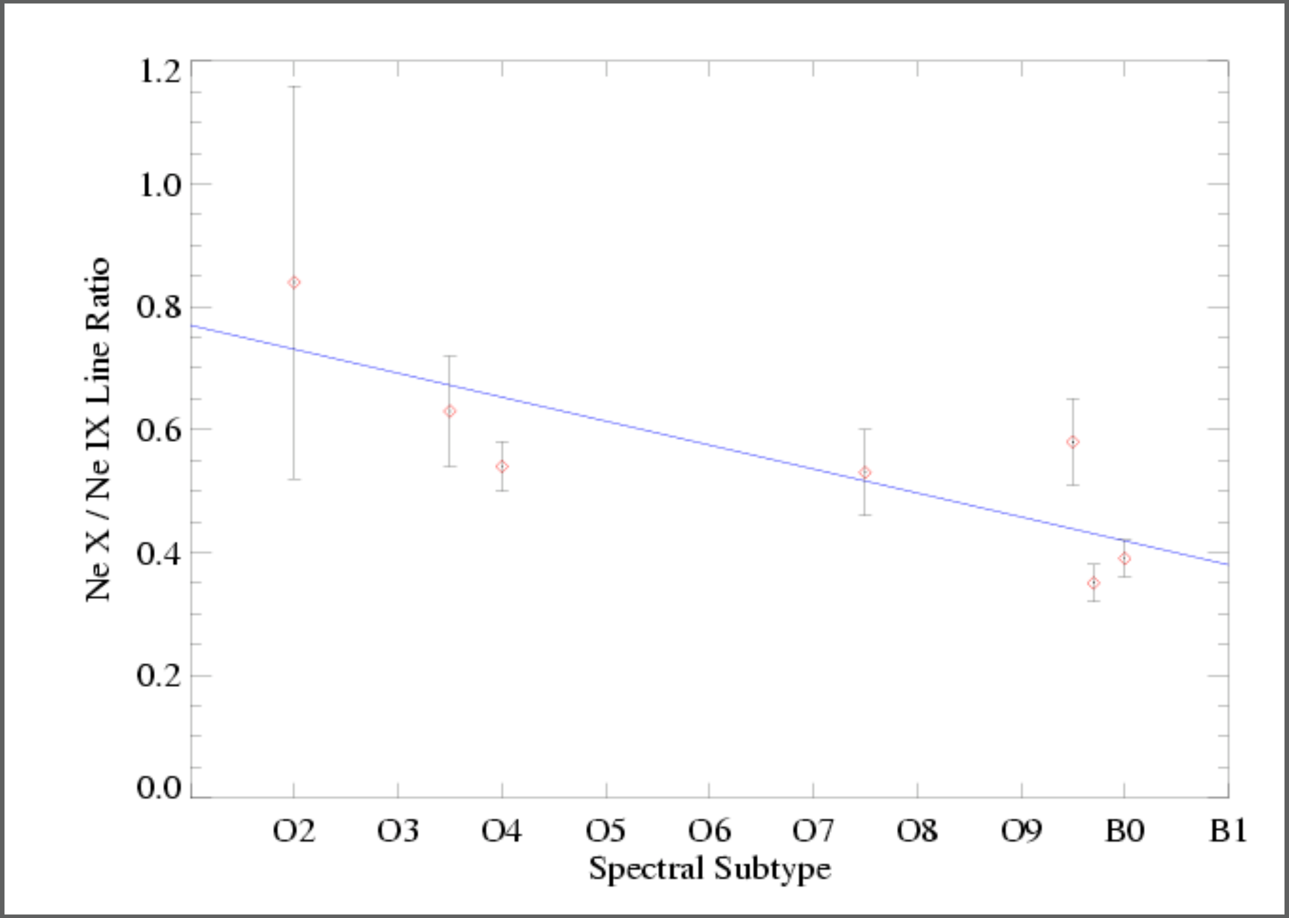
Wind *absorption* appears to explain most of the trend



Little evidence for a residual ionization trend



…but maybe a second-order effect



Conclusions

X-ray emitting plasma kinematics: consistent with wind-shock model

But line profile shapes indicate mass-loss rates are lower than expected (~3 X for highest mass stars; up to 10 times for lower mass stars)

Global spectral trends also show the importance of wind absorption - *question*: consistent with lower mass-loss rates?