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Si IV AND C IV RESONANCE LINES AS INDICATORS OF MASSIVE STARS IN STARBURST GALAXIES

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ABSTRACT

We investigate the use of the ultraviolet lines of Si IV and C IV to study the initial mass function of massive stars in starburst galaxies. Radiatively driven wind models of stars with different metal content are computed. The resulting wind parameters are used as an input for line-profile calculations of Si IV and C IV. We describe the metallicity dependence of the equivalent widths of these lines for representative hot star models. We show that the ratio of the Si IV and C IV line strengths decreases with decreasing metallicity under the conditions typically prevailing in stellar winds. We also show that in a combined spectrum of a galaxy, in which main-sequence stars dominate the UV spectrum, this ratio is expected to increase with decreasing metallicity for a constant initial mass function. The possible contribution of interstellar lines to the integrated spectrum is also discussed. We find that spectral synthesis models do not allow one to derive parameters of the initial mass function as has been done previously. The mass-loss characteristics of massive stars *directly* affect the predicted line strengths, and they enter in an *indirect* way by modifying the evolutionary history of the stars. Both effects are not accounted for in synthesis models presently in existence.

Subject headings: galaxies: stellar content — stars: abundances — stars: massive — ultraviolet: spectra

1. INTRODUCTION

Starburst galaxies as a class of objects have been described by Balzano (1983). These galaxies experience star formation at a rate that can only be maintained in equilibrium if the duration of the star formation activity is short compared to the life of a galaxy (Weedman 1987). Multiwavelength studies in the radio, infrared, optical, ultraviolet, and X-ray regions hint at the presence of a population of massive stars formed during the burst (see, e.g., Rieke et al. 1980 for M82 and NGC 253, and Weedman et al. 1981 for NGC 7714). Observational evidence for populations of hot, massive stars in starburst galaxies has been derived from *indirect* indicators such as, e.g., large amounts of molecular gas, the raw material for star formation (Lo 1987), the presence of red supergiants, which are the evolutionary successors of OB stars (Terlevich et al. 1990), or from a large number of supernova remnants, the final stage of a massive star (Riecke et al. 1985). *Direct* observational support for hot, luminous stars in starburst galaxies by measuring their spectral signatures has been scarce. At optical wavelengths early-type stars can dominate the integral light in a starburst but they show only very weak absorption lines, which makes them hardly distinguishable if an older, less massive stellar population and/or H II regions are present (Bica, Alloin, & Schmidt 1990; Melnick, Moles, & Terlevich 1985). On the other hand, observations of various ultraviolet spectral features in starburst galaxies obtained with the *IUE* satellite provide the most powerful evidence for the presence of OB stars (Joseph, Wright, & Prestwich 1986; Fanelli, O'Connell, & Thuan 1987, 1988). Interpretation of spectral features such as the ultraviolet resonance lines of triply ionized silicon and carbon in terms of photospheric and wind absorption in OB stars can be justified on the basis of observational data accumulated for a large sample of individual Galactic stars (see Walborn, Nichols-Bohlin, & Panek 1985). Recently, Sekiguchi & Anderson (1987a, b) made use of observed Si IV/C IV line ratios in a sample of starburst galaxies to infer the mass distribution of the underlying OB star population. By calibrating this ratio using Galactic OB stars they derived a relation between the Si IV/C IV ratio and spectral type. Evolutionary models then provided a correlation between this ratio and the stellar mass. Sekiguchi & Anderson (1987a, b) could demonstrate the sensitivity of the line ratio to the slope of the assumed initial mass function. Scalo (1990) discussed the usefulness of the Si IV/C IV line ratio in starburst galaxies to derive properties of the initial mass function, such as the slope and the lower and upper cutoff mass. A fundamental assumption made by Sekiguchi & Anderson (1987a, b) is that OB stars in starburst galaxies have the same average chemical composition as OB stars in the solar neighborhood. This assumption was necessitated by the fact that ultraviolet observations of large numbers of OB stars were available only for the solar neighborhood. Starbusts are confined to the nucleus of the host galaxy or they occur in extranuclear giant H II regions or H II galaxies. The observed Galactic metallicity gradient of $\delta[M/H] \approx -0.08$ kpc^{-1} (Maeder, Lequeux, & Azzopardi 1980) suggests that OB stars formed at the Galactic center are more metal-rich than their counterparts in the solar neighborhood. Therefore we would expect that the properties OB stars in a nuclear starburst are different form stars in the solar neighborhood even if the average chemical composition of the starburst galaxy is comparable to our Galaxy. The H II galaxies, on the

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other hand, are known to be often metal-deficient (Campbell 1988), so that again the composition of stars newly formed will be different from solar. Therefore Sekiguchi & Anderson's (1987a, b) assumption of constant chemical composition may not be correct and the consequences must be addressed. We consider the work by Sekiguchi and Anderson as a pioneering first step in deriving information on the initial mass function in starburst galaxies. The aim of our paper is to point out possible problems with the application of the method and to indicate directions for improvements.

We investigate the origin of the ultraviolet Si IV and C IV resonance lines in OB stars. We present model calculations for the formation of these lines in the wind of OB stars spanning a wide range of metallicities. Section 2 describes the stellar wind models. These models are input for line-profile calculations of Si IV and C IV (§ 3). The influence of photospheric and interstellar absorption lines on the total line strength is discussed in § 4. The limitations of the Si IV/C IV line ratio to study the initial mass function in starburst galaxies are outlined in § 5. Finally, § 6 presents our conclusions.

2. STELLAR WIND MODELS FOR OB STARS

Stellar winds with mass-loss rates on the order of $10^{-7}\ M_\odot\ \mathrm{yr}^{-1} < \dot{M} < 10^{-5}\ M_\odot\ \mathrm{yr}^{-1}$ and terminal velocities of 2000 km $\mathrm{s}^{-1} < v_\infty < 4000\ \mathrm{km\ s}^{-1}$ have been observed in Galactic O stars (e.g., Lamers 1988). These values have been derived, e.g., from analysis of resonance lines of highly ionized metals observable in the satellite UV. Typical lines such as N V $\lambda\lambda$1238/42, Si IV $\lambda\lambda$1393/1402, or C IV $\lambda\lambda$1548/50 partly partly originate in wind zones at about 10 stellar radii from the photosphere and allow the determination of $\dot{M}$ and v_∞ (Garmany et al. 1981).

The massive outflows are initiated and maintained via momentum transfer to the wind by scattering of photospheric photons in absorption lines formed in the wind. Castor, Abbott, & Klein (1975) developed the first hydrodynamic models for winds in O stars. Since then, the original theory has been refined considerably, and the stellar wind properties predicted by models agree with observed values to within the uncertainties. The status of the wind theory has recently been reviewed by Kudritzki (1989).

Since the wind solution of the models depends on the radiative force and hence on the line opacities, the theory predicts the dependence of the stellar wind properties on the chemical composition of the star (Abbott 1982; Kudritzki, Pauldrach, & Puls 1987). This prediction cannot be properly compared to observations in Galactic stars. The galactocentric metallicity gradient of $\delta[M/H] \approx -0.08\ \mathrm{kpc}^{-1}$ (Maeder, Lequeux, & Azzopardi 1980) is too small to produce an observable effect in stellar winds of stars in the solar neighborhood. An attempt to test the theoretical prediction in a sample of O stars in the Magellanic Clouds, which have metal abundances roughly 1/3 (LMC) and 1/10 (SMC) solar, with observed mass-loss rates proved inconclusive (Leitherer 1988). The observational errors are too large to prove or disprove the theory (for a recent review, see Leitherer 1990). However, in view of the good agreement between theory and observations for stars with solar composition, it is reasonable to expect—at least qualitative—agreement for stars with nonsolar chemical abundances, too.

The wind models presented in this paper here have been computed with a radiation-hydrodynamics code described by Leitherer et al. (1989). In short, we solve for the steady state solution of the equation of motion for the wind including the acceleration contribution by spectral lines. The line list compiled by Abbott (1982) comprises about 250,000 transitions and is essentially complete for the first six ionization stages of hydrogen through zinc.

The excitation and ionization balance in the wind is treated with a modified recombination theory (Abbott & Lucy 1985). *On the average*, the line strengths are reproduced in reasonable agreement with observations although serious discrepancies may exist for *individual* lines. Mainly, this affects lines arising from transitions in trace ions whose ionic abundances are very sensitive to the wind parameters and where small errors in the computation of the ionization balance generate large discrepancies in the line strengths. Therefore, more sophisticated non-LTE calculations (Pauldrach 1987) are required if such wind models are to be used to predict the abundances of specific ions. However, since *on the average* the modified recombination theory produces reliable results, the wind solutions are rather insensitive to such discrepancies in specifiec lines.

A set of four stellar-wind models representing different evolutionary states of hot massive stars has been computed. Input parameters are the stellar mass M, luminosity L, effective temperature T_{eff}, and the chemical composition. The stellar parameters, which have been taken from Maeder & Meynet's (1988) evolutionary calculations, are summarized in Table 1. This parameter set corresponds to:

1. A zero-age main-sequence star of initial mass 60 $M_\odot$ (denoted 60/ZAMS);
2. A star with an initial mass of 60 $M_\odot$ at the end of core-hydrogen burning (60/TAMS);
3. A zero-age main-sequence star of initial mass 25 $M_\odot$ (25/ZAMS), and
4. A star with an initial mass of 25 $M_\odot$ at the end of core-hydrogen burning (25/TAMS).

The values for the elemental abundances of a Population I star with $Z = Z_\odot$ have been taken from Kurucz (1979). The metal abundances of his list were scaled by factors of 3.0, 1.0, 0.33, 0.10, and 0.0333 to obtain 20 models covering a wide range of metallicities. Observationally, the two ZAMS models can be identified with an early (60/ZAMS) an a late (25/ZAMS) O dwarf. The 60/TAMS star has an approximate spectral type of B0 Ia$^+$–B1 Ia$^+$, and the corresponding spectral type of the 25/TAMS model is B0 Ib–B1 Ib. We selected these stellar parameters as being fairly representative for the massive star population in a starburst galaxy. Moreover, these stars span a wide range of luminosity and temperature so that the metallicity effect on the stellar-wind properties of massive stars at different locations in the Hertzsprung-Russell diagram (HRD) can be investigated. The stellar flux emerging from the photosphere has been approximated by a low metal abundance ($Z = 0.1\ Z_\odot$) line-blanketed ALTAS6 model atmosphere (Howarth & Lynas-Gray 1989). We interpolated linearly between the published T_{eff} and log g grid points. Note that we assumed the photospheric radiation field to be unaffected by a

TABLE 1

PARAMETERS OF THE FOUR STELLAR MODELS

$M/M_\odot$	log ($L/L_\odot$)	T_{eff} (K)	log g	Evolutionary State
60........	5.37	49300	4.2	60/ZAMS
46........	5.96	24500	2.7	60/TAMS
25........	4.90	38700	4.3	25/ZAMS
23........	5.26	24800	3.1	25/TAMS

change in Z, i.e., the same model photosphere has been used for all wind models with the same $T_{\rm eff}$ and log g but different Z. This assumption is supported by the fact that the energy distribution of the $Z = 0.1\ Z_{\odot}$ model is nearly identical to that of a model with $Z = Z_{\odot}$ (Kurucz 1979) for $\lambda > 300$ Å. Kudritzki et al. (1991) investigated the consequences of varying Z on the photospheric flux and reached the same conclusions. There are differences at shorter wavelengths, but published *hydrostatic* model atmospheres are not trustworthy for $\lambda < 228$ Å (see Pauldrach 1987), because they produce too large He^+ absorption edges. Therefore it is difficult to assess the physical significance of such differences. Abbott (1982) studied the importance of individual wavelength regions for the computed radiative acceleration and found that virtually all driving lines are at $\lambda > 300$ Å. The 60/ZAMS model certainly has the largest error in this regard because it has the largest flux around 300 Å. Since this paper is to discuss the principal physical effect of the metal abundance on the Si IV/C IV line ratio, our assumption to neglect the influence of Z on the photospheric radiation field is justified. As will be shown below, other, much larger uncertainties exist, which preclude a quantitative application of such models to starburst galaxies at present.

Table 2 lists the parameters of the resulting stellar wind models. A converged hydrodynamic model predicts the stellar mass-loss rate $\dot{M}$ and the velocity field of the outflow, including v_∞. The five columns of Table 2 give the model designation, the metal content relative to the Sun, the stellar mass-loss rate, the terminal velocity of the wind, and the velocity law parameter β (see eq. [2], below). The mass-loss rates and the terminal velocities of the models with $Z = Z_{\odot}$ are typical for what is observed in Galactic early-type stars (see Bieging, Abbott, & Churchwell 1989). As compared to the $Z_{\odot}$ model, models with lower Z have lower mass-loss rates. This is a consequence of the lower metal content of the star, which generates less line opacity in the wind, and a smaller radiation force results. In the metallicity range $0.1 < Z/Z_{\odot} < 1$, which is of most relevance for starburst galaxies, we find that

$$\dot{M} \sim Z^{0.6 \text{ to } 0.7} \tag{1}$$

(see Table 2). Lower mass-loss rates for lower metal abundances are not specific for one particular set of stellar parameters but are generally obtained for hot massive stars (see Leitherer & Langer 1991). Hence, the theory of radiatively driven winds predicts the stellar wind properties of hot stars in galaxies with different metallicities to be systematically different.

Maeder & Meynet's (1988) evolutionary models assumed a metallicity-dependent mass-loss rate following the relation $\dot{M} \sim Z^{0.5}$. This is rather close to the relation found in this paper so that our set of wind models and the adopted evolutionary models are consistent in this respect. There are, however, differences in the sense that Maeder & Meynet's (1988) mass-loss rates at $Z = Z_{\odot}$ are larger on the average than those computed in our models. Since mass loss on the main sequence is not high enough to affect stellar evolution significantly (Leitherer & Langer 1991), the stellar parameters taken from Maeder & Meynet's models are consistent with our wind models despite the higher mass loss-rates adopted by Maeder & Meynet (1988). In contrast, mass loss is of crucial importance for stellar evolution in the post–main-sequence phase, and even slight modifications of the mass-loss properties during the phase translate into a completely different evolutionary behavior of evolved stars. We will readdress this point in our discussion of the massive star population of some well-observed starburst galaxies like, e.g., NGC 7714.

TABLE 2

HYDRODYNAMIC PARAMETERS OF THE WIND MODELS

Model	log $(Z/Z_{\odot})$	log $(\dot{M}/M_{\odot}\ \mathrm{yr}^{-1})$	v_∞ (km s^{-1})	β
60/ZAMS........	0.48	−5.55	3800	0.8
	0.00	−5.86	4190	0.7
	−0.48	−6.15	3430	0.7
	−1.00	−6.55	2340	0.7
	−1.48	−7.18	1920	0.7
60/TAMS........	0.48	−5.19	690	0.7
	0.00	−5.69	810	0.7
	−0.48	−6.10	1680	0.8
	−1.00	−6.37	1470	0.8
	−1.48	−6.65	1064	0.9
25/ZAMS........	0.48	−6.99	3080	0.8
	0.00	−7.34	3980	0.8
	−0.48	−7.67	3320	0.7
	−1.00	−8.06	2020	0.6
	−1.48	−8.96	1050	0.6
25/TAMS........	0.48	−6.79	2670	0.8
	0.00	−7.03	2330	0.9
	−0.48	−7.21	1620	0.8
	−1.00	−7.67	1290	0.8
	−1.48	−8.21	1130	0.7

3. THEORETICAL Si IV AND C IV PROFILES

In this section we predict the sensitivity of the Si IV and C IV wind lines to the metallicity. We calculated the P Cygni profiles of Si IV $\lambda\lambda$1393/1402 and C IV $\lambda\lambda$1548/50 formed in the winds of our set of standard stars given in Tables 1 and 2.

The profiles are calculated with the SEI method (Lamers, Cerruti-Sola, & Perinotto 1987). In this method the source function of the lines is calculated by means of the Sobolev approximation whereas the equation of transfer in the wind is solved exactly. The analysis of the ultraviolet spectra of Galactic OB stars demonstrates that the line profiles calculated with the method can describe the observed profiles very accurately if the wind is assumed to have a random velocity field (turbulence) on the order of $0.1v_\infty$ in addition to the outflow velocity (Groenewegen, Lamers, & Pauldrach 1989; Lamers & Groenewegen 1991). We adopt this same value of the turbulent velocity for our profile calculations. The strength and shape of resonance-line profiles formed in spherical stellar winds depend on two properties of the wind: the velocity law of the wind and the variation of the radial optical depth of the line. The velocity law of the wind is expressed in its usual representation

$$v(r) = v_\infty\left(1 - \frac{R_*}{r}\right)^\beta , \tag{2}$$

where R_* denotes the stellar radius and v_∞ is the terminal velocity of the wind. The parameter β describes the steepness of the velocity distribution in the stellar wind. Analyses of the UV line profiles of Galactic OB stars as well as theoretical radiation driven wind models show that equation (2) with $0.6 < \beta < 0.8$ is a fair representation of the actual velocity distribution in the winds of OB stars (Kudritzki 1989; Groenewe-

TABLE 3

ATOMIC DATA OF THE Si IV AND C IV RESONANCE LINES

Spectrum	λ_0/Å	f	$(n_e/n_H)_\odot$	$A(\lambda)$
Si IV.......	1393.76	0.528	4.0×10^{-5}	2.489×10^{16}
Si IV.......	1402.77	0.262	4.0×10^{-5}	1.244×10^{16}
C IV........	1548.19	0.194	3.2×10^{-4}	8.125×10^{16}
C IV........	1550.76	0.097	3.2×10^{-4}	4.063×10^{16}

gen, Lamers, & Pauldrach 1989). We typically find $0.7 < \beta < 0.8$ from our stellar-wind models given in Table 2. We will adopt $\beta = 0.75$ as a good mean value for all line-profile calculations throughout this paper.

The radial optical depth of the wind in a line as a function of wavelength, expressed in terms of a velocity shift v from the line center λ_0, is

$$\tau(v) = \frac{\pi e^2}{mc} f\lambda_0 \left\{ n_i \frac{dr}{dv} \right\}_v \tag{3}$$

(Castor 1970; Lamers, Cerrutti-Sola, & Perinotto 1987), where f is the oscillator strength, λ_0 is the wavelength of the line center, n_i is the number density of the absorbing ions, and dr/dv is the inverse of the velocity gradient. Both n_i and dr/dv are evaluated at the position in the wind where the velocity v is reached. Using the equation of mass continuity and the velocity of equation (2), $\tau(v)$ can be written as

$$\begin{aligned}\tau(v) &= 8.45 \times 10^{17} f\lambda_0 \left(\frac{n_E}{n_H}\right) \dot{M} v_\infty^{-2} R_*^{-2} \beta^{-1} q_i(v) \left(\frac{v}{v_\infty}\right)^{\beta/2-2} \\ &= A(\lambda) \dot{M} v_\infty^{-2} R_*^{-1} Z \beta^{-1} q_i(v) \left(\frac{v}{v_\infty}\right)^{\beta/2-2} \end{aligned} \tag{4}$$

with

$$A(\lambda) = 8.45 \times 10^{17} f\lambda_0 \left(\frac{n_E}{n_H}\right)_\odot , \tag{5}$$

where (n_E/n_H) is the abundance of the absorbing element E relative to hydrogen, $q_i(v)$ is the ionization fraction of the absorbing ion as a function of distance or velocity in the wind, and Z is the elemental abundance relative to the Sun. In this equation $\dot{M}$ is in $M_\odot$ yr^{-1}, v_∞ is in km s^{-1}, and R_* in $R_\odot$.

The integrated radial optical depth T of the wind is related to the column density N_i of the absorbing ions.

$$T = \int_0^1 \tau(v) d\left(\frac{v}{v_\infty}\right) = \frac{\pi e^2}{mc} f\lambda_0 v_\infty^{-1} N_i . \tag{6}$$

The atomic data of the Si IV and C IV resonance lines are listed in Table 3. For each model we adopt the ionized fraction predicted by the wind model. We assumed that the ionization fractions $q_{\mathrm{Si\,IV}}$ and $q_{\mathrm{C\,IV}}$ are constant throughout the wind. The analysis of the winds of O stars (Lamers & Groenewegen 1990) and the calculations of the wind models demonstrate that this is a reasonable assumption for the present purpose.

The line-profile parameters for the computed Si IV and C IV lines are summarized in Tables 4 and 5, respectively. T_{blue} is the integrated radial optical depth of the blue component of the doublet. The value of T for the red component is smaller by a factor of $0.5\lambda_{\mathrm{red}}/\lambda_{\mathrm{blue}}$. The corresponding profiles are shown in Figures 1–8.

The Si IV and C IV profiles with *solar abundance* are in qualitative agreement with observed line profiles in Galactic OB stars. Si IV shows no significant wind effect on the main sequence (Figs. 1 and 3), in agreement with *IUE* high-dispersion data published by Walborn, Nichols-Bohlin, & Panek (1985, hereafter WNP). The Si IV line develops a pronounced P Cygni profile due to strong stellar winds if massive stars evolve from the main sequence (see also § 5) as can be recognized in *IUE* spectra of luminous O and early B supergiants observed by WNP. Our corresponding models 60/TAMS and 25/TAMS agree with these observations (see Figs. 2 and 4, respectively). The C IV line shows P Cygni structure already for stars on the main sequence (Figs. 5 and 7). Physical conditions in the stellar wind cause the optical depth

TABLE 4

Si IV LINE PARAMETERS

Model	log $(Z/Z_\odot)$	log $(\dot{M}/M_\odot$ yr$^{-1})$	v_∞ (km s^{-1})	log $\bar{q}_{\mathrm{Si\,IV}}$	T_{blue}	W_λ(Si IV) (Å
60/ZAMS........	0.48	−5.55	3800	−4.77	7.78×10^{-2}	1.20
	0.00	−5.86	4190	−5.13	4.55×10^{-3}	0.097
	−0.48	−6.15	3430	−5.35	6.99×10^{-4}	0.014
	−1.00	−6.55	2340	−5.59	1.03×10^{-4}	<0.005
	−1.48	−7.18	1920	−6.15	3.30×10^{-6}	<0.005
60/TAMS........	0.48	−5.19	690	−0.13	4.49×10^{4}	5.30
	0.00	−5.69	810	−0.33	2.18×10^{3}	4.91
	−0.48	−6.10	1680	−0.80	2.24×10^{1}	6.91
	−1.00	−6.37	1470	−1.00	2.96×10^{0}	3.20
	−1.48	−6.65	1064	−1.01	9.68×10^{-1}	1.54
25/ZAMS........	0.48	−6.99	3080	−4.14	3.06×10^{-2}	0.445
	0.00	−7.34	3980	−4.59	9.68×10^{-4}	<0.005
	−0.48	−7.67	3320	−4.87	1.13×10^{-4}	<0.005
	−1.00	−8.06	2020	−5.05	2.47×10^{-5}	<0.005
	−1.48	−8.96	1050	−5.69	8.86×10^{-7}	<0.005
25/TAMS........	0.48	−6.79	2670	−1.08	1.93×10^{1}	8.34
	0.00	−7.03	2330	−1.23	3.43×10^{0}	5.10
	−0.48	−7.21	1620	−1.23	1.57×10^{0}	2.85
	−1.00	−7.67	1290	−1.54	1.25×10^{-1}	0.585
	−1.48	−8.21	1130	−2.12	4.15×10^{-3}	0.026

TABLE 5

C IV LINE PARAMETERS

Model	$\log (Z/Z_\odot)$	$\log (\dot{M}/M_\odot\ \mathrm{yr}^{-1})$	v_∞ (km s^{-1})	$\log \bar{q}_{\mathrm{C\,IV}}$	T_{blue}	W_λ(C IV) (Å)
60/ZAMS.......	0.48	−5.55	3800	−2.82	2.26×10^{1}	8.81
	0.00	−5.86	4190	−3.18	1.33×10^{0}	4.74
	−0.48	−6.15	3440	−3.40	2.03×10^{-1}	1.86
	−1.00	−6.55	2340	−3.64	3.00×10^{-2}	0.314
	−1.48	−7.18	1920	−4.20	9.60×10^{-4}	0.010
60/TAMS........	−0.48	−5.19	690	−0.61	1.62×10^{4}	3.83
	0.00	−5.69	810	−0.29	7.81×10^{3}	4.13
	−0.48	−6.10	1680	−0.08	3.84×10^{2}	6.04
	−1.00	−6.37	1470	−0.05	8.63×10^{1}	4.87
	−1.48	−6.65	1064	−0.05	2.88×10^{1}	3.31
25/ZAMS........	0.48	−6.99	3080	−1.60	3.46×10^{1}	7.77
	0.00	−7.34	3980	−2.04	1.12×10^{1}	4.38
	−1.48	−7.67	3320	−2.32	1.31×10^{-1}	1.37
	−1.00	−8.06	2020	−2.50	2.86×10^{-2}	0.261
	−1.48	−8.96	1050	−3.14	1.03×10^{-3}	0.005
25/TAMS........	0.48	−6.79	2670	−0.04	6.90×10^{2}	9.35
	0.00	−7.03	2330	−0.03	1.78×10^{2}	7.42
	−0.48	−7.21	1620	−0.03	8.11×10^{1}	5.28
	−1.00	−7.67	1290	−0.02	1.35×10^{1}	3.45
	−1.48	−8.21	1130	−0.01	1.75×10^{0}	1.98

in the C IV line to be higher than in Si IV line. As a consequence, the C IV shows wind effects even in main-sequence stars—in agreement with the observations (see WNP). Similar to the trend found for Si IV, C IV increases in strength if the stars are evolved (model 60/TAMS, Fig. 6; model 25/TAMS, Fig. 8). In fact, P Cygni profiles with deeply saturated absorption components are found in late O and early B supergiants (WNP).

Models with different abundances yield different line profiles, in the sense that the strength of the emission and absorption components decreases with decreasing Z. The important point to realize is that the Si IV and C IV lines show a different behavior as a function of Z due to the different optical depths of the two lines. As a consequence, *the relative strength* of the two lines is sensitive to Z.

The equivalent widths W_λ of all profiles plotted in Figures 1–8 are given in column (7) of Tables 4 and 5. The quantity W_λ is the net equivalent width as obtained by integrating *the emission and absorption components.* This is the quantity relevant for comparison with observational data of starburst galaxies, where the spectral resolution is mostly not sufficient for a detailed line-profile analysis. The dependence of W_λ(Si IV) and W_λ(C IV) on Z is plotted in Figures 9–12. We emphasize that *the equivalent widths shown in these figures do not take photospheric and interstellar* Si IV *and* C IV *into account.* The importance of the photospheric and interstellar contribution to the wind profiles will be discussed in § 6. The width W_λ(C IV) of the model 60/ZAMS (Fig. 9) varies by about three orders of magnitude over $0.0333\ Z_\odot < Z < 3.0\ Z_\odot$. The equivalent width of the $Z = Z_\odot$ model ($W_\lambda = 4.7$ Å) is in good agreement with the mean equivalent width of about 5 Å measured in Galactic early

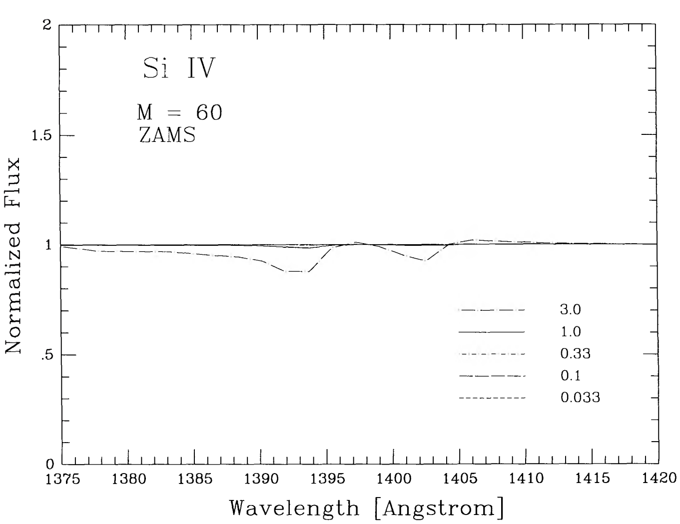

FIG. 1.—Computed Si IV wind lines for the 60/ZAMS model. Different line types denote different metallicities. The lines are virtually absent except for cases $Z = 3Z_\odot$.

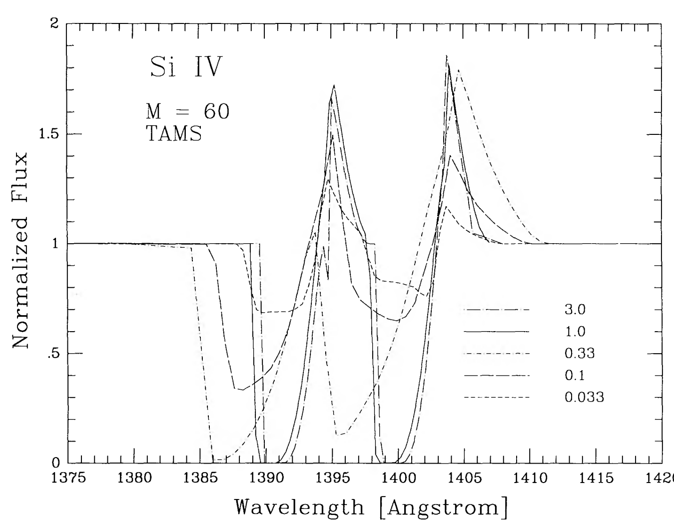

FIG. 2.—Computed Si IV wind lines for the 60/TAMS model. P Cygni profiles with strong blueshifted absorption are present for all metallicities considered.

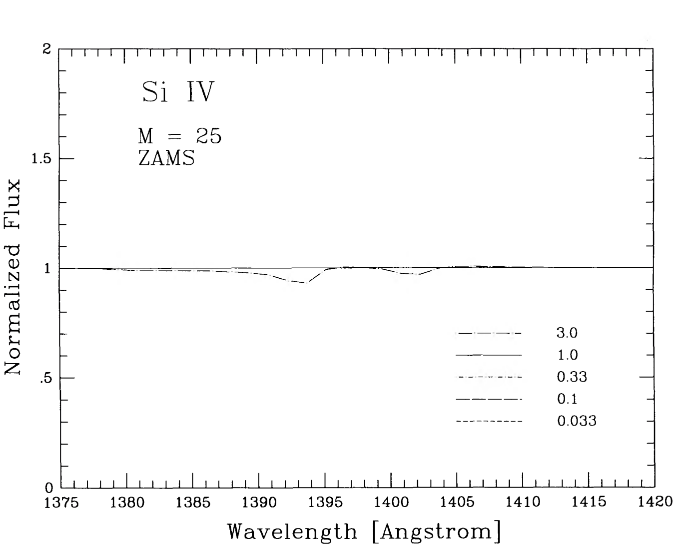

FIG. 3.—Computed Si IV wind lines for the 25/ZAMS model. Only the lines with $Z = 3Z_{\odot}$ are strong enough to produce noticeable absorption.

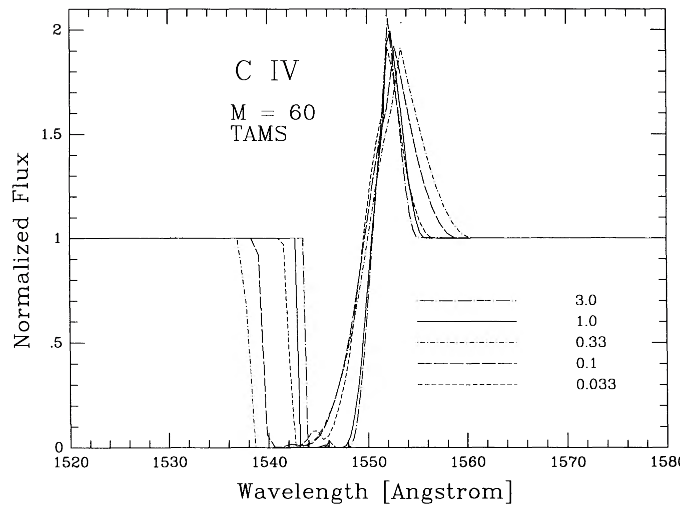

FIG. 6.—Computed C IV wind lines for the 60/TAMS model. The P Cygni profiles have strongly saturated absorption components for all five cases considered.

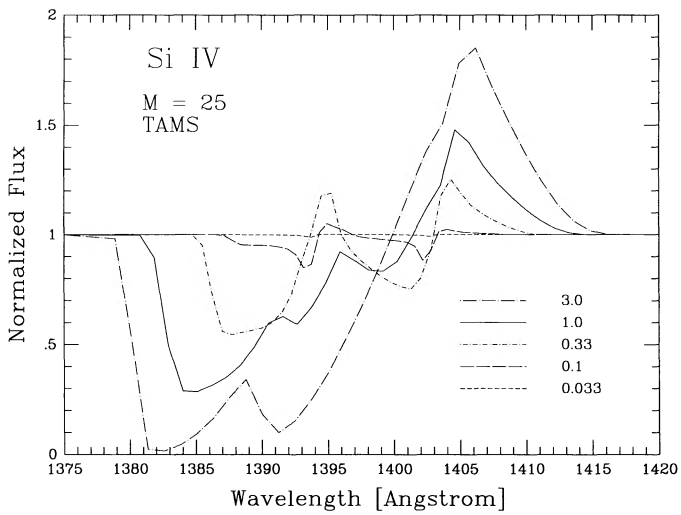

FIG. 4.—Computed Si IV wind lines for the 25/TAMS model. P Cygni profiles of varying strength depending on Z are found.

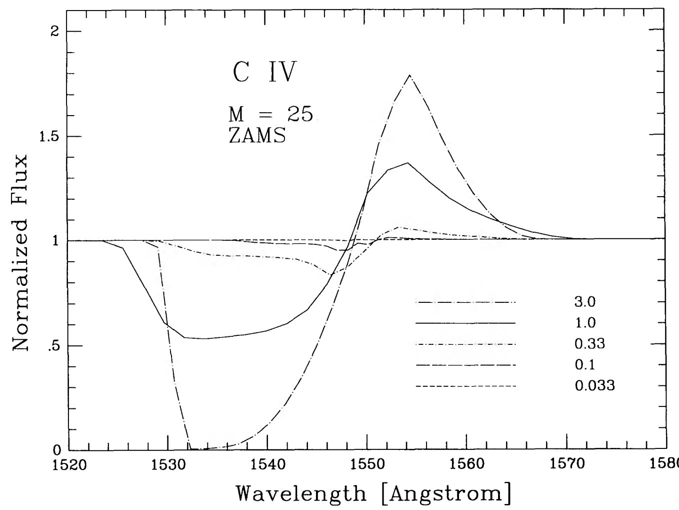

FIG. 7.—Computed C IV wind lines for the 25/ZAMS model. The same qualitative behavior of the lines as in the 60/ZAMS models can be seen.

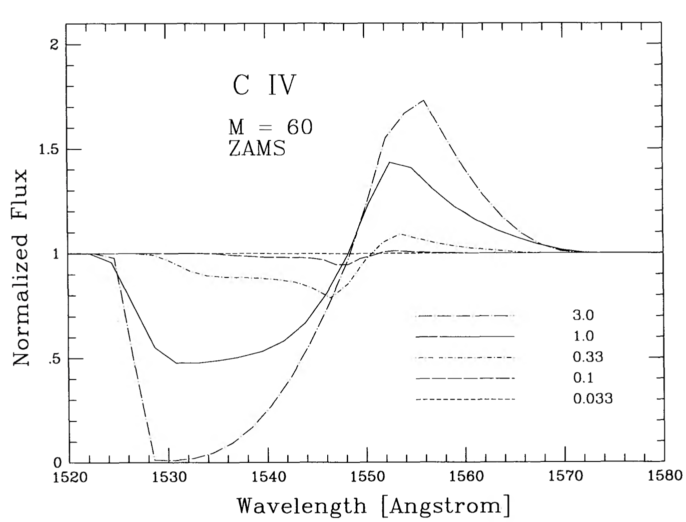

FIG. 5.—Computed C IV wind lines for the 60/ZAMS model. Unlike the Si IV line, C IV shows wind features for a star on the main sequence having solar composition.

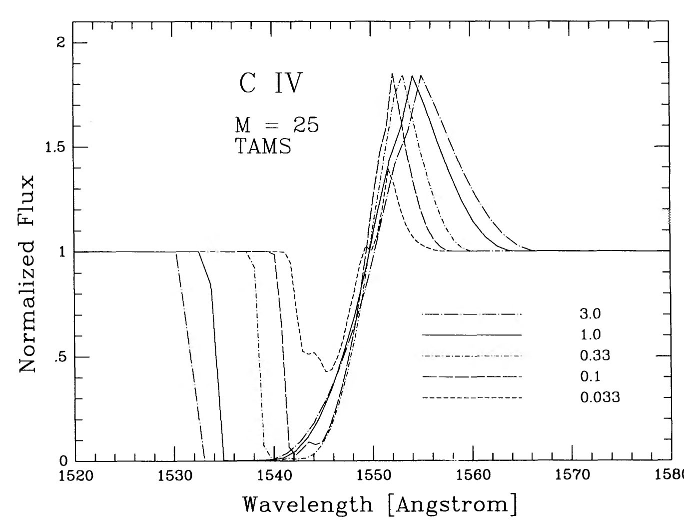

FIG. 8.—Computed C IV wind lines for the 25/TAMS model. C IV is a strong wind line for all metallicities. In this case the net equivalent width is very sensitive to the terminal velocity of the wind.

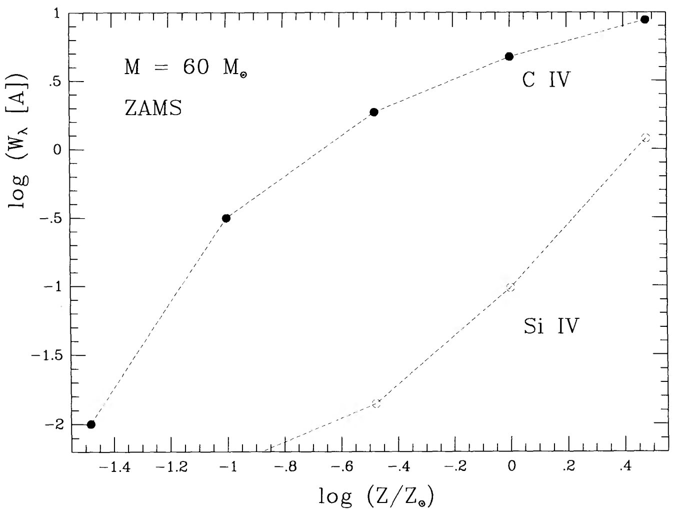

FIG. 9.—Equivalent widths W_λ of the Si IV and C IV *wind* lines vs. metallicity Z. Model 60/ZAMS.

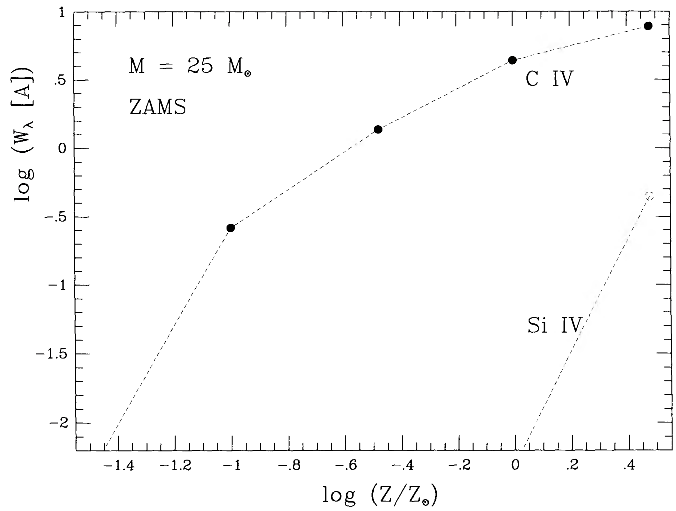

FIG. 11.—Equivalent widths W_λ of the Si IV and C IV *wind* lines vs. metallicity Z. Model 25/ZAMS.

O stars (Sekiguchi & Anderson 1987a, their Table III). The Si IV equivalent widths of Figure 9 should not be directly compared with observations because, as we will show below, the wind lines are insignificant with respect to the interstellar absorption.

The results for the 25 $M_\odot$ ZAMS star are given in Figure 11. The quantity W_λ(C IV) displays the same qualitative behavior as in the case of the 60/ZAMS model. Again, the equivalent width of the model with solar composition ($W_\lambda = 4.4$ Å) agrees quite well with the one from Sekiguchi & Anderson's (1987a) average 25 $M_\odot$ star on the main sequence. The Si IV data, on the other hand, show no *measurable* wind line. The observed equivalent width is due to photospheric and interstellar absorption (see below).

The TAMS model with an initial mass of 60 $M_\odot$ is unusual in its functional behavior of W_λ with Z (see Fig. 10). The decrease in W_λ for high Z is due to the lower v_∞ in these models. The 60/TAMS model has parameters similar to very luminous B hypergiants found in this part of the HRD (Lamers 1986). The wind parameters of the high-Z models come close to those of luminous blue variables with their denser winds and lower wind velocities. Unlike the ZAMS models, the optical depths of Si IV $\lambda\lambda$1393/1402 and C IV $\lambda\lambda$1548/50 in the TAMS models are high enough that the wind lines dominate over photospheric and interstellar lines.

Figure 12 shows the results for the equivalent widths of the model 25/TAMS. The width W_λ of Si IV (5.1 Å) and C IV (7.4 Å of the model with solar composition are in agreement with the corresponding values of Sekiguchi & Anderson (1987a, their Table V) after the photospheric and interstellar contributions of about 1–2 Å to the observed equivalent widths are taken into account.

Note the distinct variation of the *ratio* of W_λ(Si IV)/W_λ(C IV) with metal abundance. W_λ(Si IV)/W_λ(C IV) cannot be assumed to be constant—even over a comparatively small Z interval of, e.g., $0.33\ Z_\odot < Z < 3.0\ Z_\odot$. This effect is present for the models with $M = 60\ M_\odot$ and $M = 25\ M_\odot$ on the ZAMS as well as on the TAMS. The nonmonotonic behavior of the curves in Figure 10 towards high Z is due to the lower equivalent widths resulting from the lower v_∞ of these models. The

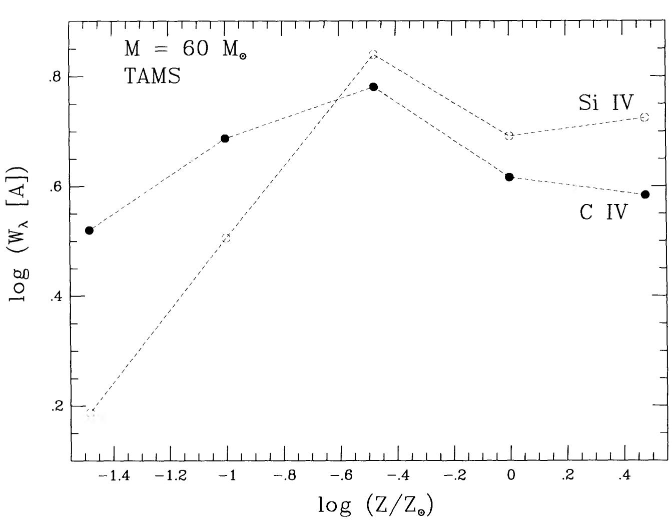

FIG. 10.—Equivalent widths W_λ of the Si IV and C IV *wind* lines vs. metallicity Z. Model 60/TAMS.

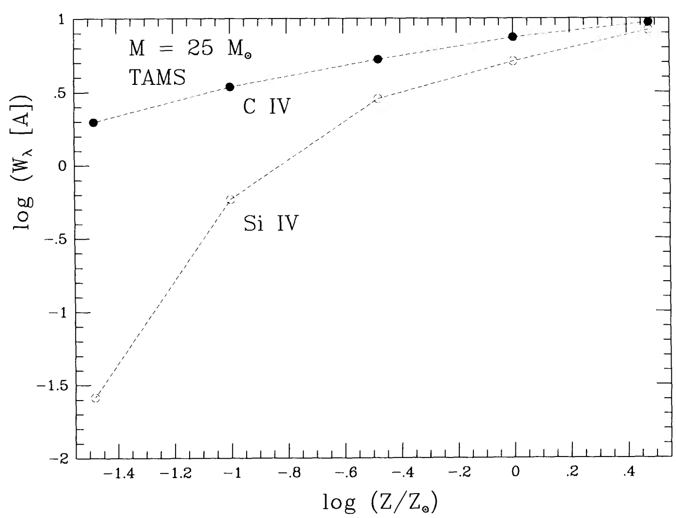

FIG. 12.—Equivalent widths W_λ of the Si IV and C IV *wind* lines vs. metallicity Z. Model 25/TAMS.

reason for this has been explained in the previous section. The cause of the Z-dependence of W_λ(Si IV)/W_λ(C IV) is due to three effects: (i) the optical depth of the wind in the Si IV λ1393/1402 and C IV λλ1548/50 lines depends directly on the abundance of these elements and therefore on Z; (ii) the models of the winds of O stars predict that the ionization fractions of Si^{3+} and C^{3+} (q_i in eq. [4]) decrease with decreasing Z (see Tables 4 and 5). This is due to the fact that the density of the winds decreases with decreasing Z, and hence the ionization balance shifts to higher stages, e.g., Si^{4+} and C^{4+}; (iii) In all models the optical depths of the C IV λλ1548/50 lines are larger than those of the Si IV λλ1393/1402 lines due to the higher ionization fraction of C^{3+} (see Tables 4 and 5). This implies that the wind lines of Si IV λλ1393/1402 and C IV λλ1548/50 are on different parts of the curve of growth, with the C IV λλ1548/50 lines closer to saturation than the Si IV λλ1393/1402 lines. As a result of this, the *ratio* W_λ(Si IV)/ W_λ(C IV) will depend on Z even if the optical depths of both lines were to depend on Z in the same way.

All the above effects combined are responsible for the results presented in Figures 9–12. However, each effect by itself—different Z, different wind density with different Z, and different q_i due to different wind density—is able to produce the same qualitative result. The basic reason for this is the different optical depth associated with Si IV λλ1393/1402 and C IV λλ1548/50 in stellar winds and the nonlinear run of the curve of growth for these ions.

The latter point is important because the dependence of W_λ (Si IV)/W_λ(C IV) on Z is modified with ionic abundances different from the ones based on the wind models. Groenewegen & Lamers (1991) discussed the uncertainties in the calculated ionic abundances and showed that the predicted ionization fractions can differ drastically from the empirical ones derived from the UV resonance lines. However, since the empirical ionization fractions of C IV λλ1548/50 are also uncertain due to saturation of the observed P Cygni profiles, it is not clear that the empirical ionization fraction should be preferred over the theoretical ones adopted here. In any case, the *qualitative* behavior of W_λ(Si IV)/W_λ(C IV) as a function of Z remains unchanged even for very different assumptions on the ionization state of the wind. On the other hand, the *quantitative* relation is rather uncertain and should be taken with care.

We note that the line *widths* of Si IV λλ1393/1402 and C IV λλ1548/50 (defined, e.g., as the FWHM of the absorption component) show the same qualitative dependence on Z as the equivalent widths. In principle, they could also be used to obtain information on the underlying stars. However, the line wings are often contaminated by other photospheric and interstellar lines which makes it difficult to measure the FWHM in low-resolution *IUE* spectra. The resulting uncertainties are much higher than obtained from the integrated equivalent widths.

4. PHOTOSPHERIC AND INTERSTELLAR Si IV AND C IV

4.1. *Photospheric Lines*

So far, we neglected the photospheric contribution to the calculated line profiles. Theoretical non-LTE calculations of photospheric Si IV lines have been performed by Kamp (1973, 1978). For early O *supergiants* the equivalent widths of the photospheric Si IV λλ1393/1402 lines are negligibly small as compared to the equivalent width of the wind lines. There is not enough of an abundance of Si^{3+} in this $T_{\rm eff}$ range to produce significant opacity. Photospheric Si IV λλ1393/1402 might be stronger than the wind line in early O *dwarfs*, but in this case the interstellar line will dominate (see below), and stellar Si IV is unobservable. These calculations have been performed for stars with solar composition. However, one should expect that the conclusion that the photospheric contribution is negligible relative to the interstellar and wind line is true for all five values of Z. The photospheric Si IV resonance lines increase in strength towards lower effective temperature due to more favorable ionization conditions for Si IV. Kamp's (1973) calculations predict an equivalent width of about 1 Å at spectral type of about O8, with a rapid increase in strength and a maximum of photospheric Si IV for early B stars. Comparison with the strength of the Si IV wind lines of our models with $Z = Z_\odot$ implies that the photospheric contribution to the total (including interstellar) observed W_λ(Si IV) is negligible in O3–O8 dwarf stars for all metallicities. Around B0, strong photospheric absorption is expected in main-sequence stars. On the other hand, strong, optically thick Si IV wind absorption prevails in B0 supergiants with $Z \approx Z_\odot$ (see Table 4). These wind lines should hardly be affected by the presence of underlying photospheric lines. For $Z \leq 0.1Z_\odot$, the wind line is predicted to become optically thin, and the photospheric line may be significant, especially in less luminous supergiants.

The theoretical predictions for the strength of photospheric Si IV λλ1393/1402 can be compared to observational data accumulated for Galactic stars (Panek & Savage 1976; Henize, Wray, & Parsons 1981; Walborn & Panek 1984; WNP). Sekiguchi & Anderson (1987a) plotted the relationship of W_λ(Si IV) and the spectral type for different luminosity classes. Their results are in full agreement with the theoretical models. On the main sequence, W_λ(Si IV) displays a pronounced maximum around spectral type B0 and approaches a constant equivalent width of 1–2 Å for spectral types O3–O8, which is mostly due to interstellar absorption (see below). High-resolution data (see WNP) confirm that photospheric Si IV is not discernible in O3–B0 supergiants due to the dominating wind feature.

Non-LTE calculations for the photospheric C IV λλ1548/50 lines have not been published. Moreover, due to the strength of the wind lines photospheric C IV lines in hot stars are not directly accessible to observations. High-resolution spectra obtained with the *IUE* satellite (WNP) confirm that the photospheric contribution to the total profile is negligibly small in the temperature-and-luminosity range covered by our wind models. Groenewegen & Lamers (1989) found from their detailed line-fitting analysis of a large number of C IV profiles that in addition to the wind lines a small (1–3 Å) contribution of photospheric origin is required to reproduce the observations. However, it is not clear if this additional contribution has stellar or interstellar origin (see below).

4.2. *Interstellar Lines*

O stars observed with the *IUE* satellite exhibit a large number of interstellar absorption lines (WNP). Most of these lines are due to transitions in resonance lines including Si IV λλ1393/1402 and C IV λλ1548/50. The Si IV λλ1393/1402 lines can be strongly influenced by interstellar contamination. Depending on the stellar spectral type, the wind properties, and the total column density of Si^{3+} along the line of sight, the observed Si IV λλ1393/1402 equivalent width can even be dominated by the interstellar lines because the equivalent width of the photospheric and the wind lines in the spectra of O stars—especially on the main sequence—is small.

Blades et al. (1988) studied the interstellar lines in the ultraviolet towards supernova 1987A. From their high-dispersion *IUE* data they find an equivalent width of about 1 Å for Si IV $\lambda\lambda$1393/1402. Several absorption components originating in our Galaxy and the Large Magellanic Cloud, which are resolved in their high-resolution data, contribute to the total equivalent width. Equivalent widths of about 1 Å due to interstellar Si IV $\lambda\lambda$1393/1402 have also been reported for Galactic O stars in the Carina region by York et al. (1990; see also Walborn, Heckathorn, & Hesser 1984). It is evident from these studies that the Si IV line strengths of massive stars measured in *IUE* low-dispersion data will be strongly affected by an interstellar contribution. These high-resolution data are consistent with the equivalent widths measured on low-resolution spectra. Sekiguchi & Anderson's (1987a) figure of W_λ(Si IV) versus spectral type clearly shows a *constant* offset of δW_λ(Si IV) $\approx$ 1–2 Å for O dwarfs. Most probably, this indicates the average interstellar absorption-line strength of Si IV $\lambda\lambda$1393/1402.

Since the C IV line profile is dominated by the strong stellar wind line for O stars of all luminosity classes, the contribution of the interstellar absorption line is of less importance for the total equivalent width than for Si IV. It should be noted that the strength of interstellar C IV $\lambda\lambda$1548/50 is comparable to that of Si IV $\lambda\lambda$1393/1402 (York et al. 1990). Since the stellar-wind line of C IV decreases considerably for lower metallicity (see Table 5), the interstellar contribution may become important in O stars in an environment with very low metal content. York et al. (1990) obtained high-dispersion *IUE* spectra of the star-forming galaxy NGC 1705. They conclude that interstellar lines are the primary contributor to the strong Si IV and C IV absorption lines observed at *low* resolution. Only in those cases where interstellar absorption can be neglected, the observed line strengths may be used to derive quantitative properties of the underlying stars.

5. APPLICATION TO STARBURST GALAXIES

5.1. Si IV *and* C IV *Produced by a Population of Main-Sequence Stars*

We showed above that the equivalent widths of the Si IV $\lambda\lambda$1393/1402 and C IV $\lambda\lambda$1548/50 lines observed in O stars are rather sensitive to the stellar wind properties. In particular, we found a strong dependence of the line strengths on the metal abundance. Generally speaking, any systematic variation of stellar parameters such as the $T_{\rm eff}$ scale or the mass-luminosity relation in extragalactic massive stars may produce a similar result.

The basic reasons for this reasons for this behavior of the Si IV and C IV lines are (i) the strong sensitivity of a radiatively driven stellar wind to any variation of stellar parameters and (ii) the different optical depth in the two lines, which affect the ratio of their equivalent widths. We restricted our discussion of the Si IV and C IV line profiles to model stars with masses of 60 $M_\odot$ and 25 $M_\odot$ in different evolutionary states. In a typical starburst galaxy the observed, integrated light in the ultraviolet spectral region is due to a large number of early-type stars with a wide mass range. Sekiguchi & Anderson (1987b) modeled the mean ratio of the Si IV and C IV equivalent widths expected from a mixture of stars of spectral types O3–B5. The average ratio R can be expressed in terms of the stellar continuum flux, $F_\lambda(m)$, the equivalent widths of Si IV and C IV in individual stars, $W_\lambda^{\rm Si\,IV}(m)$ and $W_\lambda^{\rm C\,IV}(m)$, the stellar lifetimes, $t(m)$, and the weighting function for the mass spectrum, $m^{-\alpha}$:

$$R = \frac{\int^{\Delta m} F_{1400}(m) W_\lambda^{\rm Si\,IV}(m) t(m) m^{-\alpha}\, dm}{\int^{\Delta m} F_{1550}(m) W_\lambda^{\rm C\,IV}(m) t(m) m^{-\alpha}\, dm} \tag{7}$$

R is found to be well-correlated with α, the slope of the initial mass function. Varying the IMF slope α from, e.g., 2 to 3 corresponds to a change in R from 0.62 to 0.96. The reason for this correlation is the different contribution of stars in different mass ranges to the integrated Si IV and C IV equivalent widths. Inspection of Sekiguchi & Anderson's (1987) Table 3 (which refers to main-sequence stars, see below) suggests that Si IV $\lambda\lambda$1393/1402 is strongest in early B stars, whereas C IV $\lambda\lambda$1548/50 peaks in mid-O stars. Therefore, if the equivalent widths of the C IV and Si IV lines are mainly due to main-sequence stars, these lines are formed in different regions of the stars: Si IV is mainly due to *photospheric* lines in early B stars and C IV is due to *wind* lines in mid-O stars. Si IV is a strongly saturated photospheric line in the spectra of B0 V–B2 V stars and therefore its equivalent width is expected to be insensitive to Z. The C IV line, on the other hand, originates in the winds of O stars and our calculations show that its equivalent width is expected to decrease with decreasing Z. Therefore we expect that the ratio R will *increase* with decreasing Z if the observed equivalent widths are due to a mixture of main-sequence stars in the mass range of 15 $M_\odot$ and larger. A higher than normal value of R can thus be the result of a lower metallicity or a larger value of the IMF slope α, or both. This implies that the neglect of the Z-dependence of the line ratio R will result in an *overestimate* of the value of α for galaxies with $Z < Z_\odot$ (and vice versa) if main-sequence stars dominate the contribution to the equivalent width, as assumed by Sekiguchi & Anderson 1987.

5.2. *Evidence for an Evolved Population: NGC 7714*

We can test the validity of the assumption that Si IV $\lambda\lambda$1393/1402 and C IV $\lambda\lambda$1548/50 observed in starburst galaxies is produced by main-sequence stars only. If main-sequence stars dominate, then Si IV $\lambda\lambda$1393/1402 as a photospheric line should be unshifted with respect to the systematic velocity of the galaxy. C IV $\lambda\lambda$1548/50 originates in the wind and a blueshift of the order 1000 km s^{-1} is predicted. This prediction for the radial-velocity behavior is in striking constrast with what is observed in the nucleus of the prototype starburst galaxy NGC 7714 (Weedman et al. 1981). Both Si IV and C IV are blueshifted by 1000 km s^{-1} and 500 km s^{-1}, respectively. Blueshifted Si IV $\lambda\lambda$1393/1402 indicates the presence of stellar winds which are stronger than in our wind models for a main-sequence star. Since the wind densities decrease with lower mass along the main-sequence, blueshifted Si IV cannot be due to B stars, either. On the observational side, Walborn, Nichols-Bohlin, & Panek (1985) report that Galactic O main-sequence stars show no wind effect in Si IV $\lambda\lambda$1393/1402, in agreement with our theoretical results.

Blueshifted absorption lines of C IV *and* Si IV can be understood if massive post–main-sequence stars contribute to the observed line profiles. Walborn & Panek (1984) found that Si IV $\lambda\lambda$1393/1402 displays a strong luminosity dependence in O stars. The line is weak or absent on the main-sequence and shows strong, blueshifted absorption or even a P Cygni profile in evolved O stars. An interpretation of this effect has been given by Drew (1989) and Pauldrach et al. (1990). The strengthening of the line with increasing luminosity is a direct consequence of the higher mass-loss rate at higher L, and thus the higher wind opacity.

Blueshifted Si IV strongly suggests the presence of non-negligible population of massive post–main-sequence stars in NGC 7714. We may observe a burst of star formation with an age of a few million years, the typical main-sequence lifetime of an O star. The Si IV $\lambda\lambda$1393/1402 and C IV $\lambda\lambda$1548/50 lines observed in NGC 7714 have velocity displacements differing by about a factor of 2 whereas our models show that the same terminal velocity is reached in both lines. Although the limited spectral resolution may affect velocity measurements, the radial velocity difference between Si IV $\lambda\lambda$1393/1402 and C IV $\lambda\lambda$1548/50 is probably real. However, we suggest that the two lines in NGC 7714 are due to stars in different mass regimes with different wind properties (including v_∞). Population synthesis is required to prove or disprove this hypothesis.

A starburst scenario with a significant number of post-main-sequence stars has also been proposed by Augarde and Lequeux (1985) for the interacting galaxy complex Mk 171 and by Lamb, Hunter, and Gallagher (1987) for the blue irregular galaxies NGC 1140 and NGC 4449. Spectral synthesis models assuming a star-formation rate constant with time and a negligible population of post-main-sequence stars are not applicable in this case.

5.3. *Population Synthesis of an Evolved Starburst*

Deriving properties of the initial mass function of massive stars from the ratio of the Si IV and C IV absorption lines requires detailed modeling of stellar wind properties. Variations in the stellar winds of stars in different galaxies can change the calibration between the slope of the initial mass function and W_λ(Si IV)/W_λ(C IV) obtained from Galactic stars. If evolved stars contribute to the observed equivalent ratio, the stellar wind properties enter in a second, indirect way. In this case, the spectral synthesis models heavily depend on the evolutionary history of the OB population, which in turn critically depends on the stellar mass-loss rates (see Chiosi & Maeder 1986). In § 2 we mentioned the importance of mass loss on the main sequence and during later evolutionary epochs. While mass loss has negligible evolutionary consequences for massive stars still close to the zero-age main sequence, it is of crucial importance for later stages of the evolution of massive stars. Stellar mass loss increases rapidly as soon as the stars reach the terminal-age main-sequence. Let us emphasize that *main-sequence stars and supergiants may have different meaning in terms of stellar spectroscopy and stellar evolution.* Stars are defined to be of luminosity class V and I on the basis of spectral line ratios. Traditionally, stars of luminosity class I (supergiants) are associated with post-main sequence stars beyond their core-hydrogen burning phase. This assumption is correct in low- and intermediate-mass stars but not necessarily in massive stars above about 20 $M_\odot$. In fact, a large fraction of O stars *classified* as giants or supergiants is most probably still core-hydrogen burning and—from an evolutionary point of view—they are still main-sequence stars (see Fig. 1 in Leitherer 1990). Consequently, the probability of observing supergiants (in the spectroscopic sense) in a massive stellar population is highly increased and may not be negligible even if post–main-sequence stars (in the evolutionary sense) are not expected to be present. van Bruegel et al. (1985) reported the detection of weak Wolf-Rayet emission features in NGC 7714. The presence of Wolf-Rayet stars implies that the late phase of a short starburst is observed. Although these observations need additional confirmation, they give at least some confidence that a significant population of massive post–main-sequence stars contributes to the overall spectrum of NGC 7714. In this case, relatively uncertain stellar models with mass loss covering late evolutionary phases are required and make theoretical predictions rather difficult. In addition, mixing processes occurring in the interior of evolved massive stars make stellar evolution beyond the core-hydrogen burning phase relatively uncertain—at least if such models are to be used *quantitatively* for population synthesis.

Recently Maeder (1990) published a set of stellar evolutionary models for massive stars at various metallicities. In principle, these models can be used to provide the stellar parameters required as an input for our line-profile calculations. In practice, however, the evolution of a massive star is critically dependent on the mass-loss properties during short episodes of high $\dot{M}$ (e.g., the luminous blue variable phase or the red supergiant phase), which are not necessarily controlled by radiation pressure on spectral lines and are poorly known. We speculate that the observational and theoretical errors inherent in these evolutionary models would mask any effect produced by an IMF variation if these models are implemented in a population synthesis code to predict the strengths of Si IV $\lambda\lambda$1393/1402 and C IV $\lambda\lambda$1548/50. As a future project we are planning to test this hypothesis by actually extending our line-profile calculations to a larger grid of stellar parameters and by doing a population synthesis. The purpose of the present paper, however, is to study the principle astrophysical mechanisms operating in stellar winds of massive stars and to discuss the consequences for population synthesis work of starburst galaxies.

6. CONCLUSIONS

The UV resonance lines of Si IV $\lambda\lambda$1393/1402 and C IV $\lambda\lambda$1548/50 are a sensitive tracer for the presence of hot stars in galaxies undergoing a phase of massive star formation, such as starburst galaxies. Since the Si IV and the C IV lines sample two different regions of the mass spectrum of massive stars, they are dependent on the properties of the initial mass function. In principle, parameters of the IMF, such as the slope α, can be inferred from the ratio of the equivalent widths W_λ(Si IV)/W_λ(C IV), as has been suggested in the literature. We computed a set of radiatively driven wind models together with the corresponding Si IV $\lambda\lambda$1393/1402 and C IV $\lambda\lambda$1548/50 line profiles for massive stars having 60 $M_\odot$ and 25 $M_\odot$ on the zero-age and the terminal-age main sequence, respectively. The models span the metallicity range 0.033 $Z_\odot \leq Z \leq 3.0\ Z_\odot$. We investigated the behavior of the equivalent widths of Si IV $\lambda\lambda$1393/1402 and C IV $\lambda\lambda$1548/50 as a function of metal abundance. In particular, we focussed on the validity of the assumption that the ratio of the two equivalent widths is independent of the metal content of the star. This assumption has frequently been made in previous studies when observed variations of W_λ(Si IV)/W_λ(C IV) were ascribed to variations of the IMF. It has been demonstrated in this paper that this assumption is not true.

Detailed modeling is required before Si IV $\lambda\lambda$1393/1402 and C IV $\lambda\lambda$1548/50 can actually be employed to derive parameters of the IMF quantitatively. The use of the Si IV and C IV resonance lines is severely hampered due to the following reasons:

(i) Regions of massive star formation are often embedded in gas and dust clouds. Absorption along the line of sight in such gas clouds can generate sufficient opacity so that the resulting line strengths of Si IV $\lambda\lambda$1393/1402 and C IV 1548/50 may be non-negligible with respect to the stellar lines. Observations of individual Galactic stars support this hypothesis; high-resolution data are able to resolve Si IV $\lambda\lambda$1393/1402 and C IV $\lambda\lambda$1548/50 into stellar and interstellar components, and the interstellar component turns out to be non-negligible in some cases. This effect may systematically influence the observed Si IV and C IV line strengths in distant galaxies.

(ii) Systematic differences in the stellar parameters of massive stars in starburst galaxies as compared to Galactic stars are likely to exist. Such differences may be different metal content, different helium content, a different mass-luminosity relation on the main-sequence, or a different effective temperature scale. Even relatively modest variations of one or more of these quantities can change the stellar wind properties of massive stars. As a consequence, the UV resonance lines of Si IV and C IV will deviate in their strength from what we observe in Galactic stars. If the observed, integrated Si IV and C IV lines are due to a population of main-sequence stars, some qualitative predictions for the behavior of the two lines can be made. It has been shown in this paper that Si $\lambda\lambda$1393/1402 is typically due to *photospheric* lines arising in early B stars, whereas C IV $\lambda\lambda$1548/50 originates in *stellar winds* of O stars. Given a constant initial mass function, the ratio of the two lines should be expected to be increasing with decreasing metallicity.

(iii) At least in some cases, observations of starburst galaxies indicate the presence of an evolved population of massive stars contributing to the Si IV and C IV lines. An evolved population can be inferred from the presence of *blueshifted* Si IV $\lambda\lambda$1393/1402 even without complicated modeling. Blueshifted Si IV $\lambda\lambda$1393/1402 indicates stellar winds with mass-loss rates higher than observed in main-sequence stars. This effect has been well-established observationally in Galactic stars and can be understood in terms of the prediction of the radiatively driven wind theory. However, detailed modeling of the evolutionary history of massive stars is necessary before the spectral appearance of the OB star population can be synthesized *quantitatively*. In this case, the mass-loss characteristics of the stars enter in two ways: *directly* by affecting the predicted line strengths and *indirectly* by modifying the evolutionary tracks in the Hertzsprung-Russell diagram and by modifying the stellar lifetimes. Reliable evolutionary models for massive stars at various metallicities are only beginning to become available and have not yet been implemented self-consistently in population synthesis models. Previous efforts to synthesize the massive star content of starburst galaxies on the basis of the Si IV $\lambda\lambda$1393/1402 and C IV $\lambda\lambda$1548/50 lines should therefore be considered as unreliable.

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