

# Massive Stars with Weak Winds

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**Abstract** The theory of radiatively driven winds successfully explains the key points of the stellar winds of hot massive stars. However, it has been recently found that some O- and B-type stars do not exhibit as strong wind as predicted by theory. In this work we explain the main issues concerning this topic. We also describe our analysis of the UV spectra of a set of massive stars in a Galactic star-forming region (the Orion Complex) plus two reference stars, to determine their wind properties. The wind momentum of the very young OB-stars located in the region and also one of the reference stars is smaller than expected. Our results hint that stellar weak winds may be related to luminosity, rather than age or magnetic fields.

## 1 Introduction

Massive stars are crafters of the Universe. They inject large amounts of momentum and energy into galaxies. They carve and ionize the interstellar medium (ISM), blowing isolated bubbles or combined complex super-shell structures. Massive stars also enrich the Universe with heavy elements produced during their lifetime and utter supernovae (SN) explosion.

Blue massive stars experience supersonic matter outflows known as winds, propelled by their strong ultraviolet (UV) radiation field. The wind alters the evolution of the massive star, changing the duration of the nuclear stages and final core mass and composition, the SN sub-type (Ib, Ic or II) and the final remnant left [12]. The wind of blue massive stars is also important at galactic scales. The combined effect of young massive stellar winds in star forming regions results in galactic winds [17]. The integrated light of far-away star-forming galaxies is dominated by the spectral features of the winds of massive stars [16].

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The wind is defined by two basic properties: the rate of the outflow or mass loss rate ( $\dot{M}$ ) and the asymptotic wind velocity, or terminal velocity ( $v_\infty$ ). In this work we also consider the shocks produced in the wind, parameterized by the X-ray emission ( $\log L_X/L_{bol}$ ) produced when the shock-heated matter cools down. The theory of radiatively driven winds predicts a relationship between the momentum carried by the wind  $D_{mom}$  and the stellar luminosity:

$$\log D_{mom} = \log D_0 + x \log(L/L_\odot) ; D_{mom} = \dot{M} v_\infty (R_*/R_\odot)^{1/2} \quad (1)$$

However, there is an apparent break-down of this paradigm at  $\log L/L_\odot < 5.2$ . Recent works have found that the calculated wind momentum is smaller than predicted for low luminosity early-type stars from metal poor environments like the SMC [2, 10], but there are also some Galactic cases [11]. This is known as the “weak wind problem”. We do not understand the science behind these findings yet. Some works suggest stellar magnetic fields, shocks in the wind, or an inhomogeneous outflow (porosity) as possible explanations [10, 11, 14, 6].

In this work we study the UV spectra of a sample of young OB stars, to determine their wind properties and explore whether there exists a connection between early evolutionary stage and wind strength. The UV range offers a great advantage compared to diagnostic tools in other spectral ranges ( $H_\alpha$  for instance) which are rather insensitive when the mass loss rate is small: at UV wavelengths we find resonance lines, often saturated when the wind is strong, but now very sensitive to small variations of mass loss rate (see for instance Figure 2). If the analysis cannot determine the mass loss rate, at least it will produce a tighter upper limit.

## 2 The Sample

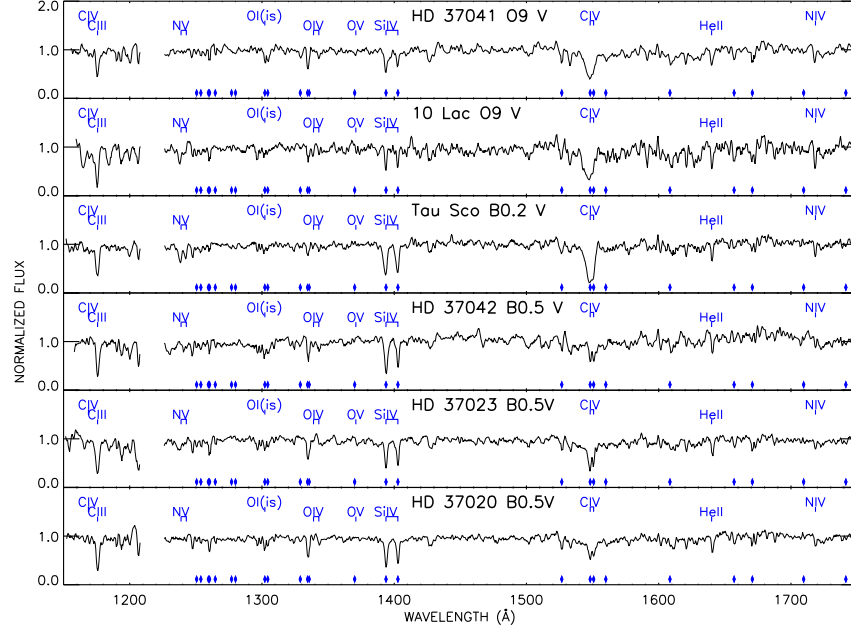
We studied a sample of O9 and B0 dwarf stars in the Orion Complex, which hosts the massive star forming region closest to the Sun. The Trapezium Cluster ( $\theta^1$  Ori), ionizes the Orion Nebula (M42), part of the complex. The stellar population of

**Table 1** Physical properties of the program stars (from [19] except otherwise indicated).

HD	Name	SpType	T <sub>eff</sub> kK	log g	R <sub>*</sub> R <sub>⊙</sub>	L <sub>bol</sub> L <sub>⊙</sub>	log Q	v <sub>∞</sub> <sup>a</sup> kms <sup>-1</sup>	$\dot{M}$ <sup>b</sup> M <sub>⊙</sub> yr <sup>-1</sup>
HD 37041	$\theta^2$ Ori A	O9 V	35	4.1	8.2	4.93	<-13.5	2995	< 1.2E-7
HD 37020	$\theta^1$ Ori A	B0.5 V	30	4.0	6.3	4.45	<-13.5	2371	< 5.8E-8
HD 37023	$\theta^1$ Ori D	B0.5 V	32	4.2	5.6	4.47	<-13.5	2829	< 6.3E-8
HD 37042	$\theta^2$ Ori B	B0.5 V	29	4.1	4.5	4.11	<-13.5	2267	< 3.3E-8
HD 214680	10 Lac	O9 V	36	3.9	8.3	5.02	<-13.5	2314	< 8.4E-8
HD 149438	$\tau$ Sco	B0.2 V	32	4.0	5.6	4.47	-13.0	2218	1.4E-7

<sup>a</sup> v<sub>∞</sub> = 2.6 × v<sub>esc</sub>, following [9]

<sup>b</sup> Calculated in this work, using v<sub>∞</sub> and Q-parameter from this table.



**Fig. 1** IUE spectra of the O9-B0.5 dwarf stars analysed in this work arranged by spectral type. The data were rebinned to steps of 0.25Å for clarity and normalized to the local continuum. The most important interstellar lines are marked with diamonds at the bottom of the spectra. The Ly $\alpha$  region has been removed for clarity. The absence of fully developed P Cygni profiles in the Orion stars is striking. CIV  $\lambda$ 1169+CIIV  $\lambda$ 1176, SiIV  $\lambda\lambda$ 1393.8,1402.8, HeII  $\lambda$ 1640.0, and NIV  $\lambda\lambda$ 1718.0,1718.5 are photospheric in all stars. CIV  $\lambda\lambda$ 1548.2,1550.8 displays an absorption trough in the O9 V stars and a small P Cygni in  $\tau$  Sco. The NV  $\lambda\lambda$ 1238.8,1242.8 doublet is always weak and absent in the spectra of HD 37041 and HD 37020.

the ionized nebula is very young, 1Myr on average [5]. [19] studied a sample of stars in  $\theta^1$  Ori and its vicinity. They performed a detailed quantitative spectroscopic analysis of optical data taken with the 2.5m Isaac Newton Telescope, to determine effective temperature ( $T_{\text{eff}}$ ), gravity ( $\log g$ ), stellar radius ( $R/R_{\odot}$ ) and wind parameters. They used spherical, line-blanketed non-LTE synthetic spectra calculated with FASTWIND [15], which also takes into account the expanding atmosphere. They found that the wind contribution to H $\alpha$ , the most powerful diagnostic line in the optical range, was not significant rendering the determination of the mass loss rate unfeasible. They could only set upper limits for the wind-strength Q-parameter ( $Q = \dot{M} / (v_{\infty} \times (R/R_{\odot})^{1.5})$ ).

We studied a subset of the stars analyzed by [19] including four targets in Orion plus 10 Lac and  $\tau$  Sco as reference stars; their parameters are listed in Table 1. We used *International Ultraviolet Explorer* (IUE) UV spectra downloaded from the INES archive [20]. The normalized spectra in the range that contains the strongest spectral lines (1150-1850Å) are shown in Figure 1.

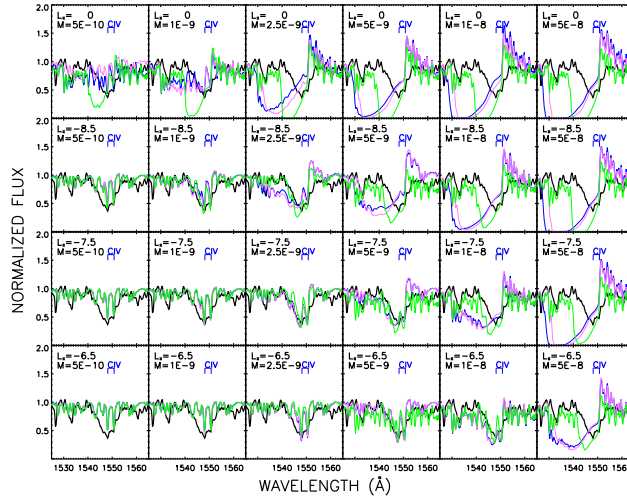
We searched for complementary Far-UV spectra of the sample stars, but only three of them had been observed in this range. The data are from the Copernicus

mission (912-1645Å range,  $\Delta\lambda=0.2\text{\AA}$ ). The advantages of using also the Far-UV is that it offers additional spectral transitions (hence providing further information to constrain the stellar parameters) and that it contains the OVI  $\lambda\lambda 1031.9, 1037.6$  doublet, the most reliable diagnostic line to date to constrain shocks in the wind [1, 4]. The observations of HD 37041 cover the  $\sim 1060\text{-}1180\text{\AA}$  range, and do not reach the OVI  $\lambda\lambda 1031.9, 1037.6$  doublet. The available observations of 10 Lac and  $\tau$  Sco span the useful  $1000\text{-}1180\text{\AA}$  region of the spectrum.

### 3 Tools: WM-basic Models

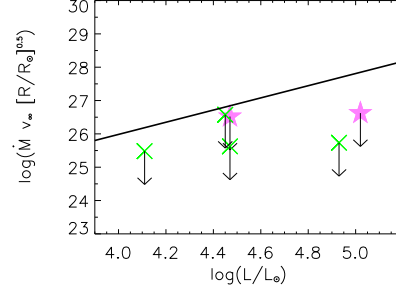
For each star we calculated a grid of spherical hydrodynamic line-blanketed non-LTE models with the WM-Basic [13] code. This code is preferred to FASTWIND for detailed UV analyses because of its more detailed treatment of spectral transitions in this wavelength range. It is also preferred to the more sophisticated CMFGEN code [7] because of its shorter computation time.

Each star's grid has its stellar photometric properties listed in Table 1 and three varying parameters:  $\dot{M}$ ,  $\log L_X/L_{bol}$  and  $v_\infty$ . The terminal velocity  $v_\infty$  is usually directly measured from the blue edge of the absorption of saturated wind P Cygni profiles (with a correction due to turbulent velocity). Since the spectra exhibit no such profiles because of the low density wind, we estimated  $v_\infty$  from the stellar escape



**Fig. 2** Observed spectra of HD 37041 (black) and the grid of models calculated for its analysis (colors) in the CIV  $\lambda\lambda 1548.2, 1550.8$  range. Each column has constant  $\dot{M}$ , that increases from left to right in the plot. Similarly, each row has constant  $\log L_X/L_{bol}$ , which increases from top to bottom: models at the very top have shocks off. Different colors represent different terminal velocities  $v_\infty$  [ $\text{km s}^{-1}$ ]=1500 (green), 3000 (pink) and 3500 (blue).

**Fig. 3** The wind-momentum luminosity relation of the Orion (green crosses) and reference (pink stars) targets analysed in this work. The black line represents the theoretical relation of [18]. All targets have weaker wind momentum than predicted by theory.



velocity [9], listed in Table 1. The grid uses this value  $\pm 500 \text{ km s}^{-1}$  (for some stars, additional models with additional values of  $v_{\infty}$  were computed).  $\dot{M}$  was calculated from  $\log Q$  and the central  $v_{\infty}$ , and then decreased to reproduce the observed profiles. We have no information regarding the amount of shocks in the wind, therefore we computed models without shocks, and three additional sets with small, moderate and high  $\log L_X/L_{bol}$  (0,-8.5,-7.5,-6.5). Figure 2 shows the grid of models run to fit HD 37041 as an example. It also shows that the CIV  $\lambda\lambda 1548.2, 1550.8$  doublet is highly sensitive to  $\dot{M}$  and  $\log L_X/L_{bol}$ .

## 4 Analysis

At first glance, the absence of P Cygni profiles in the spectra of Orion stars already hints that the stars experience weak winds. The lines that usually display strong wind profiles are: CIV  $\lambda 1169 + \text{CIII} \lambda 1176$ , NV  $\lambda\lambda 1238.8, 1242.8$ , SiIV  $\lambda\lambda 1393.8, 1402.8$  and CIV  $\lambda\lambda 1548.2, 1550.8$ . Only  $\tau$  Sco does have P Cygni profiles of NV and CIV, indicating that HD 37020, HD 37023 and HD 37042 of similar spectral type have weaker winds. The morphology of HD 37041 and 10 Lac (both O9 V) is similar. [11] reported the latter as a weak wind star.

The grid of synthetic spectra reveals that for the  $\dot{M}$  considered all lines except for CIV  $\lambda\lambda 1548.2, 1550.8$  and NV  $\lambda\lambda 1238.8, 1242.8$  are photospheric in the models as they are in the observations. Thus, we only use CIV and NV to constrain the wind parameters. We will use HD 37041 to illustrate the fitting process. At the estimated  $\dot{M}$  listed in Table 1, CIV  $\lambda\lambda 1548.2, 1550.8$  displays a P Cygni profile in all models (see Figure 2), regardless  $v_{\infty}$  and  $\log L_X/L_{bol}$ . NV  $\lambda\lambda 1238.8, 1242.8$  is photospheric (as observed) in the models with no shocks but CIV would then exhibit a P Cygni profile in disagreement with the observations. If shocks are on, NV  $\lambda\lambda 1238.8, 1242.8$  is only as weak as observed in models with mass loss rate smaller than  $1\text{E-}9\text{M}_{\odot} \text{ yr}^{-1}$ . Several  $[\log L_X/L_{bol}, \dot{M}]$  pairs fit CIV  $\lambda\lambda 1548.2, 1550.8$ , but always  $\dot{M} < 1\text{E-}8\text{M}_{\odot} \text{ yr}^{-1}$ . No simultaneous fit of both lines is achieved, but we have derived an upper limit for the mass loss rate.

## 5 Results and Conclusions

All stars were analyzed as described in the previous section. We then calculated their wind momentum following Equation 1; these are actually upper limits since we used the upper limits of mass loss rate found in this work for the calculations. Figure 3 compares the derived values to the theoretical wind-momentum luminosity relation of [18]. The wind- momentum of 4 out of six stars is well below the theoretical expectations. Only  $\tau$  Sco and HD 37020 have wind momentum close to the prediction. Note that  $\tau$  Sco has a measurable surface magnetic field (see f.i. [3]).

The UV analysis indicates that indeed the targets have weaker winds than predicted by the theory of radiatively driven winds. No distinct behaviour between Orion and reference stars is found, hinting that luminosity, rather than age, may cause their weak wind. Only  $\tau$  Sco and HD 37020 have normal wind strength.  $\tau$  Sco is known to have a magnetic field, arguing against this factor as an explanation for weak winds.

For more details, see Garcia et al. (2008) in preparation.

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