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SYNTHETIC UV LINES OF Si IV, C IV, AND He II FROM A POPULATION OF MASSIVE STARS IN STARBURST GALAXIES

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ABSTRACT

We present the first results of our study of the massive star population in starburst galaxies based on UV data. We have synthesized the Si IV λ1400, C IV λ1550 and He II λ1640 lines for both a continuous and an instantaneous burst of star formation with approximately solar chemical composition. Our code uses the latest generation of stellar evolutionary models, stellar atmosphere codes, and a library of high-dispersion *IUE* spectra of hot stars. Models were computed for various values of the IMF parameters.

Si IV λ1400 and C IV λ1550 develop P Cygni profiles when formed in strong stellar winds from the most massive stars. The velocity shifts predicted for these lines give a tight constraint on the value of the IMF upper mass cutoff: strong blueshifts in both lines are produced if stars with an initial mass larger than 30–60 $M_\odot$ are included in the models. Based on the line velocity shifts, it also seems possible to put limits on the burst age. The models show only a small dependence of the line velocity shifts on the IMF slope. We also find a significant dependence of the equivalent widths of Si IV λ1400 and C IV λ1550 on the burst age, the IMF upper cutoff mass, and the IMF slope. The He II λ1640 line shows a strong broad emission profile when formed in winds from evolved massive stars. If offers additional important clues to the burst age and the IMF upper cutoff mass.

We have compared the model parameters with data obtained for an average galaxy spectrum formed by combining low-dispersion *IUE* spectra of 13 starburst galaxies with nearly solar chemical composition. The most interesting result, based on the Si IV λ1400 and C IV λ1550 line velocity shifts and the strength of the broad He II λ1640 emission line, is that evolved massive stars with an initial mass larger than 30 $M_\odot$ must be present in most of these galaxies. We find a good fit to the data for a model of an instantaneous burst of age $\simeq 5 \times 10^6$ yr or a model for which star formation is proceeding at a constant rate for $\simeq 10^7$ yr. *Hubble Space Telescope* data with higher spectral resolution will be required to test these ideas and to allow us to fully exploit our method.

Subject headings: galaxies: starburst — stars: evolution — stars: formation — stars: mass loss — ultraviolet: galaxies

1. INTRODUCTION

The formation of massive stars in starburst galaxies is a phenomenon which is well established now from many indicators at all wavelengths. The strong optical and near-infrared hydrogen recombination lines imply the presence of very hot stars with substantial Lyman continuum luminosities (e.g., Rieke et al. 1980). Thermal infrared radiation has been detected by *IRAS* in many galaxies (e.g., Rowan-Robinson 1987), which is predominantly produced by dust heated by a large population of hot, massive stars. Wind-blown bubbles are frequent in galaxies with a large population of massive stars, e.g., M33 (Drissen, Moffat, & Shara 1991) and are caused by energy transfer from massive star winds and supernovae to the surrounding interstellar (IS) medium. However, the most powerful diagnostic of the presence of massive stars remains their direct spectral signatures (i.e., few models and assumptions are needed in this case). Unambiguous spectral features from massive stars are most easily found in the ultraviolet (UV) part of the spectrum (e.g., Weedman et al. 1981). Indeed, massive stars display characteristic profiles of Si IV λ1400 and C IV λ1550, for example, which are formed in their photospheres and/or winds (e.g., Walborn & Panek 1984a, b). Nevertheless, as demonstrated by Leitherer & Lamers (1991), a quantitative description of the stellar population in starburst galaxies covering a wide range in metal content based on the UV lines still requires a detailed modeling of the massive star wind properties.

Studies of the initial mass function (IMF) parameters in starburst galaxies based on the UV lines have already been undertaken. Sekiguchi & Anderson (1987) compared the ratio of the equivalent widths of the UV lines Si IV λ1400 and C IV λ1550 (W_{Si}/W_C) of starburst galaxies and H II regions with model values from a stellar library at solar metallicity ($Z_\odot$). They concluded that the IMF slope for a starburst must be flatter on average than in the solar neighborhood. Scalo (1990) reviewed the use of W_{Si}/W_C to determine the IMF parameters. Along with other starburst observables, Mas-Hesse & Kunth (1991) concluded that W_{Si}/W_C could also be useful to constrain the age of the starburst.

In this paper, we will demonstrate the importance of considering the velocity shifts of the resonance UV lines Si IV λ1400 and C IV λ1550 while investigating the massive stellar content of starburst galaxies. Weedman et al. (1981) had already noticed that outflows from massive stars (which result in P Cygni–type profiles for the UV Si IV λ1400 and C IV λ1550 lines in individual massive star spectra) could be recognized in the spectra of the prototype starburst galaxy nucleus, NGC

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7714. Special attention is also devoted to the recombination line He II λ1640 which appears as a broad emission line in evolved massive stars with fast and dense stellar winds. The motivation for this new project is provided by the upcoming acquisition of *HST* UV spectra of starburst galaxies at relatively high spectral resolution and high signal-to-noise ratio. With existing low-dispersion data from *IUE*, the measurement of velocity shifts and equivalent widths in galaxy spectra is of limited accuracy. However, as we will show below, some clues to the massive star population in starbursts can be gleaned even from *IUE* data.

Using the latest generation of stellar evolution models, stellar atmosphere codes, and a line profile library mostly based on *IUE* high-dispersion spectra, we synthesize (§ 2) Si IV λ1400, C IV λ1550, and He II λ1640 formed in starbursts characterized by various IMF parameters. In § 3 we compare and discuss the line equivalent widths and velocity shifts obtained from the synthetic spectra with the average values extracted from a sample of low-dispersion *IUE* spectra of starburst galaxies with nearly $Z_{\odot}$. In subsequent papers, we will present a systematic study of the equivalent widths and the velocity shifts in the UV lines of individual stars used to build the actual spectral library and we will show more applications of this method to individual starburst galaxies with high-quality *HST* spectra.

2. THE POPULATION SYNTHESIS MODEL

The line profiles of Si IV λ1400, C IV λ1550, and He II λ1640 are synthesized by summing the different contributions of stars present in the burst at different time steps. We emphasize here the fact that we do evolutionary synthesis, not spectral synthesis. We adopt Maeder's (1990) stellar evolutionary tracks at $Z_{\odot}$ for which an interpretation is done for a mass interval of 1 $M_{\odot}$. We use a time resolution of 10^4 yr to follow in detail short evolutionary phases of the most massive stars. The IMF is taken as a power-law whose slope (α) and lower and upper mass limits (M_l and M_u) are varied. Two types of starbursts are studied, one with a constant star formation rate (i.e., a continuous burst) and one with an instantaneous (delta function) burst of star formation.

The stellar spectra, which are summed by the evolutionary models to creat the synthetic lines, are taken from a library of average high-dispersion *IUE* spectra in the case of O stars and Wolf-Rayet (W-R) stars and average low-dispersion *IUE* spectra for B stars. Table 1 lists the different groups of stars used to create the average spectra representing different spectral types and luminosity classes for O stars and spectral subtypes and chemical sequences for W-R stars. The individual O and W-R star spectra were taken from the work of Howarth & Prinja (1989) and St.-Louis (1990), respectively. In the case of the B stars, we used the average spectra already combined by Fanelli et al. (1992). For late-type stars, we simply adopt a featureless spectrum (i.e., with no lines). This is acceptable since the individual UV line and continuum contributions from these stars are negligible (e.g., Mas-Hesse & Kunth 1991).

In the synthesis code, we use the spectral type calibration from Schmidt-Kaler (1982) for the O, B, and late-type stars The W-R stars, which are believed to be the descendants of stars with masses above 20–30 $M_{\odot}$, are defined by a surface hydrogen content H/He < 0.4 and log ($T_{\rm eff}$) > 4.4 (Maeder 1991). We omit the light from supernova explosions and supernova remnants since they do not represent important UV flux contributors (e.g., Blair & Panagia 1987; Blair et al. 1989). The continuum flux level in the stellar UV spectrum is calibrated using the atmospheric models of Kurucz (1992) for all types of stars except W-R stars. In the case of W-R stars, although their total UV contribution is relatively small compared to O stars (mainly because they are very numerous, e.g., W-R/O < 0.1 for a continuous burst; Robert, Drissen, & Leitherer 1992), we use the models of Schmutz, Leitherer, & Gruenwald (1992) which account for an expanding envelope.

In the UV spectral range, the stellar features are often blended with narrow IS absorption lines. In the Si IV λ1400 and C IV λ1550 lines of many late O stars, for example, it is not possible to separate the IS component from the narrow photospheric contribution. Therefore, we did not remove the IS lines present in any of the library spectra.

The synthetic profiles are created only at $Z_{\odot}$ (approximately) since we are limited to *IUE* spectra of individual stars located in the solar neighborhood. The chemical composition of these stars is close to, or somewhat below, solar. In the models, the evolutionary tracks are taken at $Z_{\odot}$ for consistency. This limitation is important to remember when comparing the synthetic spectra with observed spectra of starbursts which can cover a wide range in metal content.

2.1. *Massive Star Population in Models of Starbursts*

Figure 1 shows the relative number of massive stars computed by our synthesis code for an instantaneous and a continuous burst as a function of time using the IMF parameters: $\alpha = 2.35$ (e.g., Salpeter's slope), $M_l = 1\ M_{\odot}$, and $M_u = 120\ M_{\odot}$. The W-R stars, the descendants of the most massive stars, start to appear after $10^{6.3}$ yr, just before the B giants and supergiants. As they end their life in supernova explosions in these models (however, see Filippenko 1991), the W-R stars disappear after $\simeq 10^{6.9}$ yr in the case of the instantaneous burst. The O star population of the instantaneous burst also vanishes after $\simeq 10^{6.9}$ yr, while the number of B giants and supergiants is increasing. In the case of the continuous burst, an equilibrium between stellar birth and death is reached after 10^7–10^8 yr, which stabilizes the number of stars in the different evolutionary phases.

Although the relative number of stars changes in a simple fashion as a function of time, the important contributors to the integrated spectrum formed from these stars vary as one considers either the continuum flux or the spectral features. For example, Leitherer (1993) demonstrated that the Balmer continuum around 2000 Å is typically emitted by late O and early B stars (ZAMS masses around 15 $M_{\odot}$). The most massive stars ($M > 60\ M_{\odot}$) are responsible for the photons emitted in the H^0 and He^0 continuum (i.e., from 228 to 911 Å). Interestingly, the ZAMS masses of the contributors to the He^+ continuum (i.e., <228 Å) are only $\sim$30 $M_{\odot}$. On the other hand, objects with higher masses, $\gtrsim$30 $M_{\odot}$, are responsible for strong spectral features, in Si IV λ1400, C IV λ1550, and He II λ1640, for example, as indicated in the following section.

2.2. *Synthetic Profiles of* Si IV λ1400, C IV λ1550, *and* He II λ1640

Si IV λ1400 and C IV λ1550 are resonance lines which may be formed in the IS medium, stellar photospheres, and stellar winds. He II λ1640 is a broad recombination line observed in emission for massive stars with fast and dense stellar winds. As we will see below, in the integrated spectrum of a starburst, the dominant origin of formation of these three lines, and therefore the profile shape and strength of the lines, will be highly vari-

TABLE 1

STARS USED FOR THE O AND W-R SPECTRAL LIBRARIES

Group Name	Stars	Spectral Type	Group Name	Stars	Spectral Type	Group Name	Stars	Spectral Type	Group Name	Stars	Spectral Type
O3 V	HD 93205	O3 V		HD 48279	O8 V		HD 135591	O7.5 III((f))		BD 602522	O6.5(n)(f)p[b]
	HD 93250	O3 V((f))		HD 58509	O8 V[a]		HD 164492	O7.5 III((f))	O7–7.5 I	HD 57060	O7 Ia:fpvar
	HD 303308	O3 V((f))		HD 60848	O8 V[a]		HD 186980	O7.5 III((f))		HD 152248	O7 Ib:(n)(f)p
O4 V	HD 46223	O4 V((f))		HD 96670	O8 p[b]		HD 203064	O7.5 III:n((f))		HD 188001	O7.5 Iaf
	HD 96715	O4 V((f))		HD 99546	O8[ab]	O8–8.5 III ..	HD 19820	O8.5 III((n))		HD 192639	O7 Ib(f)
	HD 164794	O4 V((f))		HD 101413	O8 V		HD 36861	O8 III((f))		HD 193514	O7 Ib(f)
	HD 168076	O4 V((f))	O8.5 V	HD 46149	O8.5 V		HD 47129	O8 p[b]	O8 I	HD 151804	O8 Iaf
	HD 242908	O4 V(n)		HD 73882	O8.5 V((n))		HD 74920	O8[ab]		HD 152408	O8: Iafpe
O5–5.5 V	HD 14434	O5.5 Vn((f))p		HD 100213	O8.5 Vn		HD 124979	O8.5[ab]		HD 167971	O8 Ib(f)p
	HD 15629	O5 V((f))	O9 V	HD 12323	ON9 V		BD 341058	O8[ab]	O8.5 I	HD 69648	O8.5 I[a]
	HD 46150	O5 V((f))		HD 37041	O9 V[a]	O9 III	HD 1337	O9 III:(n)		HD 74194	O8.5 Ib(f)
	HD 93204	O5 V((f))		HD 45314	O9[ab]		HD 37043	O9 III		HD 96917	O8.5 Ib(f)
	CPD 592641	O5 V		HD 46202	O9 V		HD 60369	O9 III[a]		HD 112244	O8.5 Iab(f)
O6 V	HD 39680	O6 V:[n]pevar		HD 75759	O9 Vn		HD 93249	O9 III	O9 I	HD 61347	O9 I[a]
	HD 63005	O6 V[a]		HD 91651	O9 V:n		HD 116852	O9 III[a]		HD 149404	O9 Ia
	HD 91572	O6 V((f))		HD 93028	O9 V		HD 156359	O9 III[a]		HD 210809	O9 Iab
	HD 96946	O6 V:		HD 93521	O9 V[a]		HD 191423	O9 III:n*	O9.5 I	HD 30614	O9.5 Ia
	HD 101131	O6 V((f))		HD 101008	O9 V[a]		HD 193443	O9 III		HD 37742	O9.7 Ib
	HD 101190	O6 V((f))		HD 149757	O9 V[a]		HD 218195	O9 III		HD 47432	O9.7 Ib
	HD 101298	O6 V((f))		HD 193322	O9 V:((n))	O9.5 III	HD 15642	O9.5 III:n		HD 75222	O9.5 Iab
	HD 124314	O6 V(n)((f))		HD 201345	ON9 V		HD 35921	O9.5 III:n		HD 76968	O9.7 Ib
	HD 168075	O6 V((f))		HD 209481	O9 V:		HD 112784	O9.5 III[a]		HD 93206	O9.7 Ib:(n)
	HD 199579	O6 V((f))		HD 214680	O9 V		HD 156292	O9.5 III		HD 105056	ON9.7 Iaevar
	HD 215835	O6 V(n)	O9.5 V	HD 24534	O9.5[ab]		HD 189957	O9.5 III		HD 123008	ON9.7 Iab
	CPD 592600	O6 V((f))		HD 34078	O9.5 V	O7–8 II	HD 34656	O7 II(f)		HD 149038	O9.7 Iab
O6.5 V	HD 5005a	O6.5 V((f))		HD 37468	O9.5 V[a]		HD 151515	O7 II(f)		HD 152249	OC9.5 Iab
	HD 12993	O6.5 V		HD 38666	O9.5 V		HD 162978	O7.5 II((f))		HD 152424	OC9.7 Ia
	HD 17505	O6.5 V((f))		CPD 741569	O9.5 V[a]		HD 167659	O7 II(f)		HD 154368	O9.5 Iab
	HD 42088	O6.5 V	O9 IV	HD 57682	O9 IV		HD 175754	O8 II((f))		HD 167264	O9.7 Iab
	HD 54662	O6.5 V		HD 152246	O9 III-IV((n))	O9 II	HD 57061	O9 II		HD 188209	O9.5 Iab
	HD 93146	O6.5 V((f))		HD 163892	O9 IV((n))		HD 113904B	O9 II		HD 202124	O9.5 Iab
	HD 93161AB	O6.5 V((f))	O9.5 IV	HD 96622	O9.5 IV		HD 105627	O9 II-III		HD 209975	O9.5 Ib
	HD 101436	O6.5 V		HD 152218	O9.5 IV(n)		HD 153426	O9 II-III		HD 218915	O9.5 Iab
	HD 165052	O6.5 V(n)((f))		HD 164816	O9.5 III-IV(n)		HD 207198	O9 Ib-II	WNE	HD 65865	WN4.5
	HD 206267	O6.5 V((f))		HD 191201	O9.5 IV((n))	O9.5 II	HD 13745	O9.7 II((n))		HD 187282	WN4
O7 V	HD 35619	O7 V	O5 III	HD 15558	O5 III(f)		HD 15137	O9.5 II-III(n)		HD 193077	WN5+abs
	HD 36879	O7 V(n)		HD 93403	O5 III(f)var		HD 36486	O9.5 II	WNL	HD 86161	WN8
	HD 37022	O7 V[a]		HD 93843	O5 III(f)var		HD 55879	O9.5 II-III		HD 92740	WN7+abs
	HD 47839	O7 V((f))		HD 150136	O5 III:n(f)		HD 68450	O9.7 Ib-II		HD 93131	WN7+abs
	HD 48099	O7 V	O6 III	HD 108	O6:f?pe[b]		HD 92554	O9.5 II[a]		HD 93162	WN7+abs
	HD 90273	O7[ab]		HD 93130	O6 III(f)		HD 101545A	O9.5 Ib-II		HD 96548	WN8
	HD 91824	O7 V((f))		HD 152233	O6 III:(f)p		HD 118198	O9.5 II-III		HD 143414	WN6
	HD 152623	O7 V(n)((f))	O6.5 III	HD 148937	O6.5f?p[b]		HD 152247	O9.5 II-III		HD 151932	WN7
	HD 159176	O7 V+O7 V		HD 152723	O6.5 III(f)		HD 152405	O9.7 Ib-II		HD 214419	WN7
	HD 217086	O7 Vn		HD 157857	O6.5 III(f)		HD 167263	O9.5 II-III((n))	WCE	HD 76536	WC6
	CPD 592603	O7 V((f))		HD 175876	O6.5 III(n)(f)		HD 168941	O9.5 II-III		HD 92809	WC6
O7.5 V	HD 53975	O7.5 V	O7 III	HD 13268	O7[ab]	O3–5 I	HD 14947	O5 If+		HD 165763	WC5
	HD 152590	O7.5 V		HD 93222	O7 III((f))		HD 93129A	O3 If*	WCL	HD 119078	WC7
	HD 155806	O7.5 V[n]e		HD 101205	O7 IIIn((f))		HD 190429A	O4 If+		HD 136488	WC9
O8 V	HD 14633	ON8 V		HD 167771	O7 III:(n)((f))	O6–6.5 I	HD 69464	O6.5 Ib(f)		HD 156385	WC7
	HD 41161	O8 Vn	O7.5 III	HD 24912	O7.5 III(n)((f))		HD 153919	O6.5 Iaf+		HD 157451	WC9
	HD 46056	O8 Vn		HD 115455	O7.5 III((f))		HD 163758	O6.5 Iaf		HD 164270	WC9
	HD 46966	O8 V		HD 135240	O7.5 III((f))		HD 210839	O6 I(n)fp		HD 192103	WC8

NOTE.—Spectral types for O stars were taken from Walborn 1972, 1973, 1976, 1982a, b or, in the case of stars with index a, from the unpublished catalog of Garmany (see also Howarth & Prinja 1989). For stars with index b, the luminosity class is as proposed by Howarth & Prinja 1989. Spectral type for W-R stars were taken from van der Hucht et al. 1981.

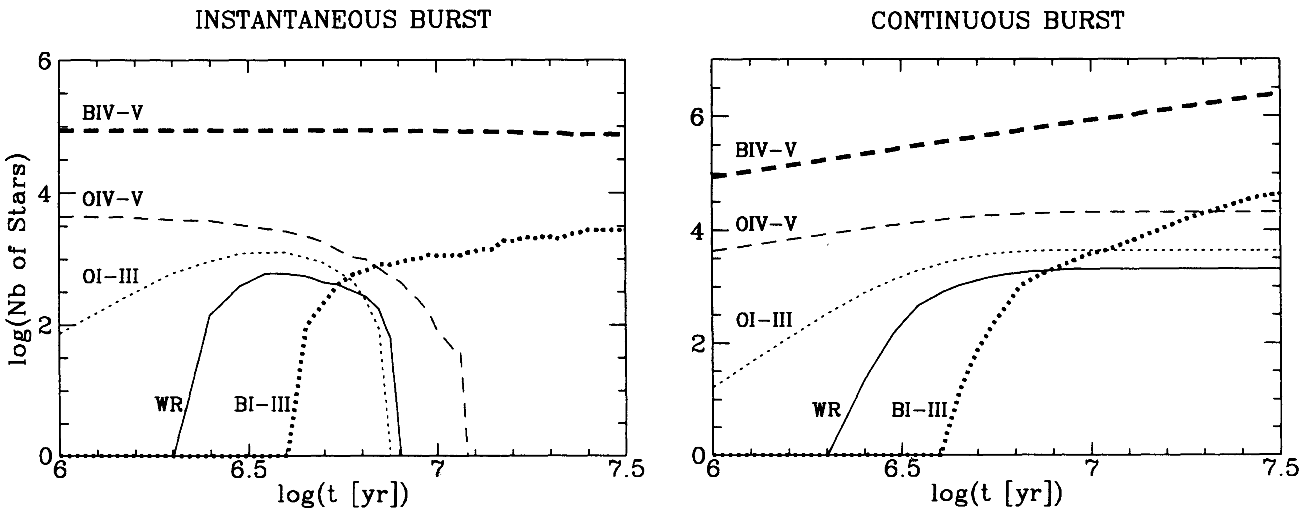

FIG. 1.—Number of stars as a function of time for an instantaneous burst of total mass 10^6 $M_\odot$ and a continuous burst with a star-formation rate of 1 $M_\odot$ yr^{-1}. Model parameters are $Z = Z_\odot$, $\alpha = 2.35$, $M_l = 1$ $M_\odot$, and $M_u = 120$ $M_\odot$.

able as a function of time and as a function of the stellar population initially considered.

The synthetic profiles of Si IV λ1400, C IV λ1550, and He II λ1640, computed for the stellar population of the instantaneous and the continuous burst described in Figure 1 are presented, at selected time steps, in Figure 2. The noise of the synthetic spectra is simply due to the noise present in the spectra used to build the stellar library.

The line profile changes due to the evolution of the stellar population are clearly recognizable in Figure 2. At $t \simeq 10^{6.5}$ yr, for the instantaneous burst, the Si IV λ1400 doublet displays a P Cygni profile (over which the IS component is superposed). Based on Figure 1, numerous O supergiants are present at this particular time. These stars, which experience a Doppler effect in their fast and dense winds, are therefore considered responsible for the peculiar profile shape observed. At $t \geq 10^{6.8}$

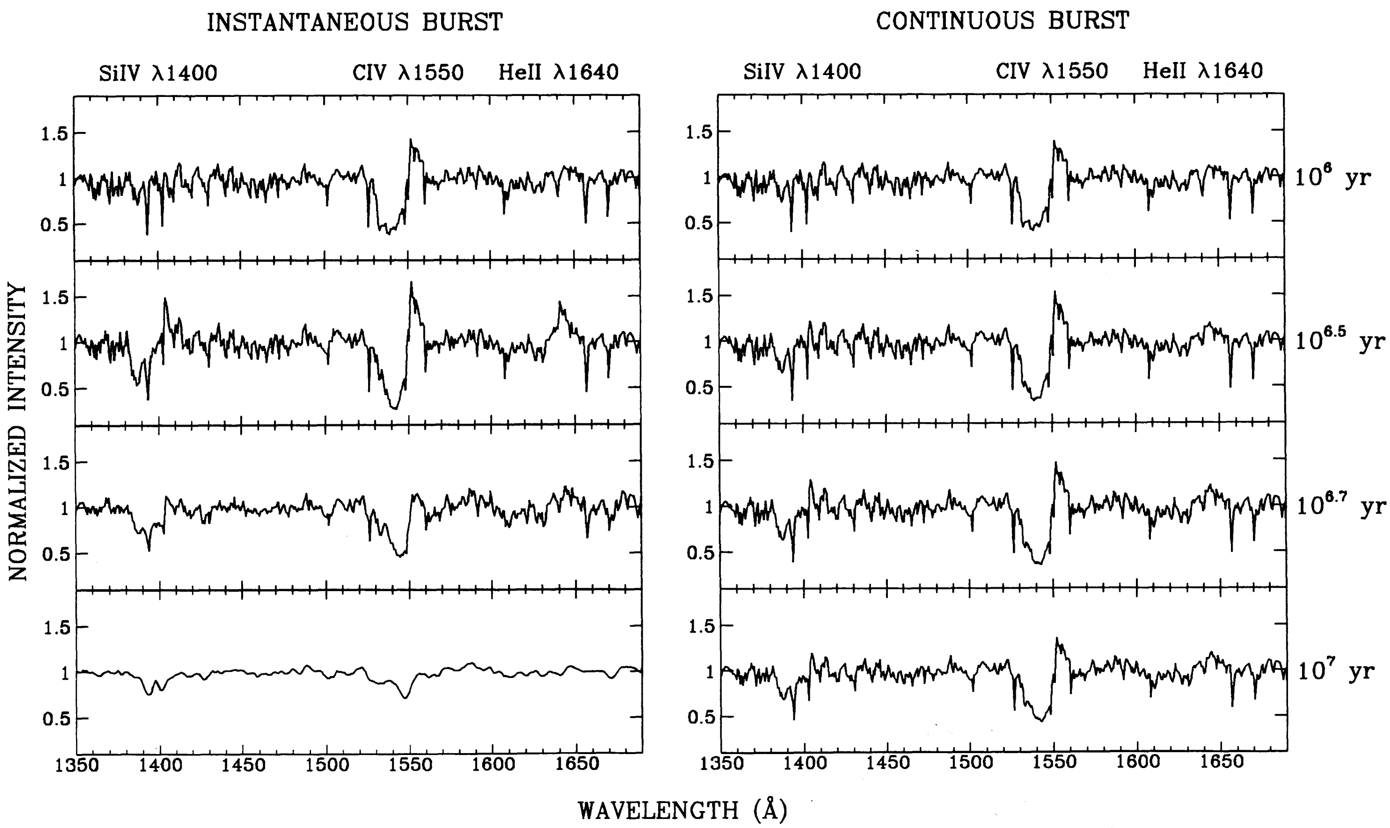

FIG. 2.—Time sequence of synthetic lines for an instantaneous and a continuous burst. Model parameters are as in Fig. 1.

yr, the Si IV $\lambda 1400$ doublet is broad but not blueshifted anymore. Collisional broadening in the photosphere of B stars, which have become the dominant contributors, is responsible for this new profile shape. (The change in the noise level at late time steps, when the lines are dominated by the B star population, is mainly due to the fact that the spectral for B stars in our stellar library are of low dispersion as opposed to the high-dispersion spectra used for O stars.)

Massive main-sequence stars with weak winds (compared to evolved stars) have a C IV $\lambda 1550$ doublet which shows a P Cygni profile at an earlier burst age than does Si IV $\lambda 1400$. This is due to a larger optical depth in the wind for the C^{+3} ion. The C IV $\lambda 1550$ line increases in strength and becomes narrower as the O supergiants become more important ($t \simeq 10^{6.5}$ yr). The line width change is caused by the reduced Doppler shift in the slower winds from O supergiants (the average velocity for late O supergiant winds is 1800 km s^{-1} compared to 2200 km s^{-1} for late O giants; Prinja, Barlow, & Howarth 1990). At late time steps, the photospheres of B stars are responsible for a weak, unshifted C IV $\lambda 1550$ feature.

The He II $\lambda 1640$ line evolves from a narrow absorption line to a broad emission line to finally no feature at all. The strongest emission is seen around $10^{6.5}$ yr, which corresponds to a peak in the W-R star population. Before this period, the photospheres of O main-sequence stars account for the narrow absorption feature.

In the continuous burst, the profiles remain identical after $\simeq 10^{6.5}$ yr due to the equilibrium between star formation and stellar death of the most massive stars.

2.3. *Equivalent Widths and Velocity Shifts in Synthetic Profiles*

We have measured the equivalent width (W) and the velocity shift (V) in the synthetic profiles for various models. The equivalent width is simply given by the integral of the flux (in our case we normalized the continuum to unity) between two fixed boundaries λ_1 and λ_2:

$$W = \int_{\lambda_1}^{\lambda_2} (1 - I_\lambda) d\lambda .$$

We integrated between the limits 1380–1415 Å for Si IV $\lambda 1400$, 1523–1576 Å for C IV $\lambda 1550$, and 1625–1655 Å for He II $\lambda 1640$. This method sums all contributions, i.e., both absorption and emission if present.

The wavelength used to calculate the velocity shift was obtained by measuring the wavelength at which the integrated absolute flux is equal to half of the total integrated absolute flux in the line:

$$V = \frac{(\lambda_x - \lambda_r)}{c} ,$$

where λ_x is given by

$$\int_{\lambda_1}^{\lambda_x} |(1 - I_\lambda)| d\lambda = 0.5 \int_{\lambda_1}^{\lambda_2} |(1 - I_\lambda)| d\lambda .$$

The rest wavelength (λ_r) for Si IV $\lambda 1400$ and C IV $\lambda 1550$ were taken from Morton's (1991) table of atomic data for resonance absorption lines. From this table, we adopted the multiplet average wavelengths (weighted by the component intensity): 1396.747 and 1549.052 Å for the two lines, respectively. For the recombination He II $\lambda 1640$ line we used Moore's (1945) value: 1640.441 Å.

A supplementary parameter, the first moment of the line, was also measured to obtain an exact description of the shape of the lines. The equivalent width, as defined here, is a poor parameter to described a P Cygni profile (e.g., a strong P Cygni profile and no line at all can both have an equivalent width of about zero). The first moment of the line is defined by

$$M = \int_{\lambda_1}^{\lambda_2} \frac{(\lambda - \lambda_r)(1 - I_\lambda)}{\lambda_r} d\lambda .$$

For a simple absorption line centered at the rest wavelength one will get $M = 0$, while in the case of a P Cygni profile, $M < 0$.

Efforts have been made to exclude IS lines while selecting the line boundaries. Unfortunately it was not possible to avoid all of them. For example, the IS line of Si II $\lambda 1527$ is often seen blended with the absorption component of C IV $\lambda 1550$ in O stars at certain evolutionary phases. Of greater concern are the IS contributions of the Si IV $\lambda 1400$ and C IV $\lambda 1550$ lines themselves. As mentioned in the previous subsection, there are time steps where these IS lines can dominate the profiles. Additional contamination of the lines may be caused by the stars themselves, e.g., the weak O photospheric lines Fe V $\lambda 1388$ and Fe IV $\lambda 1533$ (Nemry, Surdej, & Herniaz 1991). Independent of time, we have always considered the same line boundaries. When comparing the synthetic profile parameters with those observed for starbursts, one has to remember that both the spectra in the stellar library and the spectra of the starbursts will suffer from contamination by the IS lines and the stellar photospheric lines. Although the IS contribution in the two cases (the stellar library and the galaxies) may differ, we consider it important to use the same measurement technique for the synthetic spectra and the galaxies.

Figures 3 and 4 present the equivalent widths, the first moments of the line, and the velocity shifts measured in the three lines for the continuous and the instantaneous burst models using various IMF parameters. The ratio of the equivalent width W_{Si}/W_C is also drawn for comparison with previous studies. Let us first comment on the line equivalent widths for a model which considers stars in a broad range of masses (i.e., up to 120 $M_\odot$). When evolved massive stars start to appear in the synthesized galaxy (i.e., around $10^{6.5}$ yr), W_{Si} increases. As seen in Figure 2 and indicated by a large negative value of M_{Si}, at this particular time Si IV $\lambda 1400$ develops a strong P Cygni profile due to evolved massive stars with strong stellar winds. When the evolved massive stars are no longer present in the instantaneous burst Si IV $\lambda 1400$ is dominated by a photospheric and IS contribution and W_{Si} decreases.

C IV $\lambda 1550$, which already shows a P Cygni profile in massive main-sequence stars (as indicated by M_C), displays an almost constant value for W_C until $\simeq 10^{6.7}$ yr. After this period, evolved massive stars, in the case of the instantaneous burst, are disappearing and C IV $\lambda 1550$ presents a photospheric-IS absorption profile (i.e, $M_C \rightarrow 0$).

W_{He} seems to be a good indicator of when evolved massive stars with strong and dense stellar winds, like W-R stars, are present in burst. The He II $\lambda 1640$ line shows strong emission around $10^{6.5}$ yr. The value of M_{He} differs from zero, as it would be expected for a symmetrical emission line, due to the IS lines C I $\lambda 1657$ located close to the red wavelength boundary used to calculate the line parameters.

As the IMF slope is increased (Fig. 3), i.e., as the number of high mass stars is reduced relative to the number of low-mass

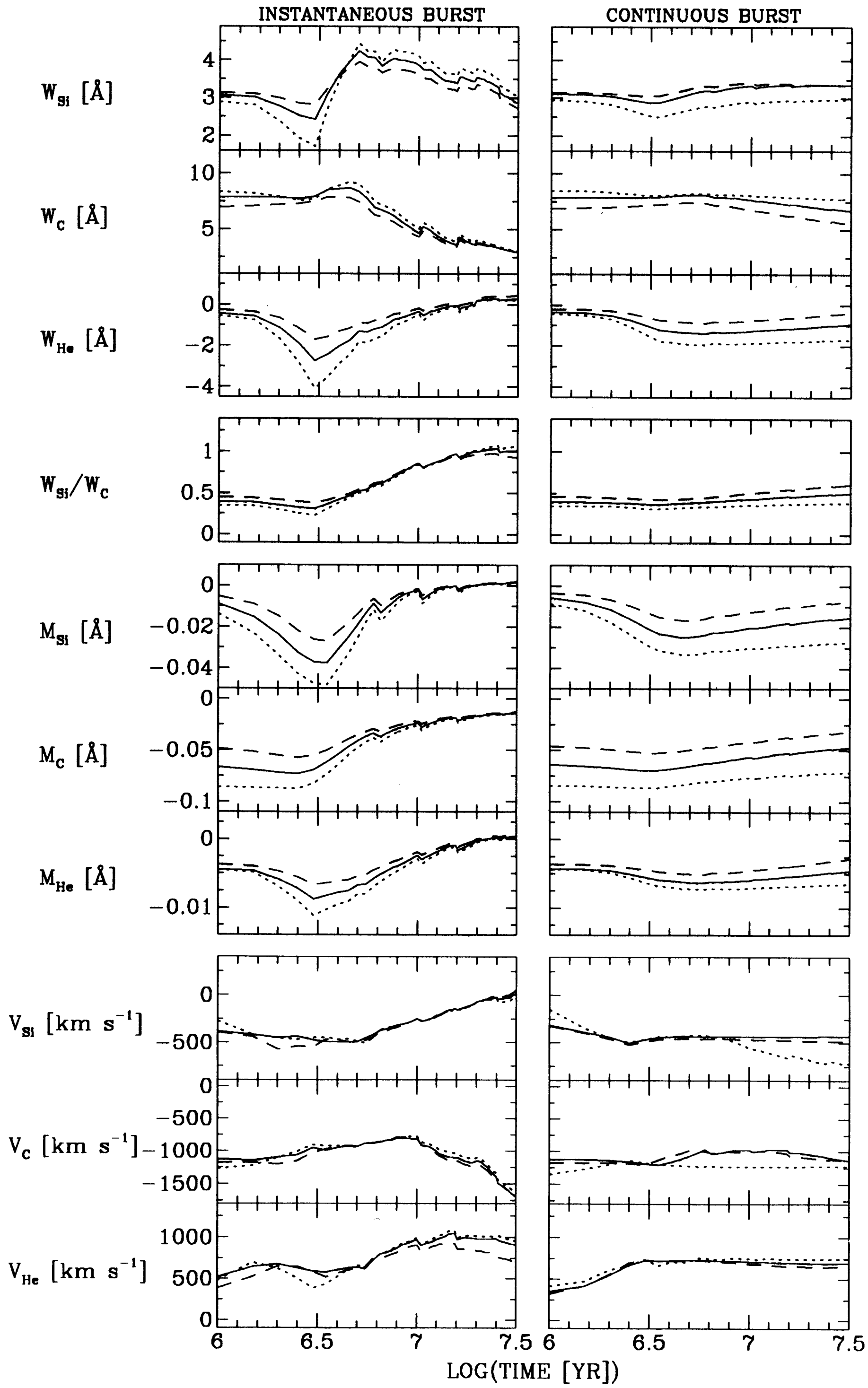

FIG. 3.—Equivalent width, first moment of the line, and velocity shift of Si IV λ1400, C IV λ1550, and He II λ1640 as a function of time for an instantaneous and a continuous burst. Results are presented for three different values of the IMF slope: $\alpha = 3.00$ (*dashed line*), 2.35 (*solid line*), and 1.5 (*dotted line*). Model parameters are $Z = Z_\odot$, $M_l = 1\ M_\odot$, and $M_u = 120\ M_\odot$.

stars, fewer important contributors to C IV λ1550 and He II λ1640 are present, which results in a decreasing value of W_C and $|W_{He}|$. At early ages of the instantaneous burst, for a large IMF slope, W_{Si} is stronger because less massive stars, which are the main contributors to this profile, dominate the population. There is only a small change of W_{Si} with time when a large IMF slope is considered because only a few massive stars are present in this case.

As seen in Figure 4, when stars more massive than 30 $M_\odot$ are missing in the burst, vitually no P Cygni profile is present in Si IV λ1400 and C IV λ1550 and no emission is seen in He II λ1640. For the instantaneous burst, for which no star is added

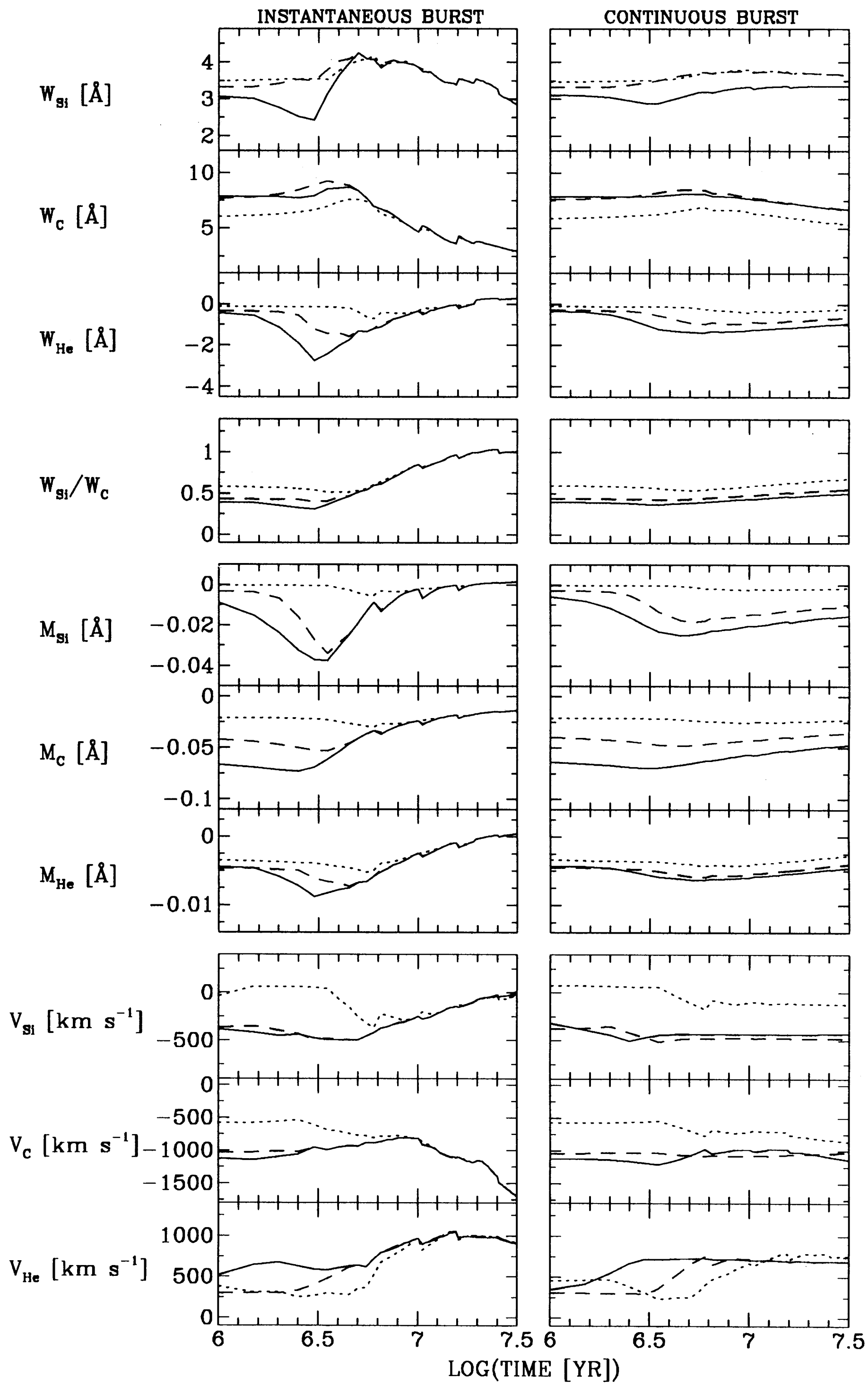

FIG. 4.—Equivalent width, first moment of the line, and velocity shift of Si IV λ1400, C IV λ1550, and He II λ1640 as a function of time for an instantaneous and a continuous burst. Results are presented for three different values of the upper mass limit: $M_u = 120\ M_\odot$ (*solid line*), 60 $M_\odot$ (*dashed line*), and 30 $M_\odot$ (*dotted line*). Model parameters are $Z = Z_\odot$, $\alpha = 2.35$, and $M_l = 1\ M_\odot$.

after the initial time, there is no distinction between the three models with M_u = 30, 60, or 120 $M_\odot$ after $\simeq 10^{6.9}$ yr. Indeed, after this critical time, stars with evolutionary timescales $\leq 10^7$ yr, if they were initially present, have disappeared and the population of stars contributing to the lines is identical in the three models.

In the case of the instantaneous burst, the increase of W_{Si}/W_C with time is caused by a decreasing number of O stars (refer to Fig. 1), which are the dominant contributors to C IV λ1550, while the number of B giants and supergiants, which become the primary contributors to Si IV λ1400, is slowly increasing. A very similar time behavior was found by Mas-Hesse & Kunth

(1991) for both types of bursts. There is a difference of the absolute value of the ratio obtained by Mas-Hesse & Kunth and us, most probably due to the different method used to define the equivalent widths (Mas-Hesse & Kunth considered only the absorption part of the profiles). We prefer to adopt our definition of the equivalent width, which includes the absorption and the emission part. This definition is more relevant to observational data of starburst galaxies where the absorption and the emission components are often blended.

Very small variations of W_{Si}/W_C are measured as the IMF slope and upper mass limit are changed. Sekiguchi & Anderson (1987), who did spectral synthesis by combining spectra from main-sequence stars only, found an increase of W_{Si}/W_C for increasing value of the IMF slope. A similar correlation was also found by Mas-Hesse & Kunth (1991) in the case of a continuous burst. For an instantaneous burst they obtained a reverse correlation after $\simeq 10^7$ yr. We believe that conclusions based on W_{Si}/W_C are very sensitive to the different method used to calculate the equivalent widths. Therefore, the parameter W_{Si}/W_C should be used very carefully when studying the IMF slope and upper mass limit of a star-forming galaxy.

Our new and most diagnostically promising results concerned the velocity shifts measured in the lines. For example, the synthesis performed by Sekiguchi & Anderson (1987), which consists of summing only the spectra of main-sequence stars, is too simplified to reproduce the velocity shifts we obtain in the UV lines.

In the case of a population covering a wide range in masses, i.e., up to 120 $M_\odot$, the Si IV λ1400 line exhibits a strong blueshift of $\simeq 600$ km s^{-1} after $\simeq 10^{6.4}$ yr when the most massive stars have developed strong stellar winds. This is mainly due to a large increase in the O giant and supergiant population as seen in Figure 1. At early phases (e.g., around 10^6 yr), Si IV λ1400 also appears to be blueshifted by $\simeq 400$ km s^{-1}. This effect is caused by the stellar feature Fe V λ1388 which is located on the blue side of the doublet. This feature generates an artificial blueshift due to our definition of the velocity shift of Si IV λ1400. In the case of the instantaneous burst, as the population of massive evolved stars dies, the P Cygni profile of Si IV λ1400 disappears and there is no line shift.

At an early burst age, a strong blueshift of $\simeq 1250$ km s^{-1} is predicted for C IV λ1550 (since the optical depth of the C^{+3} ion favors a P Cygni profile in winds of massive main-sequence stars). As the more massive stars (O stars) disappear after $\simeq 10^{6.9}$ yr, the profile is less blueshifted. Another apparent blueshift is predicted at late time steps due to the IS line of Si II λ1527, which becomes comparable in intensity to the C IV λ1550 line when C IV λ1550 weakens as the more evolved stars disappear.

We also present, for completeness, the velocity shifts measured in He II λ1640. Nevertheless, the shift measured for this line is meaningless due to the strong contamination by the IS line C I λ1657.

There is no strong dependence of V_{Si}, V_C, and V_{He} on the IMF slope (Fig. 3). Larger variations of V_{Si}, V_C, and V_{He} are predicted if the upper mass limit is highly reduced (Fig. 4). For $M_u = 30$ $M_\odot$, the most massive stars are absent and the profiles are virtually unshifted at all times.

The UV lines studied here offer no strong constraint on the lower mass limit. That is, we find no variations of the line parameters for models using different low values of M_l (i.e., < 5 $M_\odot$) since the profiles of Si IV λ1400, C IV λ1550, and He II λ1640 are dominated by the most massive star population.

3. EQUIVALENT WIDTHS AND VELOCITY SHIFTS IN STARBURST GALAXIES

Kinney et al. (1993) have published an atlas of *IUE* spectra of star-forming galaxies from which we have selected a sample of objects with a relatively high signal-to-noise ratio (i.e., S/N $\gtrsim 10$) and a chemical composition close to solar (i.e., $12 + \log(O/H) \geq 8.4$). Our sample contains 13 galaxies: Haro 15, NGC 3049, NGC 3310, NGC 3353, NGC 3690, NGC 3738, NGC 3991, NGC 4321, NGC 4449, NGC 6217, NGC 7496, NGC 7714, and UGC 5720. Although these *IUE* spectra do not represent a source of high-quality data in the context of our UV line study (due to their low signal-to-noise ratio and low dispersion), we will compare, as a first application of our method, the properties of the Si IV λ1400, C IV λ1550, and He II λ1640 lines measured in the average spectrum of these galaxies to our model predictions. The average spectrum was constructed by combining the spectra of the 13 galaxies weighted by the square of the mean signal-to-noise ratio of each spectrum. The individual galaxies are useless by themselves for a direct comparison with our model since the quality of their spectrum is very limited.

Figure 5 shows the average galaxy spectrum over which are superposed the synthetic profiles calculated for the instantaneous and continuous burst at three different time steps using $M_u = 30$, 60, and 120 $M_\odot$. The wavelength resolution of the synthetic profiles was degraded to match the resolution of the *IUE* galaxies spectra. A fairly good agreement is found for the three lines for the instantaneous burst model at $10^{6.7}$ yr and also the continuous burst model at 10^7 yr, in both cases with $M_u = 60$ $M_\odot$. For the instantaneous burst, at $10^{6.7}$ yr, a good fit is also found if we use $M_u = 120$ $M_\odot$. This is explained by the fact that the more massive stars, if initially present, have already disappeared by that time. The synthetic profiles obtained for models using $M_u = 30$ $M_\odot$ (i.e., without stars massive enough to develop the strongest and fastest winds) are too narrow on the blue side of the C IV λ1550 and (especially) Si IV λ1400 lines to fit the average galaxy spectrum well. They also do not reproduce the observed broad He II λ16400 line in the starburst spectrum. We emphasize that the broad He II λ1640 emission line cannot be confused with the narrow He II λ1640 line sometimes observed in the spectra of galaxies with nebular emission.

We do not expect a perfect agreement between one specific model and the average spectrum because, on the one hand, the average does not represent a real galaxy but a rather heterogeneous mix of individual galaxies. On the other hand, we can imagine that neither the instantaneous nor the continuous burst constitute an appropriate model for a realistic starburst galaxy. It might be more relevant to consider a burst model with a finite duration for the star formation process. Figure 5 offers one clue supporting this hypothesis. In Figure 5, as already mentioned for Figure 2, Si IV λ1400 exhibits strong emission only for a short time around $10^{6.5}$ yr in the case of the instantaneous burst. Such a strong emission component is not seen in the continuous burst models since main-sequence stars, which are continuously being born, dilute the Si IV λ1400 contribution coming from the more massive evolved stars which are responsible for the strong emission. A strong emission component is rarely, if ever, seen in the Si IV λ1400 line of starburst galaxies. Therefore, this suggests that the extreme case of the instantaneous burst is not applicable and some intermediate model between an instantaneous and a continuous burst should be considered.

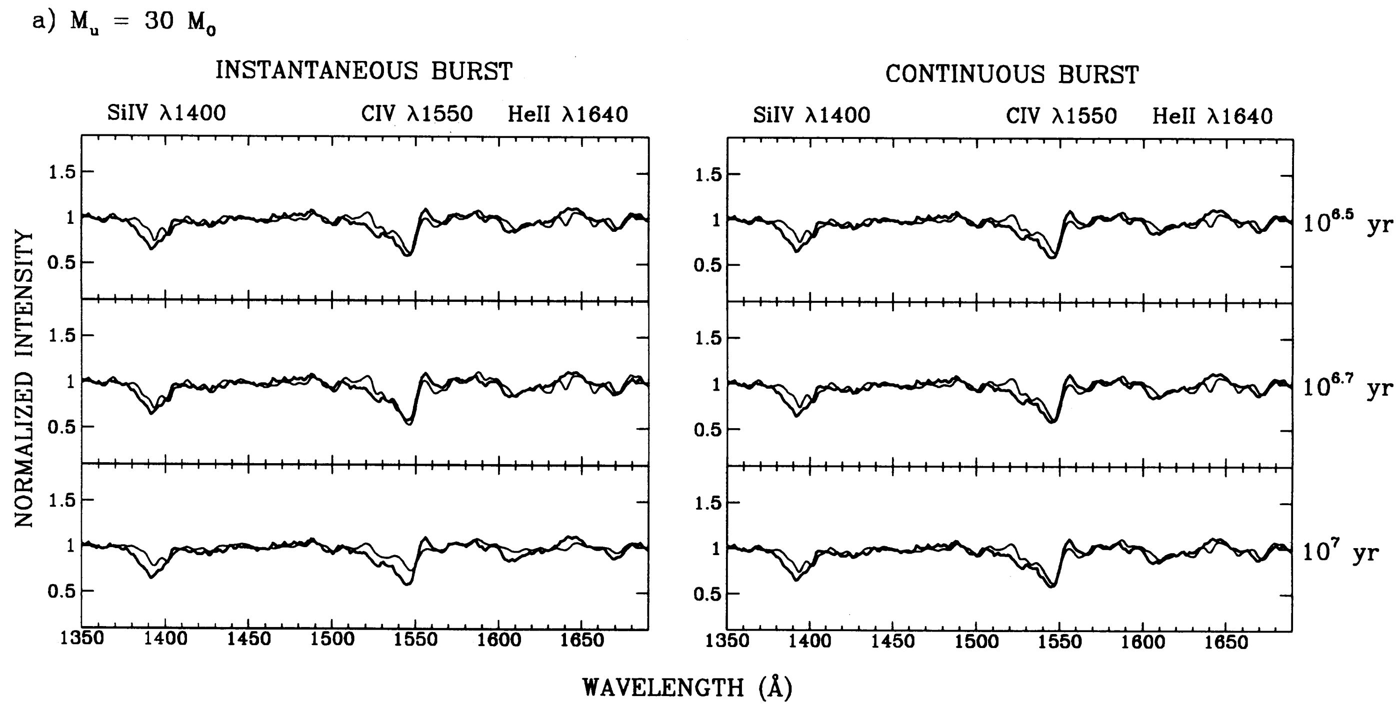

FIG. 5*a*

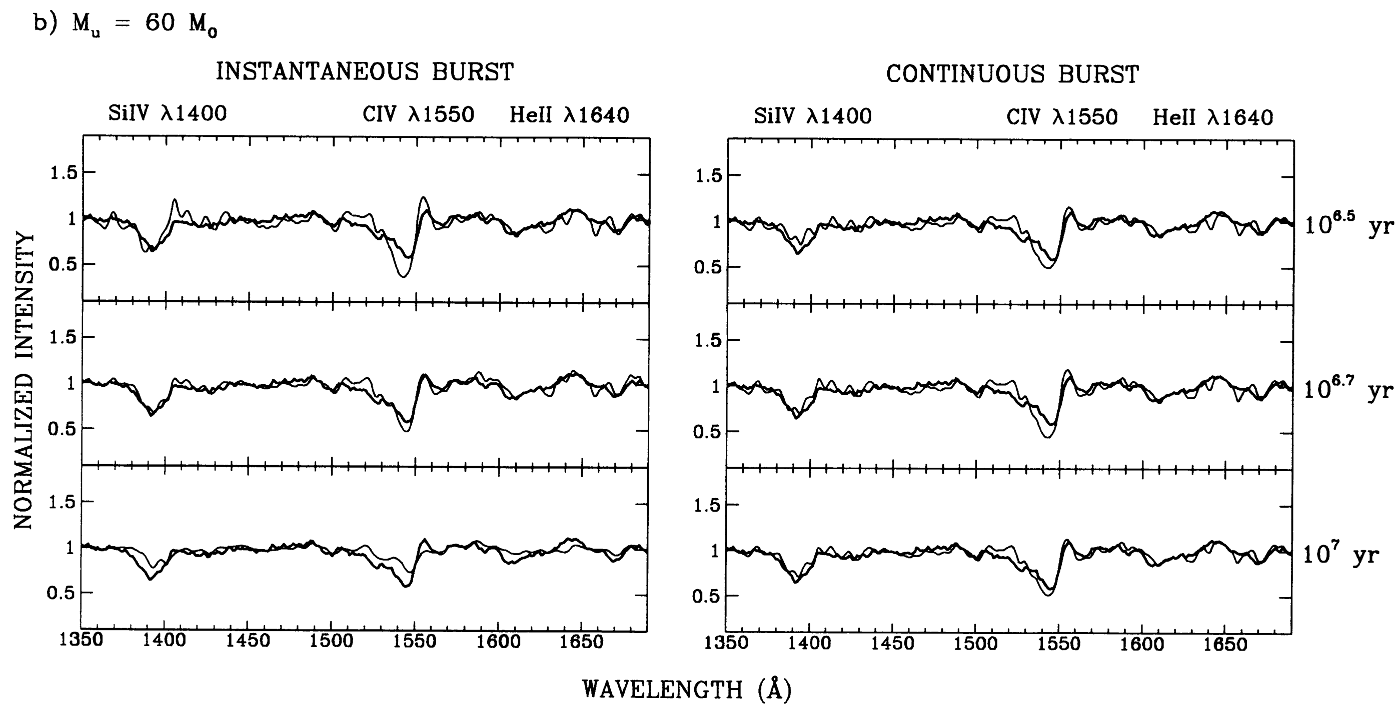

FIG. 5*b*

FIG. 5.—Superposition of the synthetic profiles (*thin lines*) on the average galaxy spectrum (*thick lines*). The synthetic profiles were calculated for an instantaneous and a continuous burst using (*a*) $M_u = 30\ M_\odot$, (*b*) $M_u = 60\ M_\odot$, and (*c*) $M_u = 120\ M_\odot$. In each case, three time steps are shown. Model parameters are $Z = Z_\odot$, $\alpha = 2.35$, and $M_l = 1\ M_\odot$.

The line parameters measured in the average galaxy spectrum are listed in Table 2. Since the values for these parameters depend principally on the choice of the level of the continuum adjacent to the lines, the uncertainties were calculated by allowing a continuum level variation of $\pm 5\%$ (i.e., the largest variation which seemed reasonable). As a check on the accuracy of the velocity scale in the *IUE* data, we also measured the mean velocity for the strongest unblended lines which are either formed in the IS medium or stellar photospheres in the starbursts: Fe II λ1608, Fe II λ2345, and Mg II λ2799. No substantial velocity shift was seen for these lines (i.e., $\bar{V} = 160 \pm 57$ km s^{-1}).

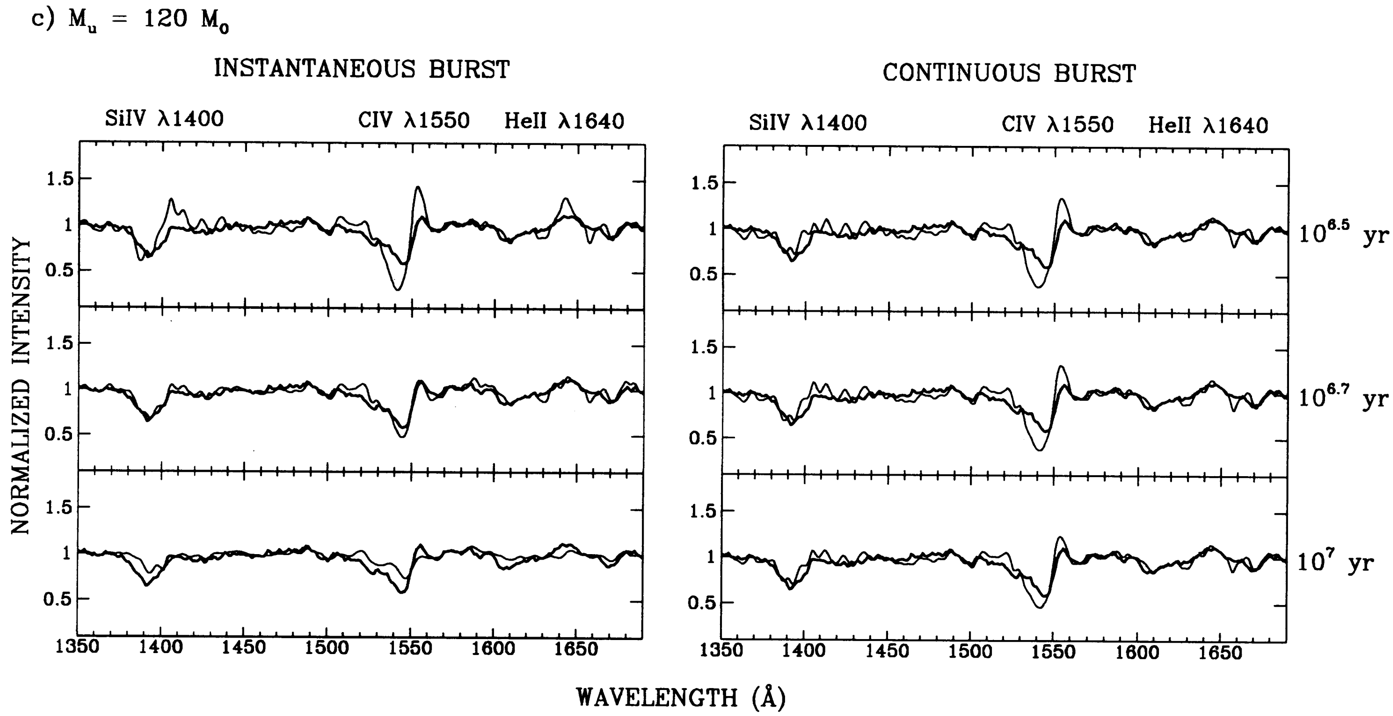

FIG. 5c

Based on our models for an instantaneous and a continuous burst (Fig. 4), the large blueshifts for Si IV λ1400 and C IV λ1550 and the strength of the emission of He II λ1640 observed in the average galaxy spectrum clearly indicated the presence of evolved massive stars with initial masses larger than 30 $M_\odot$ in most galaxies. This is in good agreement with the best fits of Figure 5. According to the velocity shifts measured for Si IV λ1400, a minimum burst age of $\simeq 10^{6.5}$ yr is predicted for either an instantaneous or a continuous burst with $M_u = 60\ M_\odot$. In the extreme case of the instantaneous burst, if one also takes into account the equivalent width measured for the Si IV λ1400 galaxy line, an average burst age of $\simeq 10^{6.8}$ yr is then deduced. This is also consistent with the constraints given by the velocity shift and the equivalent width of C IV λ1550, considering the large uncertainties of all the average galaxy parameters.

When comparing the average galaxy parameters with the model predictions one difficulty appears: the equivalent width measured for Si IV λ1400 is above the high limit given by the models. Although it was difficult to estimate the continuum level in the average galaxy spectrum compared to the model spectra, which have relatively high signal-to-noise ratio, we cannot exclude here the possibility that some additional systematic effects may modify the galaxy lines.

TABLE 2

LINE PARAMETERS FOR THE AVERAGE STARBURST GALAXY

Parameter	Value
W_{Si} (Å)	5.8 ± 1.2
W_C (Å)	7.0 ± 1.9
W_{He} (Å)	−1.5 ± 0.9
W_{Si}/W_C	08 ± 0.3
M_{Si} (Å)	−0.013 ± 0.001
M_C (Å)	−0.052 ± 0.001
M_{He} (Å)	−0.004 ± 0.002
V_{Si} (km s^{-1})	−633 ± 135
V_C (km s^{-1})	−1167 ± 181
V_{He} (km s^{-1})	+772 ± 250

Looking at the line equivalent widths of the individual stars in our spectral library, we find no stellar spectral type which displays such a large value of the Si IV λ1400 equivalent width, and C IV λ1550 and He II λ1640 values which are similar to the ones observed. Early B giants and supergiants can give line equivalent widths which are close to those measured in the average galaxy spectrum. For the early B stars, we have $W_{Si} \simeq$ 7 Å, $W_C \simeq 9$ Å, and $W_{He} \simeq 0$ Å. Also, the line profiles of these stars match the shape of the average galaxy lines well. Although early B stars can indeed be a major contributor to the average galaxy spectrum at a given time, we do not think that this alone could be a plausible explanation for the high W_{Si}. If this were the case, a narrow range in stellar masses (i.e., around 15 $M_\odot$) would be the sole contributor to the spectral feature in this wavelength range with essentially no other mass contributing.

Significant contamination of the Si IV λ1400 line by gas in the halo of our own Galaxy is unlikely to be the explanation for several reasons. (This halo contamination is not present in the library stars because these young objects are located mainly close to the Galactic plane.) First, we find no correlation between the line equivalent widths and either Galactic latitude or $E_{(B-V)}$. Second, the typical redshifts of the starbursts we have examined, which usually exceeded 1000 km s^{-1}, are large enough that the Galactic and starburst lines would be well-separated in wavelength. Finally, Galactic absorption should also be seen in the C IV λ1550 line; the mean equivalent width of Galactic Si IV λ1400 and C IV λ1550 absorption seen in *IUE* spectra of QSOs with a similar distribution in Galactic latitude to our starbursts is $\simeq$0.5–1 Å (J. C. Blades 1993, private communication).

A possible explanation could be that the IS medium in the starburst galaxies themselves is contributing to the Si IV λ1400 lines (e.g., York et al. 1990). But again, why would the Si IV λ1400 line be stronger in the starbursts, while the C IV λ1550 line is not? It may be relevant that photoionization calculations (e.g., Steidel & Sargent 1989) show that gas photoionized by ordinary hot stars will have a much greater column density in the Si^{+3} ion than in the C^{+3} ion (owing to the respective ionization potentials of 33 eV and 48 eV). On the other hand, it is most unlikely that most or all of the observed Si IV λ1400 and C IV λ1550 absorption arises in the IS medium. If this was the case, it would be difficult to understand the large blueshift seen in C IV λ1550 compared to Si IV λ1400. If contamination to the line equivalent widths to a moderate degree, the mean blueshift we measure for the Si IV λ1400 line could also be affected. In the case of contamination by IS material with small velocities, the blueshift due to the stellar population alone in the observed spectra should be large, and there should be underestimation of the number of the most massive stars. Testing this idea will require data of higher spectral resolution and signal-to-noise ratio in order to isolate the IS and stellar wind contributions to Si IV λ1400 and C IV λ1550.

4. SUMMARY

Our evolutionary synthesis of UV lines represents a method with great potential for the study of the stellar content of starburst galaxies. A major new result is the strong dependence of the velocity shifts of the Si IV λ1400 and C IV λ1550 lines on the properties of the stars formed in starburst galaxies. Whereas the equivalent widths of Si IV λ1400 and C IV λ1550 have been used before to study the population in starburst galaxies, the significance of the velocity shifts of these lines has not been recognized before as a quantitative diagnostic. We predict that a stellar-wind He II λ1640 feature is present in typical starburst galaxies containing evolved massive stars. The equivalent widths and velocity shifts predicted for the Si IV λ1400, C IV λ1550, and He II λ1640 lines are extremely useful tools to constrain the IMF parameters and the burst age.

Applying our model predictions to representative *IUE* spectra of starburst galaxies indicates that a population of stars more massive than 30 $M_\odot$ must have been present initially in the majority of the cases. This result is independent of an assumption for the burst age. For models of an instantaneous burst, an age of $\simeq 5 \times 10^6$ yr is predicted on average for the starburst sample. Our data are also well fitted by a burst in which stars are formed at a constant rate during $\simeq 10^7$ yr. A complete verification of our predictions for the Si IV λ1400, C IV λ1550, and He II λ1640 line profiles is not yet possible on the basis of the available *IUE* data. The signal-to-noise ratio and wavelength resolution of the *IUE* spectra are a severe limitation to a comparison with our models. In particular the line equivalent width is very sensitive to the adopted continuum level in the observed spectra. In addition, significant blending by nearby IS absorption lines may affect the observed parameters measured in *IUE* spectra.

High-quality data for starburst galaxies are being collected by us with *HST*. These data will allow us to test and fully exploit our method. Finally, we are developing a new stellar library of UV spectra which will give us the opportunity to study galaxies with chemical composition other than solar.

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