

# A search for O VI in the winds of B-type stars

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**Abstract.** We have conducted a survey of *FUSE* spectra of 235 Galactic B-type stars in order to determine the boundaries in the H-R diagram for the production of the superion O VI in their winds. By comparing the locations and morphology of otherwise unidentified absorption features in the vicinity of the O VI resonance doublet with the bona fide wind profiles seen in archival *IUE* spectra of the resonance lines of N V, Si IV and C IV, we were able to detect blueshifted O VI lines in the spectra of giant and supergiant stars with temperature classes as late as B1. No features attributable to O VI were detected in dwarfs later than B0, or in stars of any luminosity class later than B1, although our ability to recognize weak absorption features in these stars is severely restricted by blending with photospheric and interstellar features. We discuss evidence that the ratio of the ion fractions of O VI and N V is substantially different in the winds of early B-type stars than O-type stars.

**Key words.** stars : early-type – stars : mass-loss – ultraviolet : general

## 1. Introduction

The presence of O VI in the stellar winds of early-type stars was one of the early surprises of far-UV observations with the *Copernicus* satellite. It was originally difficult to understand how observable amounts of O VI, which is two stages above the dominant form of oxygen (O IV), exist in the winds of these stars. All but the very hottest O stars emit too few photons above the ionization thresholds for either O V (77.4 eV) or O VI (113.9 eV) for photoionization by photospheric radiation to be a viable formation mechanism. Initial attempts to explain the presence of O VI postulated the presence of high-temperature coronal zones near the base of the wind. Lamers & Morton (1976) were able to reproduce the observed amount of O VI in late O-type stars with coronal models, but could not account for its presence in the winds of stars with spectral types later than ~B0.

Instead, Cassinelli & Olson (1979) noticed that the “two stages above dominant” character of the O VI superion could be explained naturally by Auger ionization if X-rays were present in the winds of hot stars. By this mechanism, photons with  $h\nu \gtrsim 580$  eV ( $\lambda \lesssim 21.23$  Å) remove an electron from the inner shell of the O IV ion to produce O V in a highly excited state. This X-ray photoionization is followed by recombination through an Auger cascade, which results in the ejection

of an additional electron and the creation of an O VI ion; see Opendak (1990) for details. The predicted X-ray flux, necessary for O VI production, was subsequently detected by observations from the *Einstein* (Harnden et al. 1979; Seward et al. 1979) and *ROSAT* (Berghöfer et al. 1996) observatories. Since then, a variety of models have been proposed to explain the origin of these X-rays, including a deep-seated, hot corona (e.g., Cassinelli & Olson 1979; Waldron 1984), shocks due to the intrinsic line de-shadowing instability (e.g., Lucy & White 1980; Owocki et al. 1988; Feldmeier et al. 1997), and heating of plasma in magnetic loops (e.g., Cassinelli et al. 1981; ud-Doula & Owocki 2002). Although the origin of these X-rays is still uncertain, calculations by MacFarlane et al. (1993, 1994) incorporating X-rays distributed throughout the wind have demonstrated that the observed levels of superionization can be reproduced. As a result, Auger ionization is now understood to be responsible for the production of superions in the winds of hot stars.

A straightforward consequence of the Auger mechanism is that, in the presence of a sufficient flux of suitably energetic X-rays, a particular superion will be produced only as long as its parent ion (for CNO, the ion two stages below it; Opendak 1990) remains abundant. Since the dominant state of O switches from O IV to O III at  $T_{\text{eff}} \approx 30$  kK, Cassinelli & Olson (1979) predicted that O VI would not be present in spectra of stars later than ~B0.5. This was in reasonably good agreement with the survey for wind features in *Copernicus* spectra of 47 early-type stars by Snow & Morton (1976), who claimed to detect O VI in stars as late as B1. However,

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subsequent analysis of the same spectra by Morton (1979) resulted in the retraction of the detections for both B1-type stars. Consequently, the precise boundary in the H-R diagram for the occurrence of the superior O VI has remained controversial.

With the launch of the *Far Ultraviolet Spectroscopic Explorer (FUSE)* in 1999, it has once again become possible to obtain far-ultraviolet spectra of large numbers of early-type stars with high spectral resolution. Owing to its higher sensitivity, many more targets are available to *FUSE* than *Copernicus*. For example, after  $\sim 2.5$  years of operation, *FUSE* had obtained more than 200 spectra of B-type stars, whereas *Copernicus* observed  $\sim 40$  over its lifetime. The availability of this significantly larger sample of *FUSE* spectra motivated us to re-investigate the location of the temperature boundary where the production of O VI in the winds of B-type stars ceases. Our survey for stellar O VI is described in this paper, which is organized as follows. The observational material is described in Sect. 2, while the techniques used to identify weak stellar O VI absorptions is discussed in Sect. 3. Illustrative detections are presented in Sect. 4 for each spectral class, and the results of the survey are summarized in Sect. 5.

## 2. Observational material

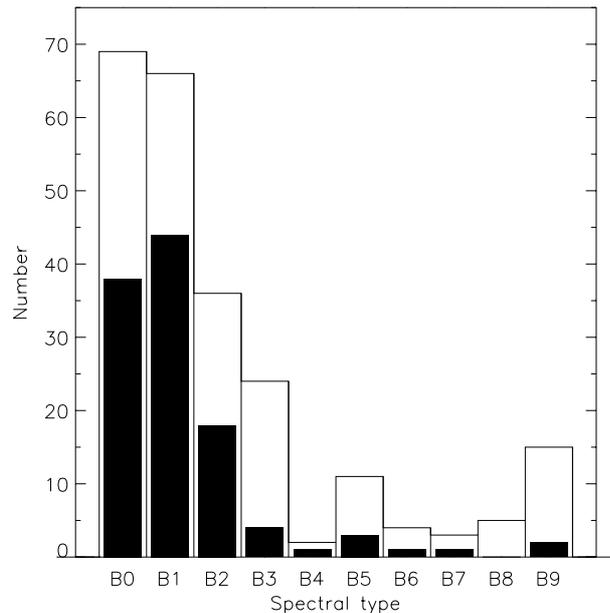
### 2.1. The FUSE sample of B-type stars

By the autumn of 2002, *FUSE* observations of 235 B-type stars were available for this survey. Most of these spectra were obtained for programs developed by the Principal Investigator Team, especially surveys of interstellar O VI in the halo and disk of the Galaxy. These spectra were supplemented by observations collected for various Guest Investigator programs for which the proprietary period had elapsed. The distribution of this sample with temperature class is illustrated in Fig. 1, in which we also coarsely indicate the distribution with luminosity class by open and shaded bars. Figure 1 shows that the sample is strongly biased toward luminous B0–B3 stars. Although subject to many selection effects, the *FUSE* sample is substantially larger than the *Copernicus* sample of 41 B-type stars (see, e.g., Snow & Jenkins 1977) that is the basis for previous efforts to set boundaries for the occurrence of stellar O VI in the H-R diagram.

### 2.2. FUSE observations and data reduction

The spectroscopic instrumentation on *FUSE* and its inflight performance have been described by Moos et al. (2000) and Sahnou et al. (2000), respectively. The B-star spectra used in this survey were generally obtained through the  $30'' \times 30''$  (LWRS) aperture. The fainter targets were obtained in time-tag (TTAG) mode, where the location and arrival time of each photon is recorded, while brighter targets were observed as spectral images in time-integrated histogram (HIST) mode. The observations of our sample were approximately evenly split between these two observing modes.

The standard calibration software, CALFUSE v. 2.0.5, was used to extract and calibrate the spectra. For TTAG data, the photon event lists for different exposures associated with a



**Fig. 1.** The distribution of Galactic B stars included in the *FUSE* survey for stellar O VI with spectral type. Shaded regions in each histogram bar indicate the number of stars with luminosity classes I–III. The sample is strongly biased toward stars earlier than B3.

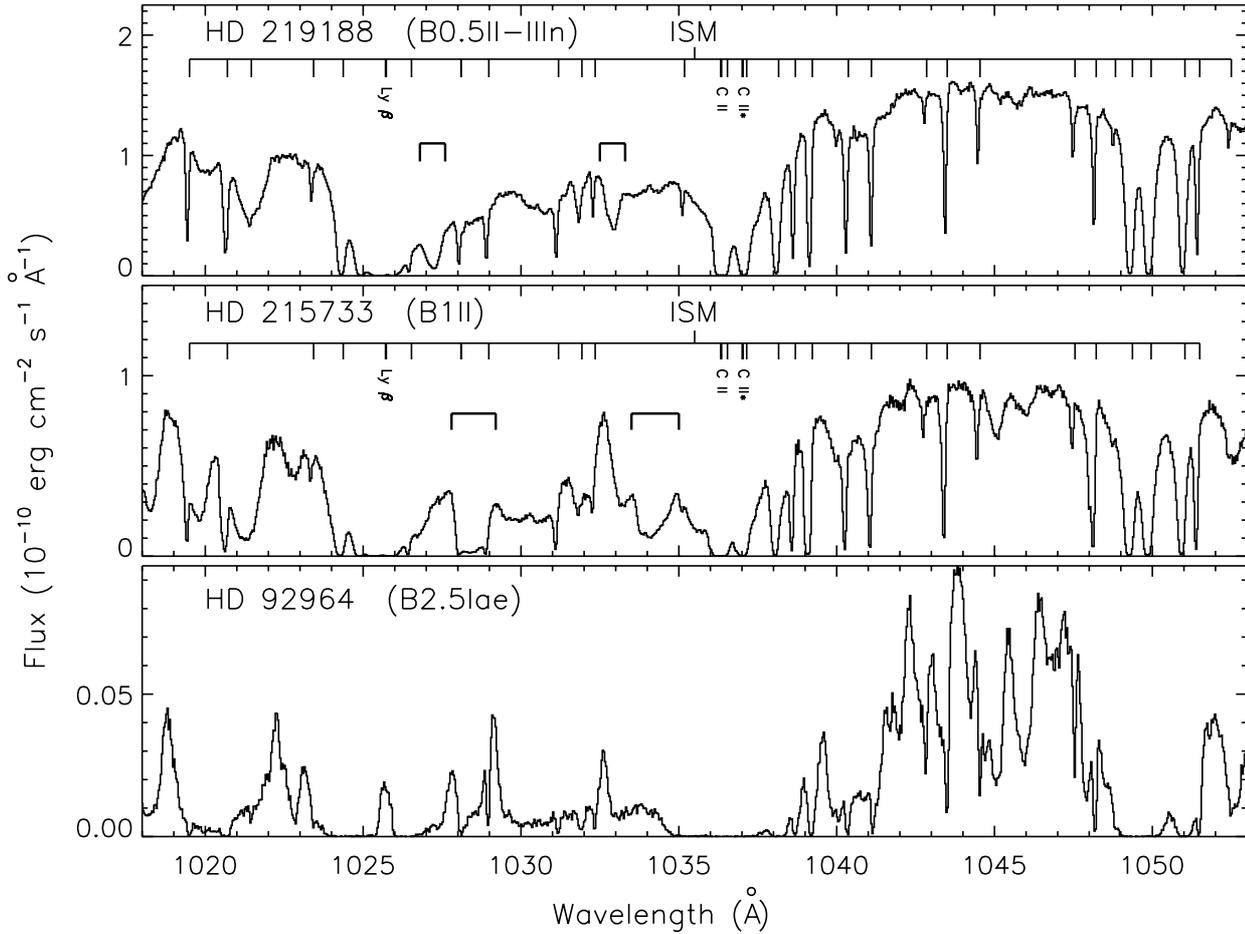
given observation were first concatenated, and the entire list was used as input to CALFUSE. Data obtained in HIST mode were processed through CALFUSE exposure-by-exposure, then aligned and coadded to obtain the observation-level spectrum. The resultant flux-calibrated spectra are in the heliocentric reference frame, and are characterized by spectral resolution of  $\sim 20 \text{ km s}^{-1}$  ( $FWHM$ ) for all instrumental configurations. However, owing to the diverse purposes for which the spectra were originally obtained, there is a wide range in the signal-to-noise ratio ( $S/N$ ) across the sample. The resultant  $S/N$  of any given spectrum depends on the brightness of the source, the total integration time devoted to it, and the extent to which systematic motions (planned or due to thermal drifts in the instrument) of the spectrum in the dispersion direction reduced the fixed-pattern noise inherent to the micro-channel plate detectors.

### 2.3. Ancillary data

Whenever possible, we retrieved archival *IUE* SWP spectra of our targets from the Multimission Archive at Space Telescope (MAST) in order to compare the morphology of stellar features at longer UV wavelengths with those accessible to *FUSE*. These data were processed with the standard NEWSIPS software, and were retrieved as MX browse files. We also retrieved low resolution ( $FWHM \sim 0.2 \text{ \AA}$ ) far-ultraviolet spectra of  $\tau$  Scorpii obtained by *Copernicus* (Snow & Jenkins 1977).

## 3. Methodology

Following Snow & Morton (1976) and Morton (1979), we sought wind features attributable to O VI on a star-by-star basis by comparing the positions and morphologies of spectral



**Fig. 2.** The observed fluxes around the O VI doublet toward three early-B stars. Combs in the upper two panels mark the position of interstellar lines, most of which are due to H<sub>2</sub>. We identified the Lyman  $\beta$  of H I at 1026 Å and the C II, C II\* absorption complex near 1037 Å that were particularly problematic “contaminants” of the wind O VI absorption. Blue-shifted O VI absorption features are indicated for HD 219188 and HD 215733 (upper two panels). Similar features could not be identified for HD 92964 (lower panel) due to strong photospheric line blanketing.

**Table 1.** Properties of ultraviolet resonance lines with wind profiles.

Ion	Abundance <sup>a</sup>	I.P. range <sup>b</sup> (eV)	Wavelengths <sup>c</sup> (Å)	log $f\lambda$ <sup>c</sup>
O VI	8.87	113.9–138.1	1031.93, 1037.62	2.137, 1.836
N V	7.97	77.5–97.9	1238.82, 1242.80	2.289, 1.988
Si IV	7.55	33.5–45.1	1393.76, 1402.77	2.855, 2.554
C IV	8.55	47.9–64.5	1548.20, 1550.77	2.470, 2.169

<sup>a</sup> – Solar-system abundances from Grevesse & Noels (1993) and Anders & Grevesse (1989), expressed as  $\log N/N_{\text{H}} + 12.00$ .

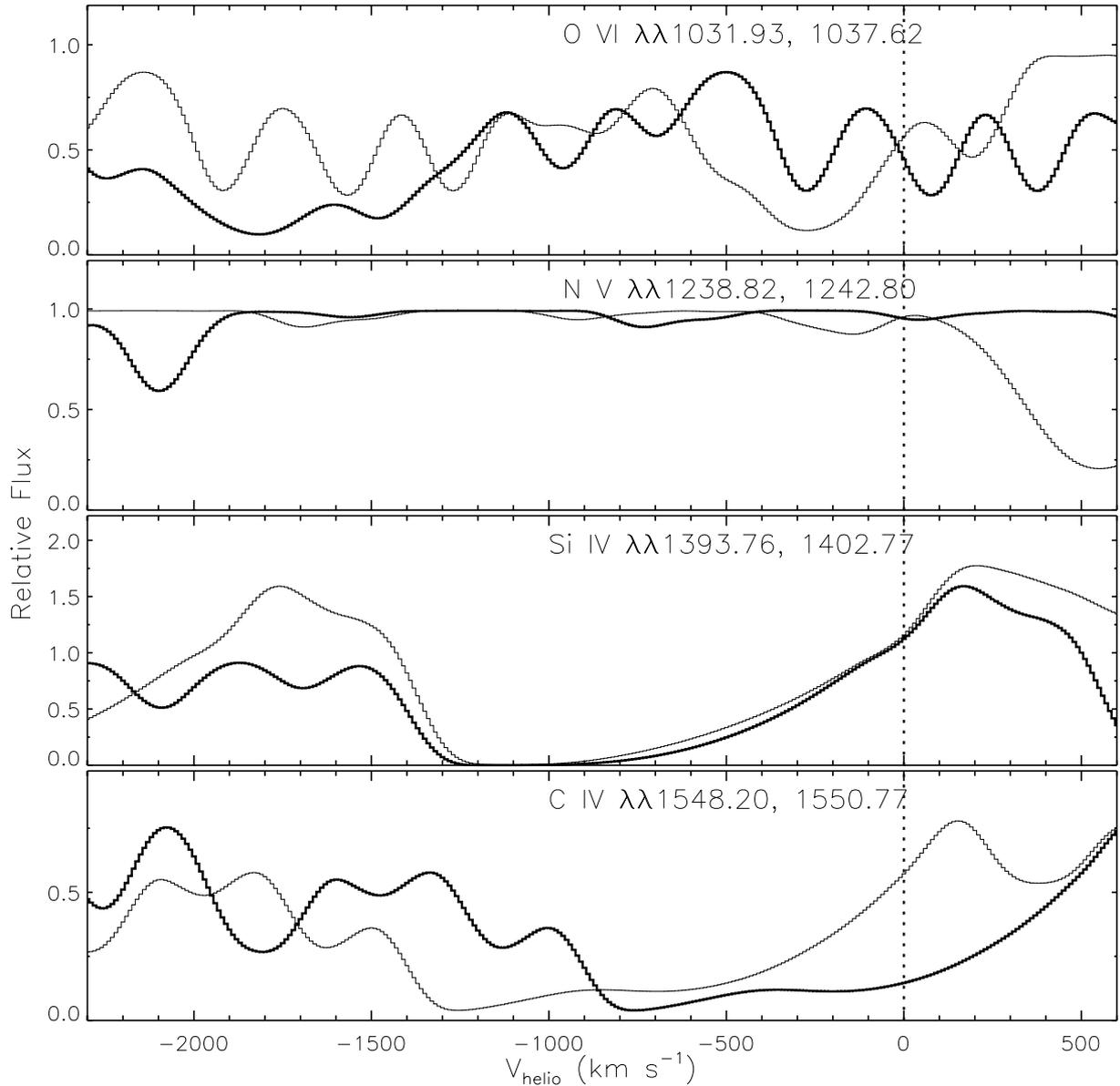
<sup>b</sup> – The ionization potentials are from Moore (1970).

<sup>c</sup> – The rest wavelengths and oscillator strengths for the blue and red components of the doublets are from Morton (1991, 2002).

features in the vicinity of the O VI doublet with bona fide stellar wind features in *IUE* spectra of the Si IV, C IV, and N V resonance doublets. The fundamental properties of these transitions are summarized in Table 1. All comparisons were made in the heliocentric frame of reference, since reliable determinations of the systemic velocity are not available for many of the stars in the sample. For O VI, we relied on *FUSE* spectra from the LiF1 channel, which has the largest effective area in the vicinity of the O VI doublet. Redundant spectra from other channels were used to verify the reality of weak features and to ensure

that fixed-pattern noise in the detector did not cause spurious detections.

This straightforward approach is limited primarily by blending with interstellar or stellar features, which becomes an increasingly serious impediment to the detection of features formed in intrinsically weak stellar winds, such as those expected for cooler and less luminous B-type stars. Figure 2 shows the effects of interstellar contamination on *FUSE* spectra of three early B-type stars in the region of the O VI doublet. The rest wavelengths of strong interstellar features are



**Fig. 3.** Synthetic spectra between  $-2300$  and  $+600$   $\text{km s}^{-1}$  of the rest wavelengths of the resonance doublets of O VI, N V, Si IV, and C IV (from top to bottom). The computed flux is plotted as a function of velocity with respect to the laboratory wavelength of the stronger (thick line) and weaker (thin line) member of each doublet. See Sect. 3 for a description of the model parameters. Since the computation did not include Auger ionization via X-rays, O VI and N V were not produced. The photospheric features in the vicinity of O VI are mostly due to Fe III.

indicated by “combs” that extend over the width in the upper two panels. Most of this contamination is caused by  $\text{H}_2$ , which typically blankets much of the spectral region accessible to *FUSE*. However, the most serious blends affecting the detection of stellar O VI are due to interstellar Lyman  $\beta$  line of H I at  $1026 \text{ \AA}$  and a mixture of C II, C II\*, and  $\text{H}_2$  absorption near  $1037 \text{ \AA}$ . Both features are generally strong for Galactic sight lines and can mask wind features at heliocentric velocities  $|\nu| \geq 1400 \text{ km s}^{-1}$  and  $|\nu| \leq 500 \text{ km s}^{-1}$  in the blue and red components of O VI, respectively. These blends severely compromise the detection of stellar wind absorption features characterized by small velocities; see, e.g., Sect. 4.1.

The complexity of the underlying photospheric spectrum also affects the detectability of weak O VI features formed in the stellar wind. For example, the lowest panel of Fig. 2 shows that photospheric line blanketing is extremely severe for giants and supergiants later than B2; see Sect. 4.3 for further discussion. As a less severe example, Fig. 3 shows synthetic spectra of an early B-type supergiant in the vicinity of the strategic wind lines, which was kindly computed for us by Dr. Paul Crowther with the non-LTE, line-blanketed model atmosphere program for the expanding atmospheres of early-type stars CMFGEN (Hillier & Miller 1998). The model corresponds approximately to a B0 supergiant with the following

parameters:  $T_{\text{eff}} = 25\,000$  K,  $\log L/L_{\odot} = 5.42$ ,  $\dot{M} = 8 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$ , and  $v_{\infty} = 1\,200 \text{ km s}^{-1}$ . The synthetic spectra were rotationally broadened by  $v \sin i = 80 \text{ km s}^{-1}$ , which is a typical value of the projected rotational velocity for the stars presented here. The models naturally produce P Cygni profiles for the C IV and Si IV resonance doublets, but the N V and O VI superions are missing because Auger ionization via X-rays were not incorporated. Figure 3 shows that the region of the O VI doublet is the most seriously affected by photospheric lines, most of which are due to Fe III. However, it is also apparent that these lines do not mimic the spacing of the components of the O VI doublet, so there is little likelihood of confusion. Nevertheless, the presence of photospheric lines frequently impaired our ability to perform a detailed optical depth comparison of wind features.

An alternative approach to identifying weak O VI wind features that are confused with stellar or interstellar lines is to search for synchronous spectral variability at the doublet separation. This approach is valid because no O VI is expected in the stellar photosphere, while interstellar lines are not expected to vary. Lehner et al. (2003) report the results of a survey for O VI variability based on multiple observations made by *FUSE*. Even though the observing schedule was not optimized for the detection of stellar wind variability, they found that  $\sim 64\%$  of the stars earlier than B1 were variable. The variability survey includes several of the B-type targets investigated here, and provides an opportunity to verify our technique for identifying O VI features based on spectral morphology alone.

#### 4. Results

Owing to the intrinsic weakness of their winds, most stars in our sample were not likely to exhibit fully developed P Cygni profiles in O VI. Instead, we expected to see blueshifted absorption that is typically stronger near the blue edge of the profile (which may or may not be the terminal velocity of wind,  $v_{\infty}$ ). Although careful inspection of the *FUSE* B-star sample produced many likely identifications of O VI wind features, it was not always possible to confirm their nature due to blending with interstellar or photospheric lines. In many cases, the variability study of Lehner et al. (2003) confirmed that these features can indeed be attributed to stellar winds. Whenever our comparison of C IV, Si IV, and O VI strongly suggested the presence of wind features in O VI and multiple observations were available, the Lehner et al. (2003) study revealed time variability in O VI.

The most compelling example is the case of HD 187459 (B0.5 Ib), where Lehner et al. (2003) found variability at wind velocities between  $-750 \text{ km s}^{-1}$  and  $-1550 \text{ km s}^{-1}$ . Figure 4 shows the observed O VI, N V, Si IV, and C IV profiles for HD 187459. The broad feature in O VI around  $-1100 \text{ km s}^{-1}$  was suspected to be blueshifted wind absorption that is also present in the Si IV and C IV profiles. Although the overlap between the interstellar H I  $L_{\beta}$  line and the O VI 1031.93 Å wind absorption prevented us from unambiguously identifying stellar O VI in HD 187459, the variability occurring at the relevant velocities supported our initial suspicion.

Even though the variability study supported our conclusions in the more clear-cut cases, it also revealed the

**Table 2.** The frequency of galactic B-type stars with O VI wind features.

Spectral type bin	% (Det./Tot.) <sup>a</sup>	
	Zs03 <sup>b</sup>	L03 <sup>c</sup>
B0 – B1 (I-III)	$\geq 34$ (13/38)	$\geq 86$ (6/7)
B0 – B1 (IV-V)	$\geq 19$ (6/31)	$\geq 56$ (5/9)
B1 – B2 (I-III)	$\geq 20$ (9/44)	$\geq 67$ (4/6)
B1 – B2 (IV-V)	0 (0/22)	0 (0/3)
B2 – B9 (I-V)	0 (0/100)	0 (0/4)

<sup>a</sup> – Det.: the number of stars with detections; Tot.: total number of objects surveyed.

<sup>b</sup> – Present study. Includes cases with unambiguous and very likely detections.

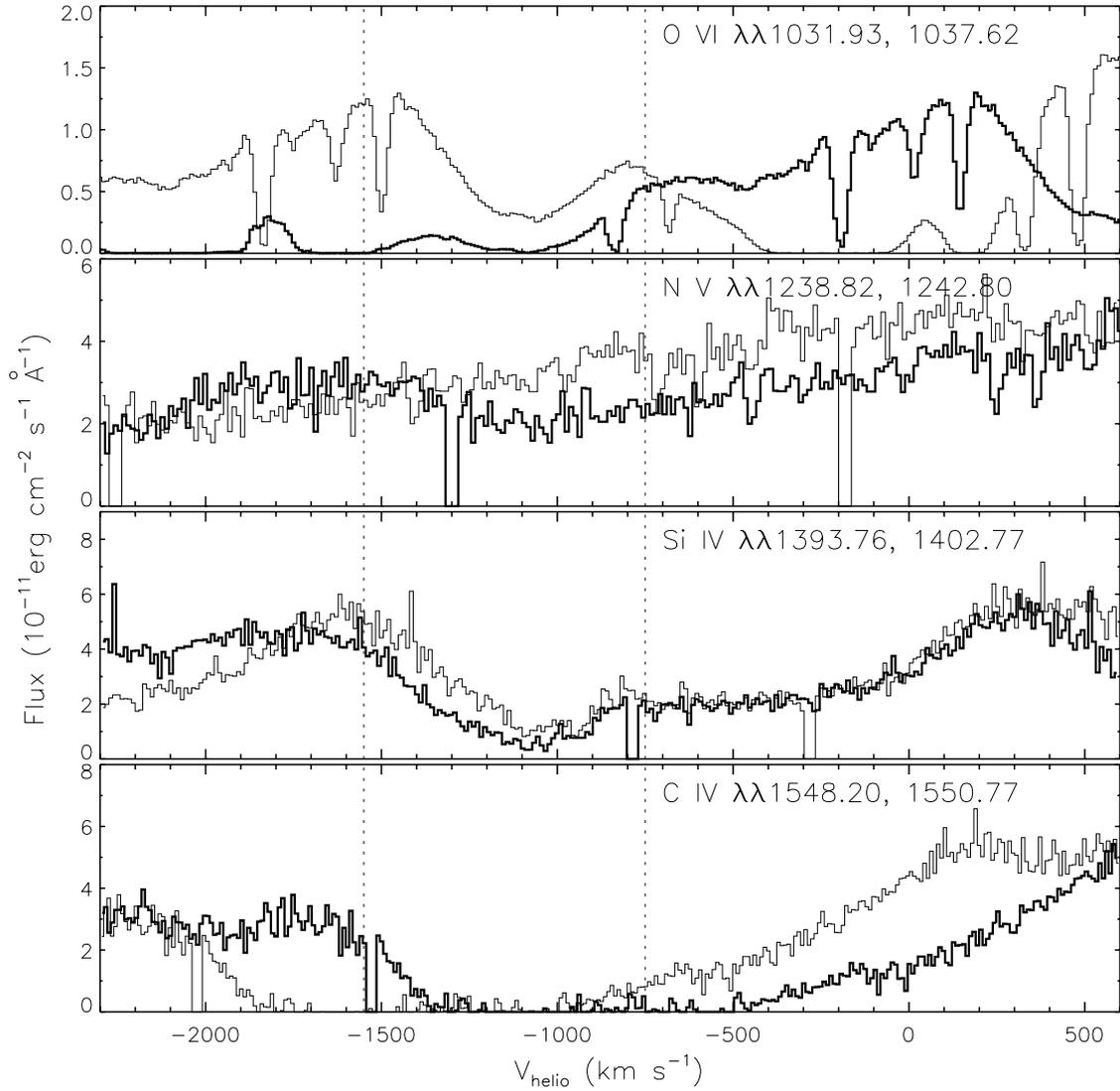
<sup>c</sup> – Variability study of Lehner et al. (2003). The statistics are for Galactic stars only.

limitations of our method. Often variability occurred in O VI when no wind features could be identified by our profile comparison. It is likely, therefore, that our detection rate seriously underestimates the true frequency of the occurrence of O VI wind features in the spectra of B-type stars. Table 2 illustrates this deficiency by comparing our detection rate with those of Lehner et al. (2003) for Galactic B stars. Table 2 also highlights the rather small number of B-type stars with multiple *FUSE* observations. Follow-up observations or time-variability studies are required to corroborate our potential detections and determine the true frequency of stellar O VI in the B spectral class.

In the remainder of this section, we present the results of the profile comparisons for stars that did provide clear evidence for blueshifted wind features in O VI (including 3 objects with spectral types as late as B1) and discuss the implications of non-detections in the spectral class B2 and beyond. The fundamental properties of these objects and the details of the *FUSE* observations are listed in Table 3. We describe these detections in order of spectral type.

##### 4.1. B0 and B0.5 stars

The presence of O VI wind absorption in the spectra of B0 dwarfs has been known since early observations with *Copernicus* (Lamers & Rogerson 1978). Detections in the fainter objects accessible to *FUSE* are not trivial, because the winds of B0 V stars are usually slow ( $v_{\infty} \lesssim 600 \text{ km s}^{-1}$ ; Prinja et al. 1990) and the O VI  $\lambda 1037.62$  profile is almost always obscured by strong interstellar C II, C II\*, and H<sub>2</sub> absorption. These problems are illustrated in Fig. 5, which compares *FUSE* and *Copernicus* spectra of the O VI doublet for three B0 V stars. A broad wind profile is clearly recognizable in both O VI lines in the *Copernicus* spectrum of the nearby, lightly reddened star  $\tau$  Scorpii, but the saturated interstellar lines mask any possible O VI  $\lambda 1037.62$  feature in HD 97471 and HD 207538. Accordingly, we used  $\tau$  Sco as a template to look for strong wind features in O VI  $\lambda 1031.93$ . For example, the spectrum of HD 97471 in Fig. 5 exhibits a prominent wind profile around 1032 Å. Remarkably, these absorptions are even stronger than the much-studied O VI lines of  $\tau$  Sco. In contrast, it is apparent from Fig. 5 that HD 207538 shows no morphological



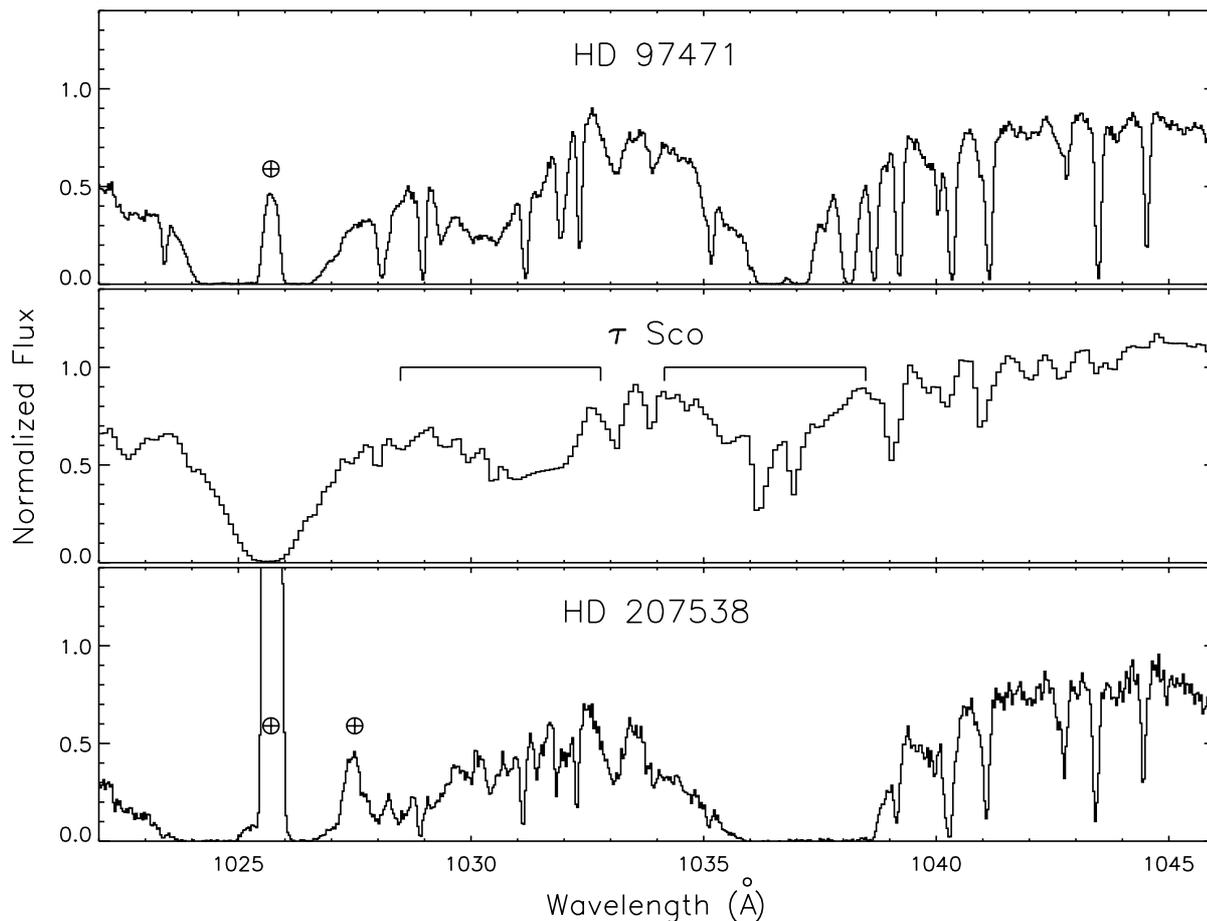
**Fig. 4.** Comparison of the observed wind profiles of HD 187459 for the resonance lines of O VI, N V, Si IV, and C IV (from top to bottom). The flux is plotted as a function of velocity with respect to the laboratory wavelength of the stronger (thick line) and weaker (thin line) member of each doublet. The velocity range where Lehner et al. (2003) observed time variability is indicated by vertical, dotted lines.

**Table 3.** Galactic B stars with O VI wind features.

ID	Sp. type	$v \sin i^a$ (km s <sup>-1</sup> )	$v_\infty^a$ (km s <sup>-1</sup> )	$E(B - V)$	FUSE program ID	Aperture/Mode <sup>b</sup>	Integration time (s)	IUE data set
HD 97471	B0 V	...	...	...	A1180404	LWRS/HIST	4200	...
HD 219188	B0.5 II-I	197	...	0.14	P1018902	MDRS/HIST	1660	SWP05653
HD 93840	BN1 Ib	95	1235	0.14	P1012701	LWRS/HIST	5318	SWP21525
HD 191877	B1 Ib	152	1160	0.18	P1028701 P2051101,02,03	LWRS/HIST LWRS/HIST	6132 28055	SWP14825
HD 215733	B1 II	84	1240	0.11	P1018602	MDRS/HIST	1932	SWP07356

<sup>a</sup> – Howarth et al. (1997).

<sup>b</sup> – LWRS: 30'' × 30''; MDRS: 4'' × 20''; HIST: histogram mode.



**Fig. 5.** Observed fluxes around the O VI doublet for three B0 V stars. HD 97471 and HD 207538 were observed by *FUSE*, while the spectrum of  $\tau$  Sco was obtained by *Copernicus*. The positions of terrestrial airglow lines are indicated by the “Earth” symbol in the *FUSE* spectra. The O VI wind features identified by Lamers & Rogerson (1978) are shown above the spectrum of  $\tau$  Sco. Similar strong features are apparent in the spectrum of HD 97471, despite the strong interstellar C II, C II\*, and H<sub>2</sub> lines around 1037 Å. However, no O VI wind features can be identified in the spectrum of HD 207538.

evidence for the presence of wind absorption at O VI. By using this method, we detected prominent O VI wind profiles in the spectra of  $\sim 19\%$  of the 31 B0 IV–V stars (see Table 2), which emphasizes the importance of superionization in the winds of B0 dwarfs.

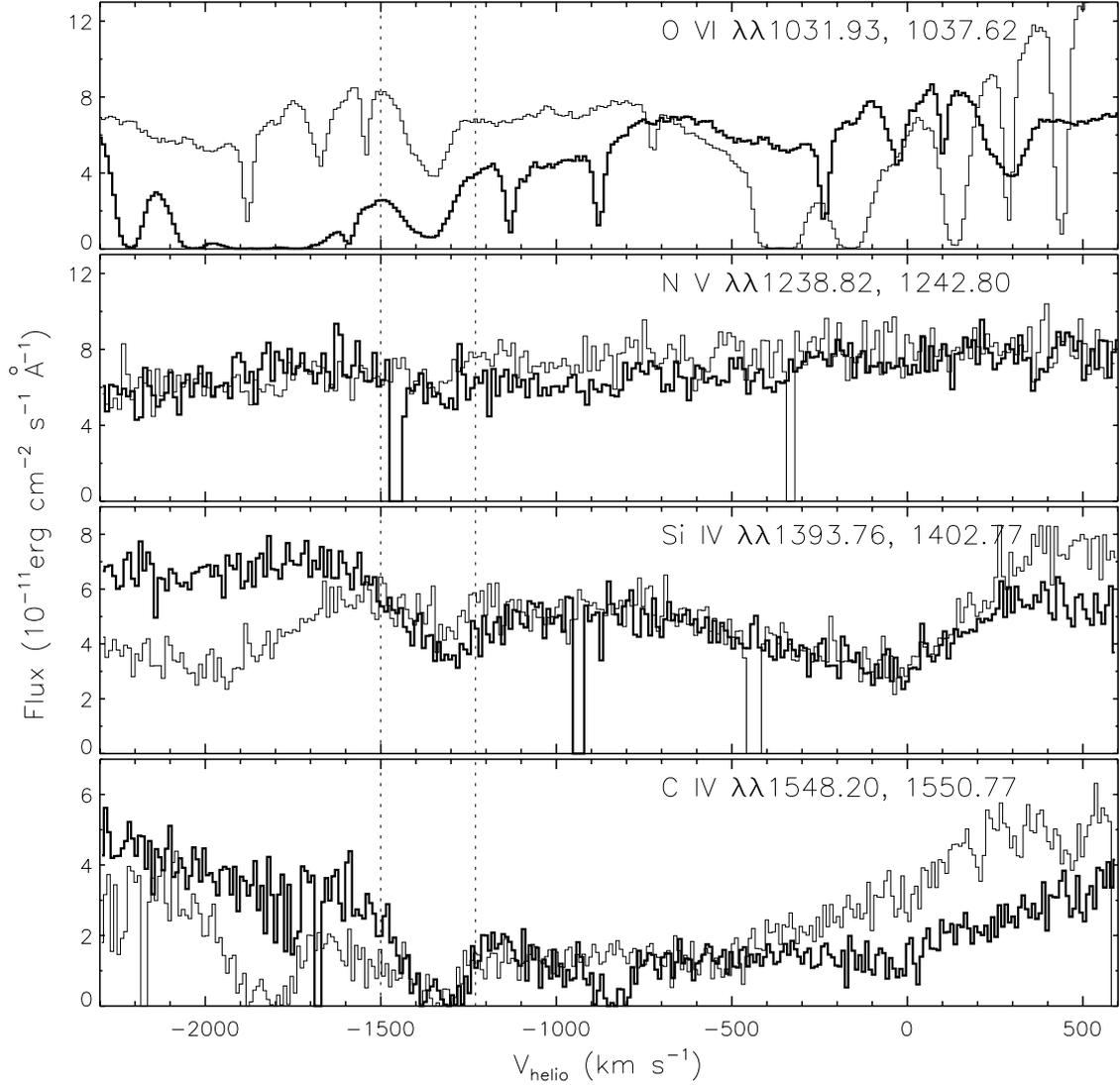
Since the terminal velocities of B0 giants and supergiants are usually larger than  $1000 \text{ km s}^{-1}$ , wind absorption in the red component of the O VI doublet is less likely to be masked by interstellar contamination. About a third of the luminous B0–B0.5 stars with *FUSE* spectra suggested the presence of O VI wind absorption. Of course, this fraction represents a lower limit on the true frequency of occurrence, since blending with interstellar and stellar features is still a problem; and indeed, not all the stars with suspected O VI absorption can be claimed as firm detections at this point. HD 219188 is clear-cut case, which is discussed in detail below.

#### 4.1.1. HD 219188

HD 219188 (B0.5 II–III<sub>n</sub>) is runaway star that has normal elemental abundances (Conlon et al. 1990), appears to be single (Gies & Bolton 1986; Philp et al. 1996), and evidently formed

far from the Galactic plane (Keenan et al. 1986). The morphology of its *FUSE* spectrum in the vicinity of O VI is compared with the well-developed P Cygni profiles in the resonance lines of Si IV and C IV in Fig. 6. Figure 6 shows a strong, narrow blueshifted absorption at about  $-1300 \text{ km s}^{-1}$  ( $\sim 0.9 v_\infty$ ) that occurs in both components of the O VI doublet. The location and width of these absorptions correspond to similar features in the Si IV and C IV wind profiles. Consequently, we interpret the blueshifted O VI absorptions as wind features that are formed predominantly in the high-velocity portion of the outflow.

HD 219188 also offers a nice opportunity to determine the optical depths of the blueshifted absorption features in the spectra of the O VI doublet. In contrast to most other targets, the effective continuum in the vicinity of these features can be placed reliably because the large projected rotational velocity ( $v \sin i = 197 \text{ km s}^{-1}$ ) broadens and smooths its underlying photospheric spectrum. Figure 7 shows the measured optical depths for each component in  $20 \text{ km s}^{-1}$  wide velocity bins (upper panel) and the derived ratio of the optical depth in the blue and red components (lower panel). Within the uncertainties, the optical depth ratio is 2, which is consistent with expectations for an optically thin plasma. Thus, the position, morphology,



**Fig. 6.** Comparison of the observed wind profiles of HD 219188 for the resonance lines of O VI, N V, Si IV, and C IV (from top to bottom). The flux is plotted as a function of velocity with respect to the laboratory wavelength of the stronger (thick line) and weaker (thin line) member of each doublet. The velocity range containing the O VI, Si IV, and C IV wind features is indicated by vertical, dotted lines. Note the serious contamination of the O VI doublet by interstellar lines.

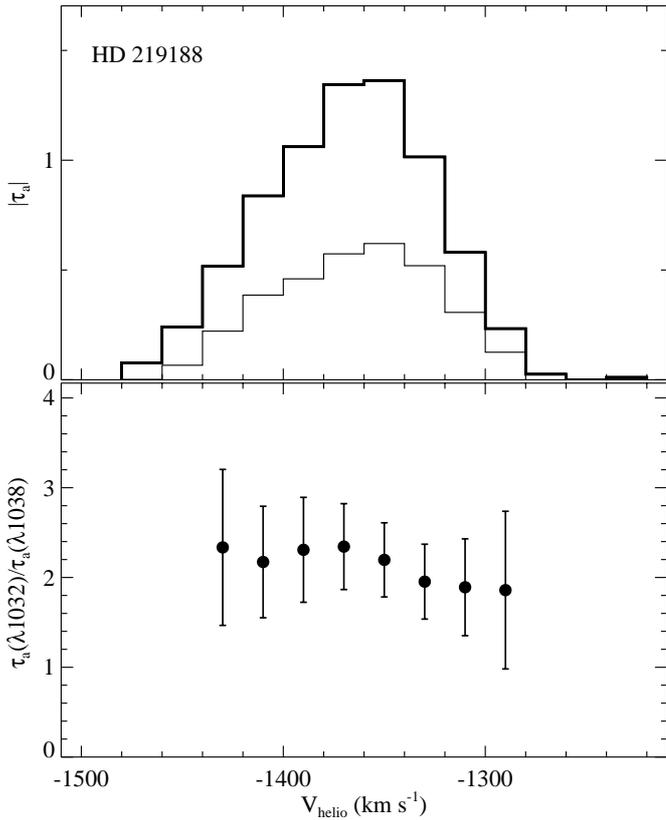
and optical depth ratio of the absorption components are consistent with the interpretation that they arise from optically thin O VI near the terminal velocity of the stellar wind.

The measured optical depth of the high-velocity component in O VI  $\lambda 11032$ , together with the absence of analogous features in the superior of N V (Fig. 6) implies that the relative ion fractions of O VI and N V are unusual. At any wind velocity, the radial Sobolev optical depth of a wind profile is  $\tau_{\text{rad}} \propto f \lambda_0 q_i A_E M (dv/dr)^{-1}$ , where  $f$ ,  $\lambda_0$ ,  $q_i$ , and  $A_E$  are respectively the oscillator strength, rest wavelength, ion fraction, and elemental abundance associated with a particular transition. For solar abundances and atomic parameters for the blue component of the O VI and N V resonance doublets, this implies  $q_i(\text{O VI})/q_i(\text{N V}) = 0.176 \tau_{\text{rad}}(\text{O VI})/\tau_{\text{rad}}(\text{N V})$ . With  $\tau_{\text{rad}}(\text{O VI}) \approx 1.4$  (Fig. 7) and assuming an upper limit on the

non-detection of  $\tau_{\text{rad}}(\text{N V}) \leq 0.1$ , the ratio is  $q_i(\text{O VI})/q_i(\text{N V}) \geq 2.5$ . In contrast, Massa et al. (2003) derived values of 0.1–1.7 for this ratio from their study of *FUSE* spectra of O-type stars in the Large Magellanic Cloud, with (mean, median) values of (0.44, 0.33). Thus, fractionally more O VI and/or less N V appears to be produced in the wind of HD 219188 than is typically produced in the winds of O-type stars.

#### 4.2. B1 stars

As discussed in Sect. 1, the detection of O VI wind features in the spectra of B1-type stars is a crucial test of theoretical predictions of the production of high ions via Auger ionization. Only 16 stars bridging this interface are contained in the



**Fig. 7.** Top panel: the measured optical depths of the blueshifted wind absorptions in the spectra of HD 219188, rebinned to  $20 \text{ km s}^{-1}$  velocity bins. The thick and thin lines show O VI  $\lambda 1031.93$  and  $\lambda 1037.62$ , respectively. Lower panel: the optical depth ratio of the O VI doublet in each velocity bins. The error bars reflect the estimated uncertainties introduced by the continuum placement around the wind features.

catalog of *Copernicus* observations published by Snow & Jenkins (1977), and the persistence of O VI has been discussed only for subsets of 10 and 2 stars by Snow & Morton (1976) and Morton (1979), respectively. The report of O VI wind absorption in spectra of  $\rho$  Leonis (B1 Iab) and  $\gamma$  Arae (B1 Ib) was retracted by Morton (1979), with the result that the temperature boundary for the occurrence of stellar O VI is still uncertain.

In contrast, the *FUSE* sample consists of 66 B1 stars of all luminosity classes. A preliminary time-variability study of a subset of this sample (Lehner et al. 2001) has already reported the presence of O VI “discrete absorption components” (DACs) in the spectra of HD 91597 (B1 IIIne). Our inspection of the full sample revealed that wind O VI is not uncommon in the spectra of B1 giants and supergiants. We detected possible blueshifted absorption in the spectra of  $\sim 20\%$  of the B1 giants and supergiants, but did not find any evidence for wind features in the spectra of subgiants and dwarfs (see Table 2). This might be a selection effect, since the winds of lower-luminosity stars are characterized by much weaker signatures, even in dominant ions. For the three stars discussed below, we detected strong absorption features that can be identified with blueshifted O VI. Together with HD 91597 (Lehner et al. 2001), these objects provide the best evidence that the superior O VI persists in the winds of stars with spectral types as late as B1.

#### 4.2.1. HD 93840 (B1 Ib)

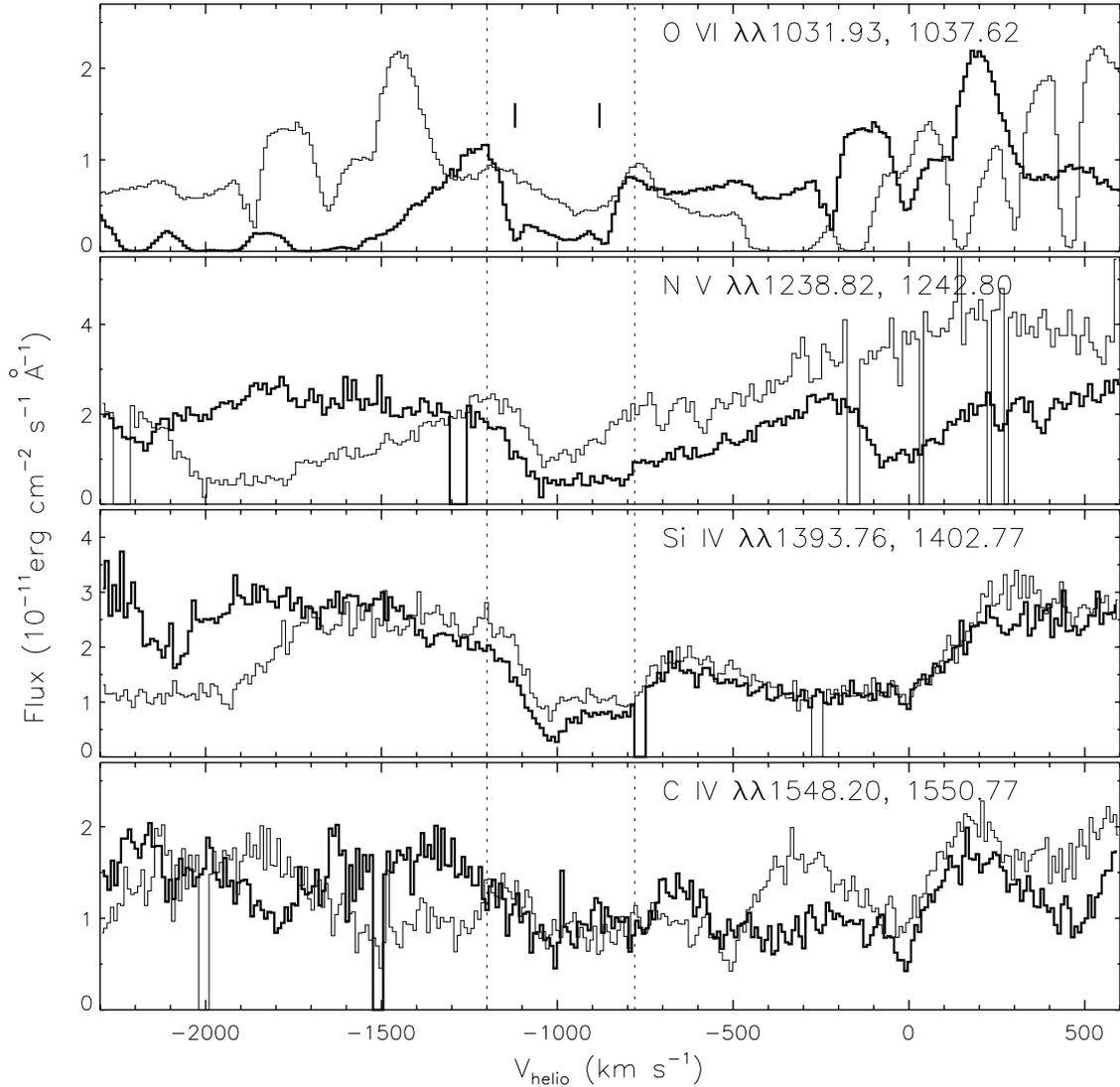
HD 93840 is a well-known supergiant that exhibits anomalous abundances due to the presence of material processed through the CNO-cycle in its atmosphere and wind (Savage & Massa 1987; Walborn et al. 1990; Massa et al. 1991). Since the CNO cycle only alters the relative abundances of CNO nuclei, the substantial overabundance of N and under-abundance of C implies that O should also be deficient compared with solar values. Figure 8 compares the UV resonance doublets of O VI, N V, Si IV, and C IV. The anomalous nitrogen and carbon abundances are apparent in the strong N V and weak C IV wind profiles, both of which are unusual for the spectral type. Blueshifted absorption is visible between  $-800$  and  $-1200 \text{ km s}^{-1}$  in both components of the O VI, N V, and Si IV doublets, and is present more weakly in the C IV doublet. Even though O is deficient and N is enhanced, the optical depths of the wind absorptions are similar, which again implies that  $q_i(\text{O VI})/q_i(\text{N V})$  is unusually large.

In contrast to the fully-developed P Cygni profiles at N V and Si IV, Fig. 8 implies that the O VI feature probably exists only in absorption, since the flux peak near  $+200 \text{ km s}^{-1}$  is consistent with the continuum level. It may be that most of the O VI wind absorption occurs in strong, comparatively narrow components near the terminal velocity. As originally recognized by Massa et al. (1991), similar DACs are visible in the Si IV lines of HD 93840. DACs are commonly observed in wind profiles of early-type stars (see, e.g., Prinja et al. 2002), and are interpreted as signatures of persistent, large-scale structures in the stellar wind. Since most models for the formation of DACs imply the presence of strong shocks, it would be very interesting to determine whether O VI is preferentially formed in the vicinity of these structures. See Lehner et al. (2003) for further evidence that O VI absorption is related to DACs.

#### 4.2.2. HD 191877 = HR 7716 (B1 Ib)

HD 191877 is a supergiant with normal elemental abundances (Wollaert et al. 1988). Figure 9 shows that its *FUSE* spectrum has deep absorption features with the separation of the components of the O VI doublet, blueshifted to approximately  $-1000 \text{ km s}^{-1}$ . The positions of these features coincides with excess absorption in the P Cygni profiles of the Si IV and C IV doublets. As with HD 219188, little or no wind absorption is apparent at the position of the N V doublet, which once again suggests that  $q_i(\text{O VI})/q_i(\text{N V})$  is larger than normally observed in the winds of O-type stars.

Since HD 191877 is one of the early B-type stars that was observed multiple times by *FUSE*, spectral variability can be used to disentangle features formed in the wind from photospheric and interstellar blends. Unfortunately, the time span between the observations was long (420 days) and the quality of the two observations was quite different. Lehner et al. (2003) classified it as variable, possibly a member of a binary system, and noted that the spectrum was too noisy to determine the range of variability in velocity reliably. Nevertheless, this cross-check corroborates the interpretation of the absorptions as wind features.



**Fig. 8.** Same as Fig. 6 for HD 93840. Interstellar lines that contaminate the O VI absorption are indicated by tick marks.

#### 4.2.3. HD 215733 (B1 II)

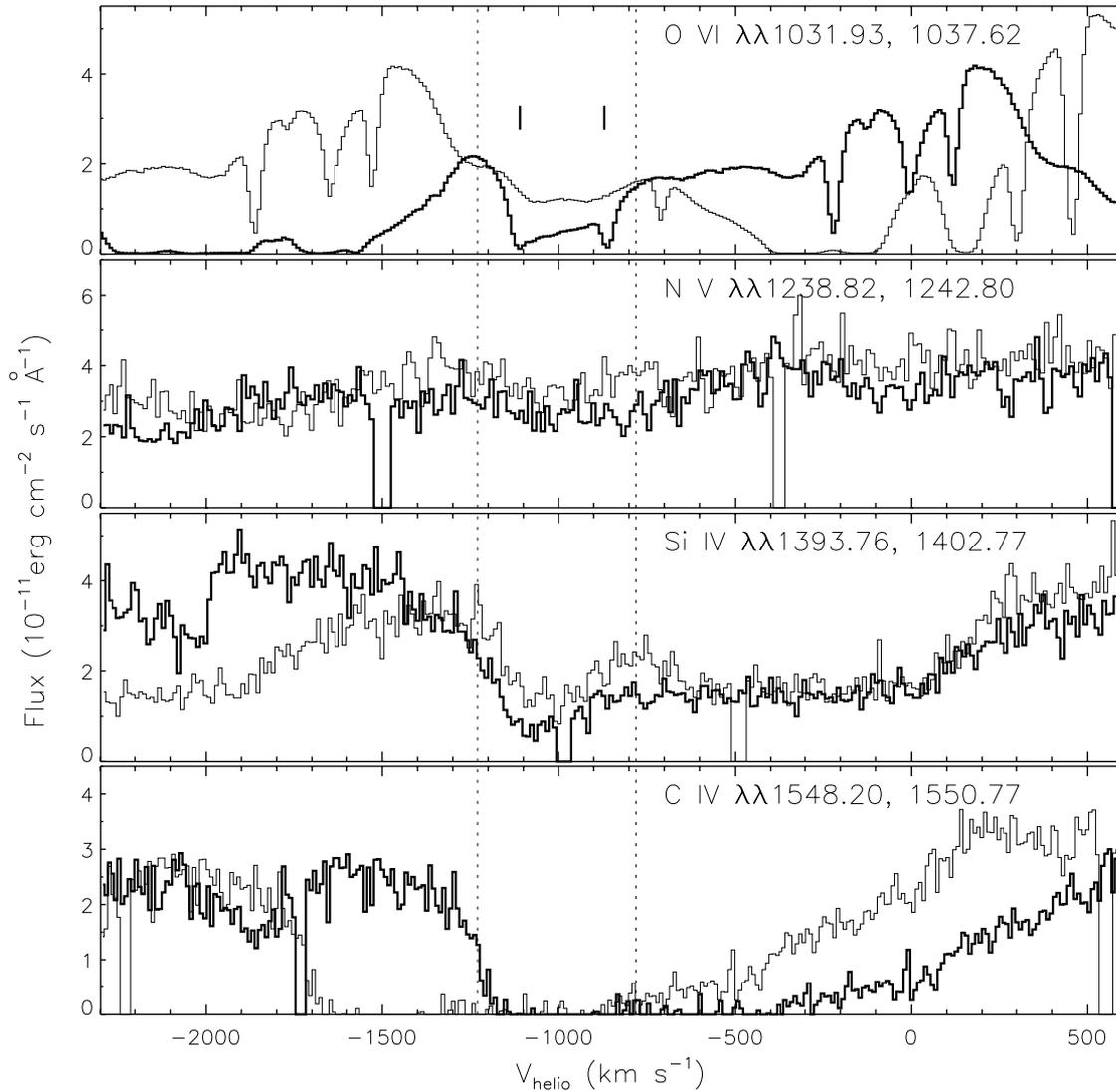
HD 215733 is a B1 II star located approximately 1.5 kpc below the Galactic plane. Although Walborn (1976) suggested that it was slightly deficient in N, subsequent analysis by Keenan et al. (1982) indicated that it has normal abundances. Figure 10 shows very strong blueshifted absorption features extending between  $-800$  and  $-1200$  km s $^{-1}$  in both components of the O VI doublet. Their positions coincide approximately with the positions of narrow absorption components in the resonance doublets of both Si IV and C IV, which otherwise exhibit well-developed wind profiles with little redshifted emission. This coincidence again suggests that O VI is formed preferentially at the larger velocities associated with these structures. As with HD 191877, there is little or no wind absorption visible in N V.

#### 4.3. B2 and later-type stars

We did not detect absorption features that could be identified with O VI for any objects with spectral types of B2 or later.

Furthermore, no time variability attributable to O VI was observed for such stars (Lehner et al. 2003), though only seven were observed more than once (see Table 2). Thus, from a purely observational perspective, we can now say definitively that B1 is the latest spectral type at which O VI wind features are detected.

However, even if O VI persists in the winds of cooler stars, the selection effects discussed in Sect. 3 work against its detection. Figure 11 shows the regions around the standard selection of resonance lines in the spectrum of HD 92964 (B2.5 Iae; see also Fig. 2). Although the wind of this supergiant has enough optical depth in the resonance lines of abundant species like C IV and Si IV to produce P Cygni profiles, it is futile to search for absorption features attributable to O VI due to the combined effects of heavy photospheric line blanketing and diminishing far-ultraviolet flux levels. Even without the devastating effects of line blanketing, the smaller terminal velocities associated with the winds of these cooler stars complicate the detection of weak absorption features, since the red component of the O VI



**Fig. 9.** Same as Fig. 8 for HD 191877.

doublet would typically be blended with interstellar lines and could not be used to search for correlated absorption or variability at the appropriate doublet separation. Thus, even if O VI were present in the winds of these cooler stars, it is doubtful that it could be detected.

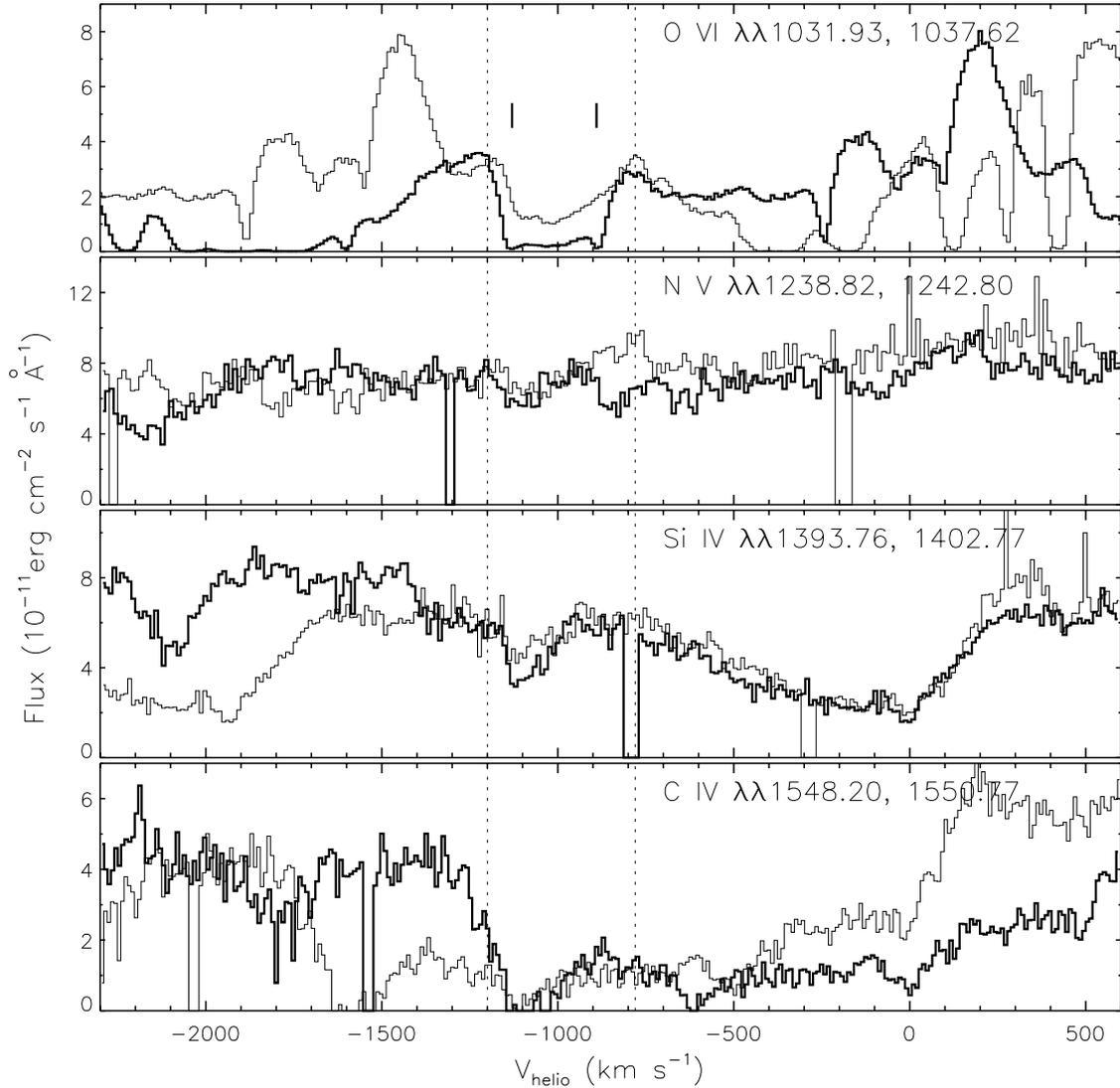
## 5. Summary

We have conducted a comprehensive search for stellar wind features in the resonance lines of the O VI superion in *FUSE* spectra of 235 Galactic B stars. This data set is substantially larger and more diverse than the sample obtained by *Copernicus*, but suffers from greater confusion due to blending with interstellar lines because the stars are systematically farther away. Although this confusion complicated the detection of weak stellar wind features in O VI, we found that:

- Blueshifted wind absorption attributable to O VI occurs in the spectra of B0 stars of all luminosity classes. The

strength of the absorption is sometimes greater than that seen in  $\tau$  Sco, which is frequently viewed as an extreme or anomalous object (see, e.g., Cohen et al. 2003). Instead, it seems that there is a class of B0 dwarfs that are similar to  $\tau$  Sco, which is just the nearest and brightest representative.

- O VI wind features persist to spectral types as late as B1, but only for more luminous stars (giants, bright giants, or supergiants). Since the winds of these objects have systematically greater optical depth than those of dwarfs, this luminosity dependence may just be an observational selection effect.
- No O VI wind absorption was detected in spectra later than B1 for any luminosity class. Although this may very well be the physically-relevant boundary of the occurrence of the O VI superion in the H-R diagram, the detection of weak absorption features in these spectra is problematic due to blending with interstellar and photospheric lines.



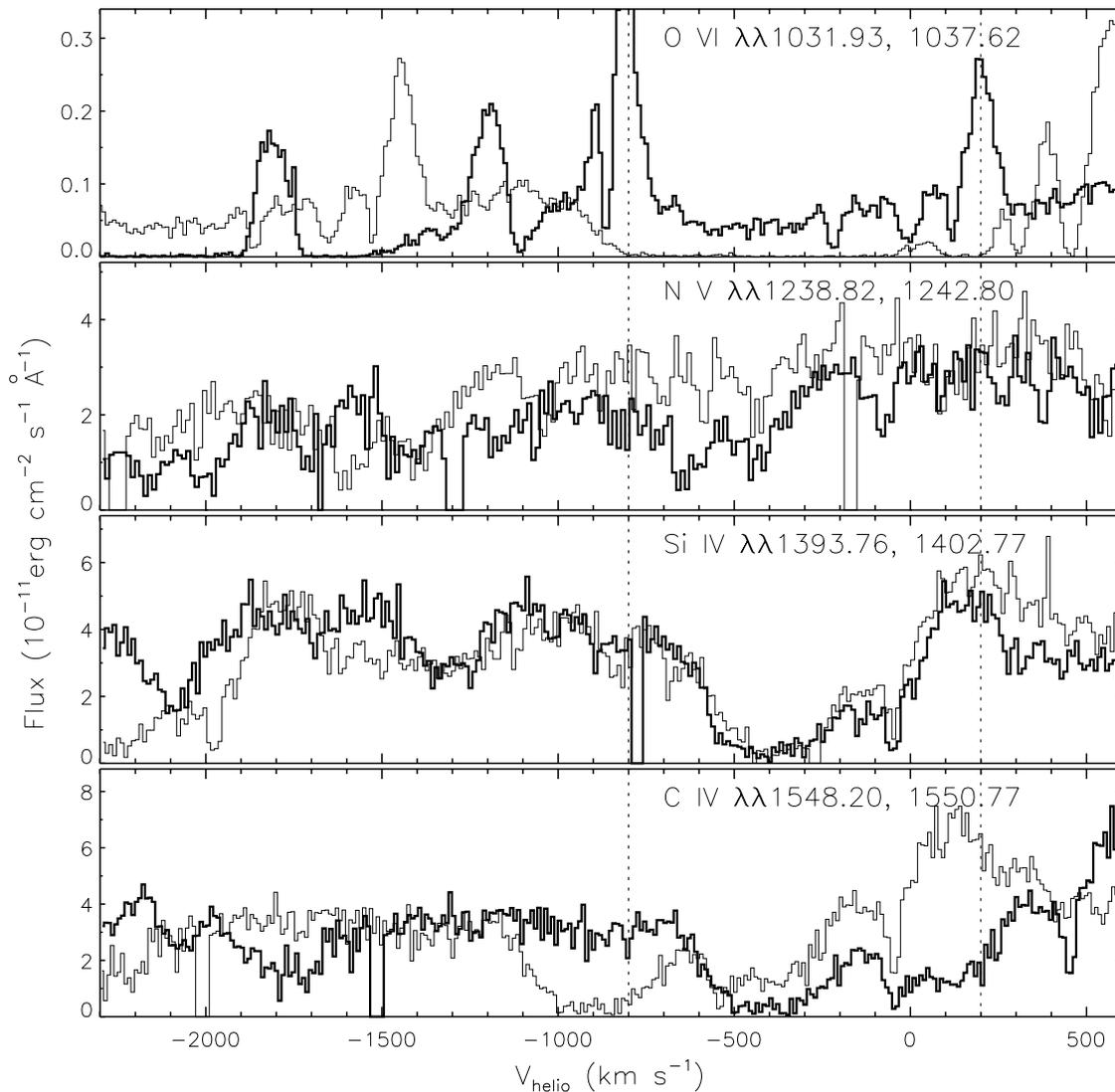
**Fig. 10.** Same as Fig. 8 for HD 215733.

- The absorption features in O VI are strongest near the terminal velocity of the wind, which suggests that superionization might preferentially occur at higher velocities in the winds of B-type stars. Lehner et al. (2003) reached a similar conclusion based on the characteristics of the variability they observed.
- The similarities in the appearance of the O VI wind absorptions in the spectra of the N-rich B1 supergiant HD 93840 and the chemically normal B1 supergiant HD 191877 indicate that the process responsible for the formation of the superion does not depend strongly on chemical composition. Irrespective of abundance anomalies, it appears that the ratio of ion fractions  $q_i(\text{O VI})/q_i(\text{N V})$  is systematically higher in early B-type stars than in O-type stars.

These findings dispel lingering doubts over whether O VI persists in the winds of stars as cool as temperature class B1. They are consistent with expectations based on the Auger

mechanism proposed by Cassinelli & Olson (1979), though unfortunately the cool boundary cannot be determined as rigorously as desired due to blending. Since lightly-reddened, nearby B-type stars are generally too bright to be observed by *FUSE*, it is unlikely that this issue will be resolved in the foreseeable future. A more fruitful avenue for further research will be to determine whether the enhanced production of O VI superions relative to N V superions in the winds of B-type stars is caused by the transition in X-ray emission properties that occurs at  $\sim\text{B1–B1.5}$  (Cassinelli et al. 1994; Cohen et al. 1997), but adequate X-ray measurements are necessary to resolve this question.

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**Fig. 11.** Same as Fig. 6 for HD 92964. The dotted vertical lines indicate the velocity region where wind signatures are expected to appear.

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