Revised Temperature Scale for Hot Massive Stars

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ABSTRACT

We analysed high resolution spectra of O-type stars with line-blanketed, hydrodynamic, non-LTE spherical models, to derive photospheric parameters, mass loss rates and wind velocities. We combined spectra from the Far Ultraviolet Spectroscopic Explorer (FUSE) in the range 905-1187Å, and IUE or HST archive spectra in the range 1150-3250Å. Synthetic spectra for the analysis were computed mainly with the WM-basic code of Pauldrach et al. (2001). Comparisons with the CMFGEN code of Hillier & Miller (1998) are performed.

The effective temperatures ($T_{\rm eff}$) derived from the consistent analysis of the far-UV and UV spectra are significantly lower ($\approx$ 15 - 20%) than values previously derived for our sample stars, and than canonical values assigned to their spectral types from different compilations (see Figure 1). The stellar luminosities are also consequently lower than previously believed. This result has great implications for our understanding of massive star evolution and for the characterization of young stellar populations, as well as for energy balance calculations of HII regions.

1. The Program. Data. Modeling

We analysed high resolution spectra of O-type stars with line-blanketed, hydrodynamic, non-LTE spherical models, to derive photospheric parameters, mass loss rates and wind velocities. We combined spectra from the Far Ultraviolet Spectroscopic Explorer (FUSE) in the range 905-1187Å, and IUE or HST archive spectra in the range 1150-3250Å. Synthetic spectra for the analysis were computed mainly with the WM-basic code of Pauldrach et al. (2001). Comparisons with the CMFGEN code of Hillier & Miller (1998) are performed.

Our overall program includes a large sample of Galactic O-type stars and a small number of representative objects in the nearby galaxies M33 and M31, the faintest stars accessible

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to the FUSE satellite. Results so far can be found in Bianchi & Garcia (2002a), Bianchi et al. (2002), Garcia & Bianchi (2003a) and references therein. In the process, we are also testing different state-of-the-art codes and comparing the results, to assess advantages and remaining limitations.

The FUSE data were taken in the $30'' \times 30''$ (LWRS) aperture, and reprocessed with the most recent pipeline. Selected, good quality segments from the different FUSE channels were carefully combined (details in Bianchi & Garcia 2002a).

To derive the stellar parameters, 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 $\lambda\lambda$1032, 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 $\lambda\lambda$1118, 1128 which is non saturated thus very sensitive to all wind parameters. Because the treatement of the sulfur ions in the extended atmospheres of O-type supergiants appeared not entirely consistent in the WM-basic models (see Bianchi & Garcia 2002a for detailed discussion), Bianchi et al. (2003) computed models with the CMFGEN code (Hillier & Miller 1998, 1999) for comparison. We find the results from the two codes to be reasonably consistent in the calculations of the ionization structure in the winds except for the treatement of the sulfur ions.

2. Results

The temperature range constrained by modeling the UV and far-UV spectra is significantly lower than previous determinations for our program objects and than canonical values attributed to their spectral type by empirical calibrations over the last decades, as shown in Figure 1.

The lower temperatures are partly due to the fact that a consistent analysis was performed over a wavelength range containing many ionization species relevant to constrain the several parameters involved. Lines in the FUSE range, including high ionization stages and lower abundance non-CNO elements (e.g. OVI, SVI, SIV, PV) in addition to the NIV, NV,

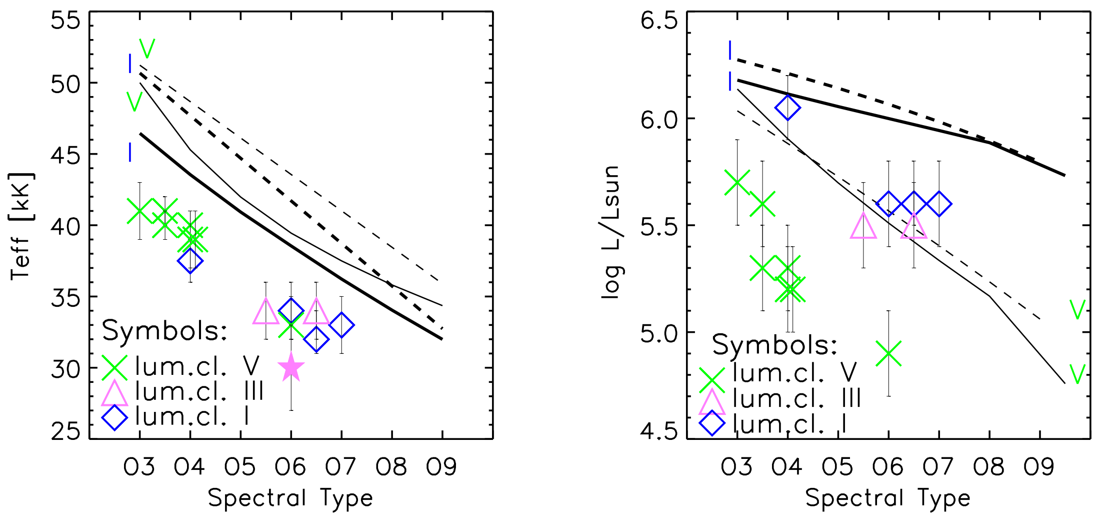

Fig. 1.— The values of $T_{\rm eff}$ and $L_{\rm bol}$ derived by our consistent analysis of wind and photospheric features for a sample of thirteen Galactic O-type stars (symbols denote different luminosity classes), and for an O6-type star in M33 (filled star), are compared to previous calibrations (Vacca et al. (1996), dashed lines, and de Jager & Nieuwenhuijzen (1987), solid lines; thick lines for luminosity class I, thin lines for luminosity class V). Results for the mid-O type stars are from Bianchi & Garcia (2002a), and for the early types from Garcia & Bianchi (2003a).

CIV and SiIV lines in the IUE/HST range, play a crucial role in uniquely constraining the stellar photospheric and wind parameters, including a quantitative assessment (for the first time) of the soft X-rays (from shocks) contributing to the wind ionization. The full line-blanketing non-LTE treatement of the stellar atmospheres is also known to produce lower $T_{\rm eff}$ than pure H+He modeling.

We are also 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 parameter values consistent with those derived from our far-UV and UV analysis.

The results (lower $T_{\rm eff}$ and luminosity 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.

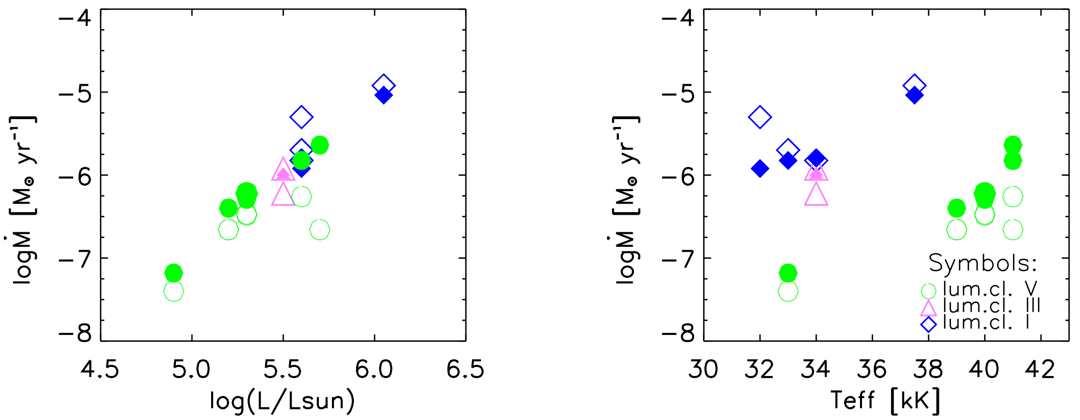

Fig. 2.— Mass loss rates derived from our consistent modeling of the spectra (hollow symbols) are compared to values predicted by the radiation pressure wind theory (filled symbols) using the recipe of Vink et al. (2000). They are shown as function of luminosity (left) or $T_{\rm eff}$ (right). There is agreement for most supergiants, while our values for dwarf stars are systematically lower than the predictions.

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