Estrelas Centrais de Nebulosas Planetárias Deficientes em Hidrogênio: Espectros Sintéticos e Análise Espectral

Graziela R. Keller[1]

Advisor: Walter J. Maciel[1]

Colaborators: Luciana Bianchi[2]
James E. Herald[2]

1 *IAG/USP*

2 *The Johns Hopkins University*

Gemini Observatory

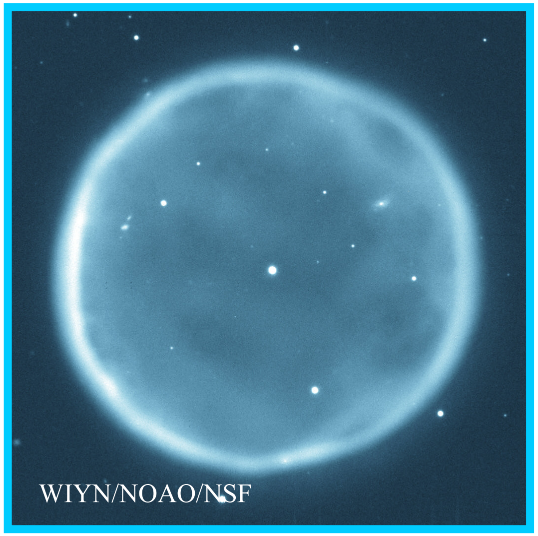
This presentation is organized as follows:

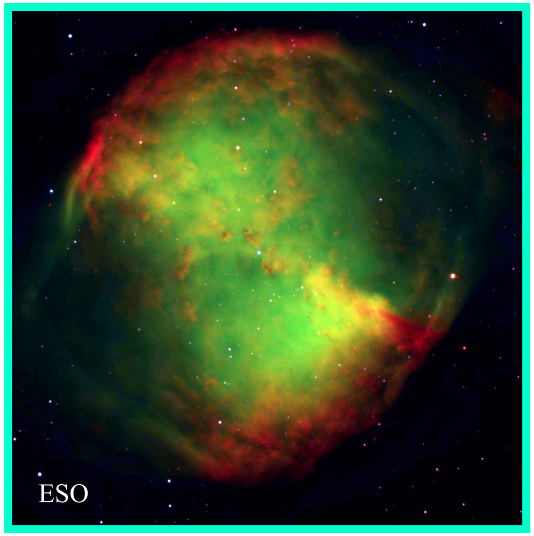
- Introduction
  - **Central Stars of Planetary Nebulae**
  - **Stellar Winds**
  - **Evolutionary Phase**
- Model Grids
  - **The CMFGEN Code**
  - **[WC] and PG1159 Grids**
- Spectral Analysis
  - **NGC 6905, NGC 5189 and Sand 3**

Introduction

Central Stars of Planetary Nebulae

- **They are Hot** – T_* between 20 – 200 kK
- **Low Mass** – M_* around 0.6 $M_\odot$
- **Surrounded by a Planetary Nebula**

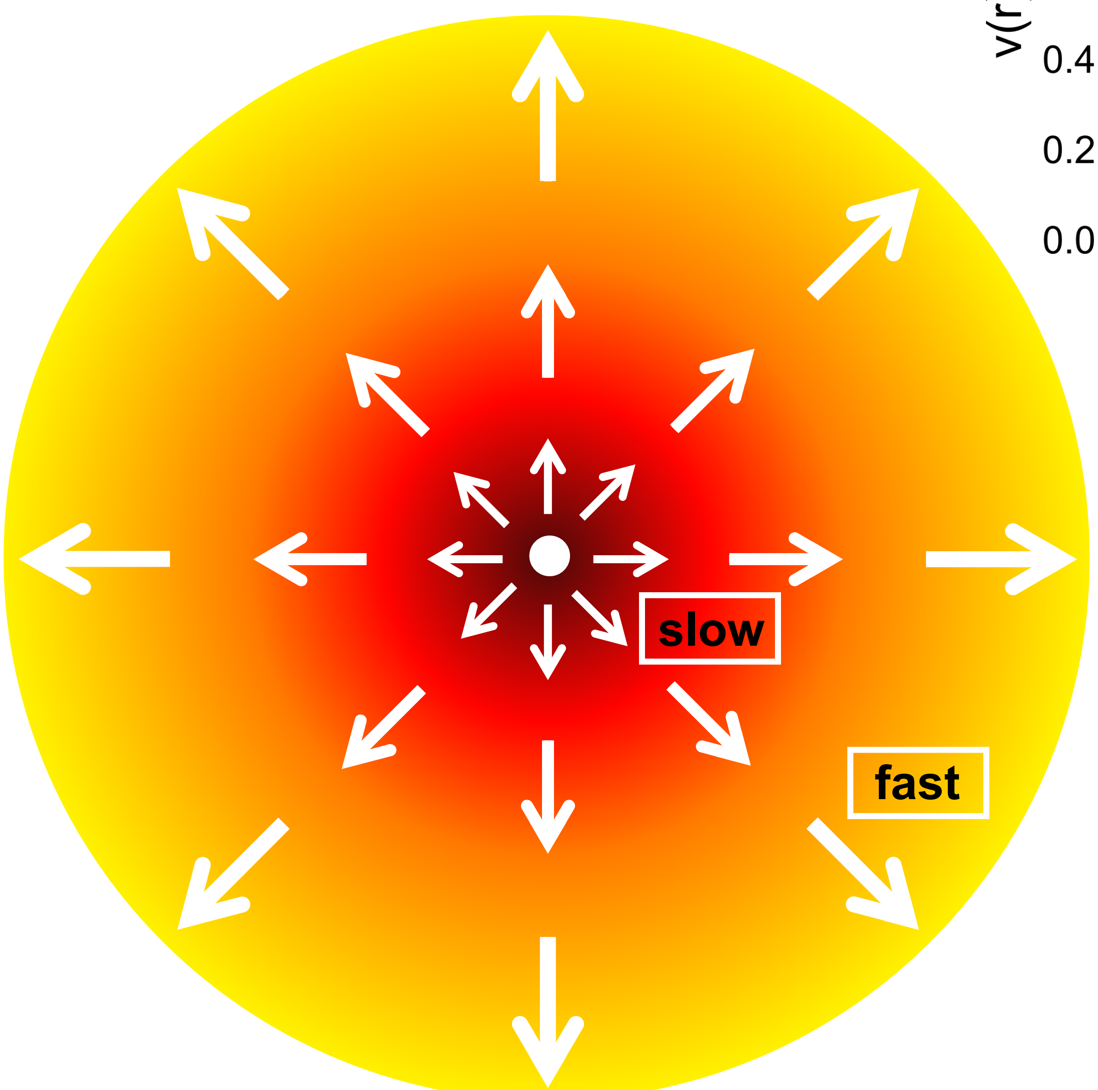


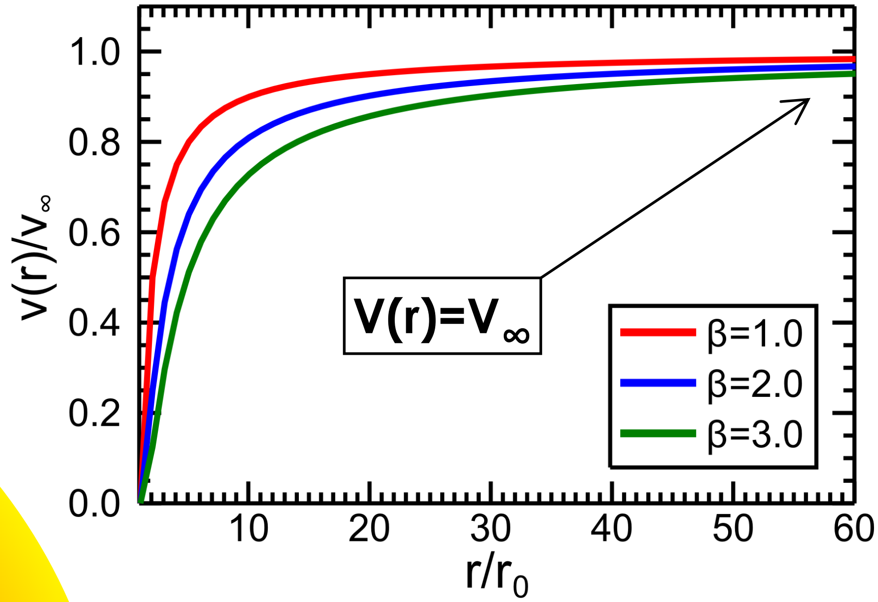


- **Present Stellar Winds** – Radiatively Driven

Stellar Wind

are continuous processes





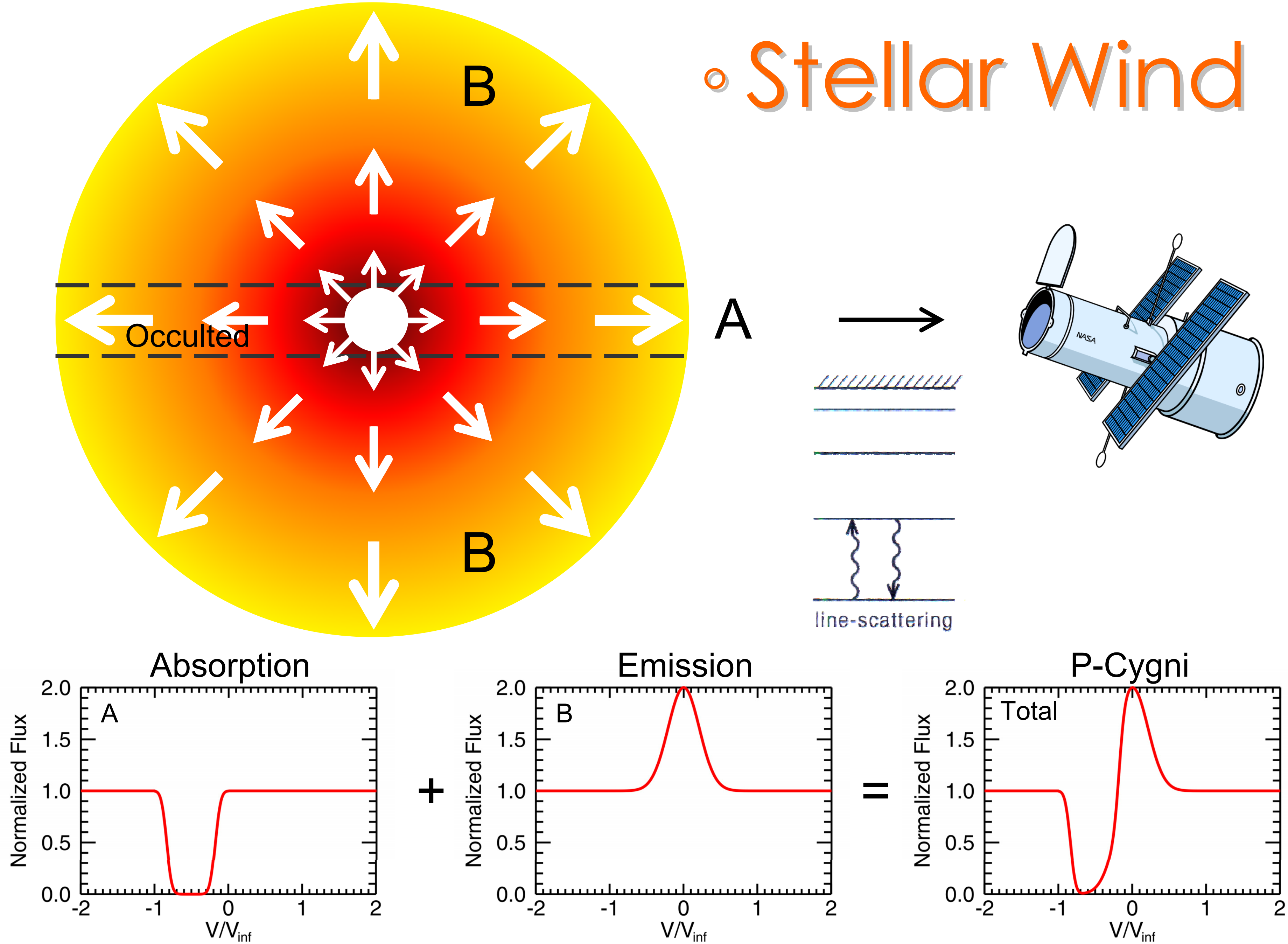
Beta velocity law:

$$V(r) = V_{\infty}\left(1 - \frac{r_0}{r}\right)^{\beta}$$

V_{∞} ≡ Terminal Velocity

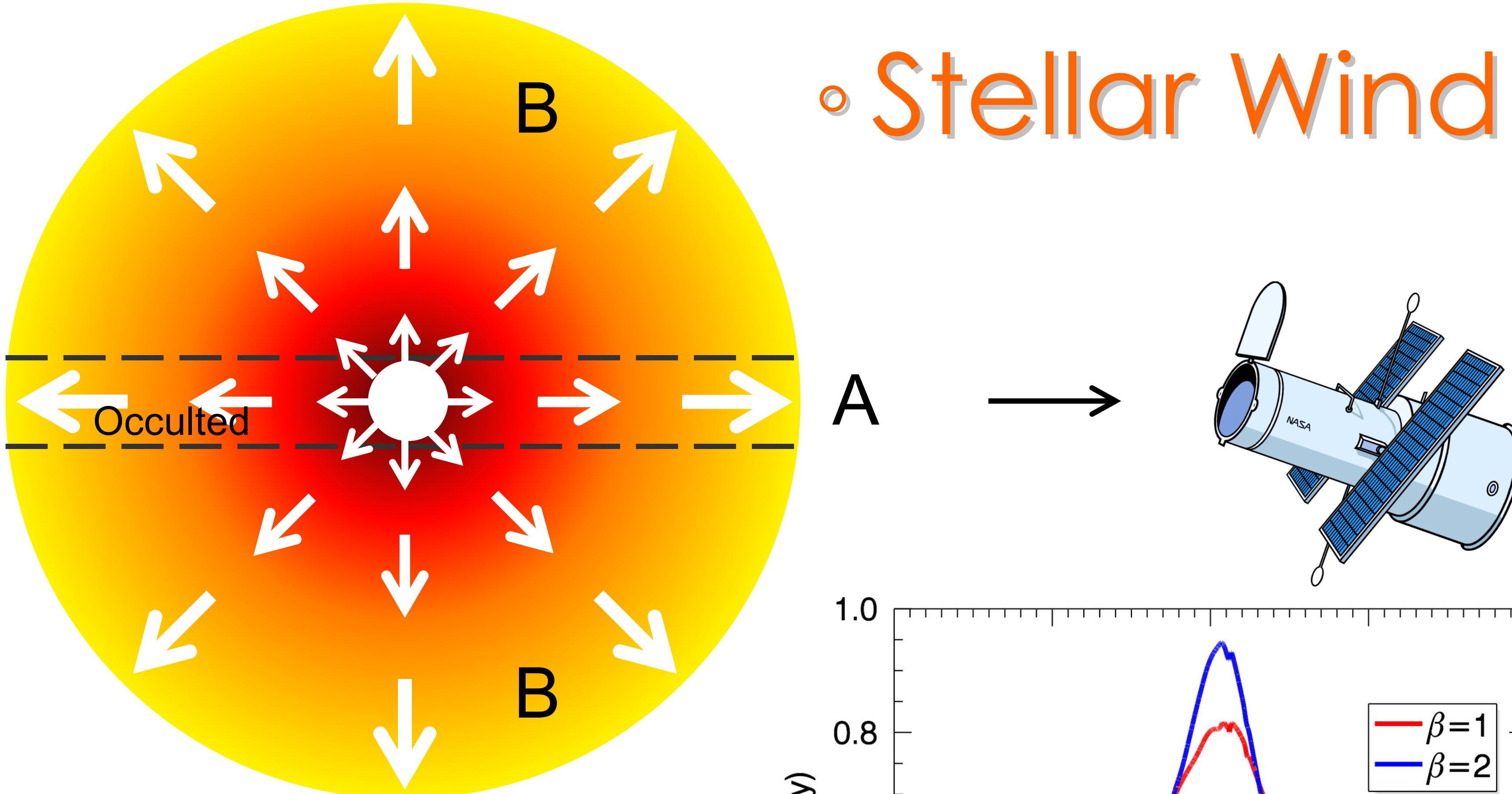
Mass-loss rate:

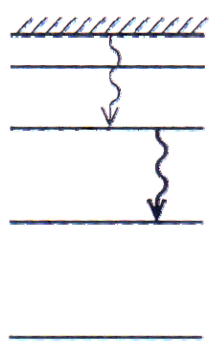
$$\dot{M} = 4\pi r^2 \rho(r) V(r)$$

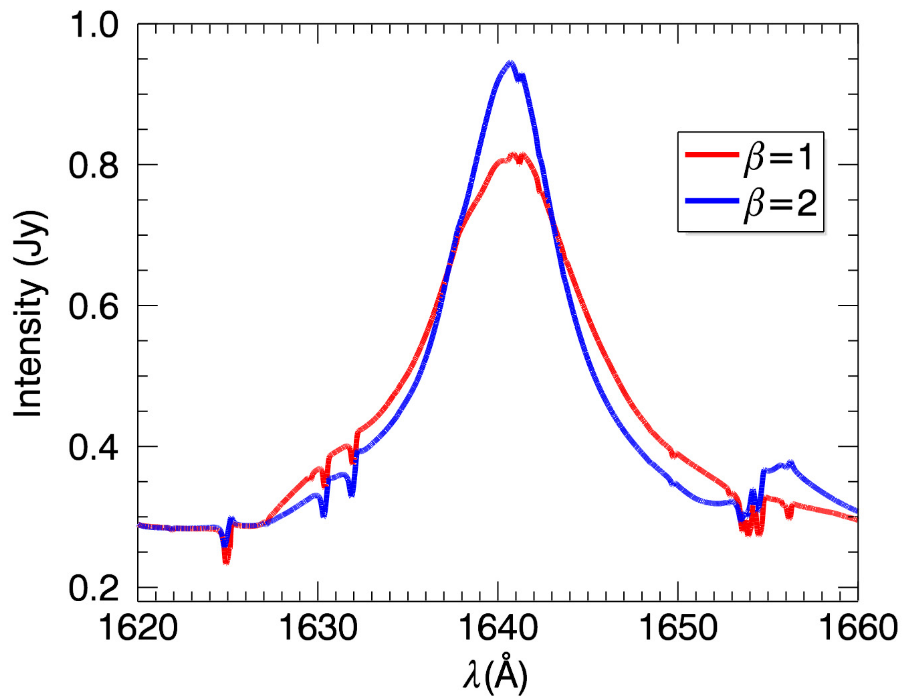


Stellar Wind
B
B
A
Occulted
line-scattering
NASA
Absorption
Emission
P-Cygni
A
B
Total
+
=
Normalized Flux
2.0
1.5
1.0
0.5
0.0
-2
-1
0
1
2
V/V_inf

Stellar Wind



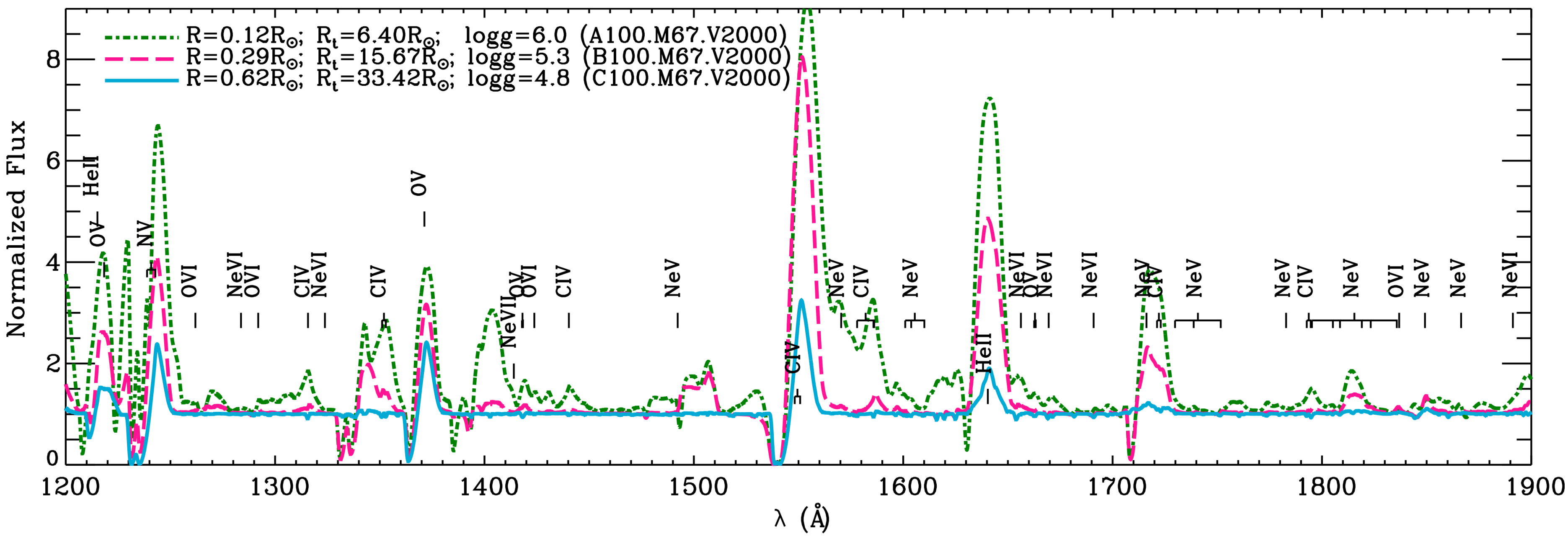




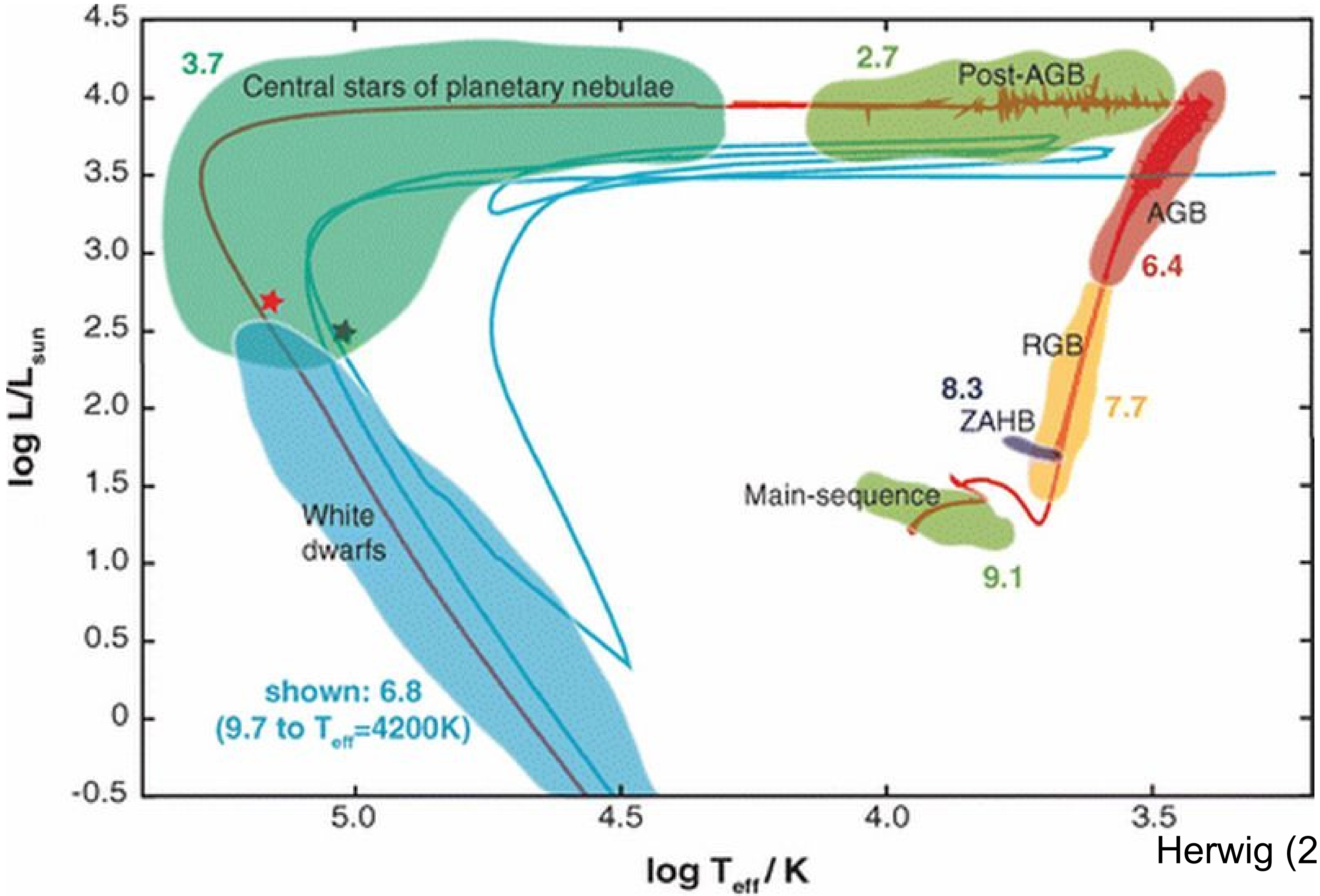
Transformed Radius is a measure of how dense the wind is and is given by:

$$R_t = R_* \left[\frac{v_\infty / 2500 \; km \; s^{-1}}{\dot{M} / 10^{-4} \; M_\odot yr^{-1}} \right]^{2/3}$$

Models with same T_*, same $\dot{M}$ and same v_∞, but different R_t:

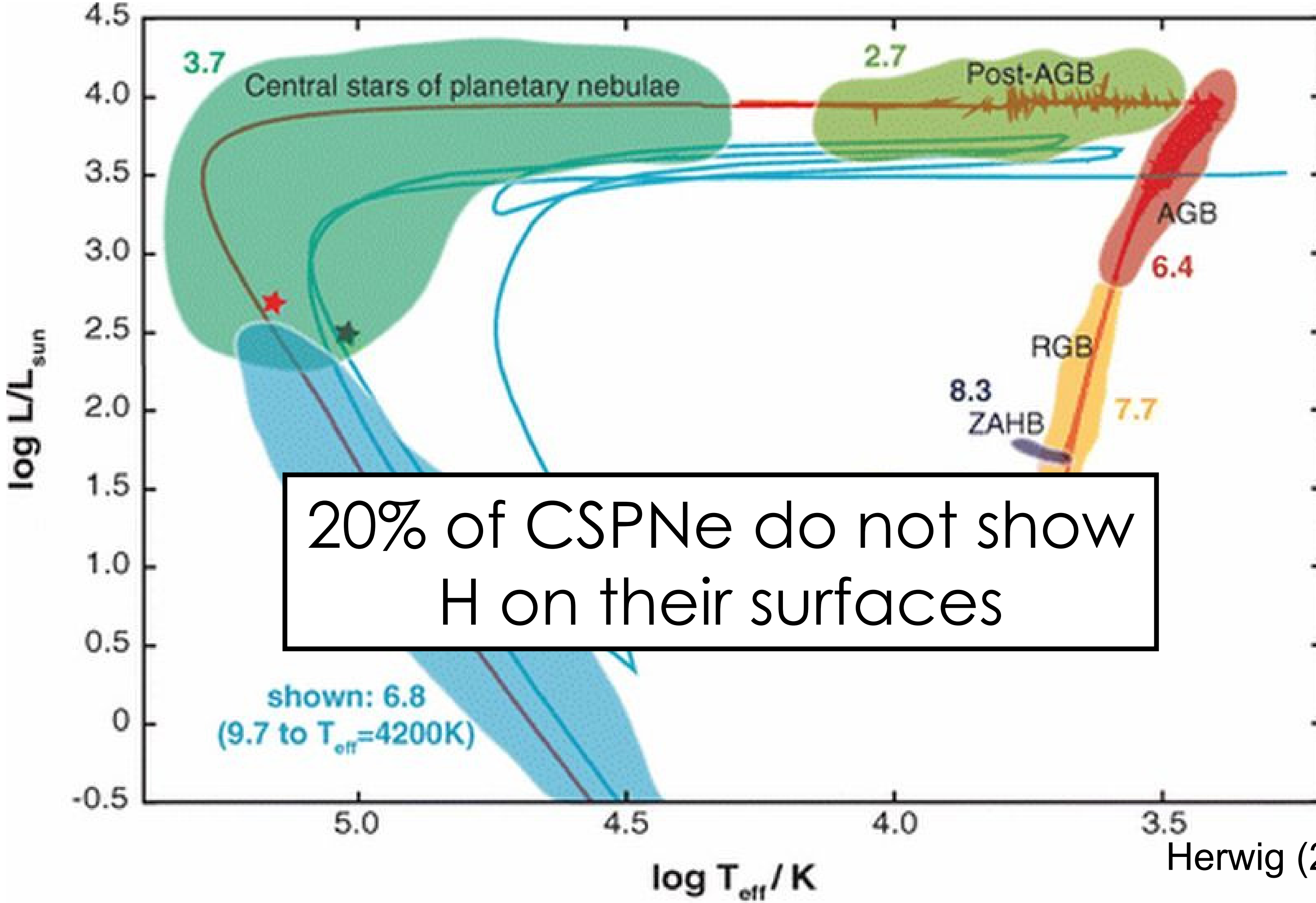


◦ Evolutionary Phase



Herwig (2005)

◦ Evolutionary Phase



20% of CSPNe do not show H on their surfaces

Herwig (2005)

◦ Evolutionary Phase

The H-deficient CSPNe are commonly divided into three main classes:

[WC] – ◈ Spectra similar to massive Wolf–Rayet stars;

◈ Strong carbon and helium emission Lines;

◈ Are divided into early ([WCE]) and late type ([WCL]) objects.

PG1159 – ◈ Occupy the region at the top of the WD cooling track;

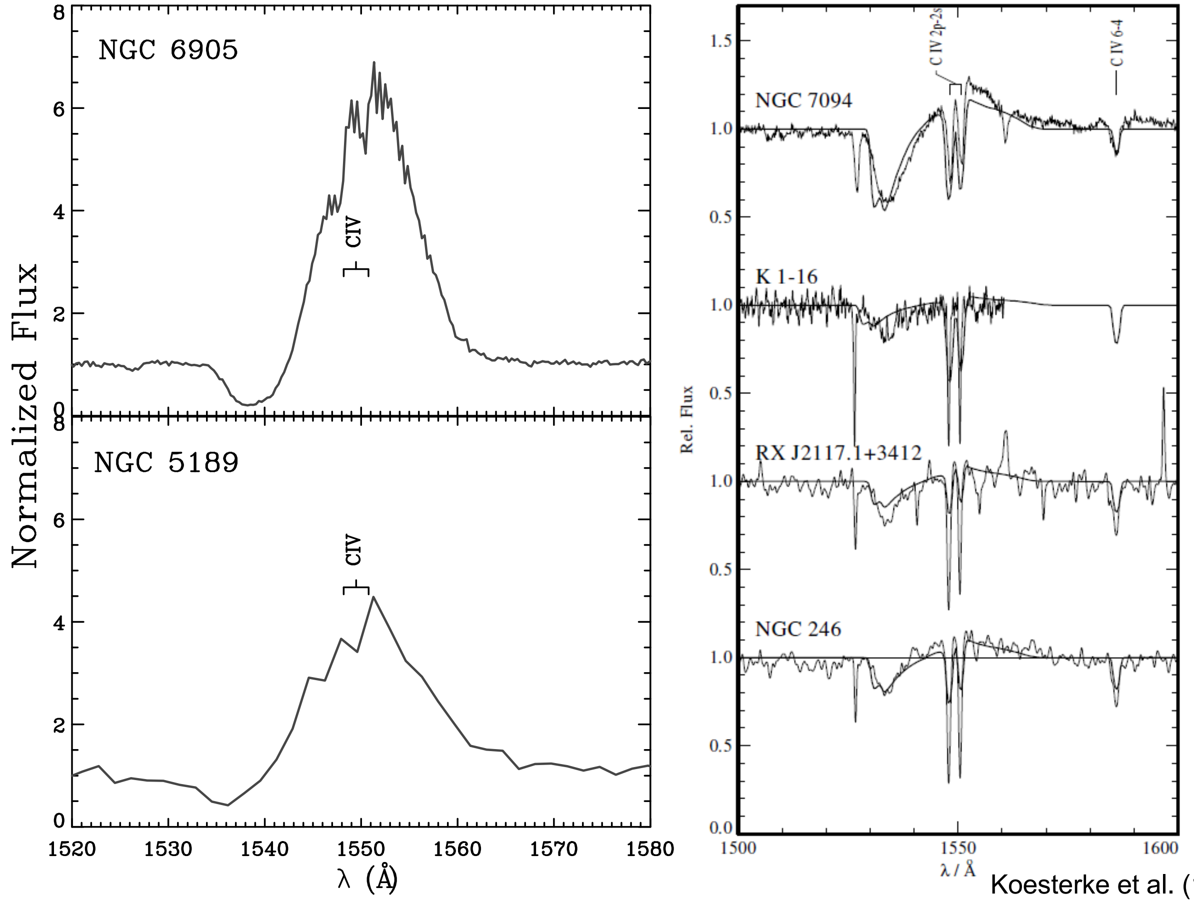
◈ Show absorption lines of highly ionized He, C, O;

◈ Show UV wind lines much weaker than the ones seen in [WC] stars;

[WC]-PG1159 – ◈ Are believed to be transition objects between the two other classes.

◦ Evolutionary Phase

[WC] X PG1159



Koesterke et al. (1998)

C IV λλ 1548.2, 1550.8 Å line

Why Study CSPNe?

◈ They are thought to be the conection between the AGB stars and white dwarfs;

◈ Their surfaces show material from the intershell region of the AGB precursor;

◈ Their winds influence the dynamics of the interstellar medium and the morfology of planetary nebulae;

◈ Their winds are an opportunity to study the line driving mechanism in a different context;

◈ The central stars ionize the planetary nebulae.

It is Important to

Obtain well determined photospheric and wind parameters

◈ The most direct way to accomplish that is:

by modeling the observed spectra
with stellar atmospheric codes

◈ The best way to perform a systematic analysis, ensure the uniqueness of the solution and limit the need for ad-hoc calculated spectra is to:

Build grids of synthetic spectra and
Determine behaviour of spectral features

In this work, we:

◈ Calculated two grids of models proper to the analysis of H-poor CSPNe ([WC]-type and PG1159), covering

Far-UV, UV, optical, and IR.

◈ Made the grids available on-line at

http://dolomiti.pha.jhu.edu/planetarynebulae.html

http://www.astro.iag.usp.br/~graziela/GRIDWEB/front.html

◈ Performed a differential analysis of the grid models to determine the best line diagnostics of stellar parameters.

◈ Used these results to perform a uniform and systematic analysis of UV and far-UV spectra of 3 [WCE] central stars.

◈ Proceeded further by varying parameters not covered by the grid.

Model Grids

Hillier & Miller (1998)

◦ CMFGEN is a state-of-the-art stellar atmosphere code which accounts for:

- Non-LTE;
- Expanding atmosphere;
- Line blanketing;
- Wind clumping;

Hillier & Miller (1998)

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$$\mathbf{f(v) = f_\infty + (1 - f_\infty)\exp(-v(r)/v_{clump})}$$

f=filling factor f_∞=0.1

Hillier & Miller (1998)

◦ CMFGEN

◈ **Does not** solve the dynamical equations of the wind. ✗

It requires the mass-loss rate and the velocity law to be supplied. In this work:

- We adopted a β-velocity law ($V(r) = V_{\infty}\left(1 - \frac{r_0}{r}\right)^{\beta}$) with β=1;
- The mass-loss rate is a free parameter.

Chemical Composition of the Grids` Models

Element	Mass Fraction
He	0.43
C	0.45
N	0.01
O	0.08
Ne	0.02
Al	5.57×10^{-5}
Si	6.99×10^{-4}
P	6.12×10^{-6}
S	3.82×10^{-4}
Fe	1.36×10^{-5}

No hydrogen

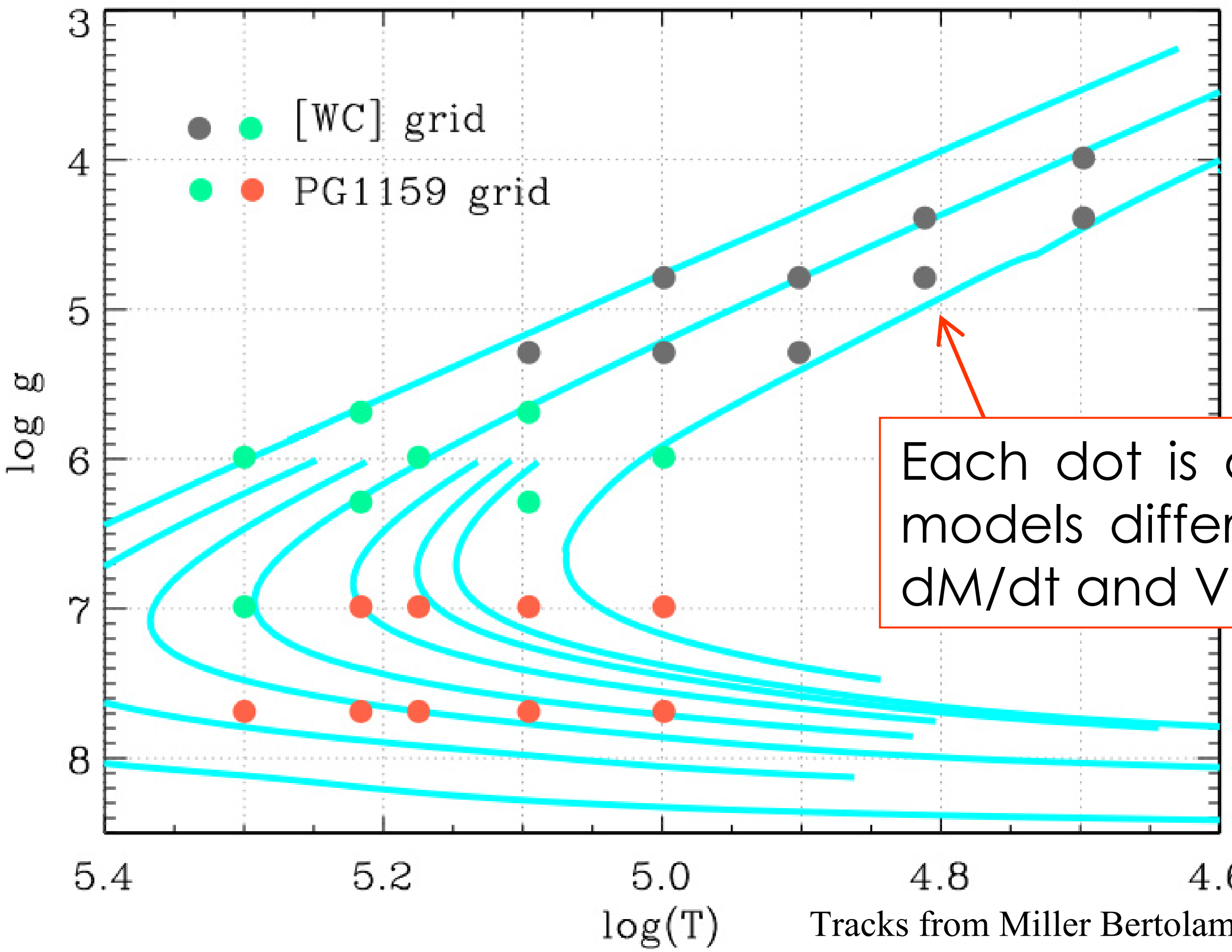
element	ions
He	I, II, III
C	II[a], III[a], IV, V
N	II[a], III[a], IV[a], V, VI
O	II[a], III[a], IV[a], V, VI, VII
Ne	II[a], III[a], IV[a], V, VI, VII, VIII, IX
Al	III[a], IV[a], V[a]
Si	III[a], IV, V[a], VI[a]
P	IV[a], V, VI
S	III[a], IV[a], V[a], VI, VII
Fe	IV[a], V[a], VI[a], VII, VIII, IX, X, XI

[a] These ions are not present in all models.

◦ THE GRIDS

[WC] grid → 199 models
PG1159 grid → 160 models

Models vary in L, T, logg, dM/dt, and V_∞ .



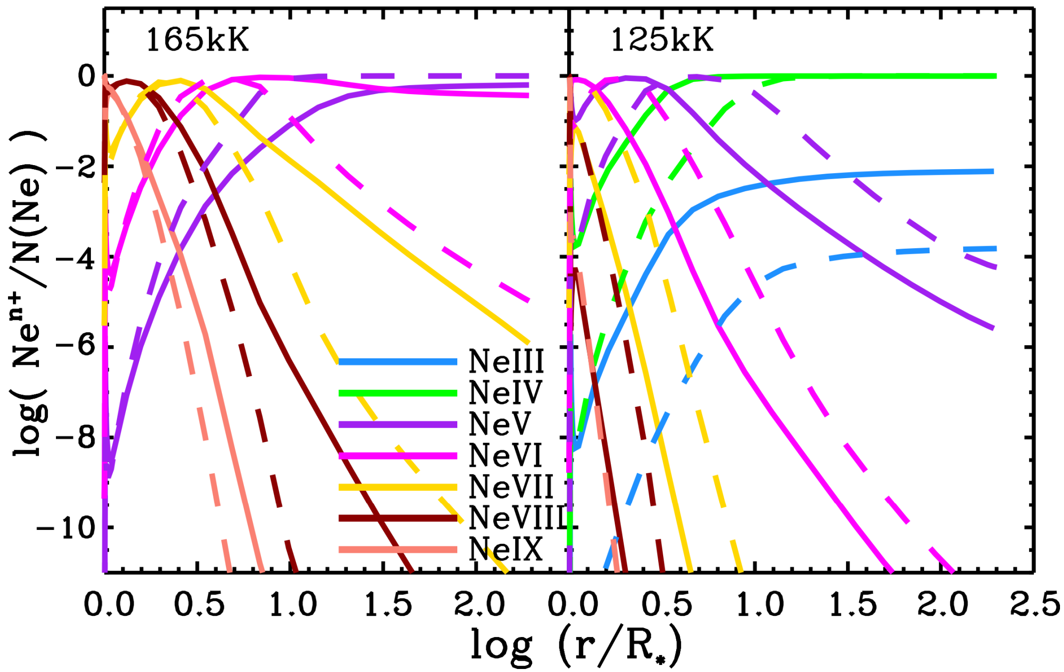
Each dot is a group of models differing only in dM/dt and V_∞.

Tracks from Miller Bertolami & Althaus (2006)

Ionization Fractions

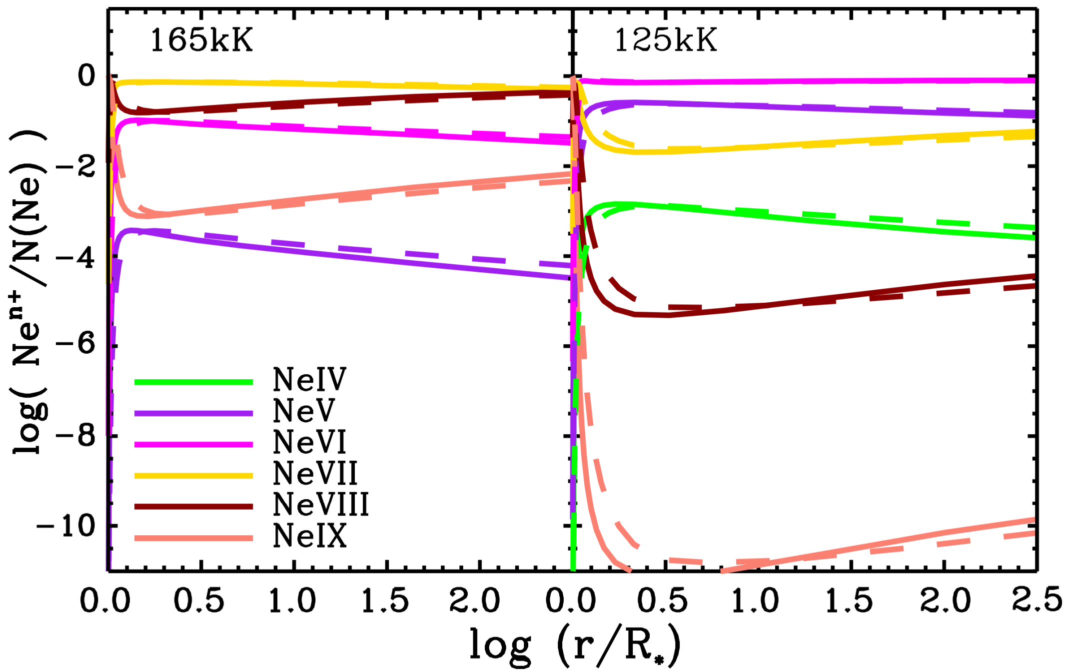
[WC] stars:

Stratified ionization structure.



PG1159:

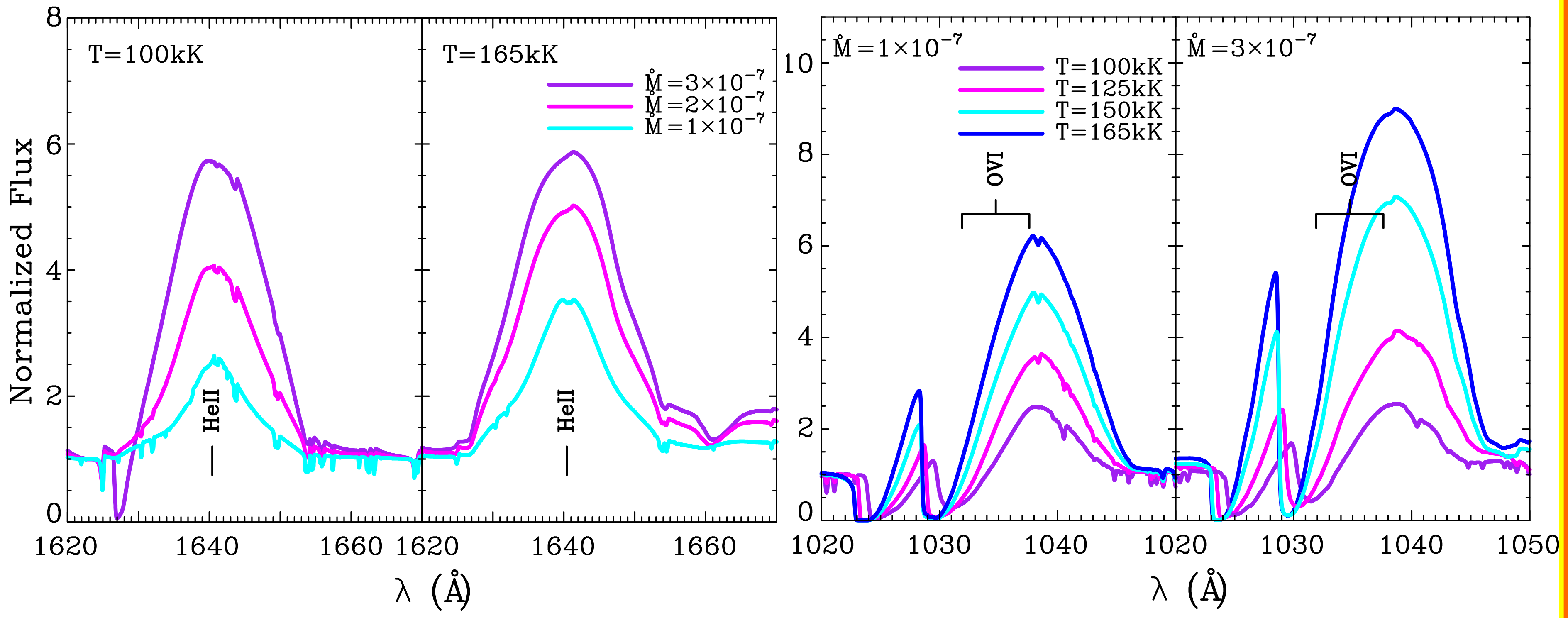
Ionization structure dominated by one level.



We find higher dM/dt increases stratification

Differential Analysis of Grid Models

We performed a differential study, showing the predicted impact of parameter variation on strengths and shapes of line profiles.



We determined the best line diagnostics of dM/dt and T_*.

Spectral Analyses

◦ NGC 6905, NGC 5189 and Sand 3

We analyzed UV and far-UV spectra of the [WCE] central stars of NGC 6905, NGC 5189 and Sand 3 using the [WC] grid to constrain their main physical parameters.

Data

Object	Instrument	Resolution [Å]	Aperture [arcsec]	Range [Å]
NGC 6905	FUSE	~0.06	30x30	905-1187
	STIS+G140L	~1.20	52x0.5	1150-1736
	STIS+G230L	~3.15	52x0.5	1570-3180
NGC 5189	FUSE	~0.06	30x30	905-1187
	IUE	~7.0	9.3x20.7	1851-3349
	IUE	~6.0	8.9x21.6	1151-1979
Sand 3	STIS+G140L	~1.20	52x2	1128-1725
	STIS+G230MB	~0.33	52x2	2198-2353
	STIS+G230MB	~0.33	52x2	2717-2871
	IUE	~6.0	8.9x21.6	1151-1979
	IUE	~7.0	9.3x20.7	1851-3349

Parameter Degeneracy

Problems:

◈ Most CSPNe do not have well determined distances;

◈ The [WC] CSPNe do not show strong photospheric absorption lines not contaminated by wind emission, such that logg can not be determined by spectral analysis;

Consequences:

◈ If one does not know the distance, or the stellar radius, one cannot know the luminosity;

◈ One has to assume a typical luminosity/radius;

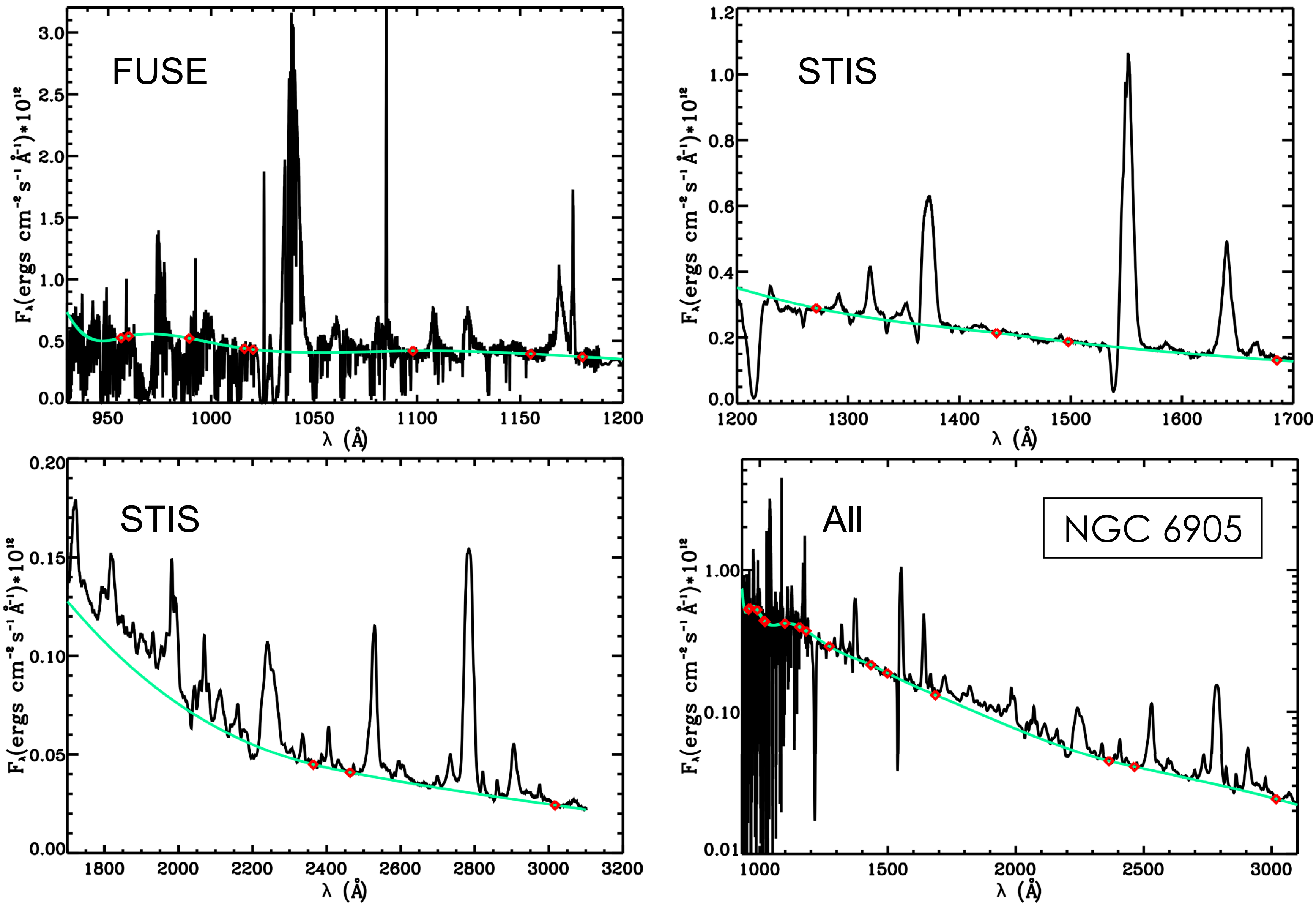
◈ One cannot know the mass-loss rate: $R_t = R_* \left[\frac{v_\infty / 2500\ km\ s^{-1}}{\dot{M} / 10^{-4}\ M_\odot yr^{-1}} \right]^{2/3}$

Thus:

◈ One can only constrain **T_*, R_t and V_∞**

◈ Distance, radius, luminosity, mass-loss rate are degenerate.

Continuum Determination



Terminal Velocity of the Wind

◈ From the blue edge of the absorption profile:

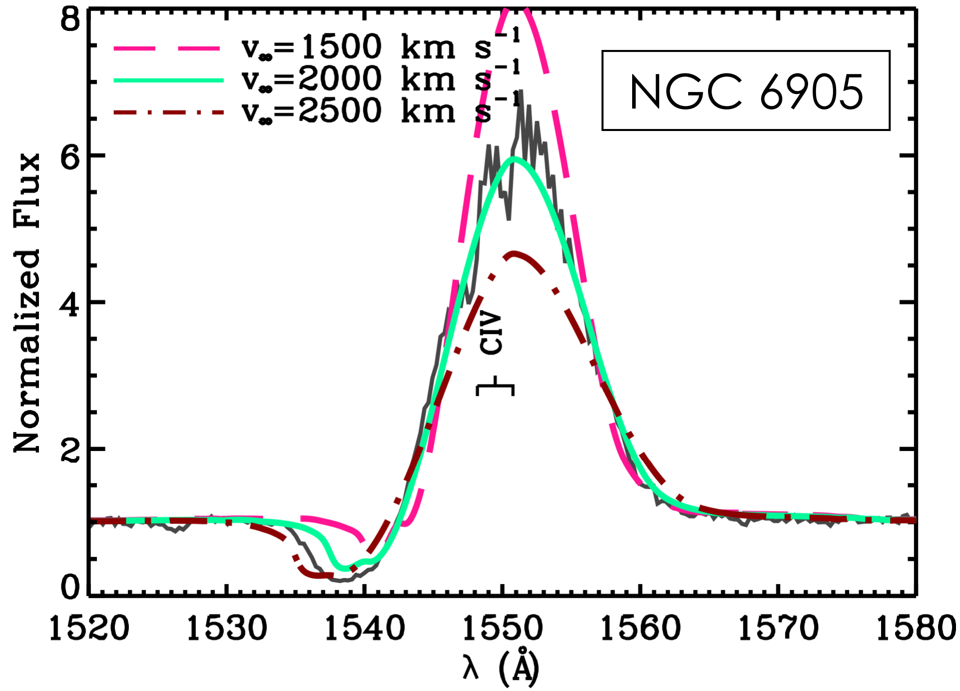
$$V_\infty \approx V_{edge} - 2 \times V_{turb}$$

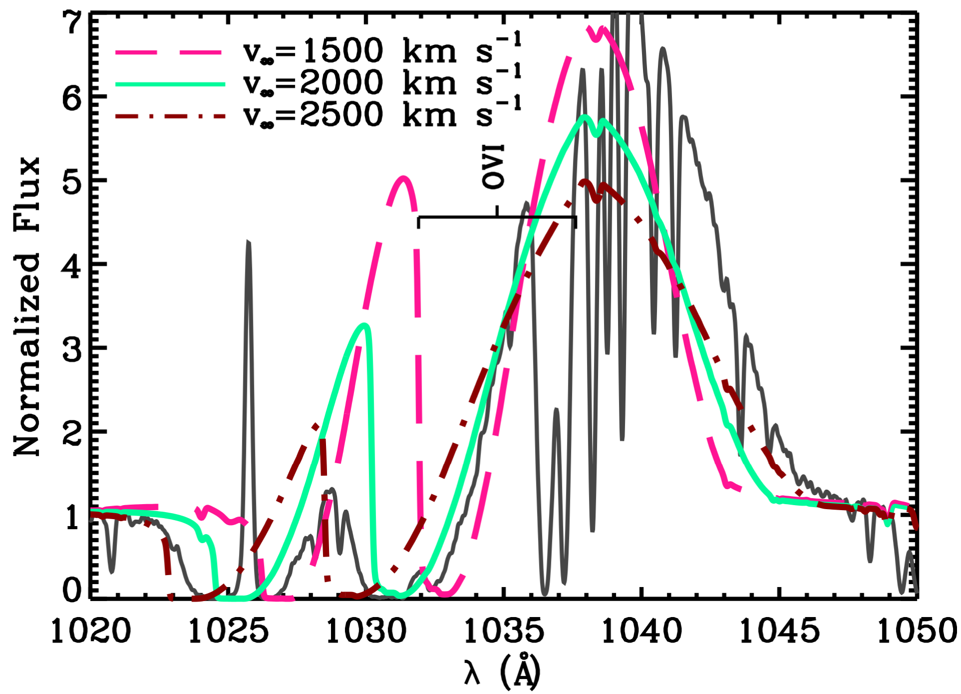
NGC 6905: V_∞ = 2170 km/s

◈ We also compared the observed profiles to models with

$$V_\infty = 1500, 2000 \text{ and } 2500 \text{ km s}^{-1}.$$

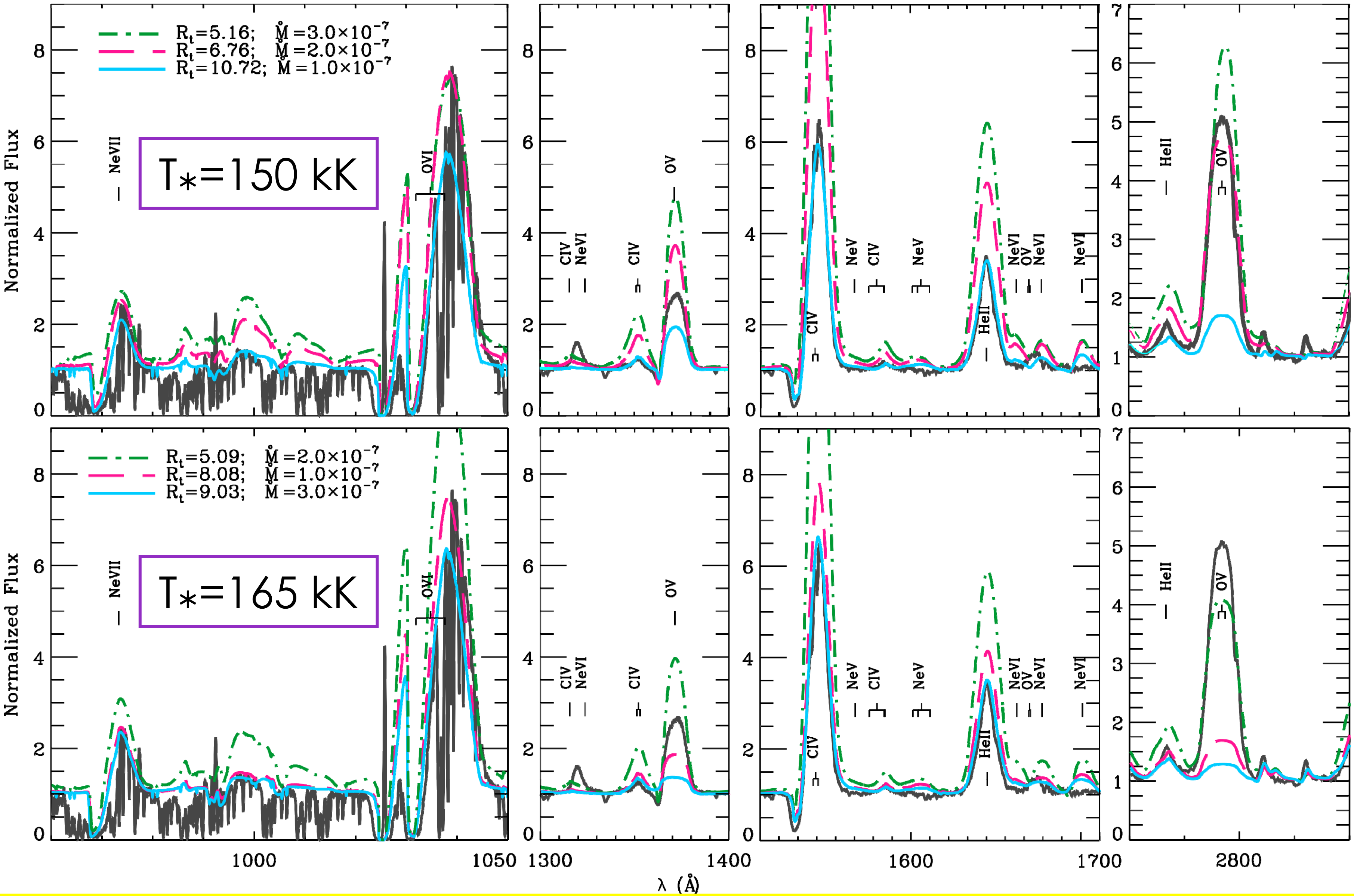
NGC 6905: Best grid models have V_∞ = 2000 km/s



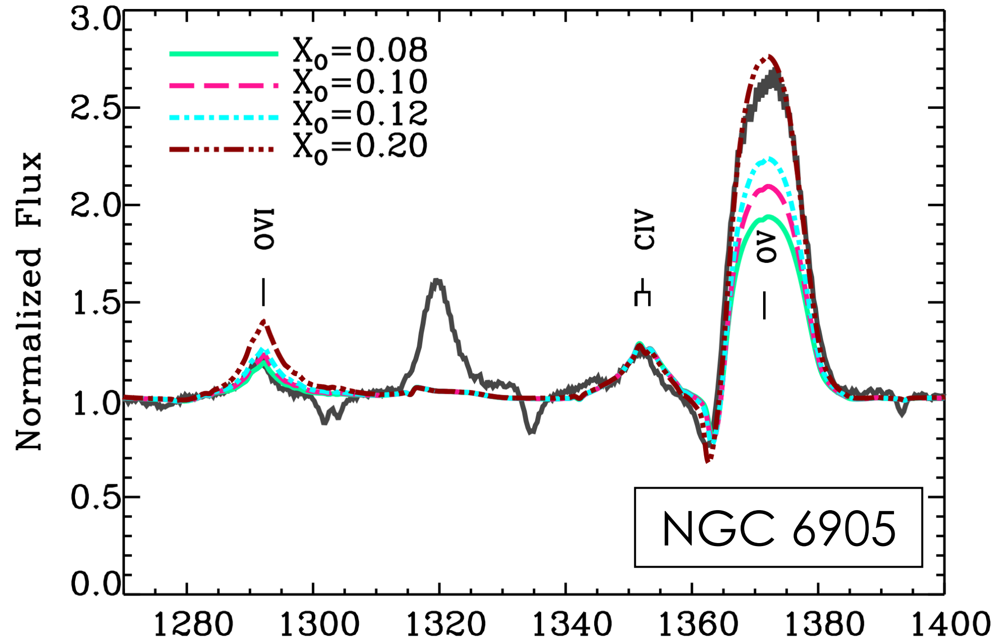


Constraining T_* and R_t

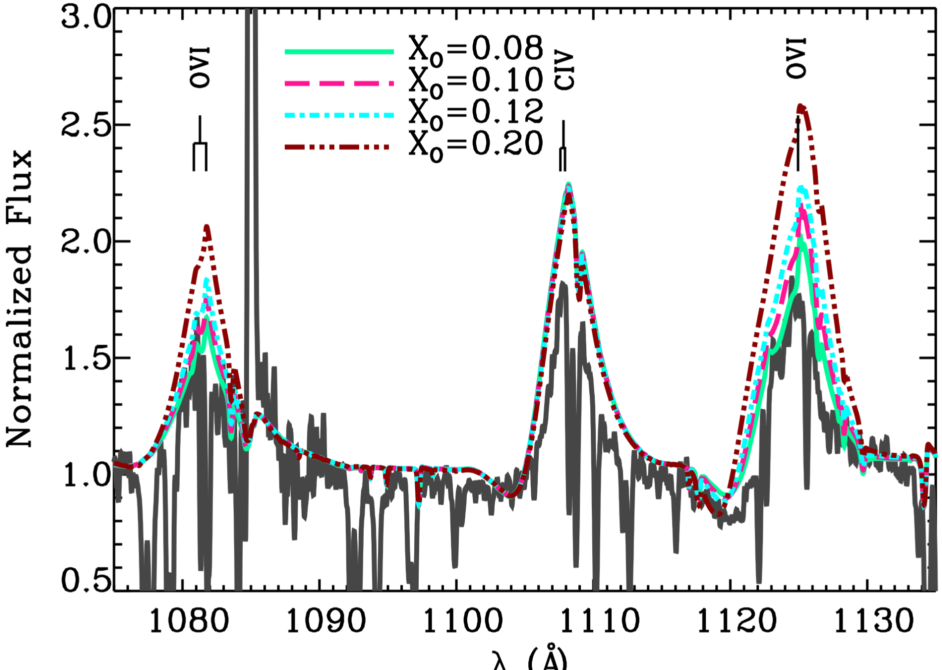
NGC 6905

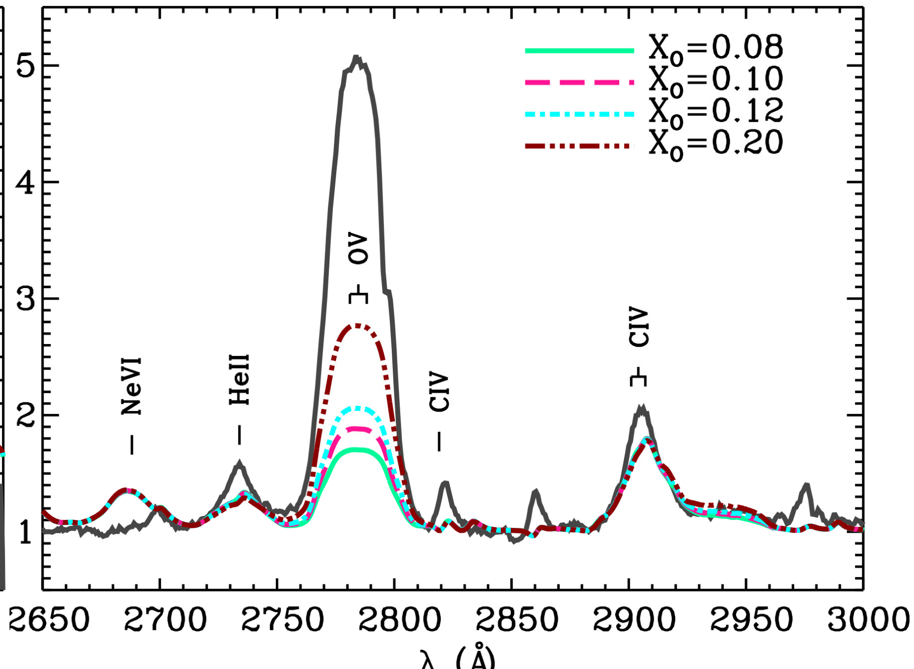


Oxygen Abundance

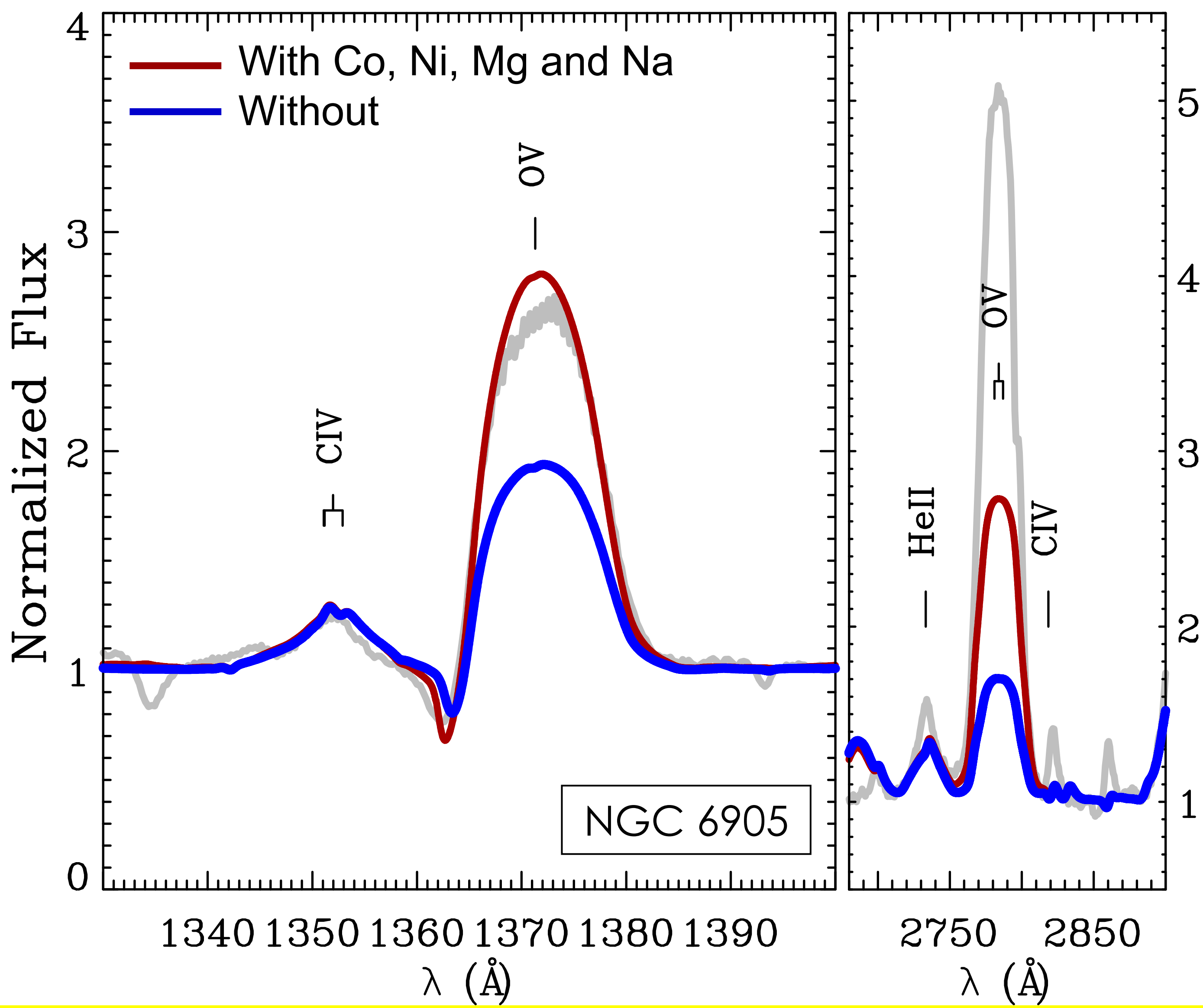


Grid models: X_O=0.08

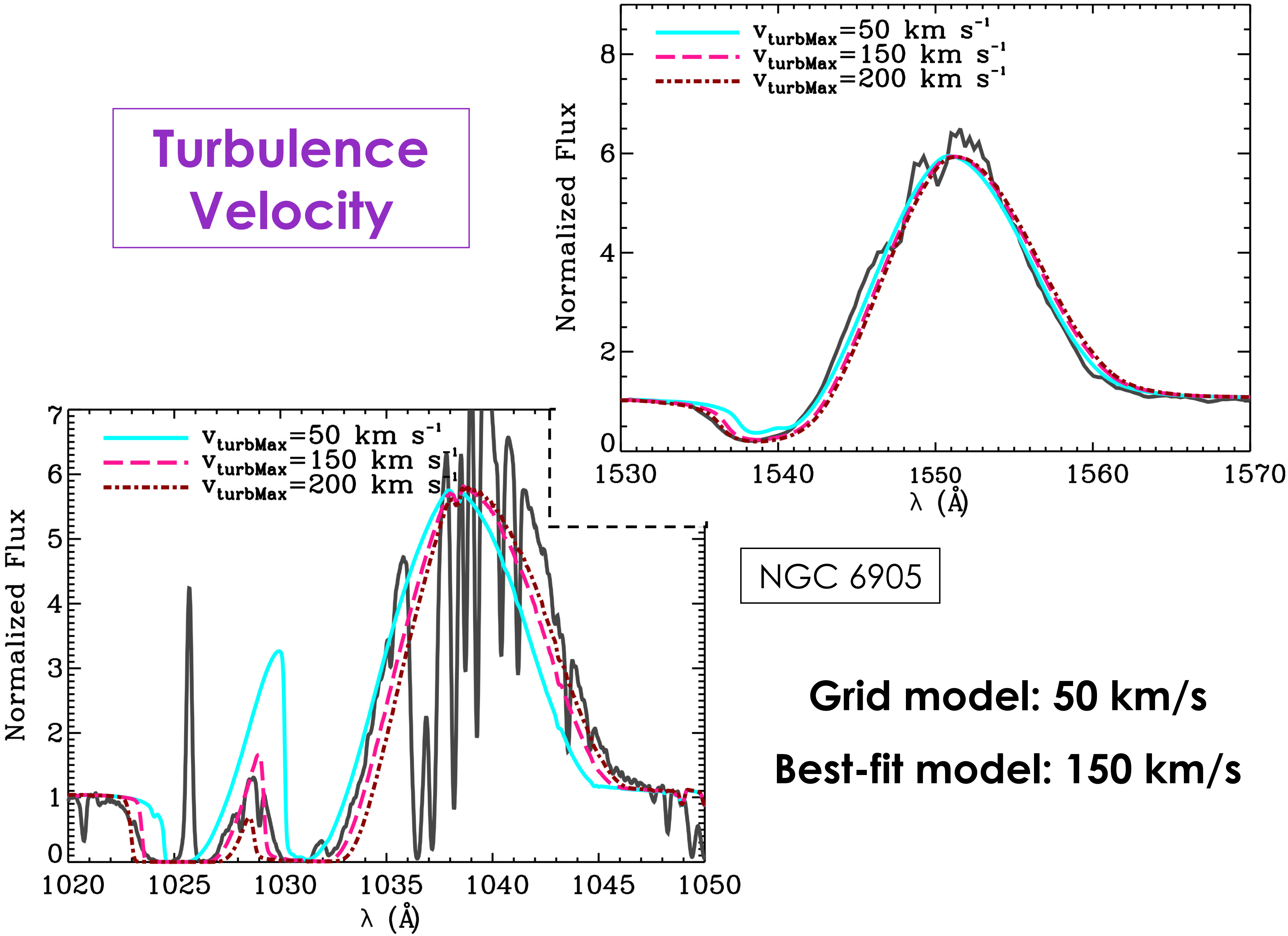




Inclusion of Additional Ions



Turbulence Velocity



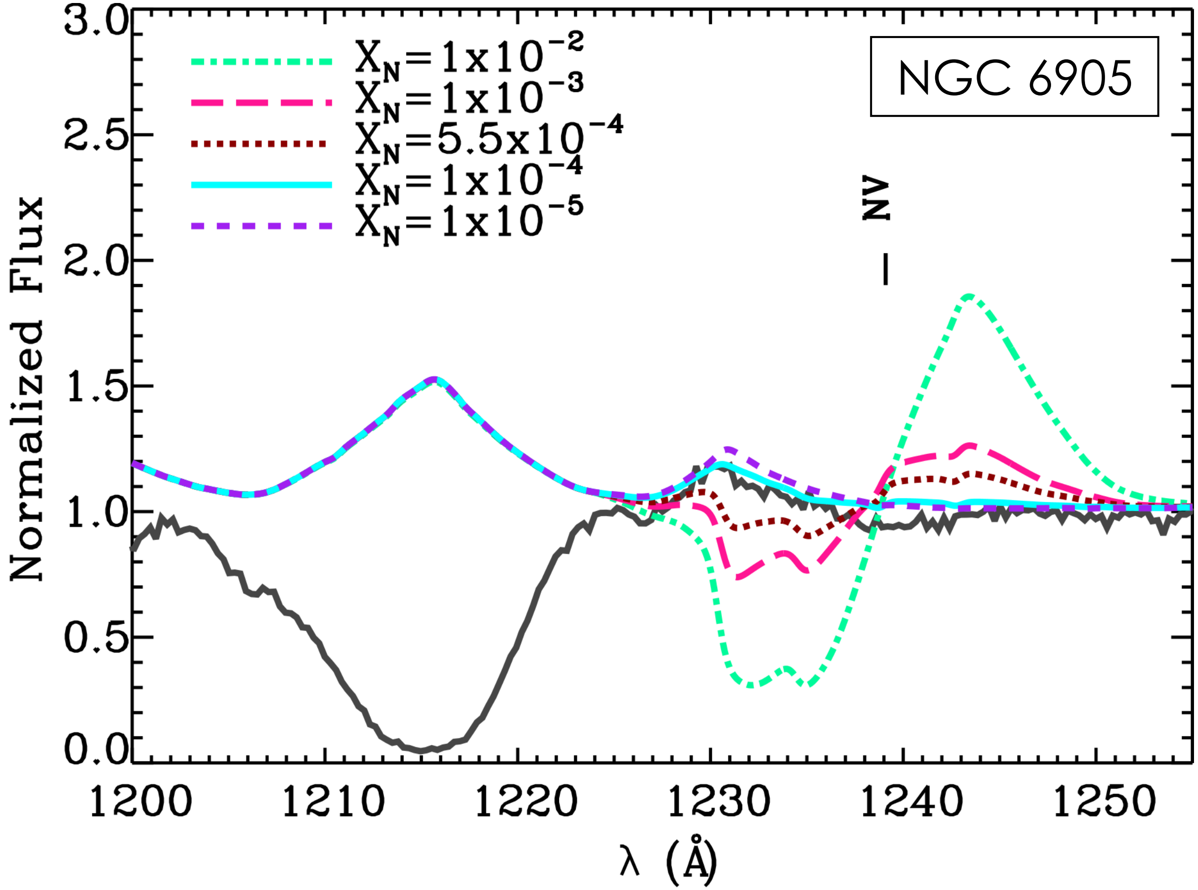
NGC 6905

Grid model: 50 km/s

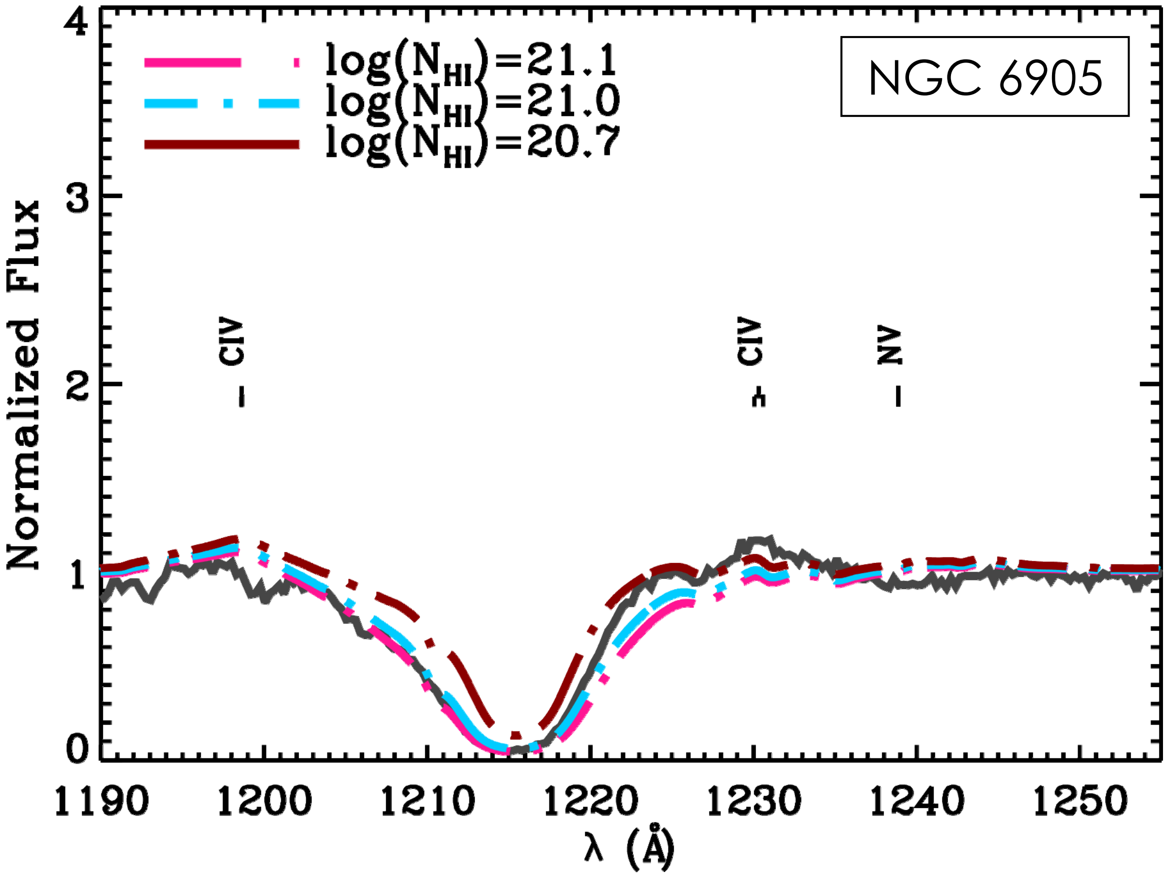
Best-fit model: 150 km/s

Nitrogen Abundance

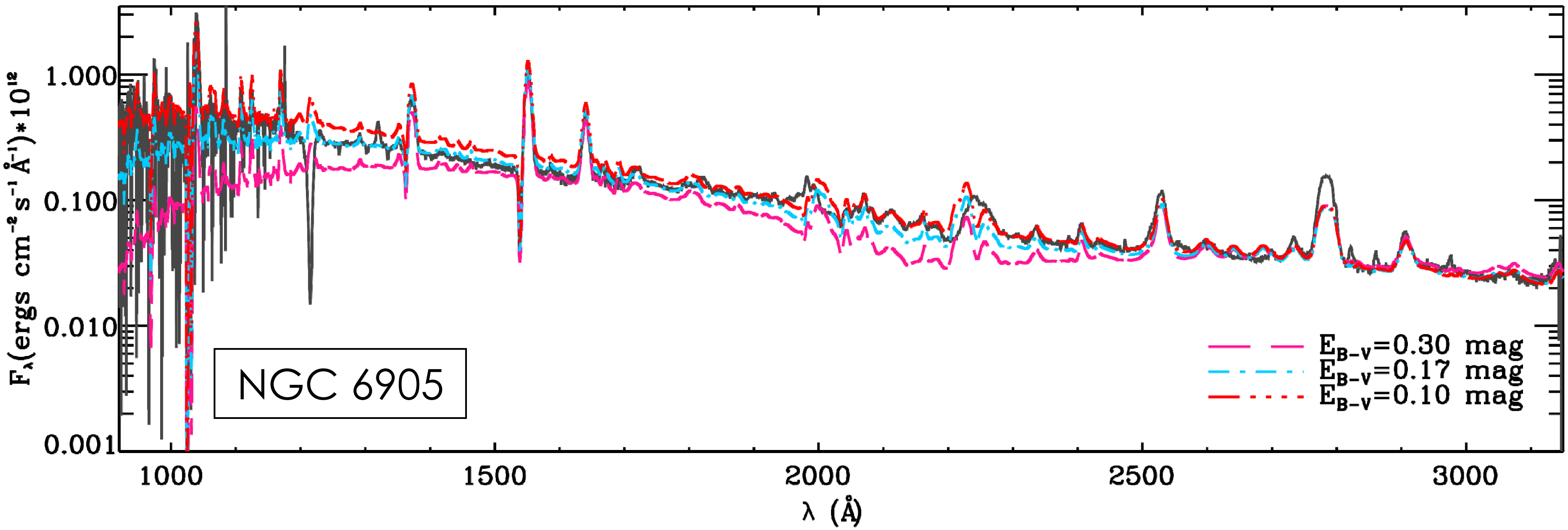
Grid models: X_N=0.01



Interstellar Lyman-α



Interstellar Extinction Curve



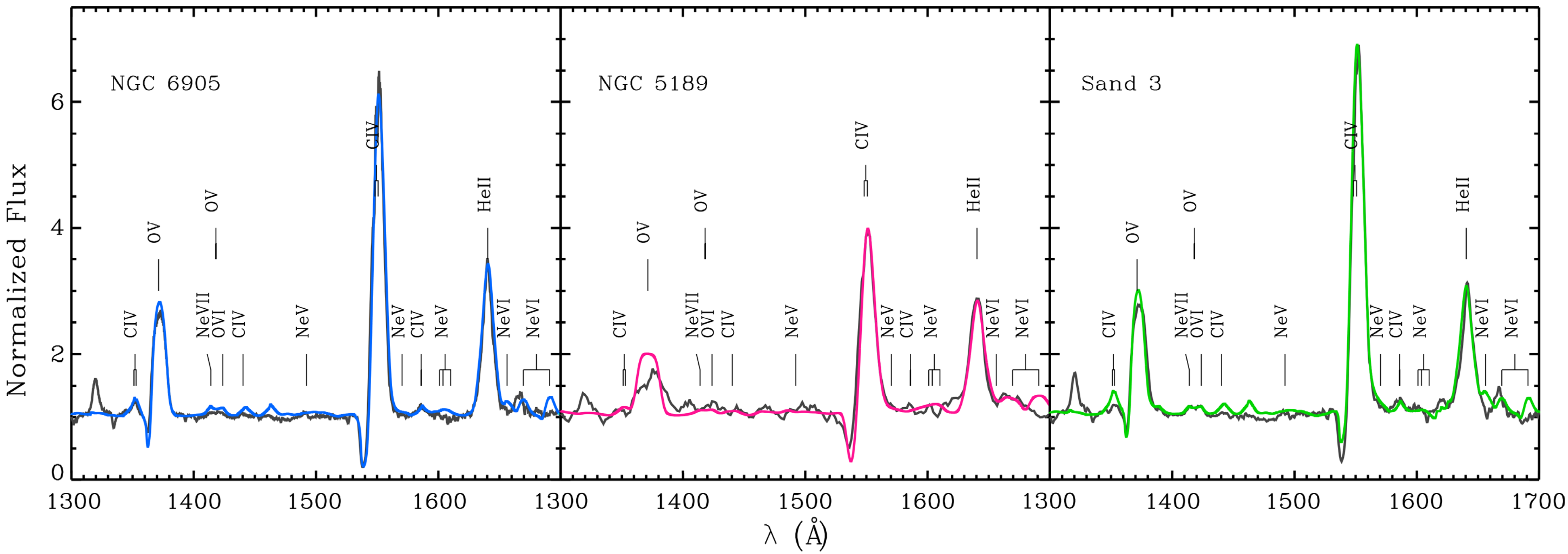
Extinction curves of Cardelli et al. (1989) with Rv=3.1

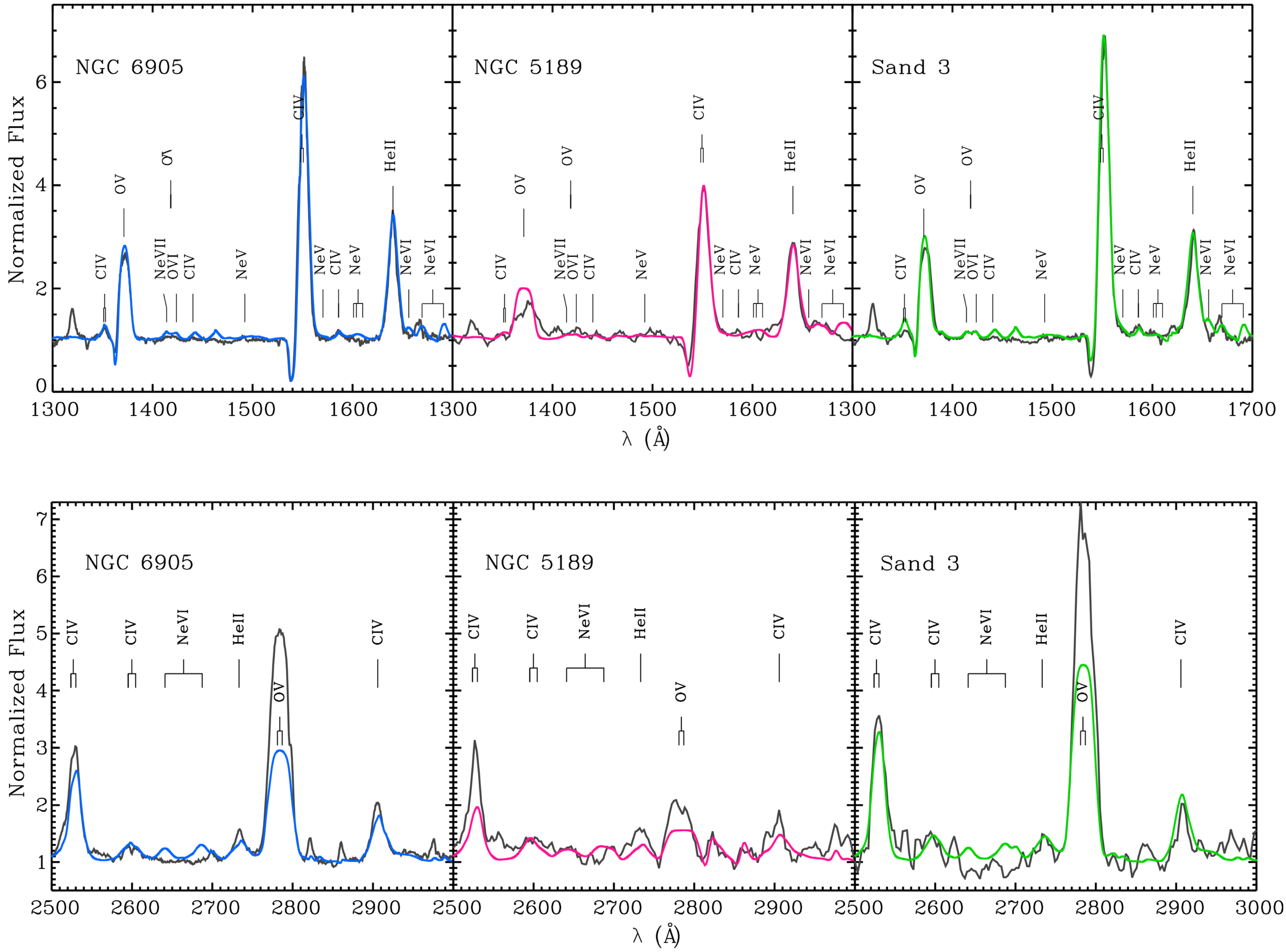
For NGC 6905, these (CCM) curves predict too strong absorptions at 2175 Å and on the far-UV.

Results for the 3 [WCE] CSPNe

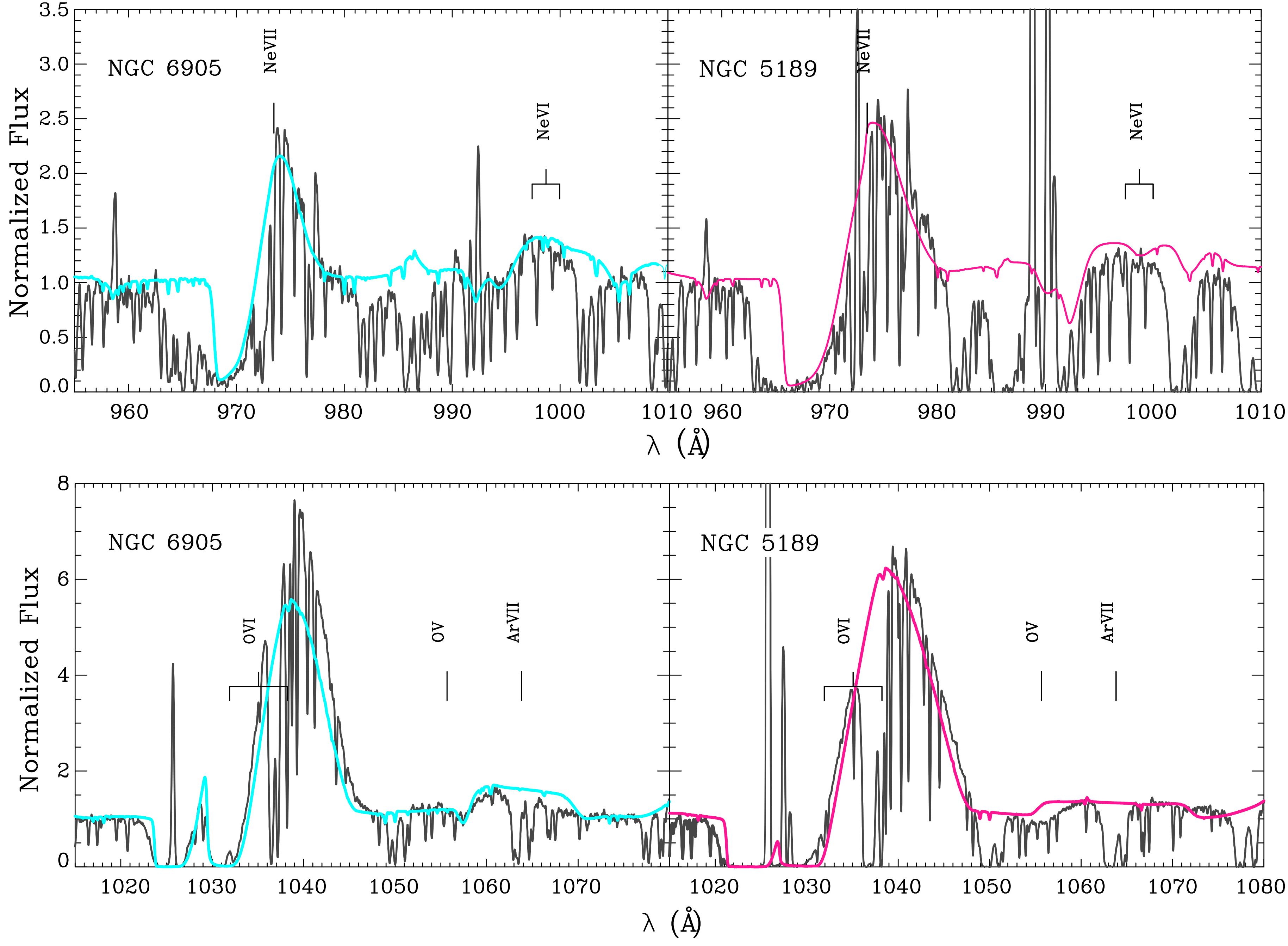
Parameters of our best-fit models

Object	T_*[kK]	R_t[R⊙]	v_∞[km/s]	X_{He}	X_C	X_N	X_O	X_{Ne}
NGC 6905	150	10.7	2000	0.44	0.45	1.1×10^{-4}	0.08	0.02
NGC 5189	165	10.5	2500	0.58	0.25	0.01	0.12	0.04
Sand 3	150	9.3	2000	0.28	0.55	0.07	0.08	0.02



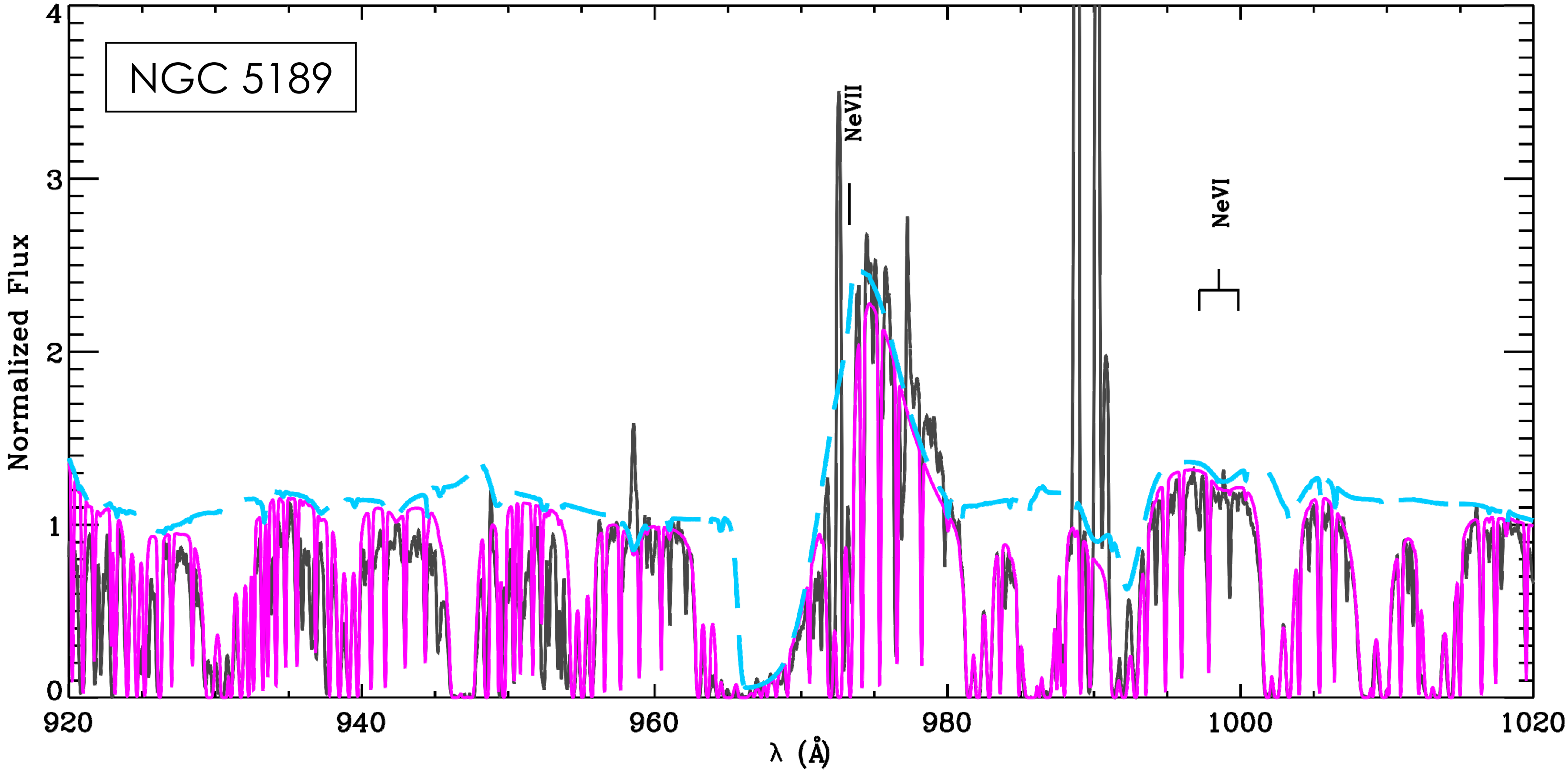


NGC 6905
NGC 5189
Sand 3
Normalized Flux
λ (Å)
CIV
OV
NeVII
OVI
NeV
HeII
NeVI

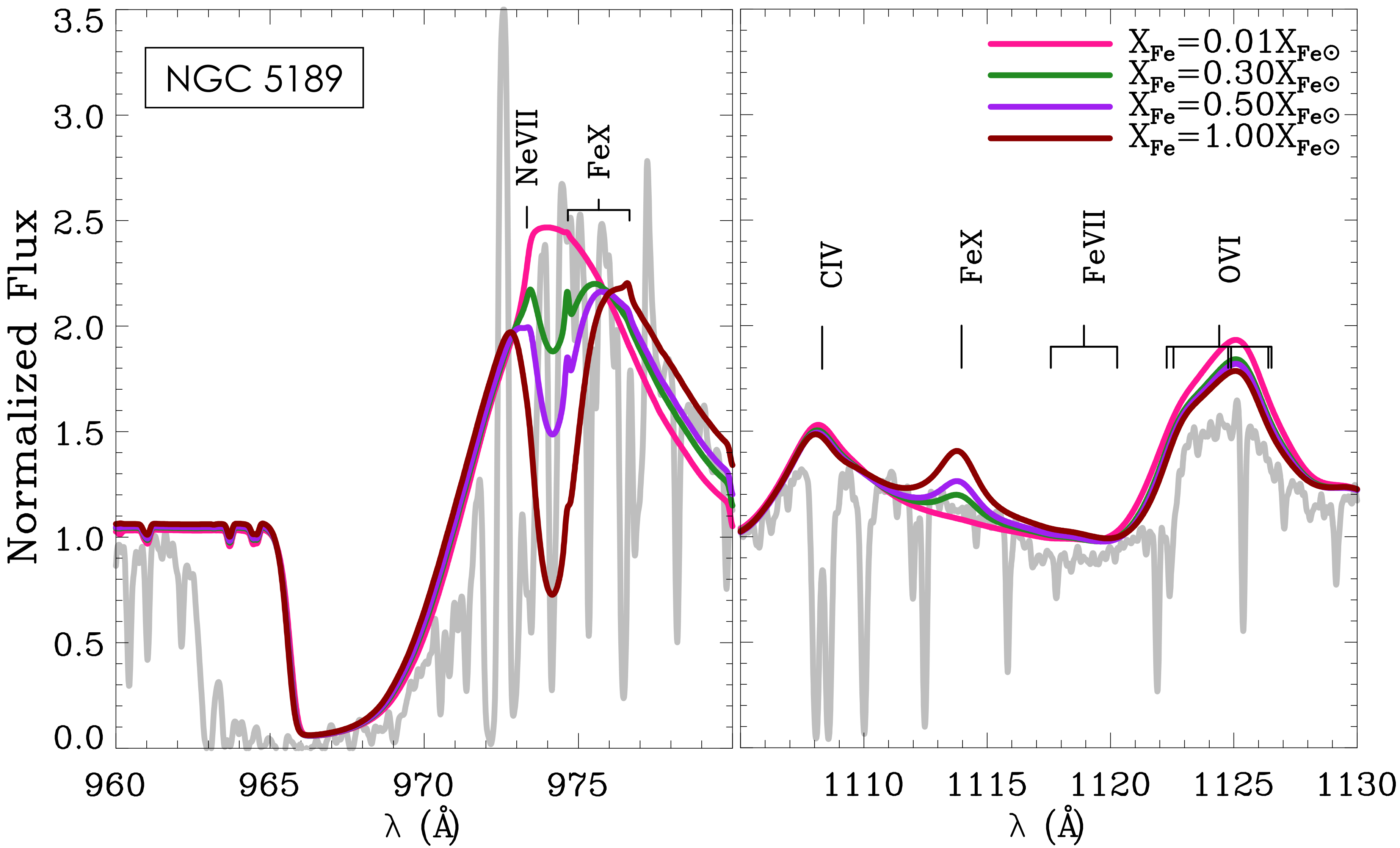


NGC 6905
NGC 5189
NeVII
NeVI
Normalized Flux
λ (Å)
OVI
OV
ArVII

H_2 Interstellar Absorption

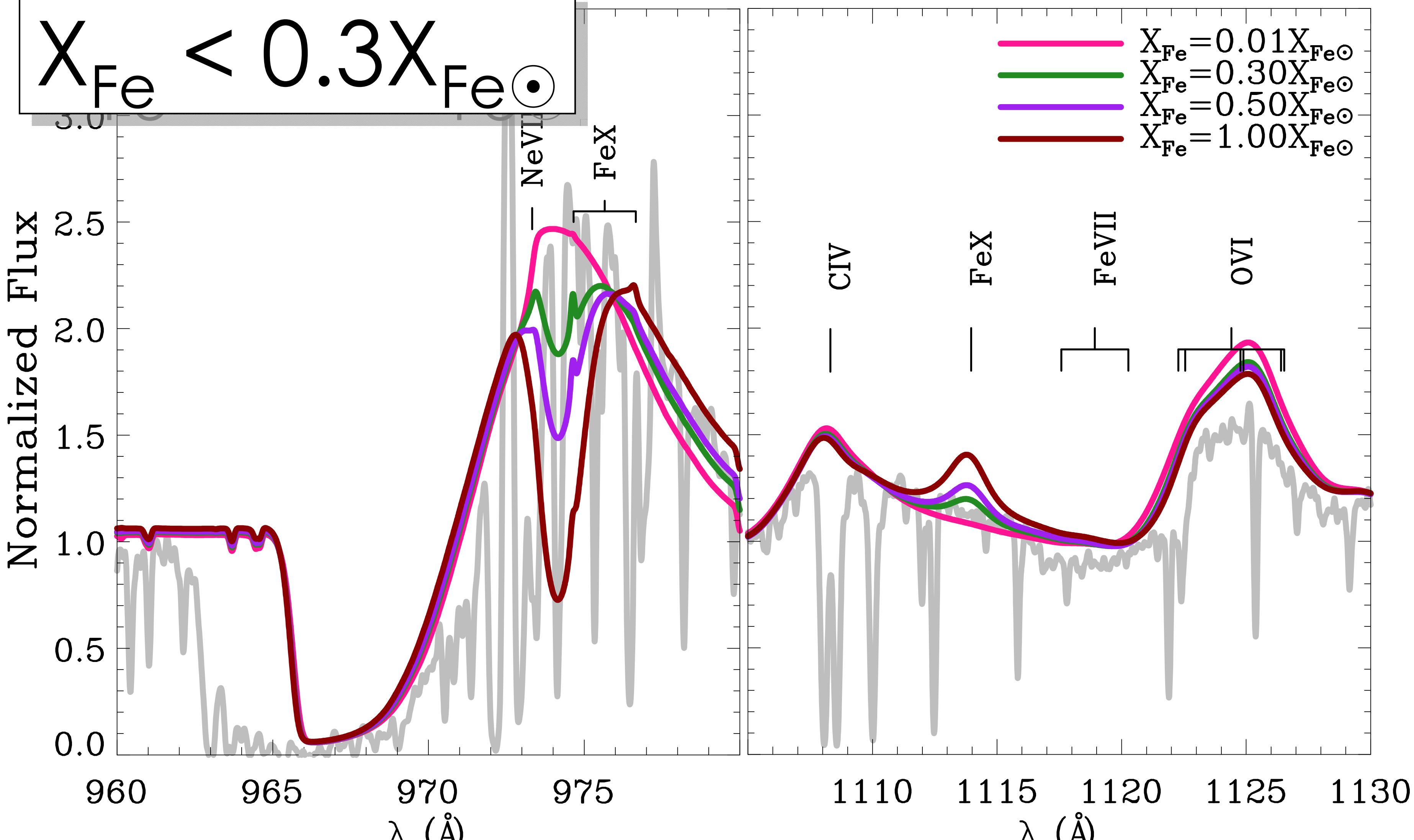


Iron Abundance



Iron Abundance

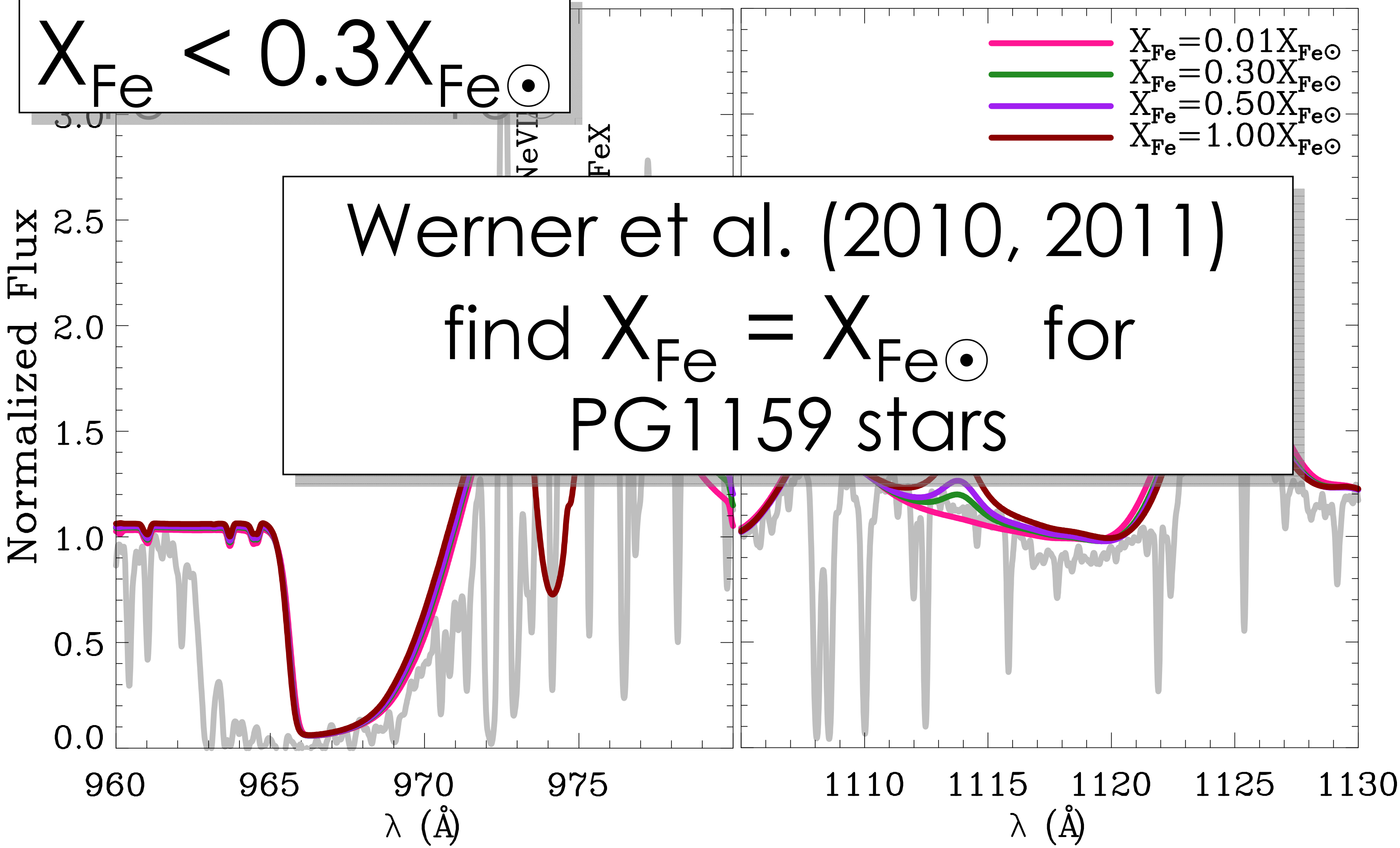
$X_{Fe} < 0.3X_{Fe\odot}$



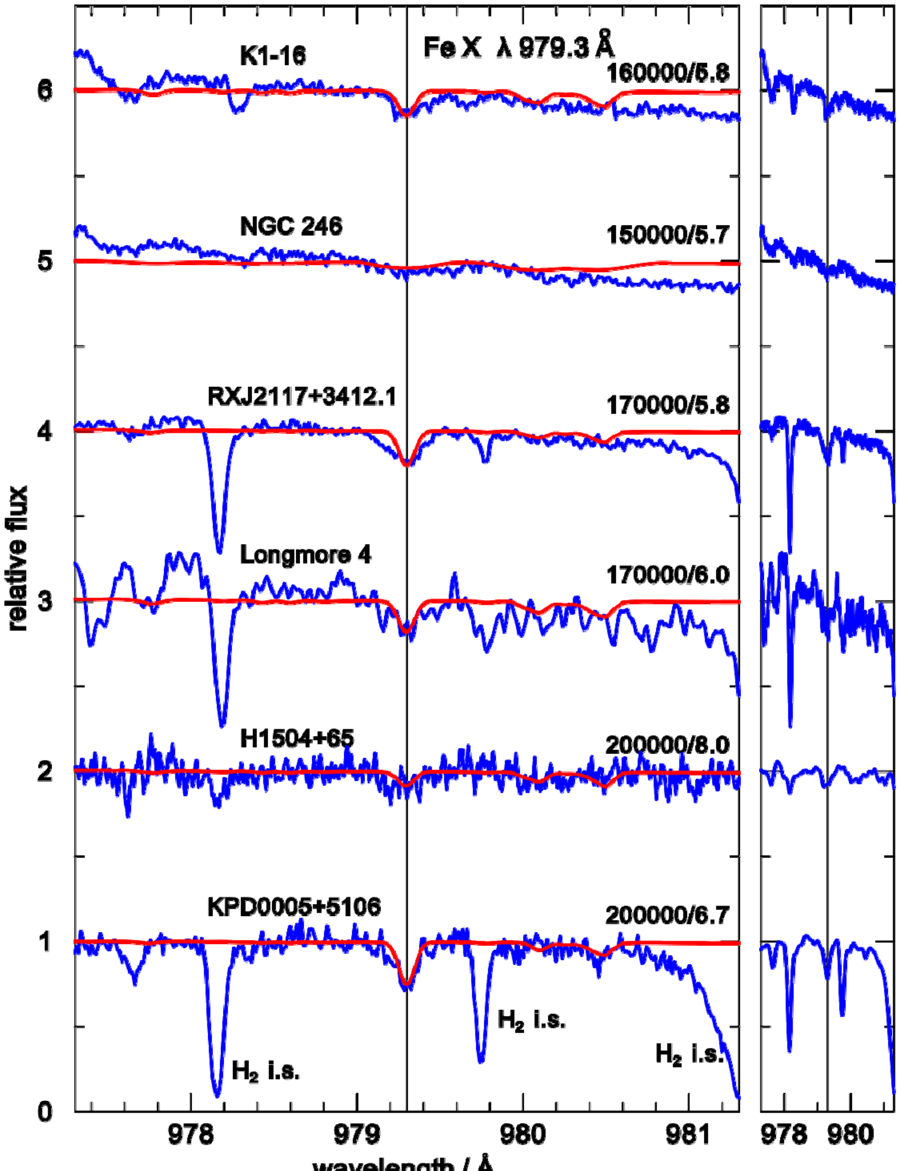
Iron Abundance

$X_{Fe} < 0.3X_{Fe\odot}$

Werner et al. (2010, 2011) find $X_{Fe} = X_{Fe\odot}$ for PG1159 stars



Iron Abundance



Werner et al. (2010, 2011)

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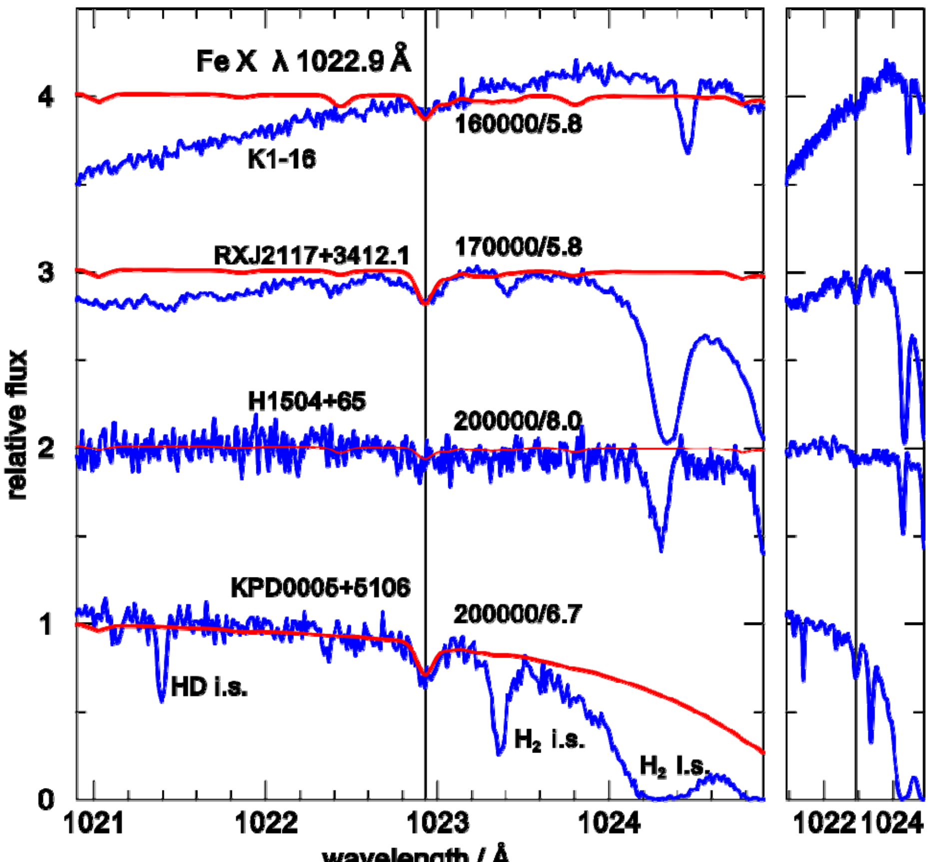

Conclusions

Summary

In order to perform a systematic analysis, ensure the uniqueness of the solutions and limit the need for ad-hoc calculated spectra we:

◈ Built grids of synthetic spectra for H-poor CSPNe;

◈ Performed a differential study, determining the predicted impact of parameter variation on strengths and shapes of line profiles.

We used these results to:

◈ Analyze UV and far UV spectra of the [WCE] central stars of NGC 5189, NGC 6905 and Sand 3 and constrain their T_*, Rt, and V_∞;

◈ Proceed further, by extending the analysis to parameters not covered by the grids.

Main Results

◈ We are making the grids available at

http://dolomiti.pha.jhu.edu/planetarynebulae.html
http://www.astro.iag.usp.br/~graziela/GRIDWEB/front.html

◈ We determined the best line diagnostics for T_* and dM/dt;

◈ We derived well determined stellar parameters;

◈ We found higher values of the turbulence velocity to improve the fit of O VI λλ1031.9, 1037.6 Å and C IV λλ1548.2, 1550.8 Å lines;

◈ We determined $X_{Fe} < 0.3\ X_{Fe\odot}$ for both central stars of NGC 6905 and NGC 5189;

◈ We found line blanketing of Ni, Co, Mg, and Na to improve the fit of the OV lines in all objects analyzed.

Plans for the Immediate Future

◈ Prepare a paper containing a comparative analysis of the 3 CSPNe analyzed.

◈ Test grids against observations of PG1159 and [WCL] stars.

◈ Expand grids with new models.

◈ Study the impact of varying the clumping filling factor and the beta velocity law on the line diagnostics.

Acknowledgements:

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The data presented were obtained from MAST.

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