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FAR ULTRAVIOLET SPECTROSCOPIC EXPLORER OBSERVATIONS OF THE STELLAR WINDS OF TWO O7 SUPERGIANTS IN THE MAGELLANIC CLOUDS

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ABSTRACT

We compare the stellar wind features in far-UV spectra of Sk −67°111, an O7 Ib(f) star in the LMC, with Sk 80, an O7 Iaf+ star in the SMC. The most striking differences are that Sk 80 has a substantially lower terminal velocity, much weaker O VI absorption, and stronger S IV emission. We have used line-blanketed, hydrodynamic, non-LTE atmospheric models to explore the origin of these differences. The far-UV spectra require systematically lower stellar temperatures than previous determinations for O7 supergiants derived from plane-parallel, hydrostatic models of photospheric line profiles. At these temperatures, the O VI in Sk −67°111 must be due primarily to shocks in the wind.

Subject headings: stars: early-type — stars: individual (Sk −67°111, Sk 80) — stars: winds, outflows

1. INTRODUCTION

The resonance lines of ionized metals are sensitive indicators of the stellar winds of OB stars, which are rarefied environments characterized by low degrees of excitation. Accessible transitions fall in the ultraviolet (UV) and far-ultraviolet (FUV) regions, where they create distinctive P Cygni profiles by scattering UV continuum photons. However, the species available to *IUE* and *Hubble Space Telescope* (*HST*)—C IV, N V, and Si IV—are not good estimators of the mass-loss rate. Unsaturated lines are usually from trace ions (e.g., Si IV), so their interpretation depends on the details of the physics used to model them. Although C IV is a dominant ion over most of the OB star domain, carbon is so abundant that the line is usually saturated and only provides a lower limit on the mass flux. Consequently, the most reliable mass-loss estimates to date come from intrinsically weaker wind diagnostics like Hα or free-free emission.

The wealth of resonance lines available in the FUV helps to overcome these problems, since they include diagnostics of abundant and rare elements that sample a wide range of ionization potential, including dominant (e.g., P V) and trace (e.g., C III) ionic species and multiple ionization stages (e.g., S IV/S VI; P IV/P V). Previous work with the *Copernicus* satellite concentrated on early-type stars in the Galaxy, many of which are severely affected by interstellar absorption (e.g., Snow & Morton 1976; Walborn & Bohlin 1996). More recent FUV spectra of targets in the Galaxy and the Magellanic Clouds were obtained by the Hopkins Ultraviolet Telescope (HUT; see, e.g., Walborn et al. 1995b) and the Berkeley spectrometer on the *Orbiting and Retrievable Far and Extreme Ultraviolet Spectrometer* (*ORFEUS*) missions (e.g., Taresch et al. 1997). The launch of the *Far Ultraviolet Spectroscopic Explorer* (*FUSE*; Moos et al. 2000) revives the possibility of using resonance lines to determine mass-loss rates for many Galactic and extragalactic OB stars.

In this Letter, we compare *FUSE* spectra of a pair of O7 supergiants, one in each Magellanic Cloud, and use non-LTE, line-blanketed model atmospheres to interpret the differences. The UV spectrum of the target in the LMC, Sk −67°111, was analyzed by Patriarchi & Perinotto (1992), but otherwise this star has received little attention. In contrast, Sk 80 (=AV 232) is a well-studied object situated on the edge of the giant H II region NGC 346 in the SMC. Its UV/optical spectrum has been discussed by Walborn et al. (1995a), and a HUT spectrum is described by Walborn et al. (1995b). Basic observational quantities for both targets are listed in Table 1.

2. OBSERVATIONS

Spectra of Sk −67°111 and Sk 80 were obtained in 1999 September as part of the *FUSE* Early Release Observation program and again in 1999 October during mirror alignment tests. These observations were made in time-tag mode through the 30″ × 30″ (LWRS) aperture (see Moos et al. 2000) and are characterized by spectral resolution of 12,000–15,000 (Sahnow et al. 2000). Since alignment of the four spectrograph channels was not maintained, the number of channels contributing to the final spectrum and the effective exposure times vary with wavelength. The effective exposure time per channel ranges from 2.7 to 4.9 ks for Sk −67°111 and 1.2 to 4.9 ks for Sk 80 and results in measured signal-to-noise ratios of 15–20 per resolution element. The spectra were processed to remove telescope motions during the alignment tests, collapsed in the spatial dimension, and calibrated in flux and wavelength. Model fits to the interstellar H_2 spectrum (see Shull et al. 2000) were used to improve the wavelength scale before resampling the spectra to a constant wavelength step of 0.13 Å.

The calibrated spectra are shown in Figure 1, along with identifications of important stellar features and the model of the interstellar H_2 spectrum for Sk −67°111. Figure 1 also

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TABLE 1
Target Stars

Object	Galaxy	Spectral Type	V	$E(B-V)$	M_V[a]	v_∞ (km s^{-1})	$T_{\rm eff}$ (K)	R_* ($R_\odot$)	log g	log ($L/L_\odot$)	log $\dot{M}$ ($M_\odot$ yr^{-1})
Sk −67°111	LMC	O7 Ib(f)[b]	12.57	0.09[c]	−6.3	1800 ± 100[d]	33,000	22	3.3	5.7	−5.7
Sk 80	SMC	O7 Iaf+[e]	12.36	0.08[c]	−6.8	1400 ± 100[d]	32,000, 37,500[f]	29, 29.3[f]	3.1, 3.3[f]	5.9, 6.2[f]	−5.3, −5.3[f]

[a] Derived assuming distance moduli of 18.5 and 18.9 for the LMC and SMC, respectively (Westerlund 1997).
[b] From Fitzpatrick 1988.
[c] Value taken from this work.
[d] From Bianchi et al. 2000.
[e] From Walborn 1977.
[f] The second value is from Puls et al. 1996.

compares the *FUSE* spectrum of Sk 80 with spectra obtained by HUT during the Astro-2 mission (Walborn et al. 1995b) and the Berkeley spectrograph during the *ORFEUS-SPAS II* mission (Hurwitz et al. 1998). This comparison emphasizes the extremely low background of the *FUSE* detectors, the reliability of the preliminary flux and wavelength calibrations, and the advantages of high spectral resolution for disentangling interstellar absorptions from stellar features.

3. COMPARISON OF WIND LINES

Two morphological differences between Sk −67°111 and Sk 80 are conspicuous in Figure 1. First, the S IV emission is much stronger in Sk 80. Since Sk 80 is substantially more luminous than Sk −67°111, this difference is likely attributable to the luminosity sensitivity exhibited by these lines (Walborn & Bohlin 1996). Second, O VI is barely present in the wind of Sk 80: no emission is visible, and only weak absorptions are detectable at the positions corresponding to the terminal velocity (v_∞). In contrast, the spectrum of Sk −67°111 exhibits a well-formed O VI P Cygni profile.

Otherwise, the most important difference between the wind lines in these stars is the smaller v_∞ exhibited by Sk 80 (see also Bianchi et al. 2000). The theory of line-driven stellar winds predicts that v_∞ should decrease with decreasing metallicity (Kudritzki et al. 1989). Previous studies with *IUE* and *HST* have shown that stars in the SMC follow this trend (see, e.g., Garmany & Fitzpatrick 1988; Prinja & Crowther 1998). After allowing for this systematic difference in breadth, the absorption and emission strengths of the P Cygni profiles are surprisingly similar, despite the substantially lower metal abun-

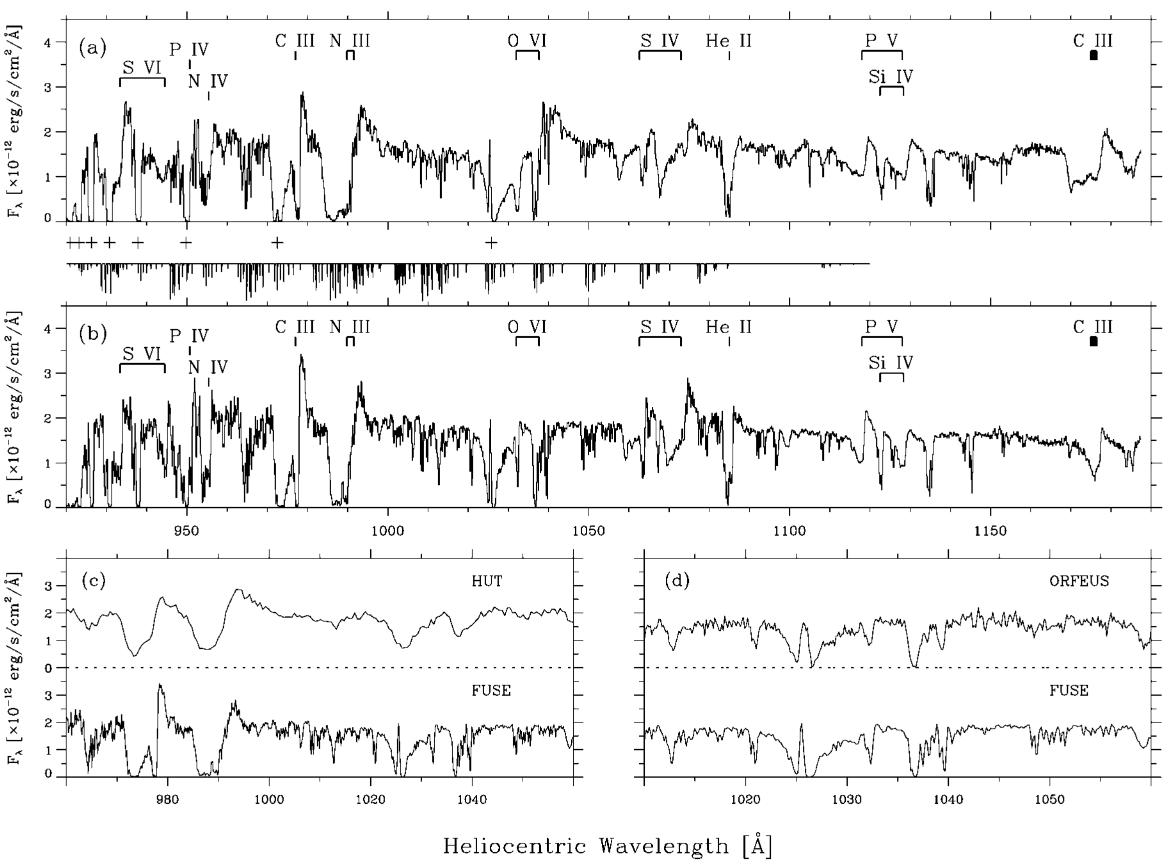

Fig. 1.—(*a*) Calibrated *FUSE* spectrum of Sk −67°111. Rest wavelengths of important stellar transitions are shown. The locations and strengths of interstellar H_2 lines are indicated between panels (*a*) and (*b*); crosses mark the positions of the Lyman series of H I. (*b*) Same as (*a*), but for Sk 80. (*c*) Comparison of spectra of Sk 80 obtained by HUT and *FUSE*. (*d*) Comparison of spectra of Sk 80 obtained by *ORFEUS* and *FUSE*.

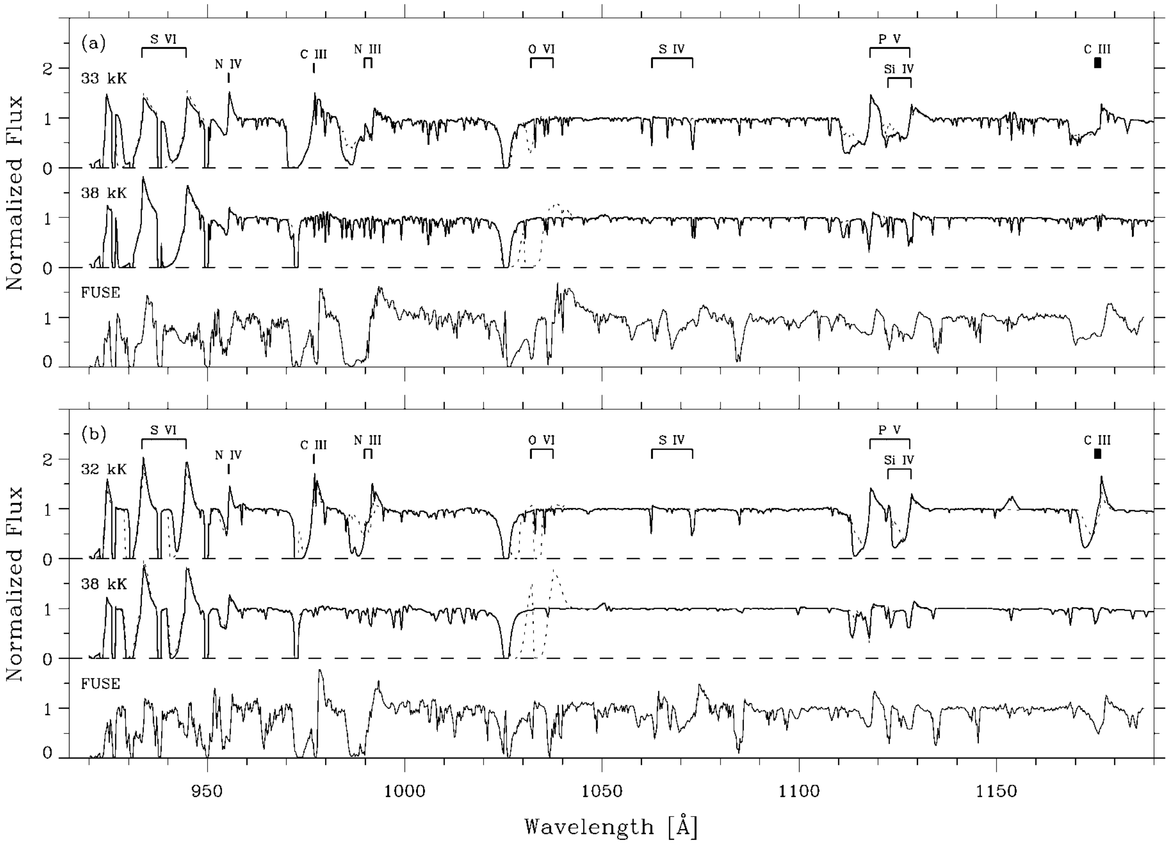

FIG. 2.—(*a*) Comparison between *FUSE* observations and synthetic spectra for Sk −67°111. The computed spectra are labeled by the $T_{\rm eff}$ of the model; dashed lines indicate the spectrum when the effects of shocks are included. Absorption by a column density of 10^{21} cm^{-2} of H I has been included in the models. (*b*) Same as (*a*), but for Sk 80.

dances typical of the SMC. Some, but not all, of the differences in profile shape are due to blends with stellar or interstellar features.

4. MODELING THE SPECTRAL MORPHOLOGY

As a first step toward understanding the origin of these morphological differences, we used the program WM-BASIC (v.1.13; A. W. A. Pauldrach, T. L. Hoffmann, & M. Lennon 2000, in preparation) to compute synthetic spectra for both targets. This program solves the hydrodynamic wind equations for specified stellar parameters; incorporates non-LTE metal line blanketing in spherical, expanding geometry; and permits the effects of strong shocks in the wind to be incorporated in the radiative transfer calculations.

We initially adopted $T_{\rm eff}$ = 38,000 K for both stars, which is the mean value for three O7 supergiants (including Sk 80) determined by Puls et al. (1996) from non-LTE modeling of photospheric lines in the plane-parallel, hydrostatic approximation. Their results for two O7 Ib stars were used to estimate log g = 3.45 for Sk −67°111, while their determination of log g = 3.30 was used for Sk 80. We adopted He/H = 0.10 by number for both stars and fixed the metal abundances at 0.4 and 0.2 $Z_\odot$ for Sk −67°111 and Sk 80, respectively. Stellar radii were determined by requiring that the model fluxes reproduce the dereddened energy distribution of each star. By using reddening laws for the Galactic foreground (Seaton 1979) and Magellanic Cloud components (Howarth 1983; Bouchet et al. 1985), we derived foreground reddening of $E(B-V)$ = 0.04 and 0.03 for Sk −67°111 and Sk 80, respectively, and internal reddenings of 0.05 for both galaxies along these sight lines. Although the total reddenings are low, they are consistent with the H I column densities of 10^{21} cm^{-2} derived for these stars from fits to the absorption wings of Lyα and Lyβ (e.g., Koornneef 1982; Fitzpatrick 1985).

For the adopted $T_{\rm eff}$, log g, and radius, depth-independent wind force multipliers (α, k, δ) were selected for WM-BASIC such that the observed values of v_∞ (Table 1) were reproduced. We also required that the mass-loss rate be approximately correct. For Sk 80, we matched the peak intensity of the Hα emission profile published by Puls et al. (1996). Since we are not aware of any Hα observations of Sk −67°111, we used the fact that its He II λ4686 is filled in [as implied by its "(f)" classification] to constrain its mass-loss rate.

Figure 2 compares the *FUSE* spectra of the targets with synthetic spectra computed for $T_{\rm eff}$ = 38,000 K. The models do not reproduce the dominant wind features in the FUV spectra of these stars. In particular, they do not predict the occurrence of C III, N III, or S IV to any significant degree. The absence of these ions implies that the initial wind models are too hot. We therefore computed cooler models characterized by $T_{\rm eff}$ = 33,000 and 32,000 K for Sk −67°111 and Sk 80, respectively. The synthetic spectra from these models are also shown in Figure 2. As expected, the cooler temperatures improve the correspondence between the appearance of the C III and N III lines and produce only minor changes in the S VI resonance lines. Although the agreement is much better, the cooler models predict P V profiles that are too strong and S IV lines that are much weaker than observed.

Neither model predicts the occurrence of O VI in the wind of Sk −67°111. To explore possible mechanisms for the production of this ion, we incorporated the extreme-UV radiation field due to strong shocks, which could be caused by the line-driven instability or the presence of other time-dependent structures in the wind (see, e.g., Owocki, Castor, & Rybicki 1988). We used the characterization of shock phenomena implemented in WM-BASIC with assumed input parameters of $L_X/L_{bol} \sim 10^{-7}$ (Chlebowski, Harnden, & Sciortino 1989) and $v_{turb}/v_\infty = 0.12$. Synthetic spectra from these models are included in Figure 2 as dotted lines. As expected, the presence of shocks increases the strength of the O VI lines in all models. At the cooler T_{eff}, the shocks also decrease the strength of N III and P V substantially. The strength of the O VI emission lobe of Sk −67°111 is not reproduced at T_{eff} = 33,000 K.

Although the modeling is still preliminary, it is clear that models with $T_{eff} \sim 32{,}000$ K are better matches to the *FUSE* spectra of Sk −67°111 and Sk 80 than models with $T_{eff} \sim 38{,}000$ K. Provisional values for the parameters of the cooler models are listed in Table 1. Even though O stars in the SMC are predicted to have weaker winds than their counterparts in the LMC, the models suggest that the mass-loss rate of Sk 80 exceeds the rate of Sk −67°111 by a factor of ∼3. Evidently the greater luminosity of Sk 80 more than offsets any reduction in radiative driving due to reduced metallicity. Although we have not yet computed model grids for different abundances of C and N that might arise from rotational mixing of CNO-cycled material into the atmosphere (Venn 1999), test calculations indicated that improved fits to the N III resonance line produce worse matches in the C III lines, since N enrichment is accompanied by C depletion.

5. DISCUSSION

The *FUSE* observations of Sk −67°111 and Sk 80 represent both a challenge to state-of-the-art model atmospheres and a unique opportunity to probe the physics of hot-star winds. We have identified two specific problems.

First, initial analysis of the FUV spectra suggests that the temperatures of both stars are lower than the values derived from fits to photospheric lines by $\Delta T \approx -5000$ K. Crowther & Bohannan (1997) also found much cooler temperatures (by ∼8000 K) from their analysis of the optical wind lines of two Galactic O8 supergiants. Thus, the currently adopted temperatures for late O supergiants may be systematically too high. Since Herrero, Puls, & Villamariz (2000) found that fits to Galactic O6 stars made with unified model atmospheres require lower temperatures than previous analyses (by 3000 and 4500 K for a dwarf and supergiant, respectively), at least part of this discrepancy may be attributed to the inadequacies of plane-parallel model atmospheres.

Second, even line-blanketed wind models with T_{eff} = 38,000 K do not predict that much O VI is present in the spectra of O7 supergiants. Instead, the strong O VI P Cygni profile exhibited by Sk −67°111 must be due to the presence of shocks from time-dependent structures in the wind. Pauldrach et al. (1994) and Taresch et al. (1997) reached the same conclusion from their analyses of the FUV and UV spectra of hotter O supergiants. The absence of a comparable O VI feature in Sk 80 is puzzling: is it a direct consequence of the reduced metal abundance, or are the shocks intrinsically weaker in Sk 80 because the wind velocities are smaller?

FUSE will observe a large sample of OB stars in the Milky Way, LMC, and SMC in order to address these and other issues. A variety of complementary analysis techniques will be used to interpret these data, which will be combined with archival *IUE*, *HST*, and optical data whenever possible. We anticipate that this work will return qualitatively new information about the properties of line-driven stellar winds.

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