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MEASURING THE IONIZATION OF O STAR WINDS

Luciana Bianchi,[1,2,3] J. B. Hutchings,[1,4] Alex W. Fullerton,[2,5] Donald C. Morton,[1,4] Raymond G. Ohl,[2]
George Sonneborn,[6] Derck Massa,[7] K. R. Brownsberger,[8] and Allan J. Willis[9]
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ABSTRACT

We present an analysis of wind line profiles from *Far Ultraviolet Spectroscopic Explorer* (*FUSE*) spectra of two O7 supergiants in the Large and Small Magellanic Clouds (Sk −67°111 and AV 232, respectively). Model fits yield the column densities of S IV, S VI, P IV, P V, N III, and N IV, providing the first direct measurement of the ionization balance in stellar winds. The ratios of S IV/S VI and P IV/P V are consistently lower in the LMC star. *IUE* and *Hubble Space Telescope* archival spectra are also used to measure N IV and N V, but the much higher optical depth makes the N V measurements inconclusive. The velocity and optical depth distributions in the wind are qualitatively similar between the two stars, when scaled to their terminal velocities. The terminal velocities are different, with AV 232 being lower (as found previously in SMC stars and linked to lower metallicity). These are the first results from a program to investigate wind ionization and velocity structure among hot stars in local galaxies, and they demonstrate the higher accuracy in measuring column densities of less abundant ions, such as phosphorus and sulfur, observable in the *FUSE* range.

Subject headings: Magellanic Clouds — stars: early-type — stars: winds, outflows — ultraviolet: stars

1. INTRODUCTION

Supersonic winds of hot stars are revealed by conspicuous P Cygni profiles in the strongest transitions of the most abundant ions/species, which are found below 2000 Å. The wavelength region accessible to *IUE* and *Hubble Space Telescope* (*HST*; longward of 1200 Å) contains strong resonance lines of C IV, N V, and Si IV. Observations of these lines in stars in a variety of environments established a strong influence of the metal abundance on the wind terminal velocity (e.g., Bianchi & Scuderi 1999 and references therein; Bianchi, Hutchings, & Massey 1996; Prinja & Crowther 1998). However, these lines are often saturated and alone are not sufficient to determine the mass-loss rate and the ionization structure of the wind. The *Far Ultraviolet Spectroscopic Explorer* (*FUSE*; Moos et al. 2000) range (905–1187 Å) includes a greater spread of species and ionization states, allowing us to disentangle abundances and wind ionization structure for hot stars.

We present early *FUSE* observations of two O7 stars, Sk −67°111 in the Large Magellanic Cloud (LMC) and AV 232 (= Sk 80) in the Small Magellanic Cloud (SMC), and compare the ionization of their winds. These are part of a *FUSE* team program to investigate hot star winds in different local environments. *FUSE* observations of similar Galactic stars have not been obtained yet, so our comparison is limited to the LMC and SMC. *Copernicus* observations reported by McCluskey, Kondo, & Morton (1975) and Snow & Morton (1976) of the O7 Ia:fp eclipsing binary star 29 C Ma (= UW C Ma = HD 57060) show very strong S IV and P V P Cygni profiles. We reexamined the archival *Copernicus* data, but found there is no significant signal at S VI and P IV. *IUE* spectra with better signal than the *Copernicus* data for C IV and N V were analyzed by Chlebowski & Garmany (1991) and by Bianchi (1982), the latter finding values of the terminal velocity from $V_\infty = 1640$ to 1800 km s^{-1}. However, we note that 29 C Ma is not a good Galactic comparison because it is variable and peculiar (O7 Ia:fpvar to O9 I) and has a hot companion that causes complex effects of colliding winds (e.g., Chlebowski, Harnden, & Sciortino 1989; Bianchi 1982).

The early *FUSE* spectra used in this Letter do not have the final accuracy that we expect to reach in future observations, but they are quite adequate to demonstrate the potential of *FUSE* observations for the analysis of broad wind lines. The line profiles are modeled with the Sobolev plus exact integration (SEI) code (§ 3) to derive the optical depth of the S IV, S VI, P IV, P V, N III, and N IV ions.

AV 232 was observed by the Hopkins Ultraviolet Telescope (HUT; Davidsen et al. 1992) during the Astro-2 mission. The HUT spectrum, shown by Walborn et al. (1995b), has a resolution of 3 Å, which is insufficient to detect and remove the effects of interstellar absorption components. The higher resolution of *FUSE* shows that this contamination is very severe.

2. THE PROGRAM STARS AND THE OBSERVATIONS

Table 1 lists relevant information on the stars and our data. All data were taken in the 30″ × 30″ (LWRS) aperture. The "X" data sets were obtained in 1999 September as part of the Early Release Observation program and include only the LiF1 channel. The "I" data sets were obtained in 1999 October during the in-orbit checkout phase as mirror alignment tests. The stars were swept through the apertures during the exposures, resulting in total exposure times in different channels ranging from 2.7 to 4.9 ks for Sk −67°111 and from 1.2 to 4.9 ks for AV 232. The standard data pipeline cannot be used to extract these spectra, and special processing was required to extract

[1] Observer with the NASA-CNES-CSA *Far Ultraviolet Spectroscopic Explorer* (*FUSE*), which is operated by Johns Hopkins University under NASA contract NAS5-32985.
[2] Center for Astrophysical Sciences, Johns Hopkins University, Department of Physics and Astronomy, 3400 North Charles Street, Baltimore, MD 21218.
[3] Osservatorio Astronomico di Torino, Pino Torinese (TO), Italy.
[4] Herzberg Institute of Astrophysics, National Research Council of Canada, 5071 West Saanich Road, Victoria, BC V8X 4M6, Canada.
[5] Department of Physics and Astronomy, University of Victoria, P.O. Box 3055, Victoria, BC V8W 3P6, Canada.
[6] Laboratory for Astronomy and Solar Physics, NASA Goddard Space Flight Center, Code 681.0, Greenbelt, MD 20771.
[7] Raytheon Information Technology and Scientific Services, Code 681.0, NASA Goddard Space Flight Center, Greenbelt, MD 20771.
[8] Center for Astrophysics and Space Astronomy, University of Colorado, Campus Box 389, Boulder, CO 80309.
[9] Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT, England, UK.

TABLE 1
Program Stars and *FUSE* Data

	Spectral Type			LSR Velocity			
Star	Value	Reference	V	Value (km s^{-1})	Reference	*FUSE* Data Sets	V_∞ (km s^{-1})[a]
LMC Sk −67°111	O7 Ib(f)	1	12.57	250	2	X0200101, I8010901	1800 ± 100
SMC AV 232	O7 Iaf$^+$	3	12.36	164	3	X0200201, I8010801	1400 ± 100

[a] Values taken from this Letter.
References.—(1) Fitzpatrick 1988; (2) Hutchings 1982; (3) Walborn et al. 1995a.

the useful data. Details of spectral extractions and final quality assessment are given in a companion Letter (Massa et al. 2000). For the I data, independent extractions by different authors resulted in data with negligible differences. All data were taken prior to telescope focusing, and the spectral resolution ranges over 12,000–15,000. This is quite sufficient for our purpose of analyzing very broad stellar lines. In this Letter, we model only line profiles (flux relative to the local continuum), so uncertainties in the absolute flux calibration are not a concern. The uncertainty in the wavelength scale is not well established in these early data. Small-scale nonlinearities might be present which would affect measurements of very narrow lines but not the fits of broad wind profiles. To obtain a conservative (when applied to wind velocities) estimate of the uncertainty, we measured identified interstellar lines near the stellar lines of interest. We found the accuracy to be comparable to the resolution for most lines and worse by a factor of 2 around the S iv and S vi lines.

We also analyzed N iv and N v lines from *IUE* archive spectra of Sk −67°111 (SWP 10991 and SWP 52745 combined) and from *HST*–Faint Object Spectrograph (FOS) archive spectra (Y14M05) of AV 232.

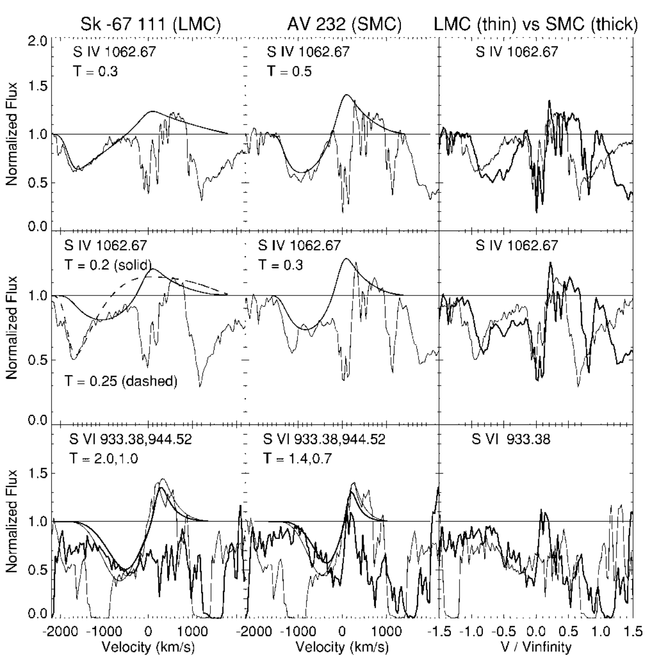

Fig. 1.—*Left and middle columns:* Model fits to the line profiles of S iv and S vi. In the S iv doublet the λ 1062.66 transition is chosen because it is the less blended (*top:* X data; *middle:* I data). For the S vi doublet, both lines are plotted: λ944.52 (*thick line*) and λ933.38 (*thin line*). Note the severe interstellar line absorptions. In the right column, the observed profiles of the two stars are compared, each normalized in width to its wind terminal velocity derived by the model. In this display, interstellar components are displaced by different amounts scaled by the terminal velocity ratio, but the similarity of the stellar features can be appreciated.

3. LINE MODELING

The *FUSE* range contains resonance lines of both S vi and S iv ions and both P iv and P v. These lines allow the first direct, empirical comparison of the wind ionization among two stars in different galaxies, without assumption or model derivation of the element abundances.

To include an abundant element from the CNO cycle, we also analyzed nitrogen lines. The N iii resonance line λ989.799 is blended with two lines from a slightly excited level: λ991.577 of almost equal strength and λ991.511 of negligible intensity. For N iv, only excited transitions are available—λ955.334 in the *FUSE* range and λ1718.550 in the *IUE*/FOS range. Finally, the resonance doublet of N v λλ1238.821, 1242.804 from the *IUE*/FOS data was also modeled, although the uncertainties increase rapidly with high optical depths.

The observed P Cygni profiles are modeled with the SEI method (Lamers, Cerruti-Sola, & Perinotto 1987) using the parameterization adopted by Bianchi, Vassiliadis, & Dopita (1997). The velocity law in the wind is expressed as

$$w(x) = \frac{v(x)}{V_\infty} = w_0 + (1 - w_0)\left(1 - \frac{1}{x}\right)^\gamma, \qquad (1)$$

where $x = r/R_*$, R_* is the photospheric radius, and w_0 is the initial velocity at the base of the wind. The optical depth of the transition is expressed as

$$\tau(w) = \left(\frac{T}{I}\right)\left(\frac{w}{w_1}\right)^{\alpha_1}\left[1 - \left(\frac{w}{w_1}\right)^{1/\gamma}\right]^{\alpha_2}, \qquad (2)$$

where w_1 is the maximum velocity shift in the line profile as a fraction of the full terminal velocity, T is the total optical depth, and

$$I = w_1 \int_{w_0/w_1}^{1} y^{\alpha_1}(1 - y^{1/\gamma})^{\alpha_2}\, dy. \qquad (3)$$

The normalization factor I ensures that T_i (optical depth of a given line of the ion i) is proportional to the column density N_i of the given ion, $T_i \propto f\lambda N_i V_\infty^{-1}$ (see, e.g., Bianchi et al. 1994). Photospheric absorption has not been included in the fits shown. Inclusion of a photospheric profile will visually improve the match to the observed profile around zero velocities, but would not affect the resulting wind parameters.

The results are shown in Figures 1–3. The I data contain all four channels and thus include both S vi and S iv lines, while only S iv is included in the X data. Because the stellar line profiles show variability in time, as discussed by Massa et al. (2000), we use only results from the I data for comparison of the two ions. However, we also fit the S iv lines from the X data to quantify the variability of the optical depth (Fig. 1). These profiles appear to have a stronger absorption, and

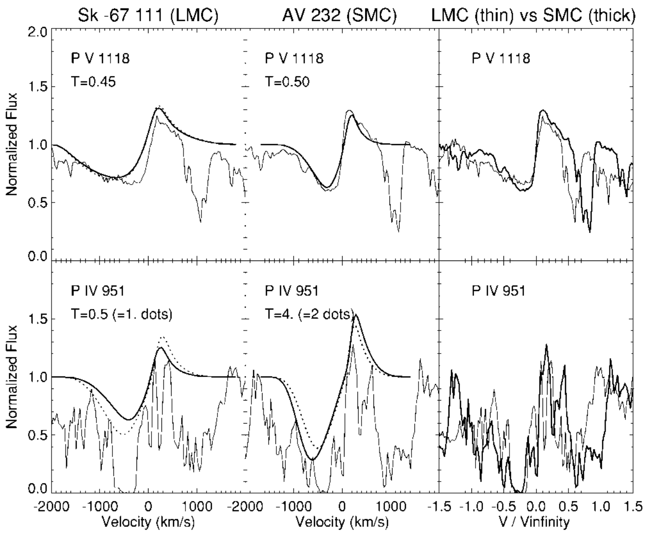

FIG. 2.—SEI fits of P V λ1117.98 and P IV λ950.66. The second is severely contaminated by interstellar absorptions. The solid and dotted lines show the range of allowable models given the interstellar contamination. Columns are as in Fig. 1.

smoother profile, than the I data. The S IV profiles in the I data show several narrow dips, possibly due to wind clumps. If the observed narrow dips are produced by strong inhomogeneities in the stellar wind, the column density would be higher than in the smooth fit (see Fig. 1 [*dotted model*] and Table 2).

The profiles of S VI λλ933.38, 944.52 are heavily absorbed by interstellar lines (molecular hydrogen in particular), which makes it difficult to identify good portions of the profile to model. Because the lines arise from the same multiplet, their optical depths should be in the ratio of their oscillator strengths, with all other model parameters (optical depth law, turbulence, and velocity law) being the same. By forcing the total optical depth to be in the ratio 2 : 1, we derived the best fits shown in Figure 1, where both S VI blue and red components are plotted, each in velocity scale relative to its appropriate rest wavelength. In this way it is easier to identify the bona fide (stellar) parts of each profile.

4. CONCLUSIONS

SEI profile fitting provides a direct measure of the total optical depth of each transition, which is proportional to the total column density of the ion in the wind (e.g., Bianchi et al. 1994). Our results thus yield the column density ratio of

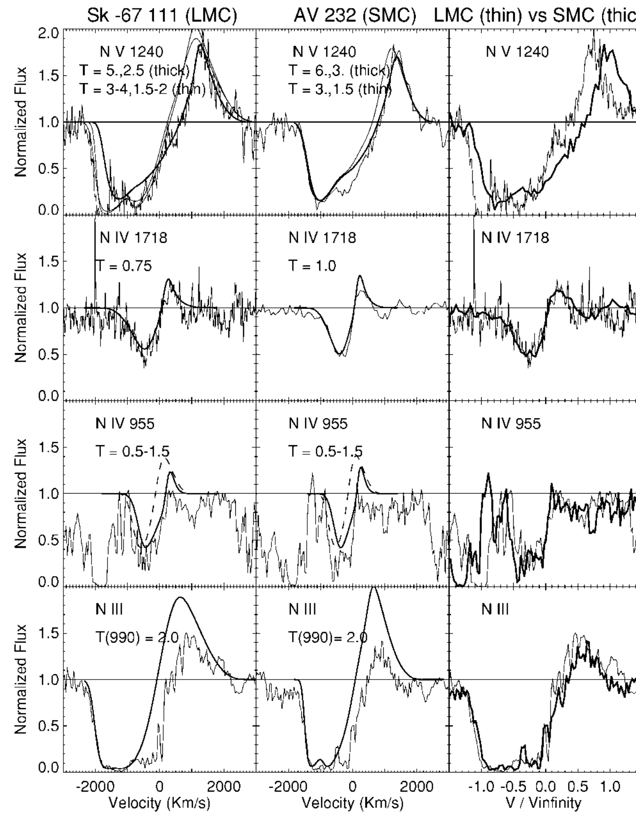

FIG. 3.—SEI fits of the nitrogen lines; columns as in Fig. 1. The top two lines are from *IUE* and FOS data (Sk −67°111 and AV 232, respectively); the FOS data have lower resolution and higher signal-to-noise ratio. The two bottom lines (N IV and N III) are from the *FUSE* data. Both N IV transitions are from an excited level. The N III feature contains two equally strong lines: λ989.799 from the ground state and λ991.577 from an excited level.

different ions of the same element, which can be used to constrain atmosphere and wind models. The results are given in Table 2. The ratios of N_i(S IV)/N_i(S VI) and N_i(P IV)/N_i(P V) are smaller in Sk −67°111 than in AV 232.

For small optical depths (≲2), the uncertainty from the model fit is small: an optical depth value different by ±0.05 would create a very obvious mismatch to the data. For some lines, a source of uncertainty is the location of the true stellar profile and local continuum, due to the strong interstellar absorptions in the *FUSE* range. To derive the uncertainties of the values quoted in Table 2, we varied all fit parameters within acceptable ranges, as well as the placement of the local continuum. Re-

TABLE 2
COLUMN DENSITIES FROM SEI LINE MODELING

Transition	Data	*f* Value	*f* Reference	Sk −67°111 *T*	Sk −67°111 N_i ($\times 10^{15}$ cm^{-2})	AV 232 *T*	AV 232 N_i ($\times 10^{15}$ cm^{-2})
S IV λ1062.664	*FUSE* X	0.0593	1	0.30 ± 0.05	3.2 ± 0.5	0.5 ± 0.05	4.2 ± 0.4
	FUSE I	0.0593	1	0.20 ± 0.05	2.2 ± 0.5[a]	0.3 ± 0.05	2.5 ± 0.4
S VI λ933.378	*FUSE* I	0.439	2	2.00 ± 0.10	3.3 ± 0.2	1.4 ± 0.1	1.8 ± 0.1
P IV λ950.657	*FUSE* I	1.56	3	0.75 ± 0.25	0.3 ± 0.1	3.0 ± 1.0	1.1 ± 0.4
P V λ1117.977	*FUSE* I	0.473	2	0.45 ± 0.05	0.6 ± 0.1	0.5 ± 0.05	0.5 ± 0.05
N III λ989.799	*FUSE* I	0.123	4	2.00 ± 0.50	11.1 ± 2.8	2.00 ± 0.50	8.7 ± 2.2
N IV* λ955.335	*FUSE* I	0.133	4	1.00 ± 0.50	5.3 ± 2.7	1.00 ± 0.50	4.2 ± 2.1
N IV* λ1718.551	*IUE*/FOS	0.171	4	0.75 ± 0.10	1.7 ± 0.2	1.00 ± 0.10	1.8 ± 0.2
N V λ1238.821	*IUE*/FOS	0.156	4	4.00 ± 1.00	14.0 ± 3.5	4.50 ± 1.50	12.3 ± 4.1

[a] Using *T* = 0.25, which includes the narrow absorption component, N_i(S IV) becomes 2.69 ± 0.54.

REFERENCES.—(1) Reistad & Engstrom 1989; (2) Morton 1991; (3) Froese-Fischer & Godefroid 1982; (4) Wiese, Fuhr, & Deters 1996.

gardless of the model results and their accuracy, a visual inspection of the line profiles normalized to the wind terminal velocities (see *right column*, Figs. 1–3) reveals a remarkable similarity between the two stars. It also reveals that in the LMC star S IV and P IV are weaker, S VI is stronger, and P V is in an intermediate situation, which suggests a correlation of the differences with the ionization potentials. These qualitative differences are quantified by the measurements of the column densities in Tables 2 and 3.

The SEI fits also yield a measurement of the wind terminal velocity. The best values from all the lines analyzed in this work are given in Table 1: $V_\infty = 1400$ km s^{-1} for AV 232 and $V_\infty = 1800$ km s^{-1} for Sk $-67°111$. The wind velocity derived by line fitting is more accurate than values estimated simply from the edge of the absorption, since microturbulence in the outflow is taken into account (a turbulence of $0.1V_\infty$ was found from our fits, which is typical for this type of star). Previous determinations of wind velocities from *IUE* spectra (e.g., Patriarchi & Perinotto 1992; $V_\infty = 2090 \pm 220$ km s^{-1} for Sk $-67°111$ and $V_\infty = 1410 \pm 200$ km s^{-1} for AV 232) are consistent with our results (noting that we have removed the intrinsic velocity of each star) and the respective uncertainties. Haser et al. (1994) found $V_\infty = 1400$ km s^{-1} for AV 232 from a similar SEI modeling of different lines.

In summary, we have measured column densities of S IV, S VI, P IV, P V, N III, N IV, and N V in the winds of two O7 supergiants in the LMC and SMC, respectively. The ratio between ions of sulfur and phosphorus is different in the two stars. This might be due to the different luminosity and/or different density in the wind, which can be expected if the mass-loss rates are different (because the metallicities are different). The wind reaches a significantly higher velocity in the LMC star, consistent with the globally different metallicity and with previous findings. However, the optical depth distribution of ions through the wind is qualitatively similar in the two stars, once the difference in velocity is removed (*right column*, Figs. 1–3). This work demonstrates the unique capability afforded by the *FUSE* data to further our knowledge of hot star winds. First, the ability to measure different ionization stages of the same element allows us to constrain the ionization in the wind, thus refining mass-loss and element abundance determinations, which we will pursue in more complete modeling. Second, while the strong wind lines in the *HST/IUE* range (beyond 1200 Å) are usually saturated and yield only lower limits to optical depth estimates, lines from less abundant elements in the *FUSE* range have low optical depth, which can be measured with much greater precision by model fitting (Table 2).

TABLE 3
MEASURED IONIZATION RATIOS

Ratio	Data	Sk $-67°111$	AV 232
N_i(S IV)/N_i(S VI)	*FUSE* I	0.65 ± 0.17[a]	1.39 ± 0.25
N_i(P IV)/N_i(P V)	*FUSE* I	0.59 ± 0.21	2.14 ± 0.74
N_i(N III)/N_i(N IV*)	*FUSE* I	2.09 ± 1.17	2.09 ± 1.17
N_i(N IV*)/N_i(N V)	*IUE*/FOS	0.12 ± 0.03	0.15 ± 0.05

[a] Using $T = 0.25$, which includes the narrow absorption component, N_i(S IV)/N_i(S VI) = 0.81 ± 0.17.

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