How Hot are Hot Stars?: New Temperatures for mid-O types from FUSE data

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Abstract

We are analysing high resolution spectra of Galactic O-type stars from the far-UV to the optical. Here we show first results from combined spectra from the Far Ultraviolet Spectroscopic Explorer (FUSE) in the range 905-1187Å, and IUE archive spectra (1150-3300Å). The spectra were analysed with line-blanketed, hydrodynamic, non-LTE models to derive photospheric parameters, mass loss rates and wind velocities. In the UV and far-UV range, the model spectra were computed with the WM-BASIC code (Pauldrach et al. 2001). The wind lines in the far-UV range, such as OVI and PV, in addition to the NIV, NV, SiIV, CIII and CIV lines in the UV range, play a crucial role in constraining the stellar parameters, and in assessing the role of X-rays (produced by shocks) in the wind ionization. Results for mid-O types indicate that the temperatures are ≈ 3000 to 6000 K lower than the canonical values currently assumed for their spectral types. The uncertainties are smaller than the discrepancy. These findings have important implications for our understanding of the massive star evolution (comparison with theoretical evolutionary tracks), in particular the derivation of masses and time-scales, as well as for energy balance calculations of H II regions.

Introduction

Hot massive stars play a primary role in the chemical evolution of the universe, because of the rapid and effective production of heavy elements during their fast life cycles. They also play a crucial role in the ionization of HII regions, and in the dynamics of the interstellar medium, by sculpting vast bubbles with their highly supersonic stellar winds and intense UV radiation, thus influencing the physical conditions of the interstellar medium, as well as star formation. Dust characteristics also differ in starburst environments compared to average field properties.

But the parameters of massive stars are elusive for several reasons, compared to the more easily characterized lower mass portions of HR diagrams. Massive stars are rare, they evolve rapidly, and photometric data at optical wavelengths are rather insensitive to their hot temperatures (e.g. Bianchi et al. 2001a, Massey 1998 for a review), making their global characterization uncertain without detailed spectroscopy. Even when adequate data are available, modeling is complicated by the need of calculating the ionization in non-LTE conditions, and of taking into account the hydrodynamics (mass loss effects and acceleration) and sphericity effects, all non negligible.

Data and modeling

We present first results from a comprehensive program aimed to analyze (by consistent modeling) high resolution spectra from the optical regime to the far-UV wavelength range, of hot stars covering a range of spectral types and luminosity classes. This paper explores the properties of O 6 type Galactic stars of different luminosity classes.

Table 1 lists relevant information on the program stars compiled from the literature, and the data used in our analysis. The FUSE data were taken in the 30″x 30″(LWRS) aperture. The data were reprocessed with pipeline version 2.0.5, which provides a major improvement in the spectral extraction, background subtraction, and wavelength calibration (Dixon, Kruk & Murphy 2001). Selected segments from the different *FUSE* channels were combined (details in Bianchi et al. 2002).

Spectral classification of hot stars is somewhat complex, due to wind and metallicity effects; variability and peculiarities are not uncommon. Therefore, we took great care of selecting as "bona fide" as possible objects representative of mid-O spectral class.

To derive the stellar parameters consistently, we computed synthetic model spectra with mass loss in the UV and far-UV range using the WM-BASIC code (Pauldrach et al. 2001). The code computes the underlying atmosphere and the synthetic spectrum by solving the wind hydrodynamics with non-LTE line blanketing treatement, and including effects of sphericity and expansion. By modeling the whole 905-2000Å range, we derive $T_{\rm eff}$, log g, $L_{\rm bol}$, V_∞, $\dot{M}$, and information on the ionization. Soft-X rays produced by shocks in the wind affect the ionization of most observed stages (to different extents) and were taken into account in the ionization calculations, as this was proven necessary to reproduce all the observed lines consistently. In particular, O VI λλ1032, 1037 is entirely produced by X-ray ionization. X-rays also significantly affect the relative strength of N V (and C IV) versus Si IV in the IUE range, and - to a lesser extent - the strength of P V λλ1118, 1128 which is non saturated thus very sensitive to all wind parameters. The effect of X-ray ionization is parametrized by the quantity $L_{\rm x}/L_{\rm bol}$, whose values are found by varying this quantity as a free parameter to reproduce the observed ionization (see example in Figure 2). Existing X-ray flux measurements for our objects are reported in Table 1 for comparison with our value of $L_{\rm x}/L_{\rm bol}$ determined by the spectral fit. While the measured $L_{\rm x}/L_{\rm bol}$ in Table 1 is the radiation escaping the star, $L_{\rm x}/L_{\rm bol}$ determined by the spectral fit reflects the X-rays absorbed within the stellar envelope. The comparison gives some insight into the geometry of the shock region.

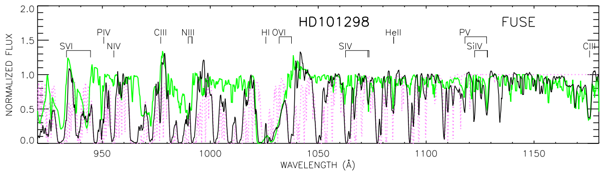

Figure 2a. The FUSE spectrum of HD 101298 (black line), the best fit stellar model (green) with $T_{\rm eff}$=32000 K, log g=4.0, log $L_{\rm bol}/L_{\rm sun}$=4.89, $\dot{M}$=4 x 10^{-6} $M_\odot$ yr^{-1}, V_∞=2900km s^{-1} , $L_{\rm x}/L_{\rm bol}$ = -7.4 . The interstellar absorptions are repeated (pink dots) as in Figure 1a.

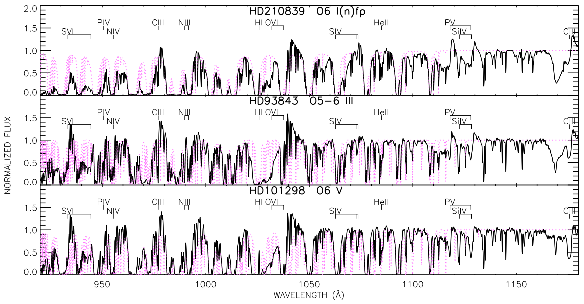

Figure 1a. Sequence of spectra of O6-type stars of different luminosity class in the FUSE range (black). Note the O VI emission common to the three stars, and the dependence of S IV , C III λ 1175 and P V on luminosity. These transitions are also very sensitive to the mass loss rate. To guide the eye to recognize the *bona fide* stellar features, we show models of H_2 absorptions (pink dotted line), calculated with column densities appropriate for each star's E(B-V). We did not attempt to precisely fit the interstellar lines (which is beyond our purpose, and is pursued by other authors in the FUSE science team) - H_2 models are shown only to identify which parts of the stellar features are not affected by the interstellar medium absorptions, and therefore were given weight in the stellar model fits.

Results

Table 1. Program stars and datasets

Star	Sp. Type (reference)	V	LSR Velocity [km s^{-1}]	Distance (Kpc) [Kpc]	V_{rot} [km s^{-1}]	log L_X [ergs s^{-1}]	FUSE datasets [ergs s^{-1}]	IUE datasets
HD101298	O6 V;O 6V((f))	8.16	-0.7	2.3,2.4	86; 84	32.58±.30[a]	P1025201	SWP06939
	(1,2)		(4)	(5,6)	(7,8)			
HD93843	O5 III(f)var;O6 III(f)	7.33	-9.9	2.5	120;100	33.07±.30[a]	P1024001	SWP07723
	(1;3)		(4)	(6)	(7,8)			
HD210839	O6 I(n)fp	5.1	-75.9	0.5,0.8	214;214;250	32.19±.32[a]; 31.81[b]	P1163101	SWP52623
(λ Cep)	(1)		(4)	(5,6)	(7,8,9)			

(a) measurements from *Einstein* satellite in the 0.2-3.5KeV range (Chlebowski et al. 1989); for HD210839 L_X has been re-scaled to the Hipparcos distance given in column 5, as the distance used by Chlebowski et al. 1989 (0.8Kpc) was very different

(b) measurements from the *ROSAT* satellite in the 0.1-2.4KeV energy band (Bergoefer et al. 1996), scaled as in previous note

References: (1)Walborn 1973 ; (2)Walborn & Panek 1984; (3) Walborn 1972; (4) Conti et al. 1977 ;(5) Perryman et al. 1997; (6) Garmany et al. 1982; (7) Conti & Ebbets 1977; (8) Penny, 1996; (9) Herrero et al. 2000

From a vast set of model calculations we determined the best fit to the observed spectra, and constrained the uncertainty range of each parameter. This procedure required a much larger set of models than just varying the effective temperature and adopting reasonable values for the other parameters, but provided a check for the uniqueness of our solutions as well. In fact, variations of different parameters can compensate each other's effect on the line profiles. Therefore, we varied $T_{\rm eff}$ in small steps (500 to 1000 K), and computed a large number of models at each $T_{\rm eff}$ value, with wide combinations of all other parameters. In Figure 2a and 2b we show a model fit for one of the program stars as an example. Note the good match of **all** the observed lines in both the FUSE and IUE range, proving that the models are actually adequate to reproduce lines from different layers of the envelope. A large part of the O VI profile is not affected by the interstellar absorptions, and it is perfectly matched by the model. This line is very sensitive to $L_{\rm x}/L_{\rm bol}$ and to the mass loss rate. Although the resonance lines of S VI fall in a wavelength range heavily absorbed by interstellar hydrogen, making flux normalization difficult, they are also well matched by our models. The S IV components at λλ1072.9, 1073.52 are also well matched (its component at λ1062.67 is buried in a strong H_2 absorption).

The fit shown in Fig. 2 for the O6 V star in our sample is obtained for $T_{\rm eff}$= 32,000 K. Acceptable fits could be obtained for $T_{\rm eff}$ up to 36,000 K, by varying *ad hoc* the other parameters, but $T_{\rm eff}$= 37,000 K is excluded. For the giant and supergiant stars the $T_{\rm eff}$ range was similarly constrained (33000 - 36000 K).

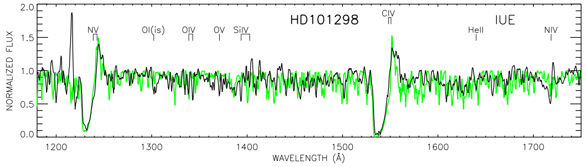

Figure 2b. The same model fit shown in Fig. 2a, in the IUE range (green = model, black = IUE spectrum).

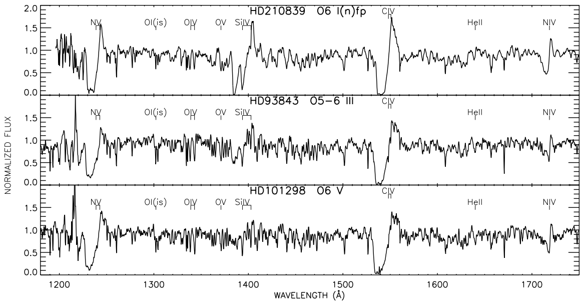

Figure 1b. The sequence of spectra in IUE range. Here the strongest luminosity indicator is the Si IV doublet, which is also extremely sensitive to the mass loss rate, thus helps constraining this parameter. The strong P Cygni profiles of C IV and N V are saturated thus rather insensitive to mass loss rate variations within a wide range; however, because they are fully developed profiles and not affected by interstellar absorptions, they are useful to precisely determine the terminal velocity.

Conclusions

The temperature ranges derived by modeling the UV and far-UV spectra of the O6 stars, $T_{\rm eff}$= 32000 K – 36000 K, are significantly lower than previous determinations and than canonical values attributed to their spectral type by empirical calibrations over the last decades. For instance, HD 210839 has been analysed in the optical range by Herrero et al. (2000), who found $T_{\rm eff}$=41,500 K from plane-parallel, hydrostatic model analysis, but $T_{\rm eff}$= 37,000 K by analysing the same data with spherical models including mass loss. Puls et al. (1996) derived for the same star $T_{\rm eff}$= 38,000 K and $\dot{M}$= 7 10^{-7} $M_\odot$ yr^{-1}. Vacca et al. (1996) derived a $T_{\rm eff}$ calibration of O-type stars compiling determinations based on plane-parallel, non-LTE pure H and He hydrostatic models. Their calibration gives $T_{\rm eff}$= 41,710, 42,640, 43,560 K for O6 I-III-V types respectively. De Jager & Nieuwenhuizen's (1987) calibration gives $T_{\rm eff}$= 38,200 to 39,500 K from supergiants to dwarfs, less discrepant, but still significantly higher than our findings. We are analyzing optical spectra for the program stars, and we find good match to the Balmer lines - when mass loss and line blanketing are included - for parameters consistent with the values derived from our far-UV–UV analysis. More detailed analysis of the other optical lines is in progress. This study is also being extended to a larger number of stars. While it is being recognized that the use of models with full line blanketing treatement, and sphericity, in the optical range yields $T_{\rm eff}$ values lower than found by simplified (pure H and He) treatements, we also find in some cases that the values of $T_{\rm eff}$ and log g derived in previous determinations can still somehow reproduce the lines in the IUE range (by varying the other free parameters), but can not reproduce all the lines observed in the FUSE range with the same parameters combination. This indicates that the extension of the analysis in the far-UV is essential to determine the fundamental parameters of hot stars.

The results (lower $T_{\rm eff}$ values than previously found) have enormous implications for our understanding of the ionization and energy balance of HII regions, as well as in the context of evolution of massive stars. The photons emitted below the Lyman limit, which can only be inferred by accurate $T_{\rm eff}$ determinations at longer wavelengths, are driving the ionization of the surrounding medium.

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