Current Status of Modeling Wolf-Rayet Atmospheres

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General Thoughts

Key assumptions

- Beals model (hot core surrounded by dense out-flowing wind)
- Spherical (but some exceptions)

Key requirements

- Atomic data
  - Line and continuum cross-sections
  - Collision rates
  - Charge exchange
- Do details matter?
  - Accurate wavelengths?
  - Completeness of opacities?
  - All species?

Clumping

- Volume filling factor approach
- Macro-clumping
- Shell models
- Fragmented winds (Dessart and Owocki)
- Inhomogenous models are intrinsically 3D, but may be globally 1D.

General Thoughts

Hydrodynamics

- Smooth
- Clumped
- Time dependent
  - Do “static” solutions exist?

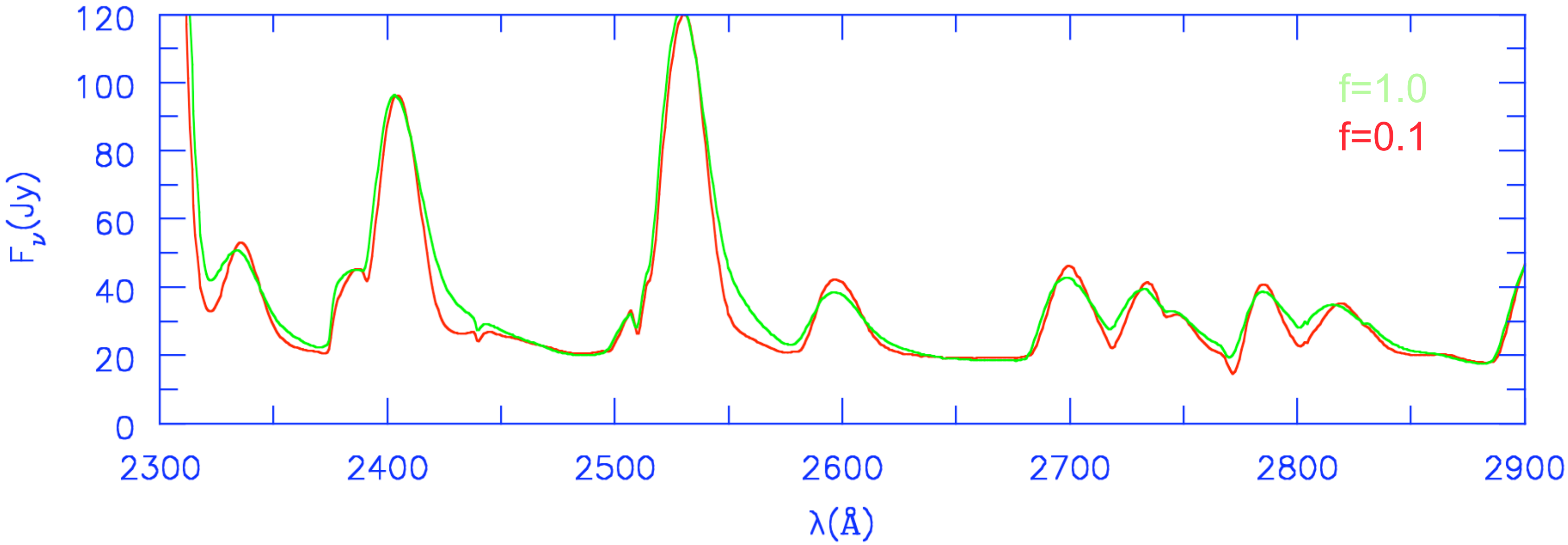
Stellar issues

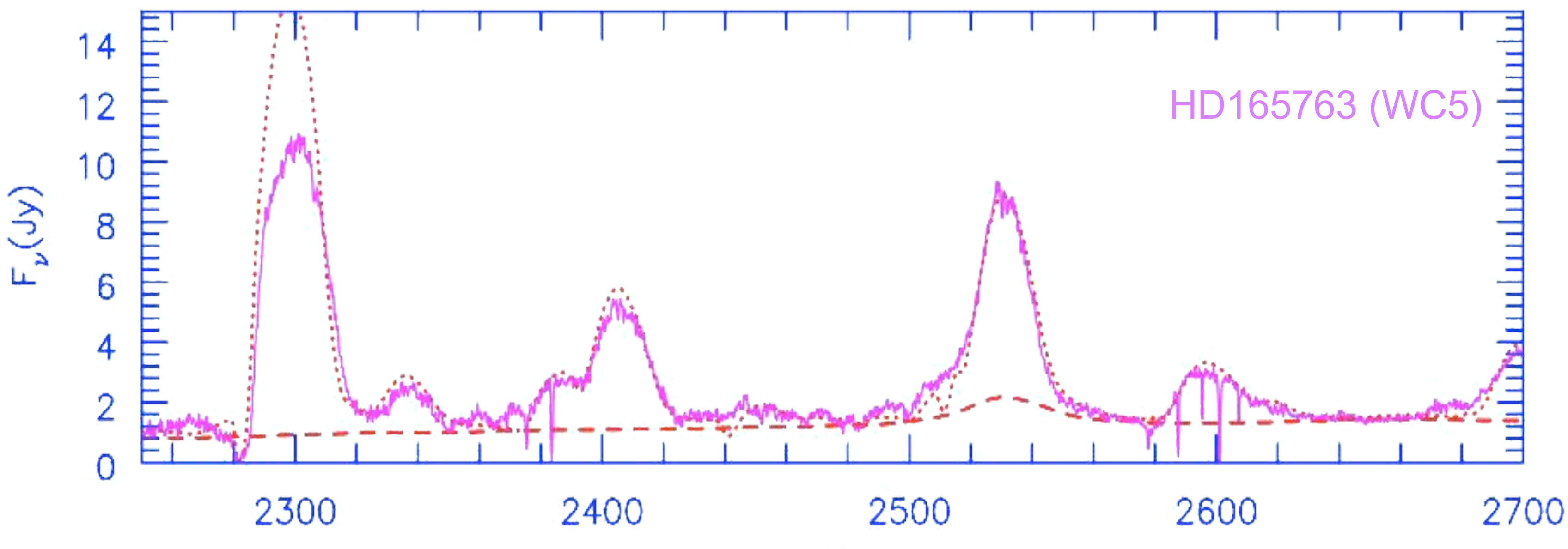
- Pulsations
- Instabilities near Eddington limit

Other issues

- Distances
- Reddening (E(B-V) and R)

Hillier & Miller (ApJ, 1999)





Reliability

Abundances

Accurate H/He

CNO (50%)

Fe (factor of 2?)

Abundances not strong function of model.

Vinf

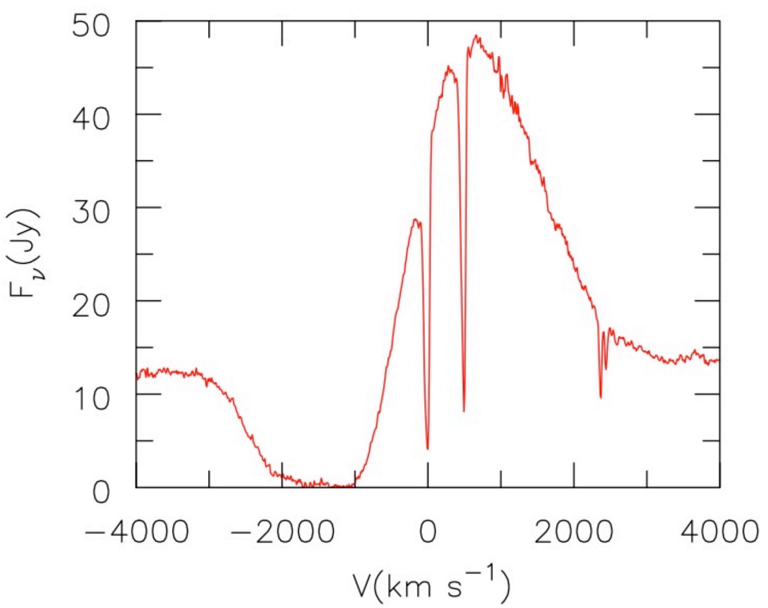
10% (turbulence; meaning?)

Mass-loss rates

$M_{dot}/\mathrm{sqrt}(f)$ -- some dependence on β

f (factor of 2)

f(r)?



Luminosities

50%?

Factor of 2 (or more) increase in L when line blanketing included?

Reliability

Radii

Wind dependent.

Biased by assumptions.

Hydrodynamics: values more consistent with evolution?

Thick winds $\Rightarrow$ difficult to constrain observationally.

Effective temperatures

As for radii

V(r)

Thick winds $\Rightarrow$ difficult to constrain observationally.

Hyrodynamics?

Stellar masses

Binaries.

Mass loss rates (sensitive to Γ)

Mass loss Rates from 1st Principals

Fe Opacity bumps (OPAL, Opacity Project)

Nugis & Lamers (2002, A&A, 389 162)
Graefener & Hamann (2005, A&A, 432, 633)
Graefener & Hamann (2008, A&A, 482, 945)

* Optically thick stellar winds
* Critical point is sonic point
* Opacity increases through critical point

Require T(sonic)

160,000 K (hot bump)
40,000 to 70,000 K (cool bump)

* No guarentee that Mdot set by critical point can be driven to infinity.

* Multiple critical points?

Momentum Equation

$$v\frac{dv}{dr} = -\frac{GM(1-\Gamma)}{r^2} - \frac{1}{\rho}\frac{dP}{dr} + g(rad)$$

where

$$g(rad) = \frac{4\pi}{\rho c}\int_0^\infty (\chi_\nu - \chi_{es})H_\nu d\nu$$

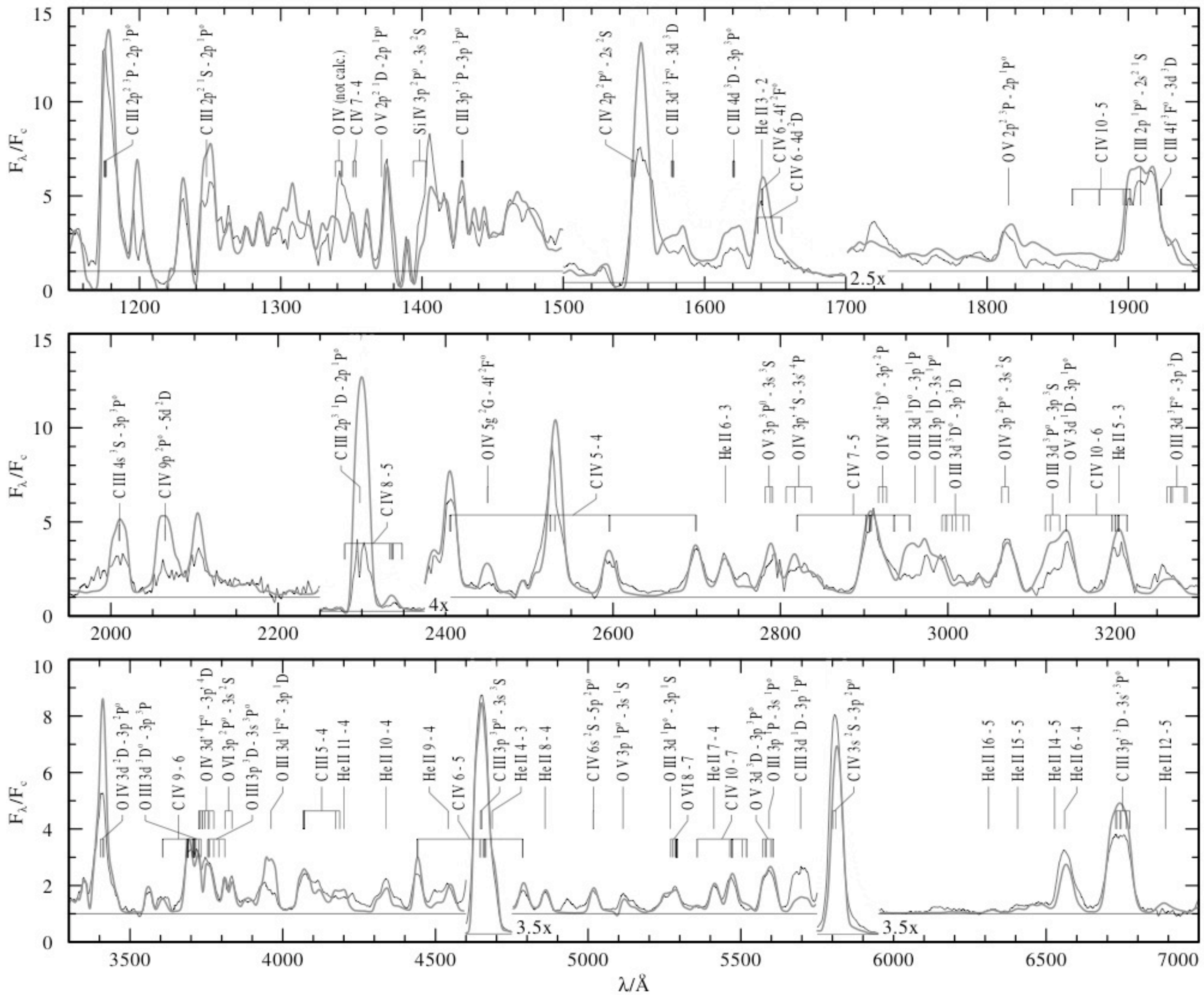
With a=sound speed we have

$$v\frac{dv}{dr}\left(1-\frac{a^2}{v^2}\right) = -\frac{GM(1-\Gamma)}{r^2} + g(rad) + \left[\frac{2a^2}{r} - \frac{da^2}{dr}\right]$$

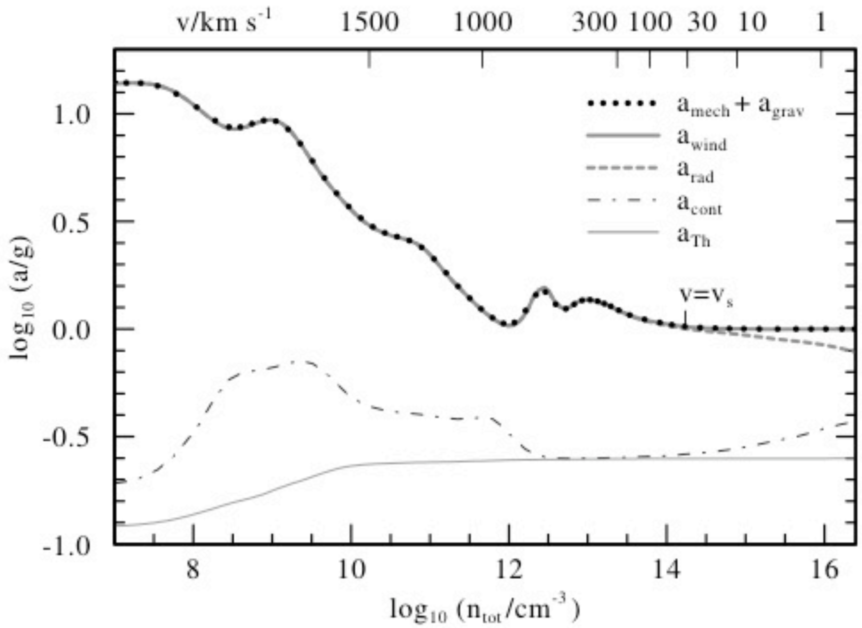
Continuum driven: The Fe bump is caused by million of lines (pseudo continuum).

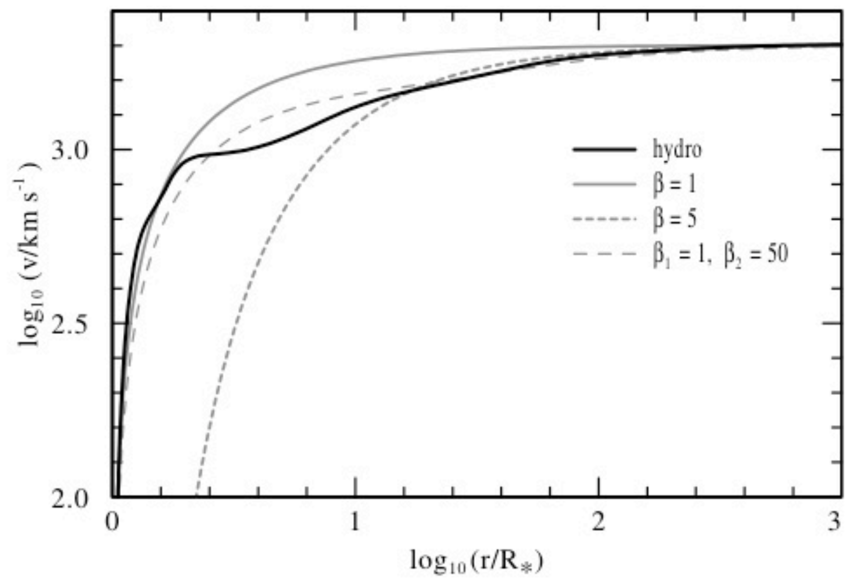
g(rad): only weak dependence on dv/dr

HD165763 (WR111; WC5)



Graefener & Hamann (2005, A&A, 432, 633)

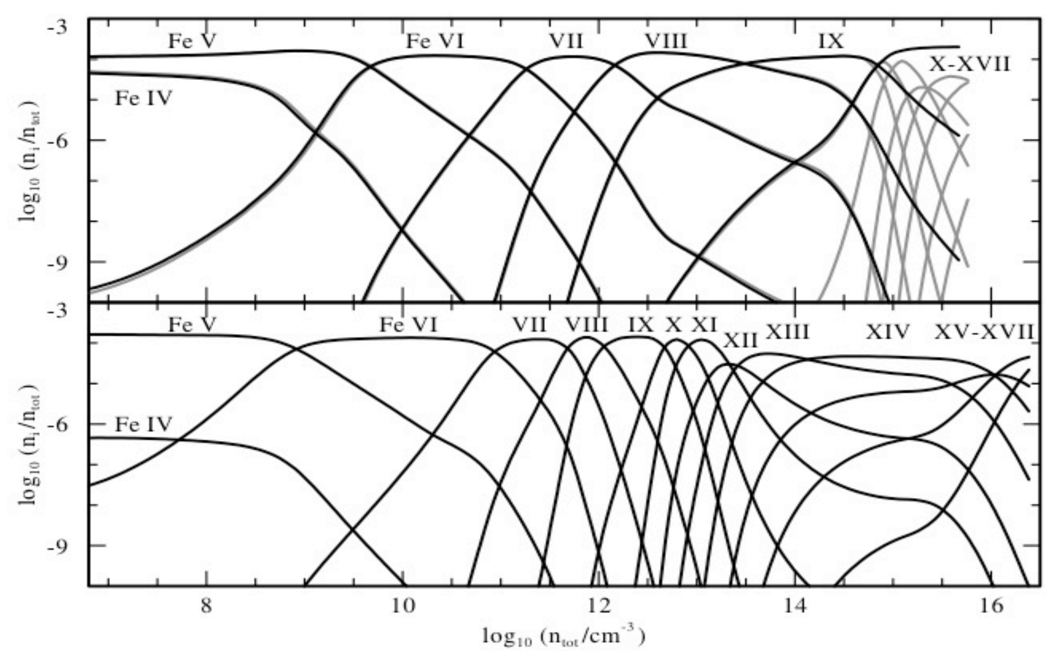




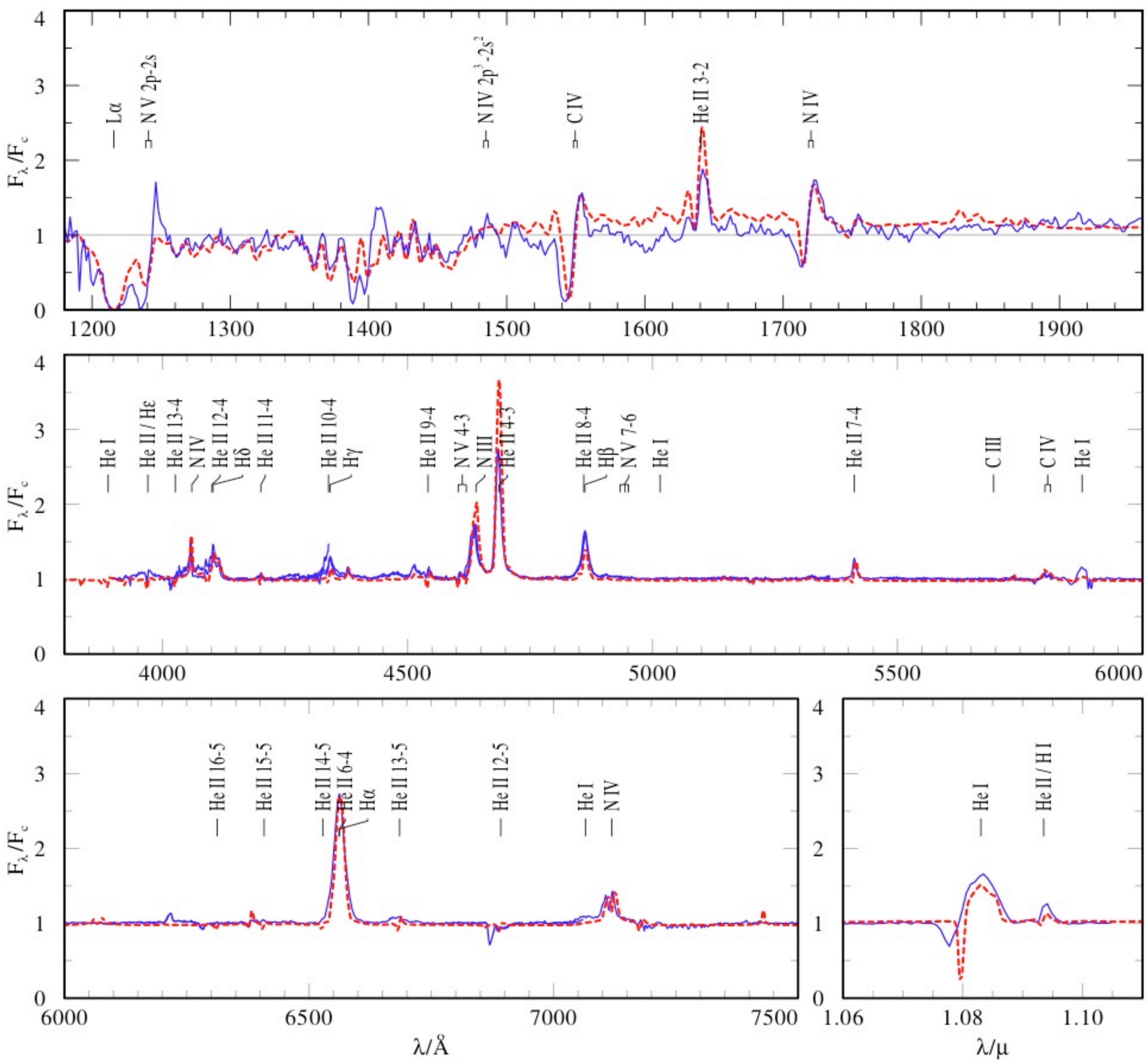
For WCE, WNE stars necessary to include very high ionization stages of Fe.

Graefener & Hamann (2005, A&A, 432, 633)

CAK alpha close to 0 (i.e., winds driven by thin lines.)



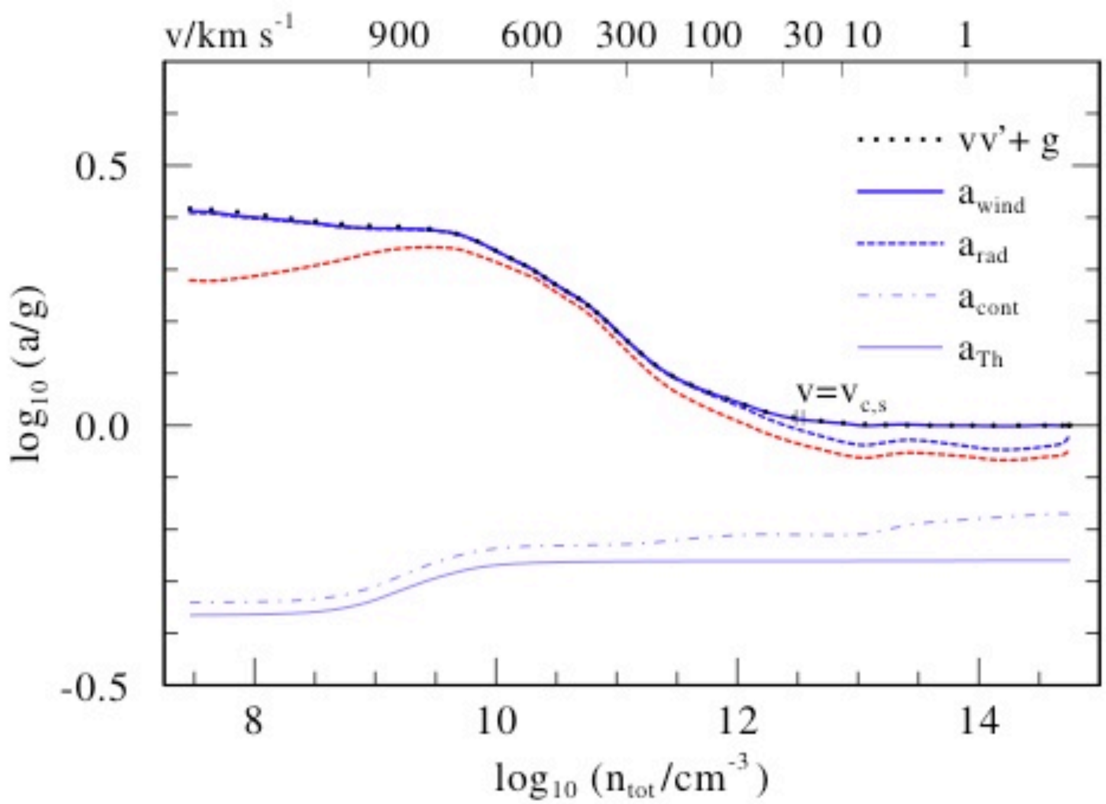
WR22 (WN7+0 system; HD 92270)



Graefener & Hamann (2008, A&A, 482, 945)

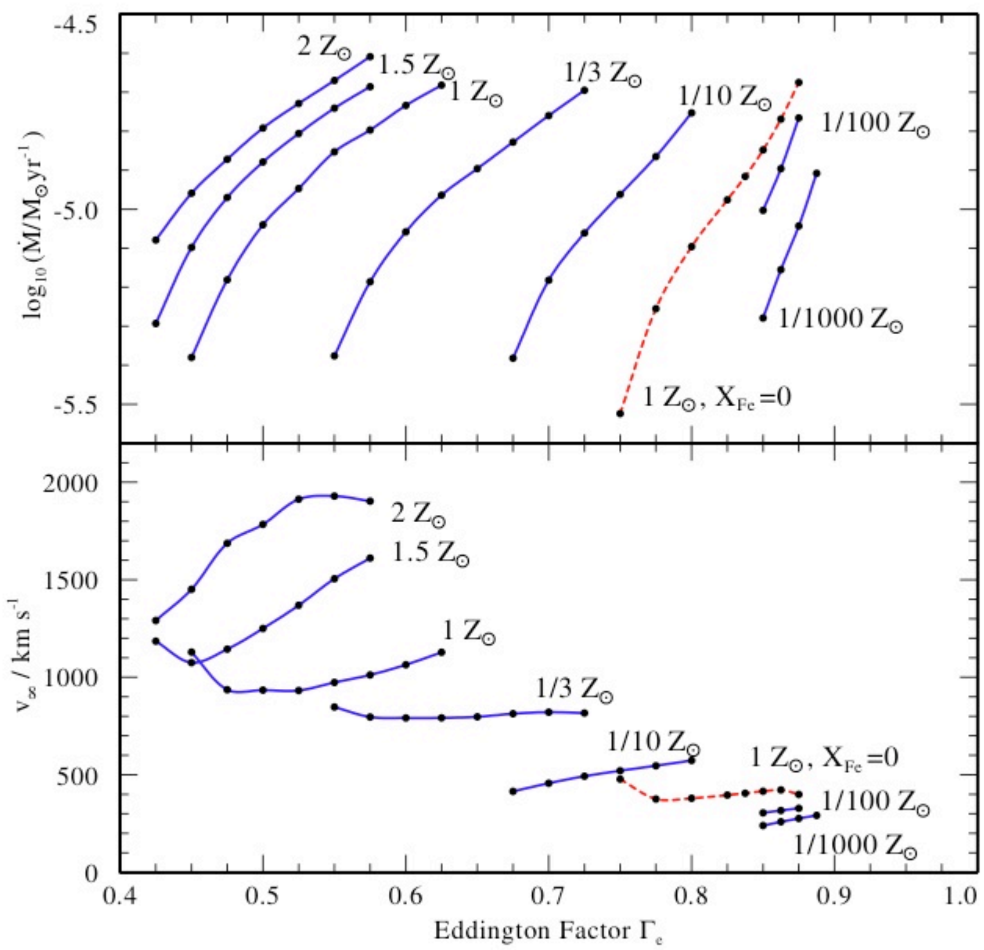
WR22: Dynamical Comparison

Blue (VD=100 km/s); Red (VD=50 km/s).



Graefener & Hamann (2008, A&A, 482, 945)

Mass loss rate is a strong function of the Eddington Parameter (Γ)



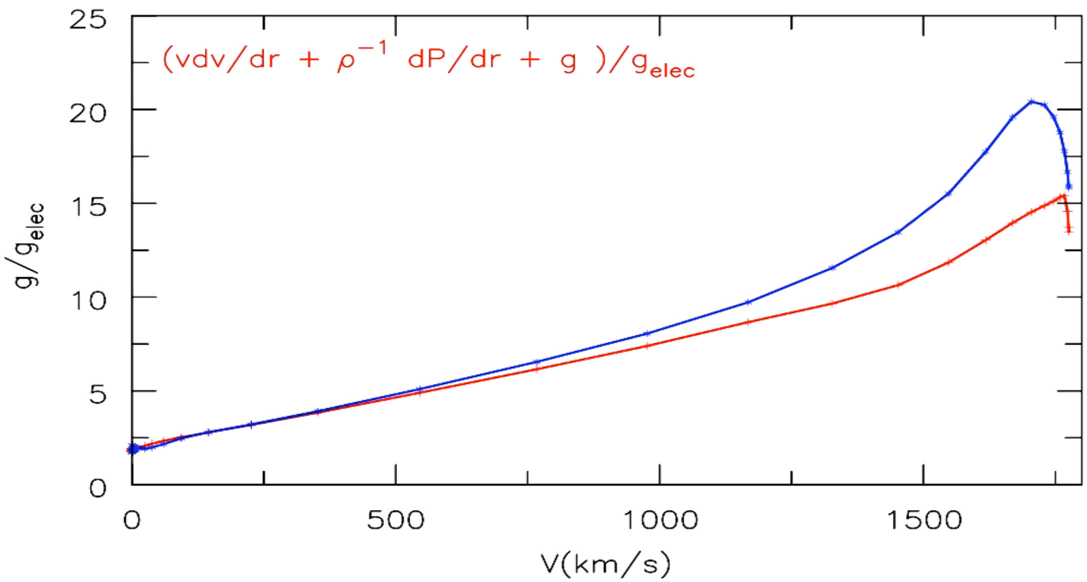
Models computed for fixed L(=2 x 10^6 $L_\odot$)

Graefener & Hamann (2008, A&A, 482, 945)

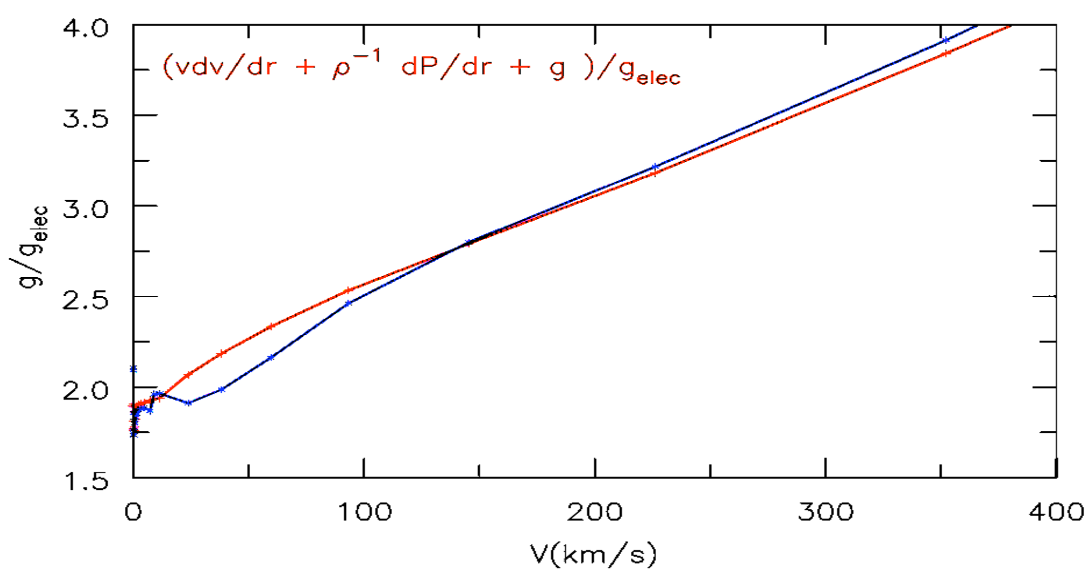
HD 92740 (WN7)

$L = 2 \times 10^6\ L_{sun}$
$M_{dot} = 2.0 \times 10^{-5}\ M_{sun}/yr$
$T_{eff} = 44{,}000$ K
Mass = 87 M_{sun}
V_{inf} = 1785 km/s

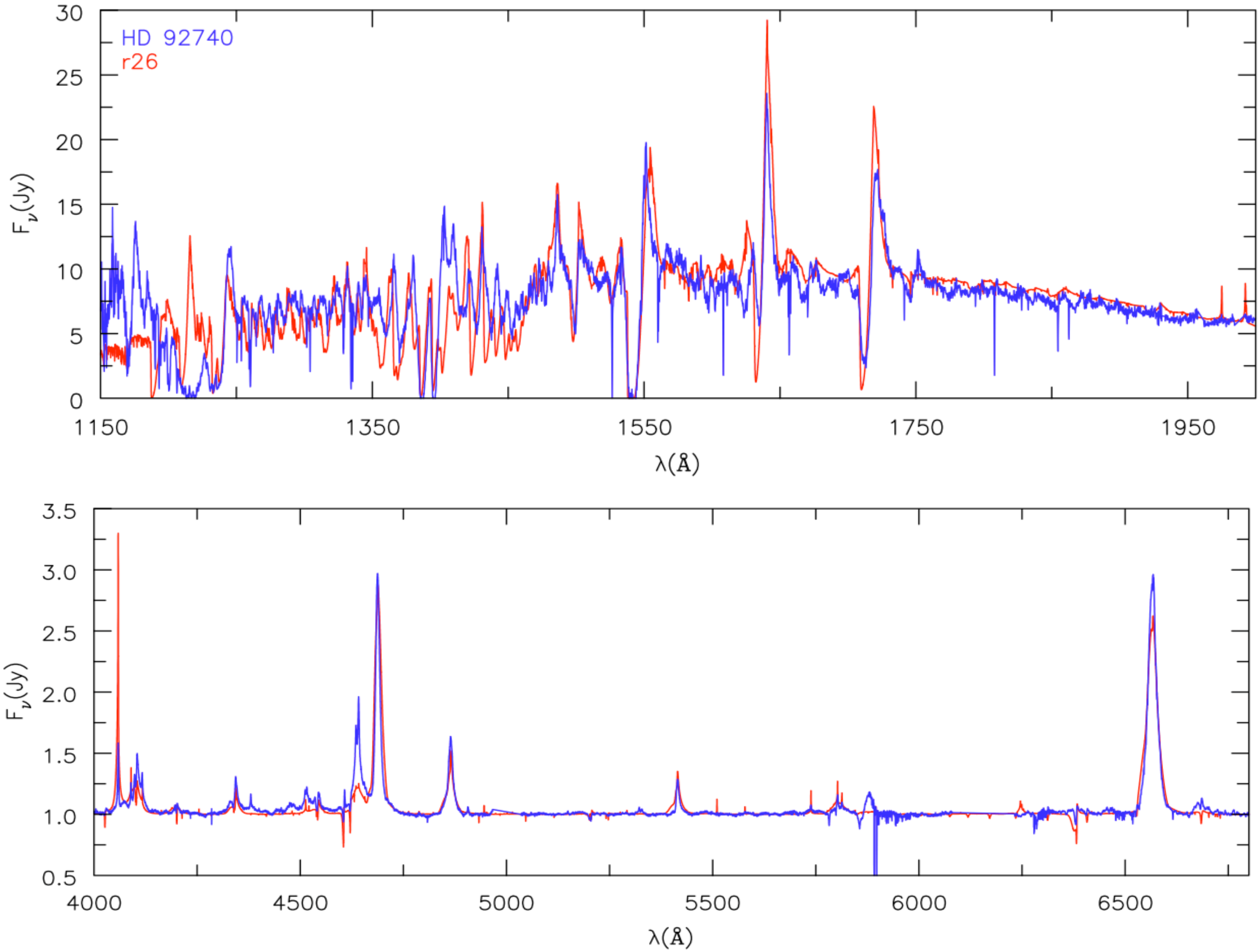
V(cl) =30 or 100 km/s ?

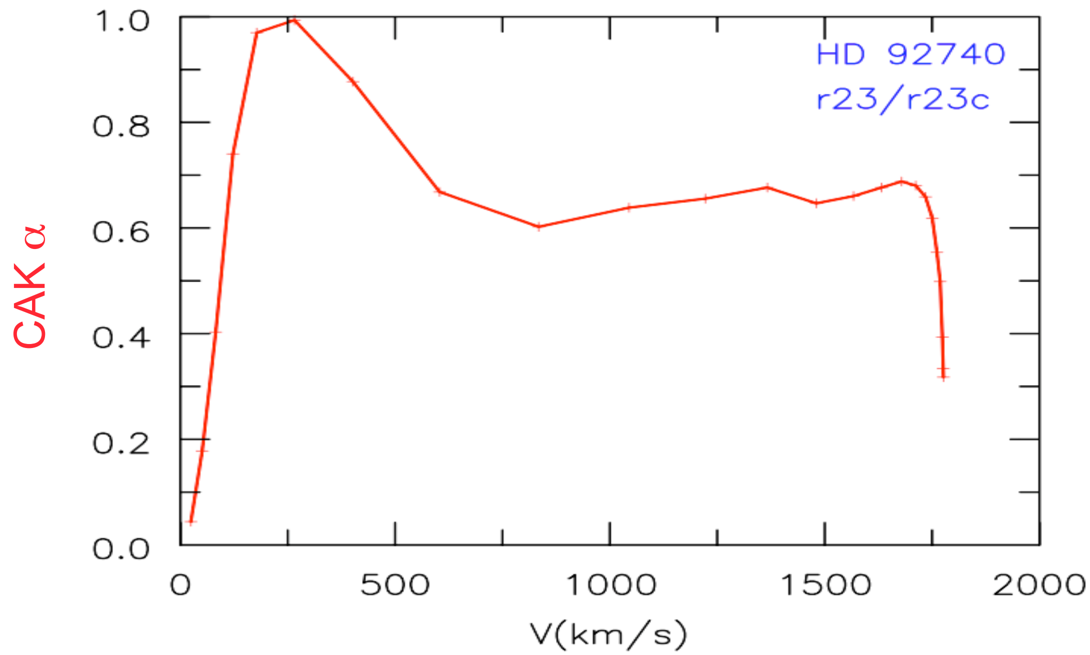


Species included
H, He, C, N,O, Ne,
Si, S, Cl, Ar, Ca, Fe, Ni

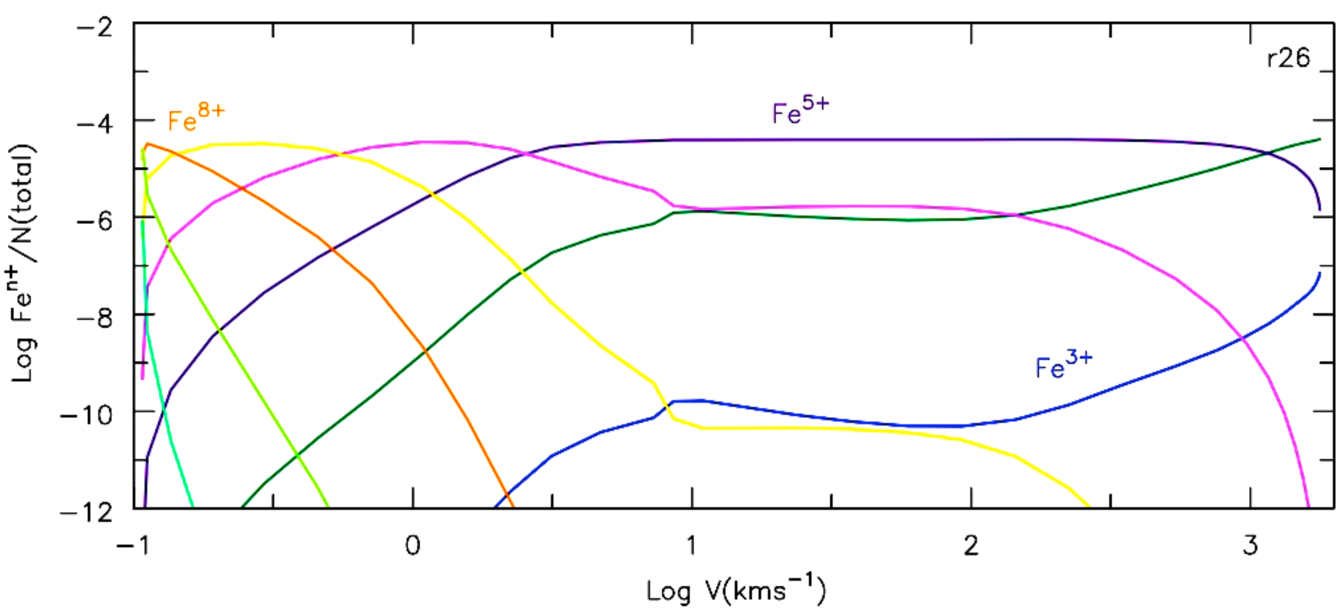


Model with current parameters is a “little too hot”. Low ionization features (e.g., NIII 4640, HeI 5876) are too weak.





HD 92740
r23/r23c
CAK α
1.0
0.8
0.6
0.4
0.2
0.0
0
500
1000
1500
2000
V(km/s)



r26
Fe^{8+}
Fe^{5+}
Fe^{3+}
Log Fe^{n+}/N(total)
−2
−4
−6
−8
−10
−12
−1
0
1
2
3
Log V(kms^{-1})

Pulsations

Strange Mode Instabilities

Occurs when radiation pressure is important.

Opacity modified acoustic waves.

Glatzel & Kiriakidis (1993, MNRAS, 263, 375)

Glatzel & Kaltsshmidt (2002, MNRAS, 337, 743)

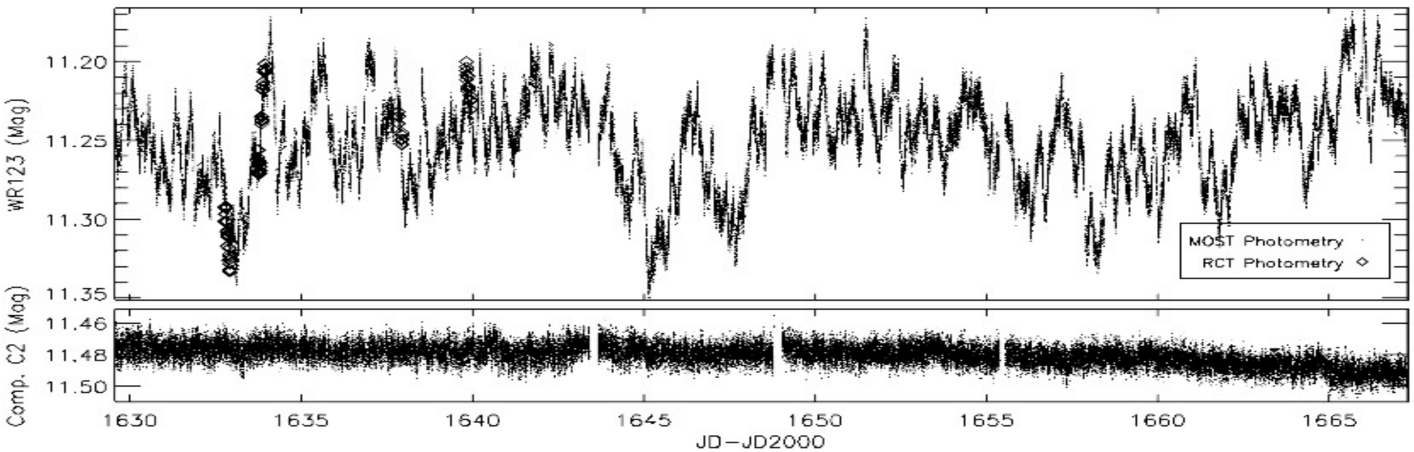
Glatzel (1994, MNRAS, 271, 61)

MOST observations: HD 165763 (WC5, WR111):

No coherent fourier amplitudes greater than 50 parts/ million for periods < 2.4 hr). Expected periods: 10 to 30 minutes.

Moffat et al. (2008, ApJ, 679, L45)

Pulsations



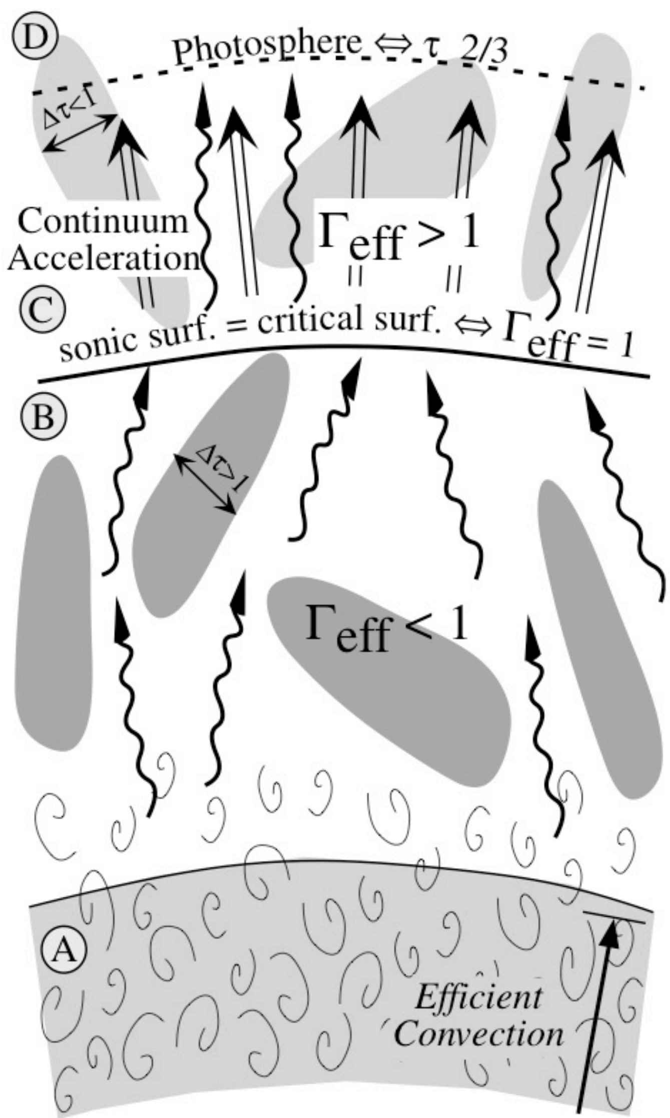
MOST observations of WR123 (WN8)

- Lefévre et al., Ap J, 2005, 634, L109
- Stable 9.8 hour period.
- < 2 mmag (10 $d^{-1} < f < 1400$ d^{-1})
- Complex power spectra with amplitudes 5-20 mmag.
- WR103 (WC8) shows similar complex power spectra.

Dorfi , Gautschy, & Saio, 2006, A&A, 453, L35

- Pulsation periods consistent with 10 hours.
- Pulsations damped/modified by wind
- Motions outer layers not synchronized with the pulsations
- Velocities of ~100 km/s (up & down)

Hydrodynamic Instabilities in Atmospheres Near the Eddington Limit



Shaviv, 2001, MNRAS, 326, 126

Instabilities

> 0.5 to 0.8

Lead to inhomogeneities

Continuum driven winds

Larger mass-loss rates.

Super Eddington Luminosities.

Eta Carinae

Novae

Modeling with Clumping

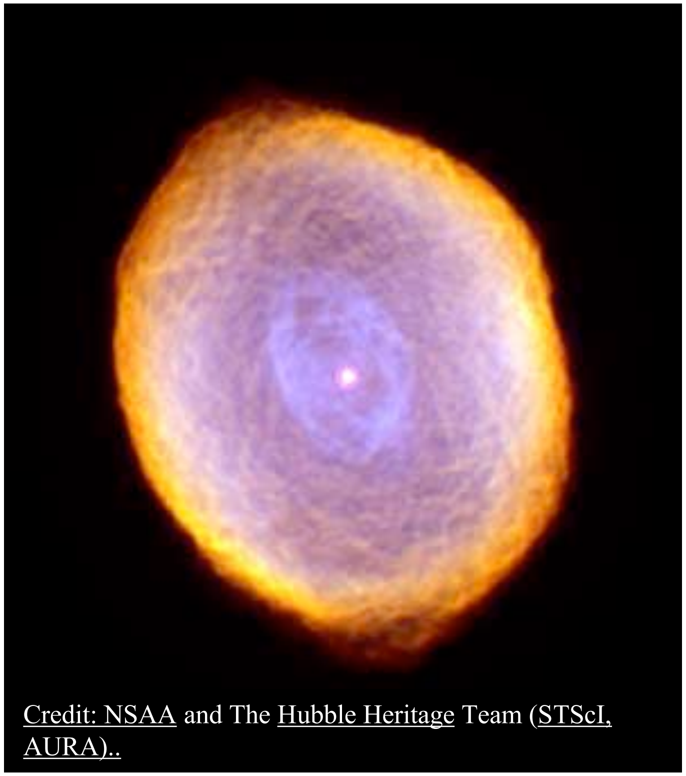
The answer you get depends on the nature of the clumps. To constrain the effects of clumping it is essential that we understand the clumping mechanism and hence the type of clumps.

Disks: Macroscopic clump.

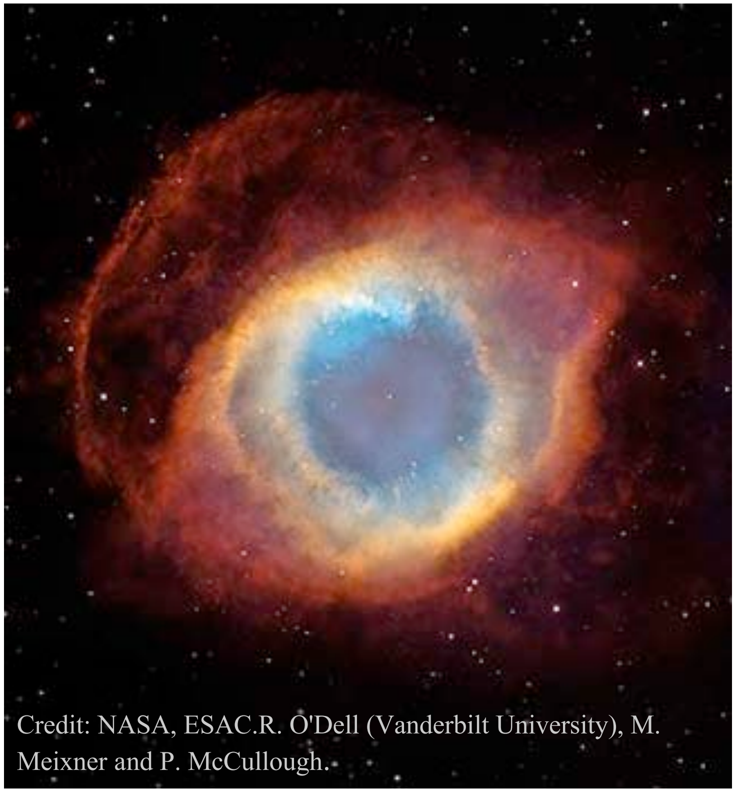
Bullets: Can have lots of mass but can’t be seen spectroscopically.

Balls or pancakes --- effects, for example, porosity.

Nature of interclump medium?



Credit: NSAA and The Hubble Heritage Team (STScI, AURA)..



Credit: NASA, ESAC.R. O'Dell (Vanderbilt University), M. Meixner and P. McCullough.

General Thoughts

Specification

Size & density distribution.

Velocity profile and distribution.

Nature of the interclump medium.

Amount of mechanical energy deposited, and where.

Effects

Allow lower mass-loss rates

Enhanced emission (density squared effects)

Porosity

Different lines and continuua can have distinct responses, but many are (surprisingly) similar (e.g., $\propto \rho$ or ρ^2).

Potential problems (Williams 1992, ApJ, 392, 99)

Degeneracy

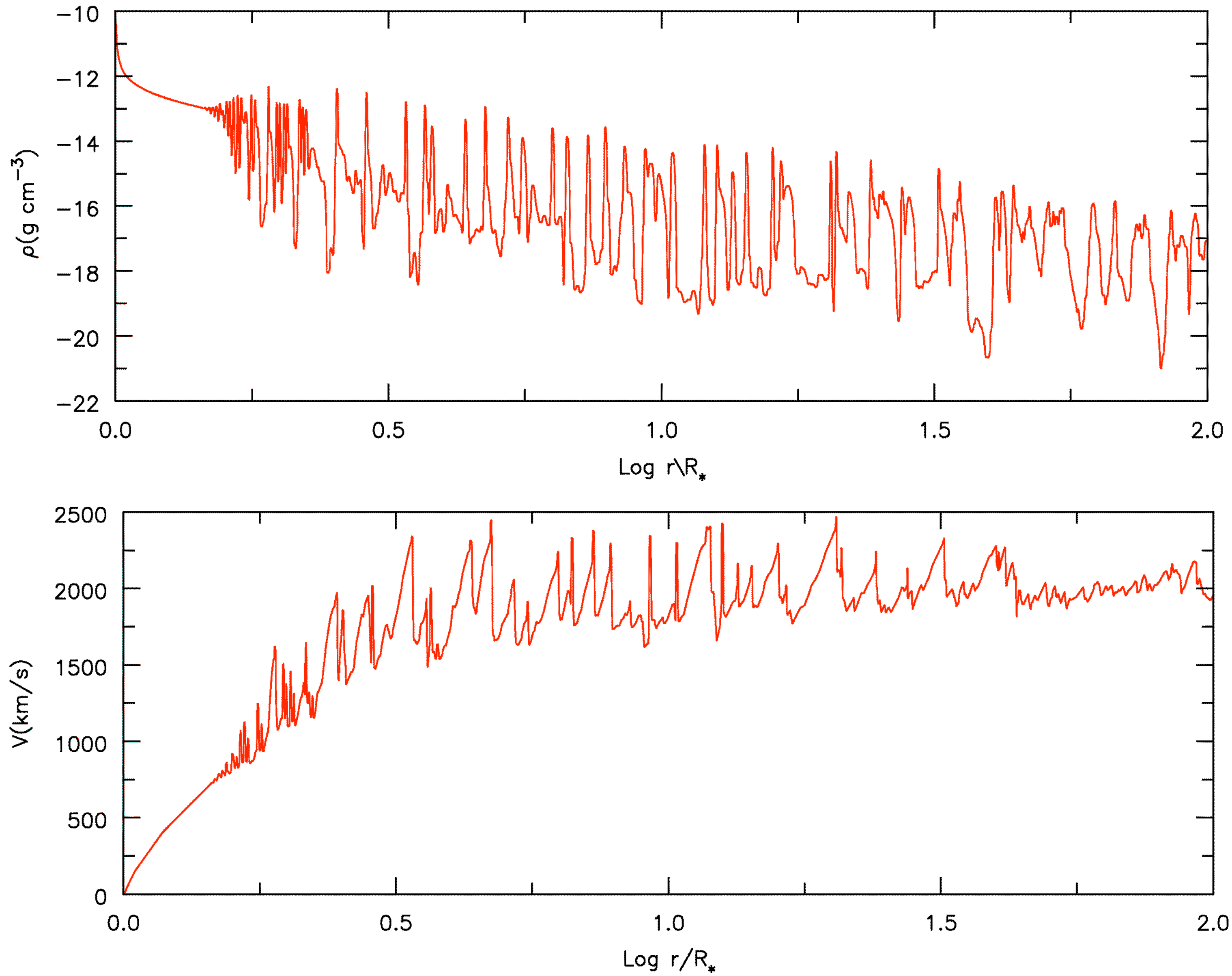
Optically thick clumps.

Clumps can have their own ionization structure.

Shielding

Non-spherical (driven: rotation, pulsations, inhomogeneities)

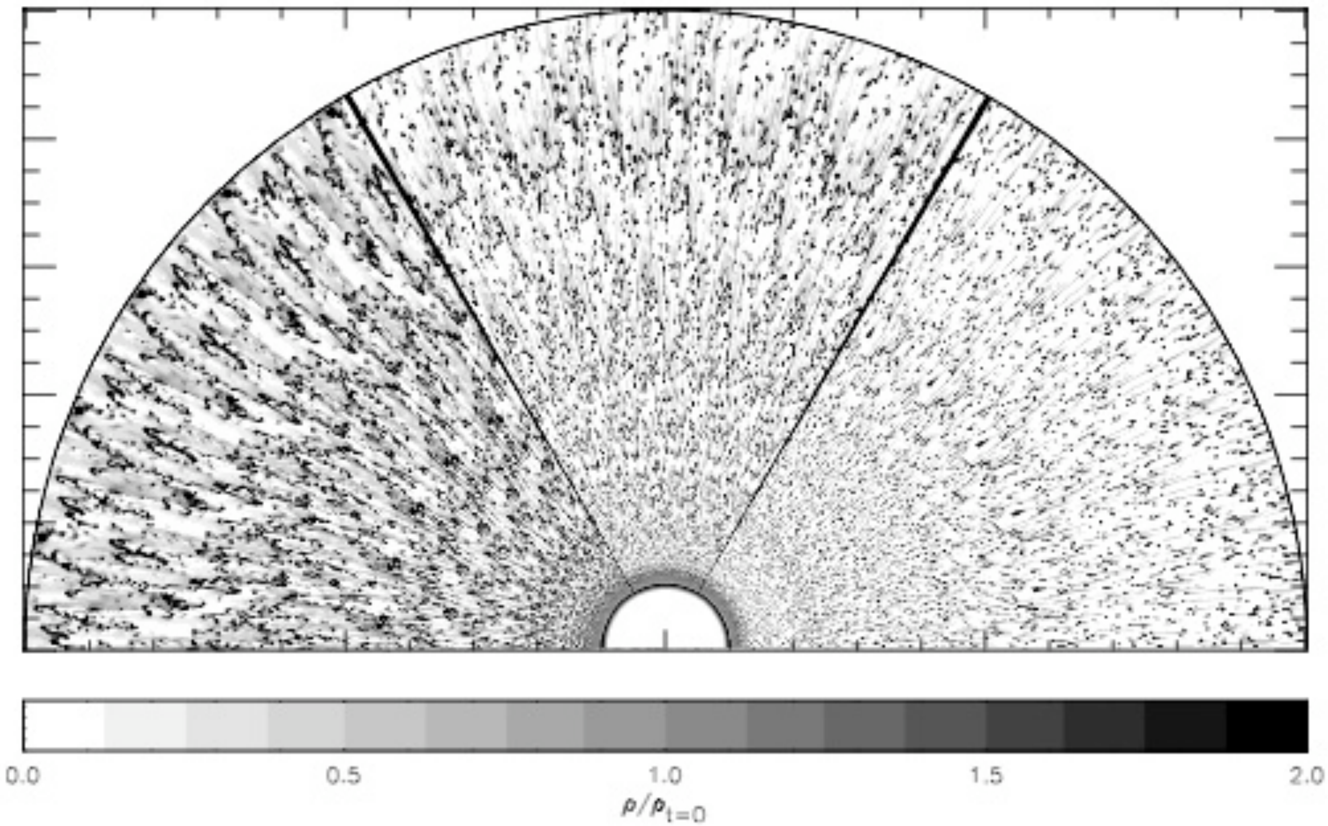
Owocki (Zeta Pup model)



e.g., Owocki, Castor, Rybicki, 1988, ApJ, 335, 914

2D Instability Simulations

Dessart & Owocki (2005, A&A, 437, 657)



Lateral Scale

- Transverse Sobolev length (r/v) ~ 1 degree
- Lateral scale set by grid resolution?
- Diffuse radiation field crucial.

Computational Issues

Computing the spectrum (i.e., the formal solution) from a clumped model, whose populations are known, is feasible. The difficulty is computing the non-LTE populations.

Possible exception: Scattering resonance line arising from an ion which is the dominant ionization stage.

Non-LTE modeling

Homogeneous models:

t(2D) > 100 t(1D)

t(3D) > 5000 t(1D)

Inomogeneous models:

t(3D) > 10^6 t(1D)

Can't do full problem: Need approximations.

Volume Filling Factor Approach

Assume medium is clumped, the clumps are uniform, and the fractional volume of the clumps is f. If the clumps are small compared to the photon mean-free path, then:

$\rho(\text{clump}) = \rho(\text{smooth}) / f$

$\chi(\text{eff}) = f\,\chi(\text{clump})$

$\eta(\text{eff}) = f\,\eta(\text{clump})$

Under these assumptions, calculation is exact.

The real world:

Approximation excellent for continua, but poor (?) for lines, since scale length of clumps is of order the Sobolev length.

Question

What is the accuracy when assumptions are not met?

How?

Many diagnostics

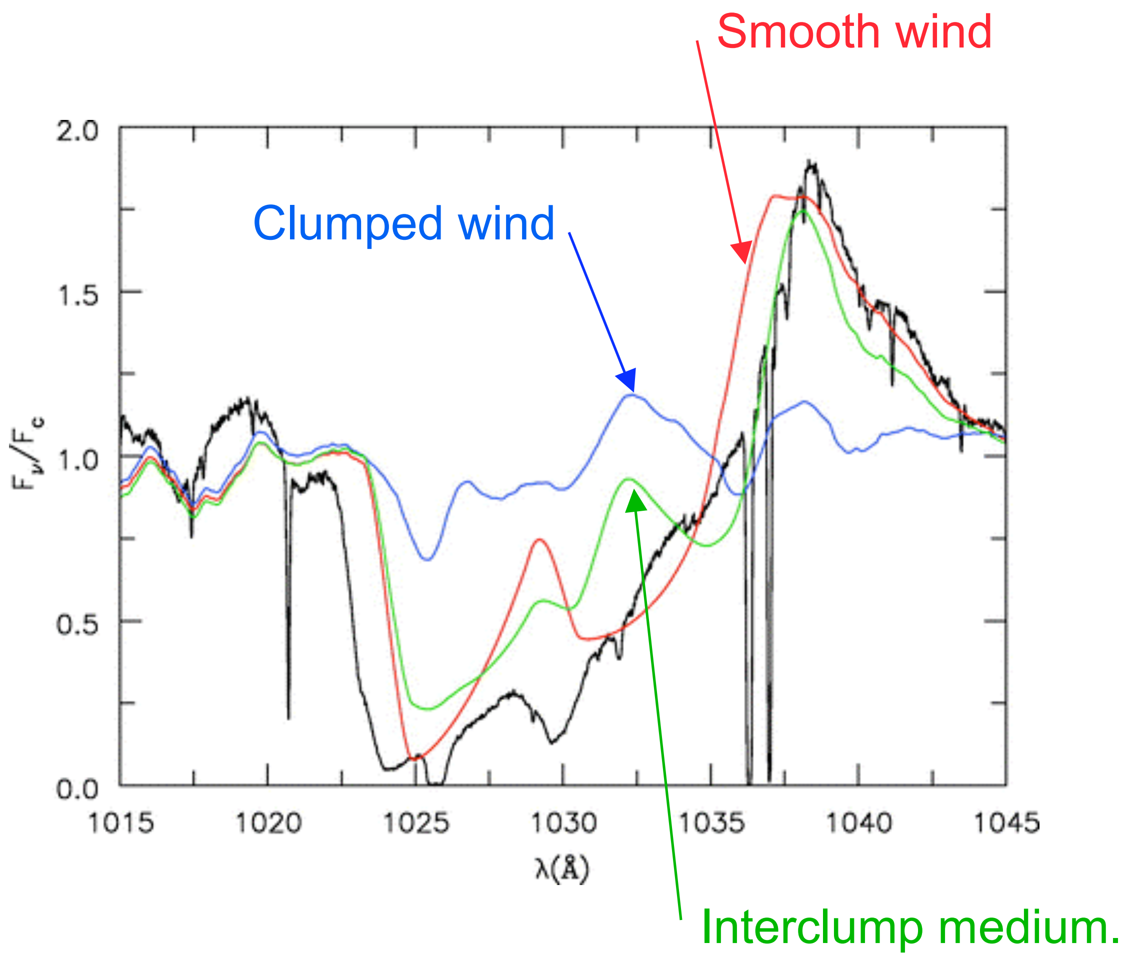
Alternative techniques

Support

Variability Observation (e.g., Lepine & Moffat, 2008)

2D simulations (e.g., Dessart & Owocki 2005)

OVI
Zeta Pup



Zsargo et al. (2008, ApJ, 685:L149)

Macro Clumping

Oskinova et al. (2007, A&A, 476, 1331)

An approximate formulation for handling optically thick clumps.

- Apply model to Zeta Pup
- Reasonable fit to observations
- Has significant “spatial” porosity.
- Is porosity important for explaining X-ray line profiles.

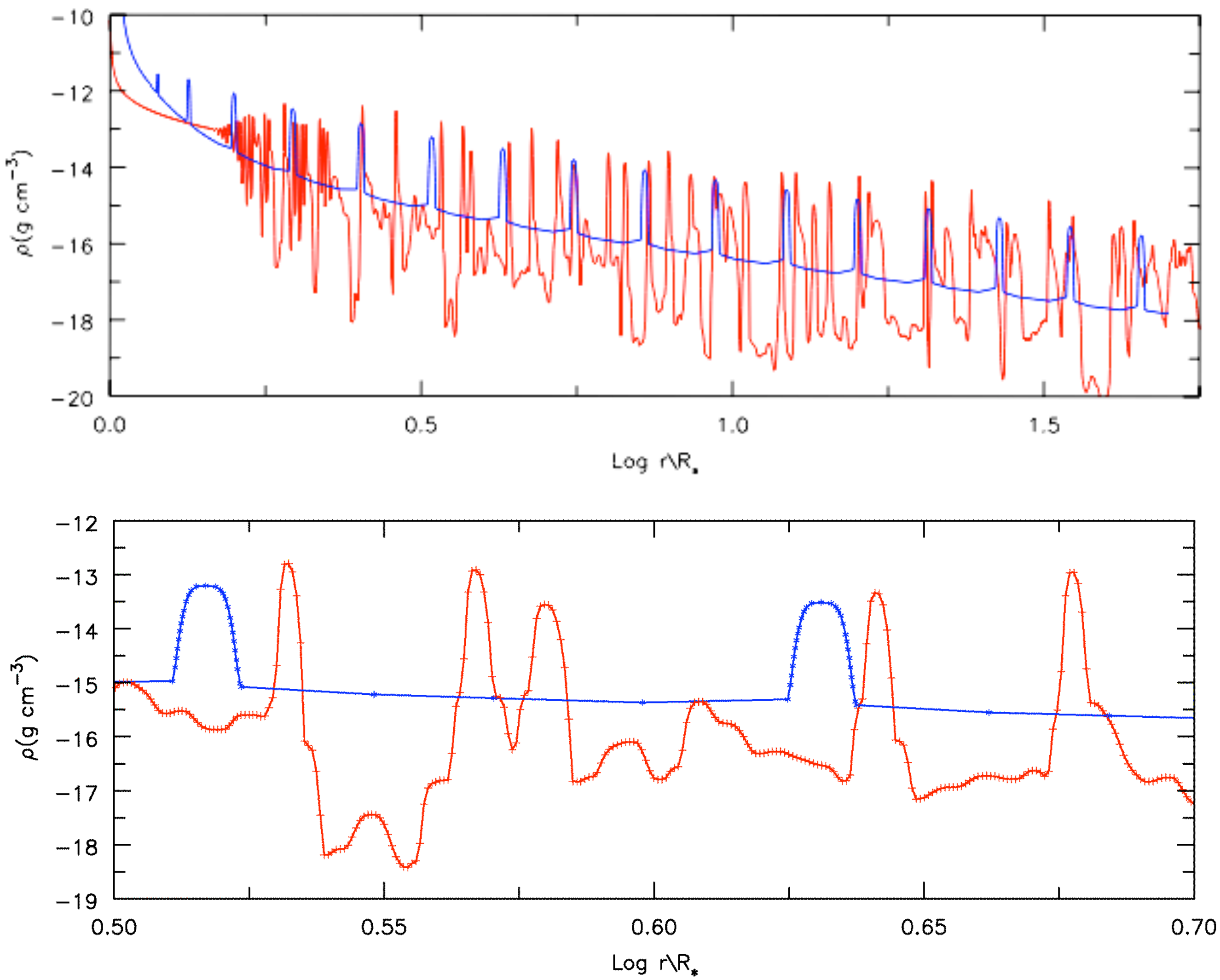
Mass loss rates

- Lower than smooth wind results.
- Higher than that obtained using volume filling factor approach.

Shell model

Artificial but can be solved “exactly”
Useful for studying effects that will arise in other clumped models.
Alternative techniue.

"Shell" like density structure adopted for transfer models (blue line). Red line shows radiative instability model computed for Zeta Pup by Owocki (private communication).



- For AV83 (O7 Iaf+; not shown), an shell clumping approach gives a "similar" spectrum to that obtained using the filling-factor approach, but detailed analysis required.

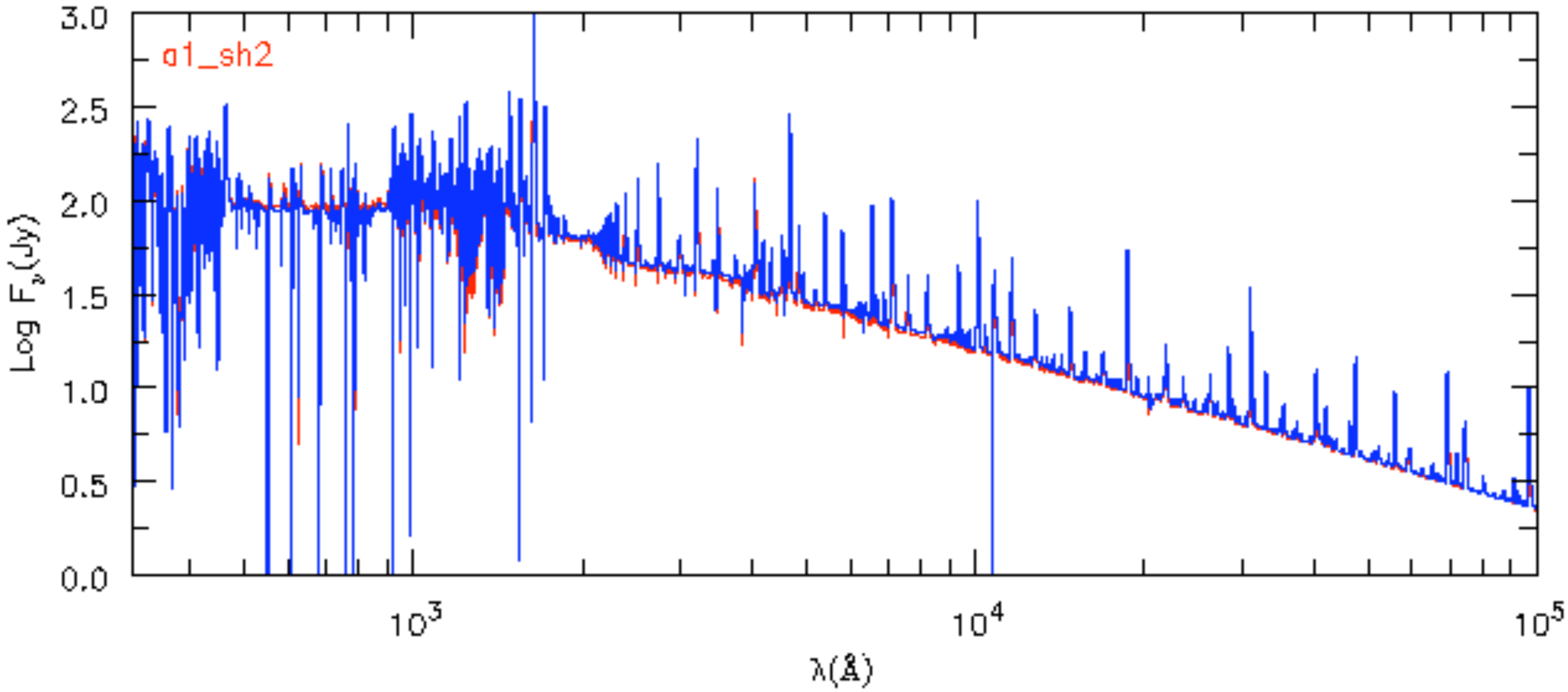
- For a WN5 star, the shell clump model gives a similar continuum, but generally weaker lines. The lines and continua behave differently because continuum photons generally have much greater mean free paths (hence shells are "effectively" thin) than do line photons (shells may be "effectively" thick). Since the lines are inconsistent with the continuum, clumped model is invalid —— thinner clumps?

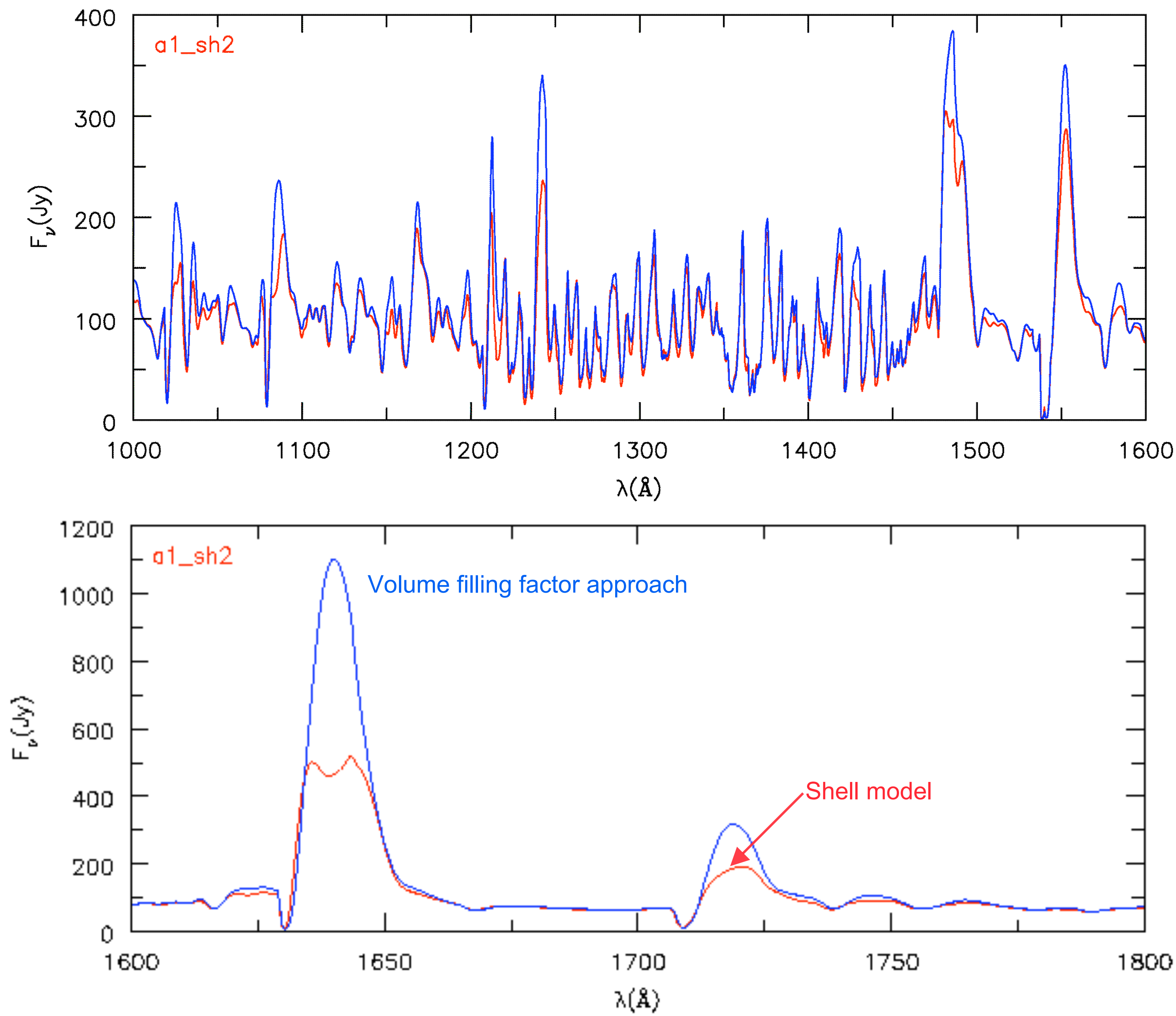
WN5 Model

$R_* = 2.5 R_\odot$ f=0.1 (V ~ 100km/s)

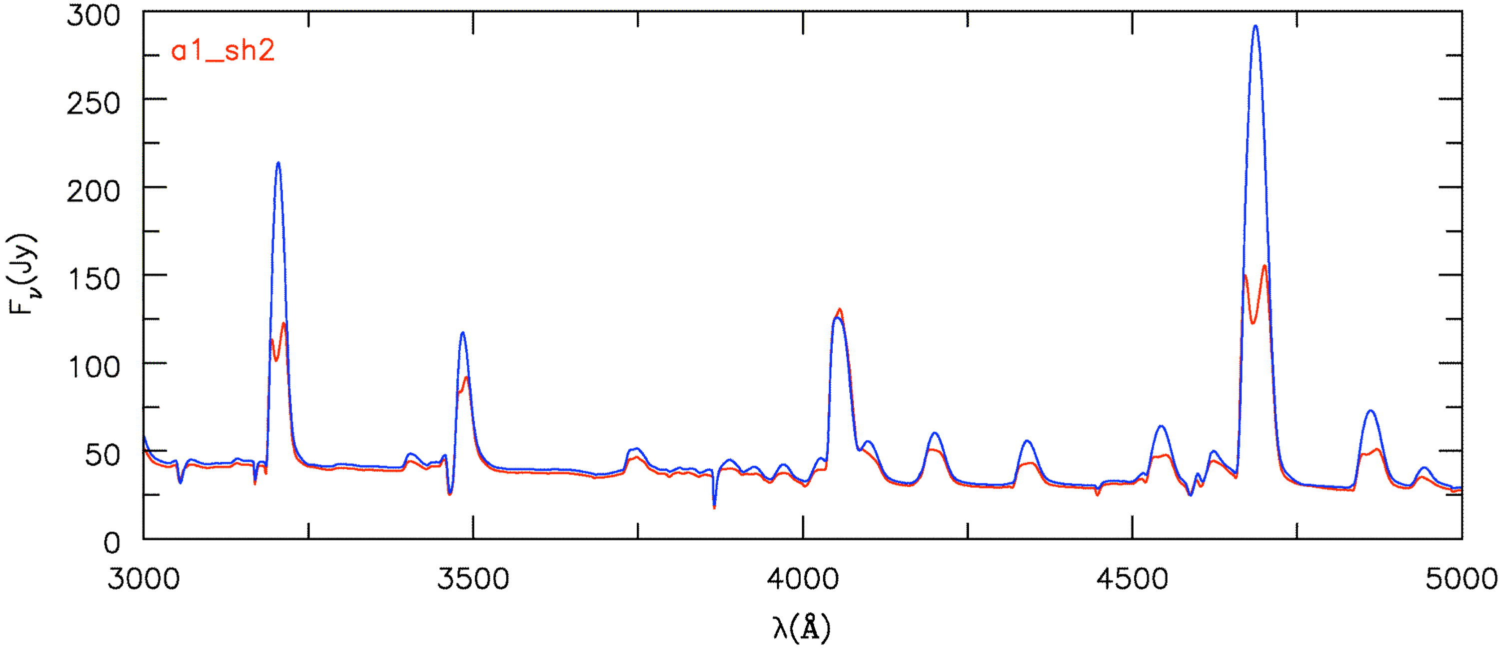
$L = 3 \times 10^5 L_\odot$ $\dot{M}$dot=2.5 x 10^{-5} $M_\odot$/yr

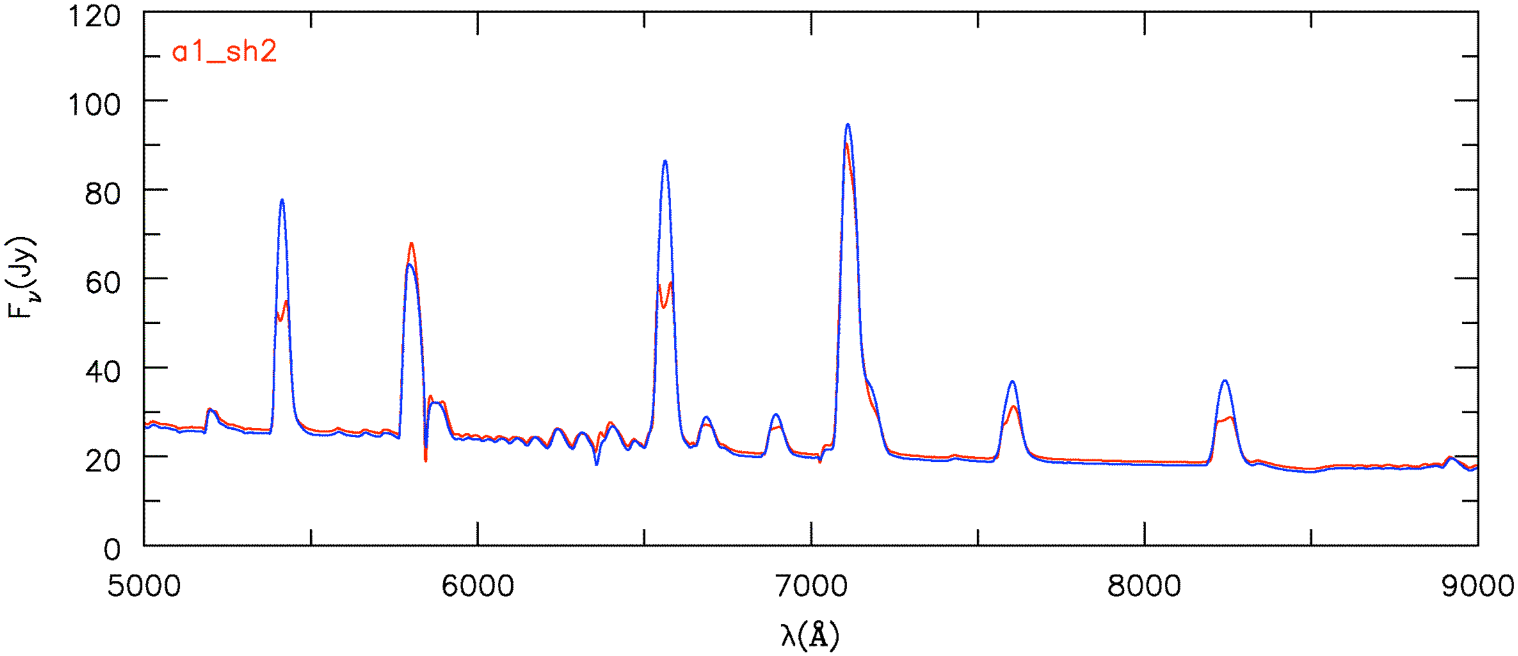
Teff = 85,000K



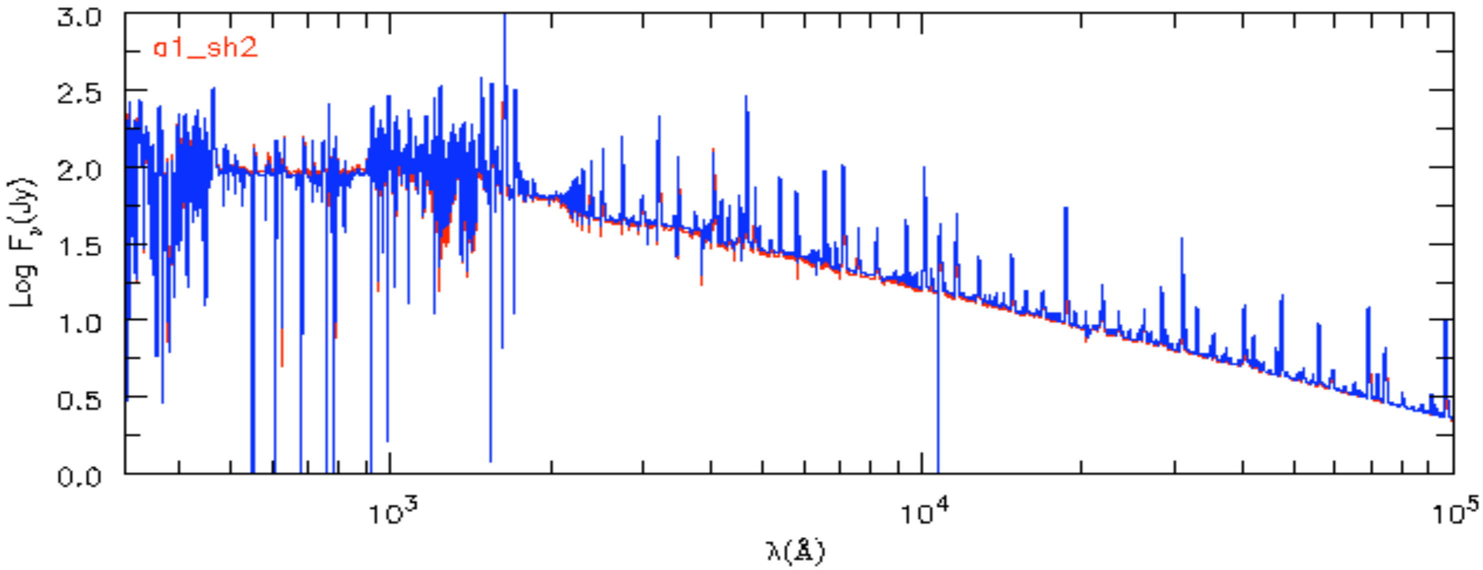


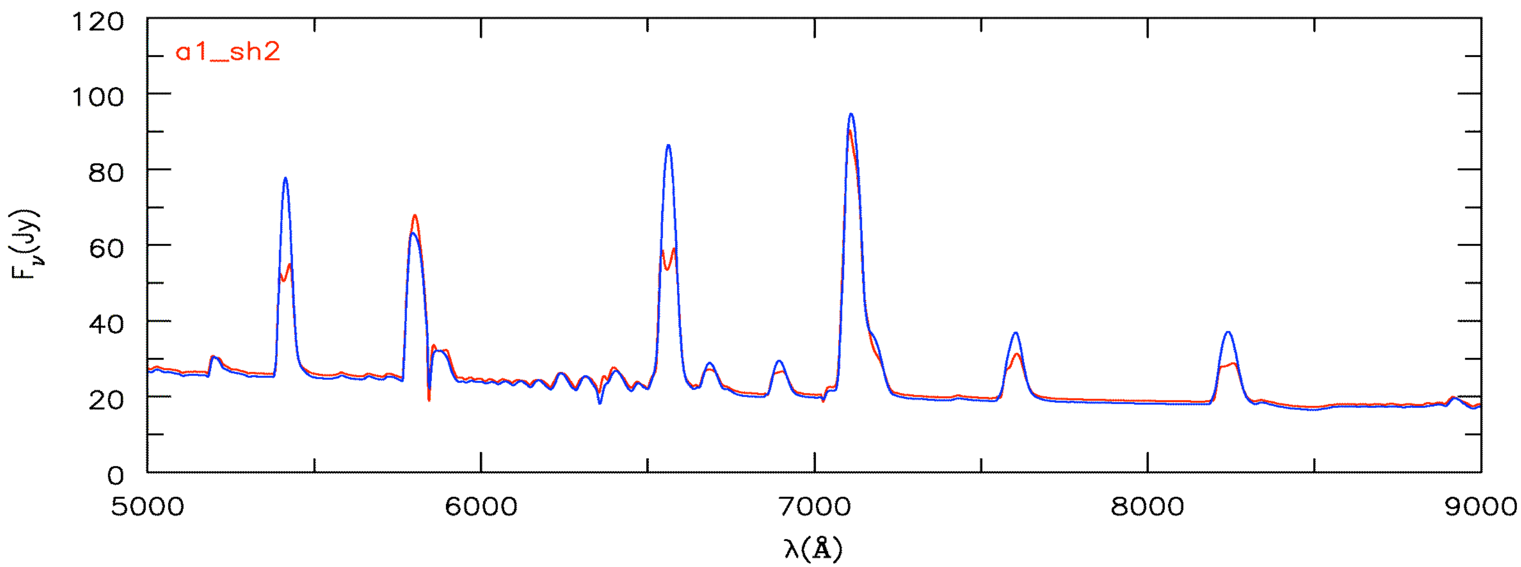
a1_sh2
F_ν(Jy)
λ(Å)
a1_sh2
Volume filling factor approach
Shell model
F_ν(Jy)
λ(Å)


a1_sh2
300
250
200
150
100
50
0
3000
3500
4000
4500
5000
λ(Å)
F_ν(Jy)


a1_sh2
120
100
80
60
40
20
0
5000
6000
7000
8000
9000
λ(Å)
F_ν(Jy)

Inconsistent!
Continuum matched but lines do not.





Conclusions

- The Fe opacity bumps play a key role in initiating W-R winds. Other effects (e.g., pulsations) may be needed for some W-R subclasses.

- Accuracy of current W-R models (particularly radii and effective temperatures) is limited by uncertainties in the wind hydrodynamics and clumping.

- Due to the LARGE number of parameters needed to parameterize clumping, need to use ALL available diagnostics (radio to X-ray spectra, variability) to provide constraints.

- Filling factor approach is useful, but results need verification by other means.

Urgently needed

Alternative approaches to handling clumping

Handling of complex velocity fields ——> additional diagnostics

Additional theoretical insight into clumping structure, and its variation in the wind.

Linking X-rays/structure.

THE

END