A Revised Temperature Scale for Massive Stars

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ABSTRACT

A consistent analysis, based on non-LTE codes with sphericity and mass loss, of different ionization species in the far-UV and UV spectra of O-type stars allowed us to constrain the long-time uncertain ionization equilibrium in the stellar winds, to quantify the role of soft X-rays from shocks and to reconcile otherwise discrepant UV line diagnostics. The modeling initially performed with the WM-basic code led to a revised (downwards) $T_{\rm eff}$ scale for Galactic O-type stars, a result with important implications for the energy-balance calculations in HII regions and for massive star evolution. A further analysis using the CMFGEN code, including clumping effects, allowed us to resolve the remaining discrepancies in the modeling of UV lines, in particular the PV line in the far-UV, and to reconcile mass loss and photospheric parameters derived from optical and UV lines.

Key words: UV spectroscopy, optical spectroscopy, hot massive stars, stellar parameters, mass loss

1. Introduction

Understanding massive star evolution has important manyfold implications. Massive stars play the most significant role in the chemical evolution of galaxies, by processing large amounts of material on extremely fast time scales. Their supersonic winds drive the dynamics of the surrounding medium, regulating the subsequent formation of less massive stars as well as the chemical enrichment of the ISM. Our interpretation of the upper part of the H-R diagram, and ultimately of the integrated properties of star forming regions in distant galaxies, stands on an accurate measurement of the fundamental parameters (temperature, luminosity, mass, mass loss) of massive stars. While a detailed analysis of multiwavelength spectra can only be performed for a few stars at a time, statistical H-R diagrams in a variety of environments can easily be derived from the spectral types, thanks to multi-object spectrographs available on very large ground-based telescopes. Therefore, an accurate calibration of spectral type *versus* physical parameters (in a variety of environments) is important.

2. Modeling massive star spectra from far-UV to optical

We analysed far-UV (FUSE), UV (IUE or HST) and optical spectra of hot massive stars in the Galaxy, to determine wind and photospheric parameters (T_{eff}, L_{bol}, log g, mass loss rate, wind velocity). Unprecedented consistency and accuracy can be reached thanks to the different ionic species disclosed by the FUSE range which allows us to solve the long-standing uncertainties in the wind ionization (e.g. Bianchi et al. 2000, Bianchi & Garcia 2002, Garcia & Bianchi 2004, 2006).

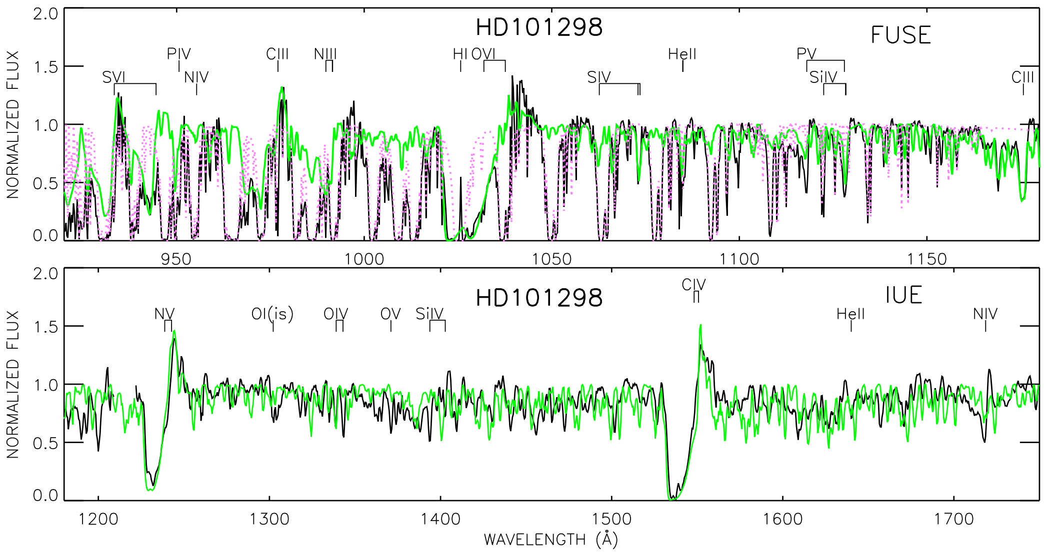

Figure 1: Fit (WM-basic model, in green/grey) of FUSE and IUE spectra (black) of HD 101298, from Bianchi & Garcia (2002). We also show the model of the H_2 plus HI absorptions (pink/dotted line) in the FUSE range, necessary to identify which parts of the stellar features are not affected by ISM absorptions. Note the good match of the stellar model to the OVI P Cygni lines, to the red component of SIV (the blue component is masked by interstellar absorption), and to the uncontaminated parts of the SVI doublet (emission of the blue line, absorption of the red line).

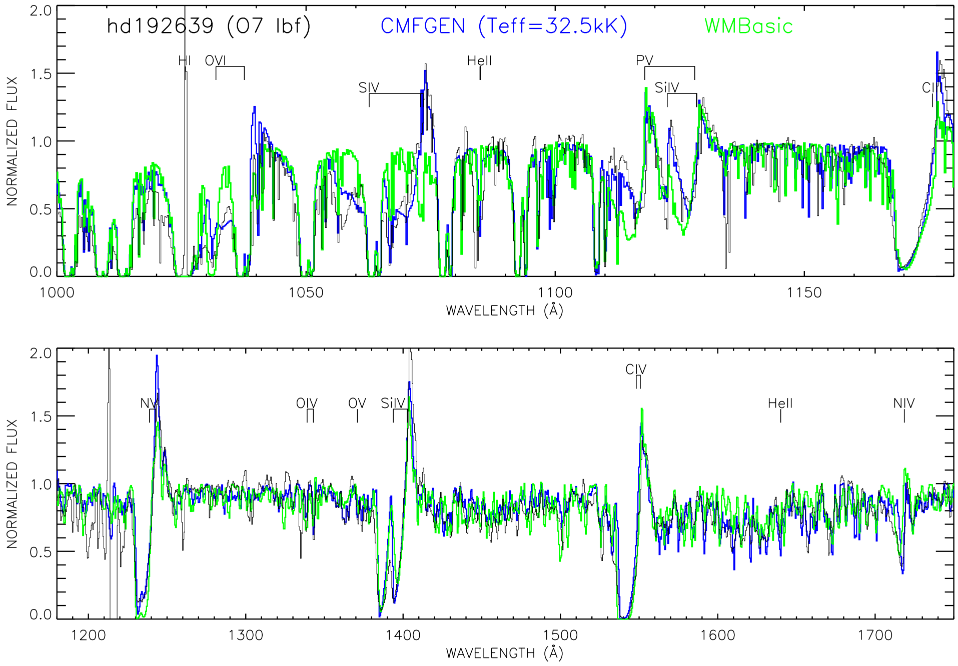

Figure 2: While consistent fits were achieved for stars of luminosity class V with WM-basic models, this code could not reproduce some features in the spectra of O-type supergiants, notably SIV and PV (green/light grey). Consistent modeling of all far-UV and UV lines is achieved by including X-rays from shocks and clumping in the wind models, using the CMFGEN code (blue/dark model). With such modeling we were also able to reconcile the remaining discrepancies among determinations of $T_{\rm eff}$ and mass loss rate from optical and UV diagnostics, as shown in the next figure.

The results for the current sample were obtained by modeling consistently FUSE far-UV (range 905-1187Å) and IUE/HST UV (range 1150-3250Å) spectra with line-blanketed, hydrodynamic, non-LTE spherical models. Grids of synthetic spectra for this analysis were computed initially using the WM-basic code (Pauldrach et al. 2001), that solves the wind hydrodynamics with non-LTE line blanketing treatement, and includes effects of sphericity and expansion. Soft-X rays produced by shocks in the

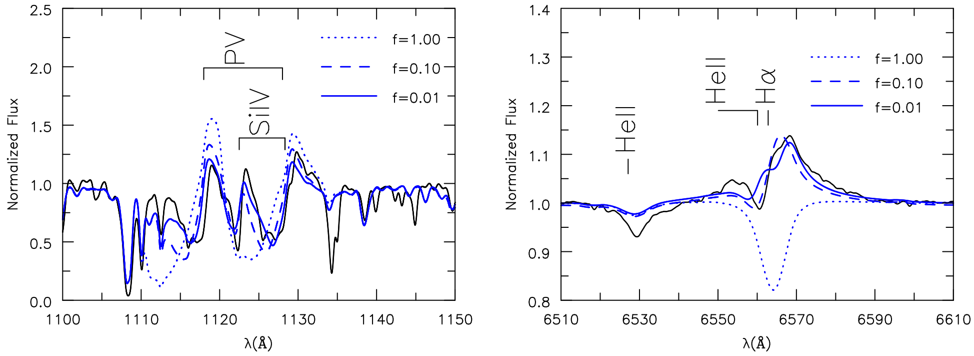

Figure 3: The PV (FUSE range) and Hα lines for the O7I star shown in the previous figure: CMFGEN models with differing clumping factors are shown (blue/grey). Note that fit to *each* of these lines could be achieved, regardless of clumping, also by changing mass loss rate and other parameters values, but such solutions are not unique, and in fact typically gave inconsistent results in previous works. The combination of several crucial lines, allows us to find a solution that fits all diagnostics with the same model.

wind affect the ionization of most observed stages (to different extents) and were taken into account in the calculations. Their parametrization is constrained by lines in the FUSE range, in particular OVI $\lambda\lambda$1032, 1037. A further analysis of a subsample using the CMFGEN code (Hillier & Miller 1998, 1999) confirmed the lower $T_{\rm eff}$ values, and allowed us to reconcile the remaining discrepancies among UV and far-UV lines from the WM-basic analysis, and most importantly to extend the analysis to the optical range. With the inclusion of clumping and soft X-rays in the winds, we were able to fit *consistently* lines from the optical to the far-UV, and to finally reconcile these still slightly discrepant diagnostics. Mass loss is a major source of uncertainty in our understanding of massive star evolution (e.g. Massey 2003 for a review), hence a consistent derivation of mass loss rates from both optical and far-UV lines is an important step forward.

Lines in the FUSE range, including high ionization stages (e.g. OVI) and lower abundance non-CNO elements (e.g. SVI, SIV, PV) in addition to the NIV, NV, CIV and SiIV lines in the IUE/HST range, play a crucial role in uniquely constraining many stellar [photospheric and wind] parameters. They enabled a quantitative assessment of soft X-rays from shocks, and wind clumping, which could not be inferred from data at longer wavelengths alone, thus provided a unique, consistent solution for the parameters, and an unprecedentedly good fit to all spectral lines.

Other parameters such as log g cannot be tighly constrained from wind lines, and are best determined from photospheric (e.g. Balmer) lines in the optical range. Therefore reconciling optical and UV diagnostics with a unified model allows to determine all parameters consistently.

3. Results and Conclusions

We derived effective temperatures significantly lower (10 to 20%) than previous determinations for these stars, and than canonical values assigned to their spectral types from different compilations (see Figure 4). Luminosities are also consequently lower. This result has important implications for our understanding of massive star evolution, as well as for energy balance calculations of HII regions, and has been confirmed by several studies from other groups. Recent analyses based entirely on optical spectra of massive stars with models including sphericity and line-blanketing also derived lower $T_{\rm eff}$'s than previous works based on pure H and He models (e.g. Martins et al. 2002, 2005). Analyses based on UV and optical studies were however still inconsistent (e.g. Fullerton et al. 2006).

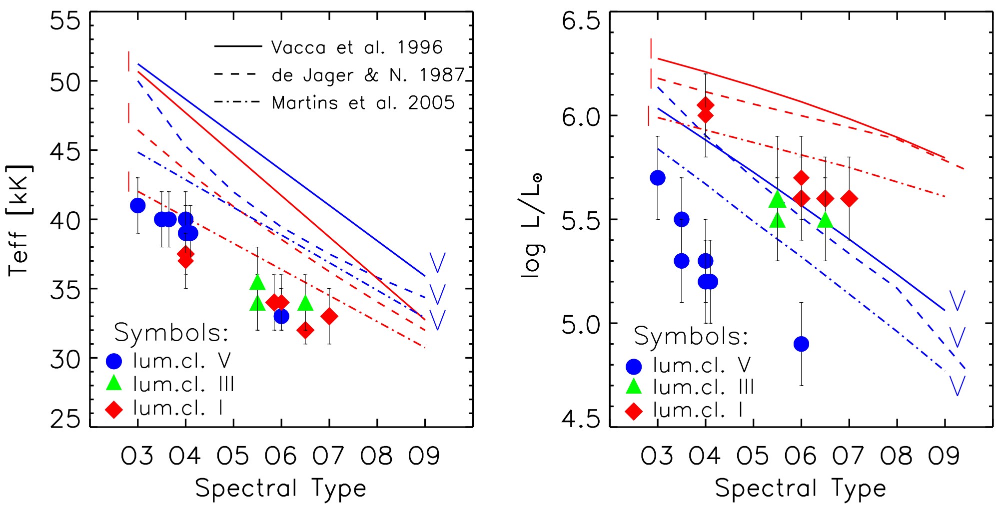

Figure 4: T_{eff} and and L_{bol} values from our consistent analysis of wind and photospheric lines for a sample of MW stars (symbols and colors indicate luminosity class). Previous calibrations and a recent optical calibration are shown for comparison. From Garcia & Bianchi (2006).

Additionally, the consistent analysis of transitions from several ionic species, including non-CNO less abundant ions (e.g. PV), by combining FUSE, UV and optical spectra, provides a thorough test of state-of-the-art codes for synthetic spectra calculations, and useful constraints to the radiation pressure wind theory.

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