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SPITZER SPACE TELESCOPE INFRARED SPECTROGRAPH (IRS) SPECTROSCOPY OF THE PROTOTYPE WOLF-RAYET STAR EZ CANIS MAJORIS (HD 50896)

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ABSTRACT

We present mid-infrared *Spitzer Space Telescope* Infrared Spectrograph (IRS) spectroscopy of the prototype WN star EZ Canis Majoris (HD 50896, WN4b). Numerous stellar wind lines of He II are revealed, plus fine-structure lines of [Ne III] 15.5 μm and [O IV] 25.9 μm. We carry out a spectroscopic analysis of HD 50896 allowing for line blanketing and clumping, which is compared to the mid-IR observations. We make use of these stellar properties to accurately derive Ne/He = $(1.2\text{–}1.8) \times 10^{-4}$ and O/He = $(4.2\text{–}4.8) \times 10^{-5}$ by number, for the first time in an early WN star. In addition, we obtain N/C ~ 40 and N/O ~ 50 by number, in perfect agreement with current predictions for rotating massive stars at the end of interior hydrogen burning.

Subject headings: infrared: stars — stars: atmospheres — stars: individual (HD 50896) — techniques: spectroscopic

1. INTRODUCTION

Wolf-Rayet (W-R) stars are descended from the most massive O stars ($M_{\rm init} > 25\ M_\odot$), and shed core-processed material in thick, line-driven winds at such prodigious rates (typically 10^{-5}–$10^{-4}\ M_\odot\ {\rm yr}^{-1}$) as to affect the evolution of the core and thus the lifetime of the star, prior to ending in a supernova explosion (Meynet & Maeder 2003). The prototype Wolf-Rayet star EZ CMa (HD 50896 = WR 6 in the catalog of van der Hucht 2001) has been studied extensively at nearly all wavelengths accessible with ground-based facilities and space observatories to understand the extreme stellar wind properties of these rare massive stars and how they interact with their local environment.

At infrared wavelengths, the continuum opacity is principally determined by free-free scattering of electrons from helium ions, and the emergent radiation originates in the outer layers of the wind where the asymptotic velocity is reached (e.g., Hillier et al. 1983). These layers are also where critical electron densities and temperatures are reached to form fine-structure lines of Ne, O, S, and other elements, that are instrumental in testing evolutionary model predictions of the surface abundances during different core burning stages.

Elemental abundances obtained from the fine-structure lines depend on the stellar parameters, particularly the mass-loss rate, which is sensitive to the degree of clumping in the wind. The role played by mid-infrared spectra, in conjunction with UV, optical, and near-IR spectroscopy, has been demonstrated for a few WN and WC stars observed with the Short Wavelength Spectrometer (SWS) on board the *Infrared Space Observatory* (*ISO*) (Morris et al. 2000; Dessart et al. 2000). Only the brightest W-R stars could be observed with the SWS, for sensitivity reasons, and observations of only five W-R stars produced spectra of suitable quality for modeling beyond 4.5 μm.

In this paper we present *Spitzer Space Telescope* Infrared Spectrograph[4] (IRS) spectra of the prototype early WN star EZ CMa. We carry out an analysis of the ultraviolet to mid-IR spectroscopy, revealing stellar and wind parameters, with which Ne/He and O/He abundance ratios are determined. Comparisons with theoretical expectations are presented.

2. OBSERVATIONS

EZ CMa was observed with the *Spitzer* IRS (described by Houck et al. 2004) on 2003 November 11, during the Science Verification phase, using all four of the IRS modules. The data were acquired with the spectral mapping AOT, with the star observed at three to five discrete positions along the lengths (cross-dispersed axes) of the slits. The 10–37.5 μm data presented in this paper are from the Short-High and Long-High (SH and LH) resolution modules ($R \equiv \lambda/\Delta\lambda \simeq 700$), and 5.3–10 μm data are from the Short-Low (SL) module ($R \sim 70\text{–}120$), using exposure times that should produce continuum signal-to-noise (S/N) ratios of around 100 in the high-resolution spectra, and 200–250 in the low-resolution spectra. The basic calibrations were automatically carried out in the *Spitzer* Science Center (SSC) pipeline, version S9.5, and then spectra were extracted and co-added interactively, using the offline pipeline.

Our analysis also makes use of archival *ISO* SWS spectra, optical spectrophotometry from Torres-Dodgen & Massey (1988), high-resolution *International Ultraviolet Explorer* (*IUE*) ultraviolet spectrophotometry from Howarth & Phillips (1986), plus Hopkins Ultraviolet Telescope (HUT) far-ultraviolet spectrophotometry (Schulte-Ladbeck et al. 1995). The unpublished SWS 2.4–4.2 μm spectroscopy of EZ CMa was obtained from the public archive, processed to the Auto Analysis Result. Further reduction to a single spectrum was carried out interactively, using SWS Interactive Analysis routines. Continuum

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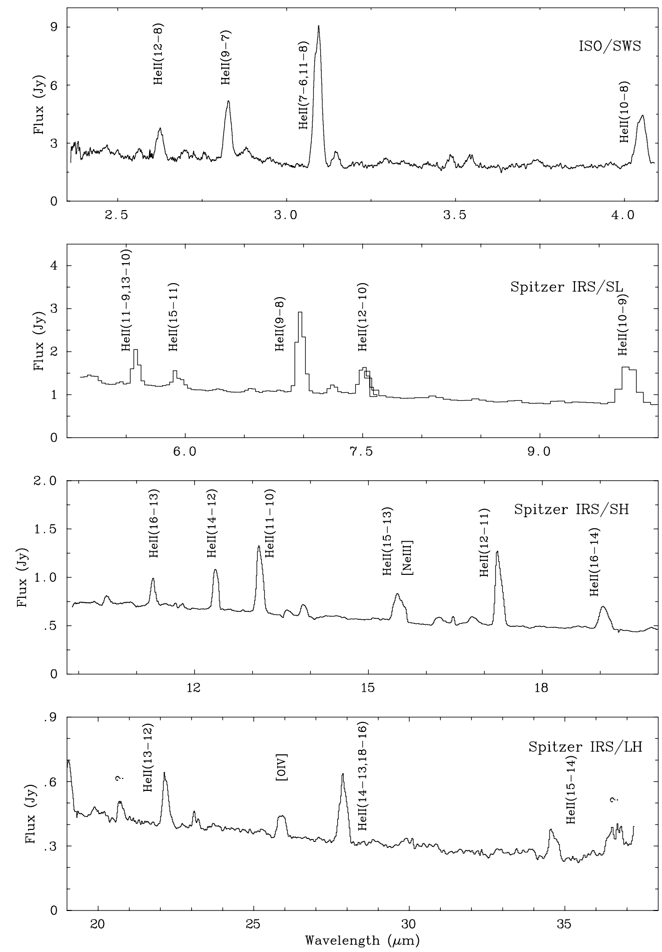

Fig. 1.—Mid-IR spectroscopy of EZ CMa (HD 50896) from *ISO* SWS and *Spitzer* IRS with the principal lines identified.

S/N ratios are around 50 in these data. Low-resolution near-IR spectroscopy of HD 50896 has previously been discussed by Hillier et al. (1983). We additionally use high-dispersion spectroscopy of HD 50896 obtained with the ESO 3.6 m Cassegrain echelle spectrograph (CASPEC), previously presented by Schmutz (1997). We adopted a distance of 1.8 kpc to HD 50896 (Howarth & Schmutz 1995), interstellar reddening of $E(B-V)=0.1$ mag (the mean from Schmutz & Vacca 1991, van der Hucht 2001), and an atomic hydrogen column density of $\log(N_{\rm H\,I})=20.7$ cm^{-2} (Howarth & Phillips 1986).

The *Spitzer* IRS and *ISO* SWS spectroscopy of EZ CMa are presented in Figure 1 together with identifications of the principal wind features. The majority of mid-IR spectral features are due to wind lines of He II, primarily the leading member in each series from He II (7–6) at 3.09 μm to (15–14) at 34.6 μm. In addition to these, we observe fine-structure lines of [O IV] 25.9 μm and [Ne III] 15.5 μm, the latter blended with He II 15.47 μm (15–13). There is no evidence for [S IV] 10.5 μm in HD 50896. The observed feature is well reproduced by a weak blend of He II 10.46 μm (21–15) and 10.50 μm (24–16) in our synthetic spectrum.

3. SPECTROSCOPIC ANALYSIS OF HD 50896

3.1. *Technique*

To date, the majority of spectroscopic analyses of WN stars have been carried out using non-LTE models that did not account for metal line blanketing or clumping (e.g., Crowther et al. 1995, Hamann et al. 1995). In only a few cases have clumped, metal line blanketed models been applied to individual stars (e.g., Schmutz 1997; Morris et al. 2000; Dessart et al. 2000; Herald et al. 2001). Such effects need to be taken into account in order to determine the fundamental parameters of W-R stars (Crowther 2003).

For the present study of HD 50896, we employ CMFGEN (Hillier & Miller 1998), which solves the transfer equation in the comoving frame subject to statistical and radiative equilibrium, assuming an expanding, spherically symmetric, homogeneous, and static atmosphere, allowing for line blanketing and clumping. The stellar radius (R_*) is defined as the inner boundary of the model atmosphere and is located at Rosseland optical depth of $\sim$20 with the stellar temperature (T_*) defined by the usual Stefan-Boltzmann relation. Consequently, the stellar radius is much smaller than the radius of $\tau=1$, such that the temperature depends directly on the assumed velocity law.

Our approach follows previous studies (e.g., Crowther et al. 1995), such that diagnostic optical lines of He I (λ5876), He II (λ4686), plus the local continuum level allow a determination of the stellar temperature, mass-loss rate, and luminosity. We were unable to employ solely mid-IR diagnostics since the IRS spectrum of HD 50896 is dominated by lines of He II, with He I weak or blended.

Our final model atom contains H, He, C, N, O, Ne, Mg, Si, P, S, Cl, Ar, Ca, Cr, Mn, Fe, and Ni. In total, 1186 super levels, 4462 full levels, and 45,485 non-LTE transitions are simultaneously considered. We assume hydrogen is absent, such that helium makes up 98% of the atmosphere. CNO abundances are varied until an optimal fit is achieved. In contrast with nitrogen and carbon, the abundance of oxygen in WN stars has proven to be rather challenging (Hillier 1988). The reason is that oxygen has a much more complicated ionization stratification in their inner winds, plus diagnostic lines are located in rather observationally inaccessible regions, typically 2800–3400 Å. Consequently, we set oxygen (and neon) abundances from the fine-structure analysis. Other elements are fixed at solar values (Grevesse & Sauval 1998; Asplund et al. 2004).

We adopt a standard form of the velocity law, $v(r)=v_\infty(1-R_*/r)^\beta$, where $\beta=1$. In contrast, Schmutz (1997) solved the hydrodynamical equation for outer wind and obtained $\beta\sim3$ with reference to the core radius. A terminal wind velocity, v_∞, of 1860 km s^{-1} is obtained from the mid-IR fine-structure line of [O IV] 25.9 μm. For comparison, Prinja et al. (1990) obtained 1720 km s^{-1} from UV observations of the P Cygni C IV λ1550 line, while Schmutz (1997) derived 2060 km s^{-1} from a fit to He I 1.083 μm.

The mass-loss rate is actually derived as the ratio $\dot{M}/\sqrt{f}$, where f is the volume filling factor that can be constrained by fits to the electron scattering wings of the helium line profiles (following Hillier 1991). We conclude that $f\sim0.1$ and can definitely exclude homogeneous mass-loss in HD 50896. In addition, the mid-IR continuum slope also reacts to different filling factors.

3.2. *Spectroscopic Results*

We compare our synthetic model with far-UV, near-UV, optical, near-IR, and mid-IR spectrophotometry [dereddened by $E(B-V)=0.10$ mag] in Figure 2. Overall, the agreement between the spectral features and continuum is excellent from 0.09 to 37 μm, with few major exceptions. For helium, all lines are reproduced better than 20%, with the exception of a few mid-IR lines, namely He II 3.091 μm (7–6), 13.12 μm (11–10), and 22.17 μm (13–12). Since fine-structure lines are not

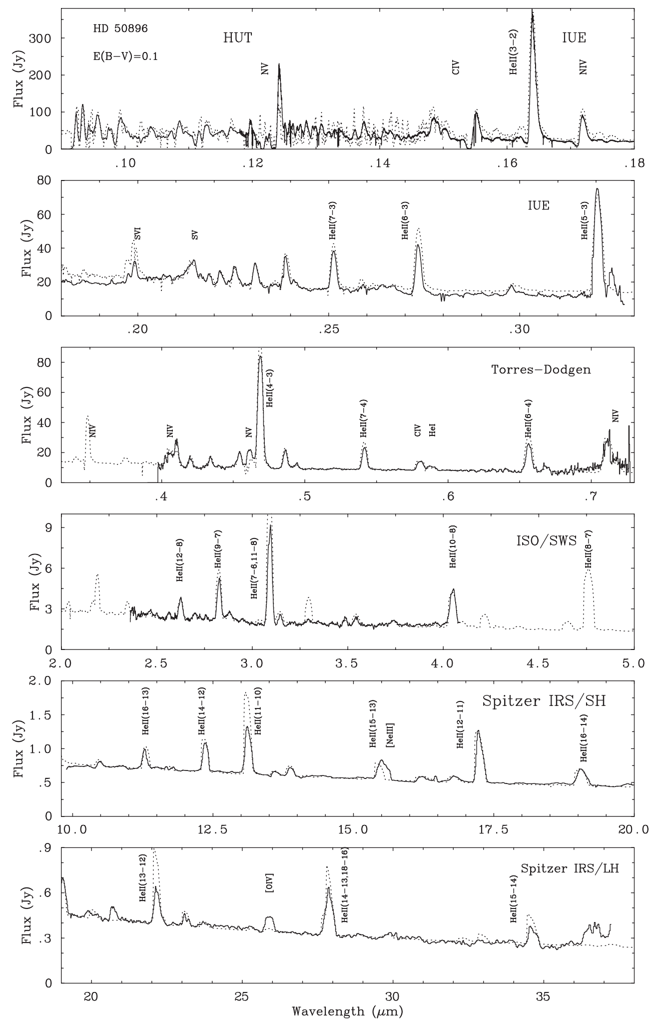

FIG. 2.—Comparison between dereddened far-UV (HUT), UV (*IUE*), optical (Torres-Dodgen & Massey 1988), near-IR (*ISO*), and mid-IR (*Spitzer*) spectrophotometry of EZ CMa with our synthetic model (*dotted lines*), corrected for interstellar atomic hydrogen with $\log N(\mathrm{H\ I}) = 20.7\ \mathrm{cm}^{-2}$ (Howarth & Phillips 1986). Note that the predictions from our non-LTE analysis are included here, such that specifically the fine-structure lines are not synthesized.

included in our synthetic spectrum, it is apparent that [Ne III] is a nonnegligible contributor to the 15.5 μm feature, the 25.9 μm line is dominated by [O IV], and there is no obvious identification for the lines at 20.7 or 36.6 μm (the latter is not [Ne III] 36.01 μm).

The stellar parameters derived for the WN4b star are presented in Table 1. We estimate elemental abundances of $\mathrm{N/He} = 2 \times 10^{-3}$ and $\mathrm{C/He} = 5 \times 10^{-5}$ by number. Hillier (1988) previously estimated $\mathrm{N/He} \leq 4 \times 10^{-3}$, $\mathrm{N/C} \sim 14$ and $\mathrm{O/N} \leq 3$ for EZ CMa, the only previous study to attempt CNO abundance determinations.

The only recent study of EZ CMa allowing for blanketing and wind clumping was by Schmutz (1997), whose results we also include in Table 1. Schmutz (1997) approached the incorporation of line blanketing in a different manner from the present approach. A Monte Carlo sampling technique was adopted, allowing for the effect of a much more thorough line opacity at the expense of full consistency in the radiative transfer problem, via the use of approximate ionization and excitation for metal species.

In addition, Schmutz adopted a He II Lyα λ303 photon loss mechanism with a particular parameter. Such a mechanism is intrinsic to the present analysis without the requirement of a parameterization, providing spectral lines adjacent to He II λ303.78 are accounted for in the calculation. Consequently, the following metal lines within $\sim$100 km s^{-1} of Lyα are included—O III λ303.70, 303.80, Fe VI λ303.70, 303.80, Ni VI λ303.71, Mn VI λ303.72, Ca V λ303.74, Cr V λ303.82, Cr VI λ303.84, and Fe V λ303.91.

Agreement between the two approaches is reasonable, given the differences in approach and choice of diagnostics. In both solutions, stellar luminosities (and hence bolometric corrections) are significantly higher than previous non-LTE studies (e.g., Hamann et al. 1995), although Schmutz (1997) obtained a rather higher bolometric luminosity, due to a combination of his photon loss mechanism and more complete line opacity, while clumping corrected mass-loss rates are much lower. Consequently, the derived momentum ratio is found to be $\dot{M}v_\infty/(L/c) = 7$, versus 30–70 in earlier studies. The agreement in mass-loss rate is consistent with the claimed precision of 0.1 dex achieved by Schmutz (1997), of relevance to the determination of elemental abundances to follow.

3.3. *Elemental Abundances: Neon and Oxygen*

We present the fine-structure lines of [Ne III] 15.5 μm and [O IV] 25.9 μm in Figure 3, including the predicted fractional contributions from [Ne III] and [O IV] (*dotted lines*) obtained from, respectively, the red line profile of [Ne III], which does not overlap with He II (15–13), and the non-LTE predicted He II (23–19) strength. The observed line fluxes of each blend is presented in Table 2. Sources of atomic data are given in Dessart et al. (2000) for [Ne III], and Hayes & Nussbaumer (1983) and Blum & Pradhan (1992) for [O IV]. We have determined elemental abundances for these ions using the numerical techniques introduced by Barlow et al. (1988), and adapted to account for a clumped wind by Dessart et al. (2000) and Morris et al. (2000). With regard to clumping, we admit that the volume filling factor in the outer wind may be considerably different than that derived from optical and near-IR recombination lines (Runacres & Owocki 2002).

TABLE 1

COMPARISON OF STELLAR PARAMETERS FOR EZ CANIS MAJORIS

Analysis	T_* (kK)	R_* ($R_\odot$)	$\log L_*$ ($L_\odot$)	$\log (\dot{M}/\sqrt{f})$ ($M_\odot$ yr^{-1})	f	β	v_∞ (km s^{-1})	M_v (mag)
Model	85	2.9	5.58	−4.0	0.10	1	1860	−4.6
Schmutz (1997)	84	3.5	5.74	−3.9	0.06	~3	2060	−4.6

NOTES.—This table shows a comparison of stellar parameters for EZ CMa (HD 50896, WN4b) derived here (labeled "Model") with those determined previously by Schmutz (1997), allowing for the clumped nature of the wind in each case with a volume-filling factor of *f*.

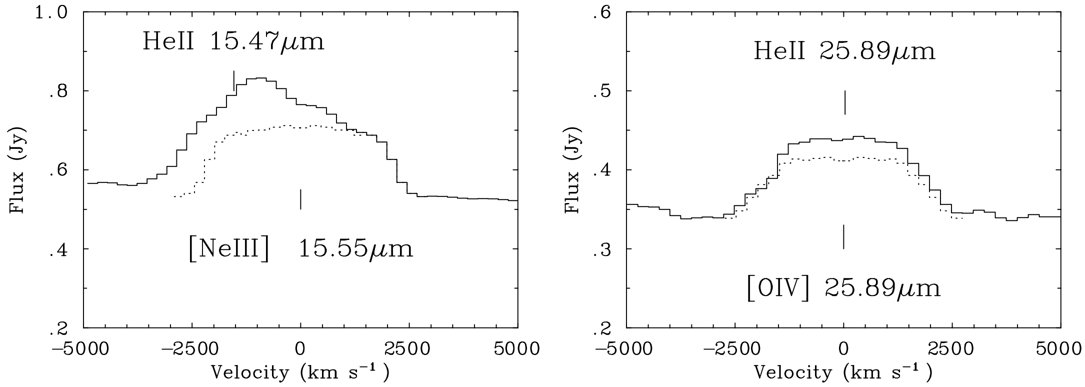

FIG. 3.—Mid-IR fine-structure lines comprising [Ne III] 15.55 μm and [O IV] 25.9 μm observed in the *Spitzer* IRS observations of EZ CMa, together with the predicted fractional contribution from the fine-structure lines (*dotted lines*) themselves (see text).

The numerical expression for the ion number fraction, γ_i, in a clumped medium (with volume filling factor f) is (in cgs units)

$$\gamma_i = \frac{(4\pi\mu m_{\rm H} v_\infty)^{1.5}}{\ln(10) f^{0.25}} \left(\frac{\sqrt{f}}{\dot{M}}\right)^{1.5} \frac{1}{F_u(T)} \frac{2D^2 I_{ul}}{\sqrt{\gamma_e} A_{ul} h\nu_{ul}}, \quad (1)$$

where D is the stellar distance, I_{ul} is the line flux of the transition with energy $h\nu_{ul}$ between upper level u and lower level l, with transition probability A_{ul}. The quantities γ_e (=1.008) and T_e (=14,000 K) are the electron number density and temperature in the line-forming region, and the mean molecular weight is μ (=4.04) for EZ CMa, with $m_{\rm H}$ the mass of the hydrogen atom. The integral part, $F_u(T)$, is

$$F_u(T) = \int_0^\infty \frac{f_u(N_e, T)}{\sqrt{N_e}} d\log(N_e), \quad (2)$$

where f_u is the fractional population of the upper level.

Following this technique, we derive $Ne^{2+}/He = 1.2 \times 10^{-4}$ and $O^{3+}/He = 4.2 \times 10^{-5}$ by number, *assuming* a fractional contribution of 67% and 85% to the observed 15.5 and 25.9 μm lines, respectively. If we were to neglect the predicted He II contribution to the observed spectral features, we would obtain $Ne^{2+}/He = 1.8 \times 10^{-4}$ and $O^{3+}/He = 4.8 \times 10^{-5}$ from this method. Applying the same technique based on the Schmutz (1997) spectroscopic results, we would derive slightly lower abundances of $Ne^{2+}/He = (1.1\text{–}1.4) \times 10^{-4}$ and $O^{3+}/He = (3.5\text{–}4.1) \times 10^{-5}$.

Of course, one needs to account for potential contributions from unseen ionization stages. Our model atmosphere identifies the following dominant ions at the outer model radius of $\sim 200 R_*$, where $\log(n_e/\text{cm}^3) \sim 9$, namely He^+, C^{3+}, N^{3+}, O^{3+}, Ne^{2+}, Mg^{2+}, Si^{4+}, P^{4+}, S^{4+}, Cl^{4+}, $Ar^{4.5+}$, Ca^{4+}, Cr^{4+}, Mn^{5+}, $Fe^{4.5+}$, and Ni^{5+}. The dominant ionization state in WN stars at large radii is predicted to be higher than for WC stars, despite similar stellar temperatures, since the effects of metal coolants is far less (Hillier 1988, 1989). Are these predictions consistent for the physical conditions at even lower densities of $\log(n_e/\text{cm}^3) \sim 5$ where the fine-structure lines form?

The absence of [S IV] 10.5 μm is consistent with a dominant ionization stage of S^{4+} for EZ CMa, while the [Ne II] 12.8 μm line is absent, so $Ne^+ \ll Ne^{2+}$, in agreement with expectation. The contribution of Ne^{3+} is uncertain, although it has a rather high ionization potential (IP = 97 eV), such that we assume $Ne/He \approx Ne^{2+}/He = (1.2\text{–}1.8) \times 10^{-4}$, depending on the contribution by He II. This is in reasonable agreement with the revised solar Ne abundance (Asplund et al. 2004) of $Ne/He = 2 \times 10^{-4}$, adjusted for the H-depleted atmosphere of an early WN star.

For oxygen, we expect that O^{3+} is the dominant ionization stage but are unable to verify the absence of fine-structure O^{2+} lines, which lie at 51.8 and 88.2 μm, longward of the IRS passband. Nevertheless, from the consistency with other relevant ions of Ne and S, we adopt $O/He \simeq O^{3+}/He = (4.2\text{–}4.8) \times 10^{-5}$. From our nitrogen abundance derived above, we find N/O = 40–48 by number. What is the expected oxygen abundance in a H-free WN star? From the spectroscopic analysis above, we derive N/C = 40 by number. This may be compared with recent predictions for (initially) rotating massive stars (Meynet & Maeder 2003). At the end of H-burning, the 60–120 $M_\odot$ tracks for initial equatorial rotation velocities of 300 km s^{-1} predict N/C = 40–45 by number, in perfect agreement. At this stage, N/O = 30–50 by number, such that the measured value lies in precisely the predicted range.

4. SUMMARY

We present *Spitzer* IRS spectroscopy for EZ CMa (HD 50896 WN4b), the first early WN star to be observed spectroscopically in the mid-IR. In addition to numerous stellar wind lines of He II, fine-structure lines of [Ne III] and [O IV] are

TABLE 2
OBSERVED MID-IR FINE-STRUCTURE LINE INTENSITIES IN EZ CANIS MAJORIS

Ion	Transition	λ	ω_u	ω_l	A_{ul}	Ω_{ul}	I_{ul}(Blend)
[Ne III]............	$^3P^o_1$–$^3P^o_2$	15.55	3	5	5.99×10^{-3}	1.65	7.45×10^{-13}
[O IV].............	$^2P^o_{1/2}$–$^2P^o_{3/2}$	25.89	4	2	5.19×10^{-4}	2.52	1.49×10^{-13}

NOTES.—This table shows observed mid-IR fine-structure line intensities (units of 10^{-12} erg cm^{-2} s^{-1}) in EZ CMa (uncorrected for potential blends with He II lines), and adopted atomic parameters, including statistical weights of the upper and lower levels, ω_u and ω_l, transition probability, A_{ul}, and collision strength Ω_{ul} at $T_e = 14{,}000$ K.

revealed, permitting an estimate of the asymptotic wind velocity, $\sim$1860 km s^{-1}, plus elemental abundances. We carry our a spectroscopic analysis of HD 50896, allowing for metal line blanketing and wind clumping, revealing generally excellent agreement with the IRS spectroscopy, plus stellar parameters supporting the earlier study of Schmutz (1997), based on an alternative line blanketing technique. We also derive $N/He \sim 2 \times 10^{-3}$ by number, with $N/C \sim 40$. From the derived clumped mass-loss rate, we obtain $Ne^{2+}/He = 1.2 \times 10^{-4}$, allowing for the contribution by neighboring He II wind lines, in comparison with $Ne/He = 2 \times 10^{-4}$ for a severely H-depleted environment, adjusted for the recent downward revision in the solar neon abundance by Asplund et al. (2004). An indication of the uncertainty in the fine-structure derived Ne abundance may be obtained by adopting the spectroscopic results for EZ CMa from Schmutz (1997), leading to a 10%–20% difference. In addition, we obtain $O^{3+}/He = 4.2 \times 10^{-5}$, i.e., $N/O \sim 48$, in excellent agreement with evolutionary predictions for massive stars at the end of core H-burning.

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