

The Chemical Composition of Star-Forming Galaxies at High Redshift

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Abstract. The prospects of deriving metallicities from restframe ultraviolet lines in distant star-forming galaxies are reviewed. Strong stellar-wind lines indicate recent active star formation. Broadened interstellar lines are most likely the result of mechanical energy input from winds and supernovae. I discuss metallicity estimates in galaxies at high redshift from a comparison with synthetic stellar-wind profiles. Observed correlations between metallicity and ultraviolet spectral properties in a local star-forming galaxy sample permit an independent method to constrain the chemical composition. If the local and the distant population have similar morphological properties, the line strengths and continuum slopes of high- z galaxies suggest Magellanic Cloud-like chemical composition.

1 The Restframe Ultraviolet of Star-Forming Galaxies

Normal star-forming galaxies at cosmological distances ($z > 2$) have become accessible for spectroscopic observations to 4 – 10-m class telescopes during the past few years. Most of the objects were discovered with the Lyman-break technique pioneered by C. Steidel and collaborators (e.g., Steidel & Hamilton 1993; Steidel et al. 1996). Additional galaxies were found serendipitously (e.g., Yee et al. 1996; Ebbels et al. 1996), mostly as a result of strong brightness amplification by an intervening lens. The Hubble Deep Field (Williams et al. 1996) has provided another incentive to search spectroscopically for distant star-forming galaxies, with a rather positive outcome (Lowenthal et al. 1997).

The best studied object to date is 1512-cB58 (hereafter cB58), a galaxy at $z = 2.723$ which is gravitationally lensed with an amplification factor of about 20 (e.g., Seitz et al. 1998). Due to its apparent brightness of $V = 20.6$, restframe ultraviolet (UV) spectra with $S/N = 50$ and at a resolution of 3.5 \AA can be obtained with 10-m class telescopes. The quality of such spectra is comparable to (or even better than) those of local starburst galaxies observed with HST between 1200 and 2000 \AA (e.g., Conti et al. 1996). Therefore it is becoming feasible to attempt a quantitative analysis of the UV restframe spectrum in order to investigate the properties of stars and gas. A particularly important question is “*What is the chemical composition of these galaxies?*” Classical abundance analyses from optical nebular emission lines are difficult, if not impossible, since most diagnostic lines are located in inaccessible windows in the near-infrared.

A Keck spectrum of cB58 was discussed by Pettini et al. (1997). The spectrum covers 1200 to 1600 \AA (restframe) and is characterized by three groups

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of absorption lines. (i) *Weak pressure-broadened photospheric absorption lines.* Typical examples are C III $\lambda 1428$ or S V $\lambda 1502$. These lines originate in hot OB stars. Strong non-LTE effects make it difficult to model the lines even in single stars. Therefore an abundance estimate from the integrated spectrum of the OB population is presently not feasible. (ii) *P Cygni profiles from hot-star winds.* C IV $\lambda 1550$ (and possibly Si IV $\lambda 1400$) show emission and blueshifted absorption components similar (but not identical to) those observed in local starburst galaxies (Leitherer 1997). The line strengths are sensitive to stellar mass-loss rates (\dot{M}) and wind velocities (v_∞) and are known to vary with starburst properties (Leitherer et al. 1995). (iii) *Strong interstellar low-ionization lines.* The spectra of most high- z star-forming galaxies show saturated interstellar lines which often reach zero intensity. The most prominent examples are Si II $\lambda 1260$, C II $\lambda 1335$, and Si II $\lambda 1526$. Most stellar-wind lines have a significant interstellar high-ionization component as well.

Almost all stellar-wind and interstellar lines in star-forming galaxies are saturated. Therefore the observed equivalent widths W are on the flat part of the curve-of-growth,

$$W \propto b \left(\ln \frac{N_{\text{ion}}}{b} \right)^{\frac{1}{2}}, \quad (1)$$

where W is quite insensitive to column density (N_{ion}) variations. W becomes primarily a measure of velocity, as expressed via the Doppler line-broadening parameter b . In what follows I am going to demonstrate how *saturated stellar-wind and interstellar absorption lines permit a metallicity estimate.* The basis of the method is the metallicity dependence of b . This holds for both stellar winds and the interstellar medium (ISM). Stellar winds are metallicity dependent due to the nature of the force driving mass loss, which is radiation pressure in metal lines. The kinematics of the ISM is affected by stellar winds and supernovae (SNe), whose effects vary with metallicity. Throughout this paper I will assume the oxygen abundance as representative of metallicity, with $12 + \log(O/H)_\odot = 8.9$.

2 Metallicity-Dependent Stellar-Wind Lines

Winds of hot stars are driven by stellar radiation pressure (Castor et al. 1975). Radiative momentum from the photospheric radiation field is transformed into kinetic wind momentum by absorption of photons in strong UV lines. Note that C IV $\lambda 1550$ contributes to the accelerating force but is only a minor constituent of the bulk of the driving lines, which are in the extreme UV. Schematically, one can write the momentum transfer as

$$\dot{M}v_\infty = \frac{L_\star}{c} f(R_\star, M_\star, \dots) Z^\alpha, \quad (2)$$

where the left-hand side of eq. (2) denotes the wind momentum, and the right-hand side the radiative momentum. The available radiative momentum is L_\star/c , modified by a second-order correction term with some dependence on basic stellar

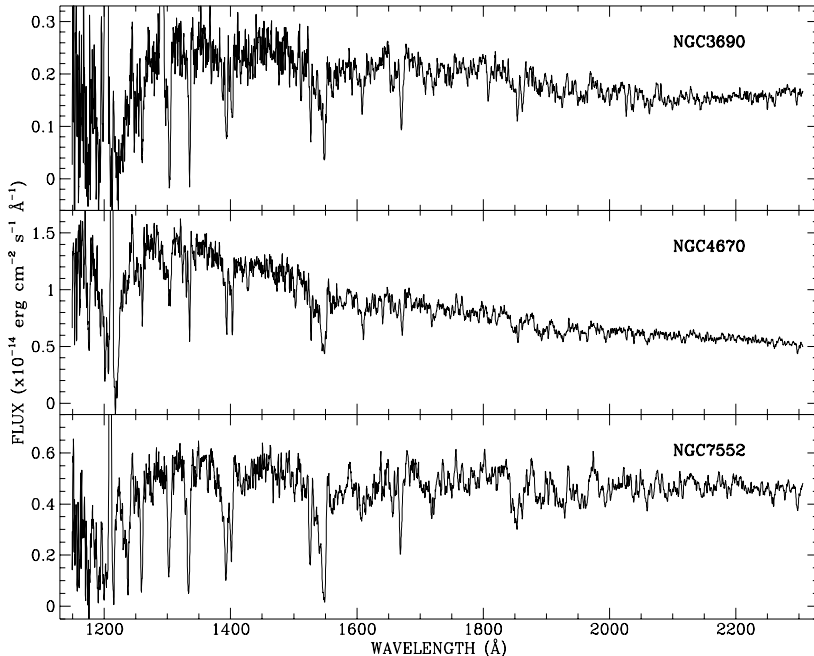


Fig. 1. HST FOS spectra of the local starburst galaxies NGC 3690 (top), NGC 4670 (middle), and NGC 7552 (bottom). The observed metallicities are $2-3 Z_{\odot}$ (NGC 3690), Z_{\odot} (NGC 4670), and $1/4 Z_{\odot}$ (NGC 7552). Note the redder continuum and increasing absorption-line strength with higher metallicity. From Robert et al. (1999).

parameters, and with an explicit metallicity dependence Z^{α} with $0.5 < \alpha < 1.0$ (e.g., Kudritzki 1998). The momentum transfer becomes less efficient at lower metallicity, therefore \dot{M} and v_{∞} decrease, and stellar-wind profiles like C IV $\lambda 1550$ are correspondingly weaker. This prediction is now fairly well established. Individual O stars in the Galaxy (within a few kpc from the Sun), in the Large Magellanic Cloud (LMC), and in the Small Magellanic Cloud (SMC) show a steady progression from stronger to weaker wind profiles (Kudritzki 1998, his Fig. 68). The latest atmosphere and wind models are capable of reproducing the observed wind profiles and their variation with chemical composition.

UV spectra of local starburst galaxies are consistent with a metallicity dependence of stellar-wind lines. HST FOS spectra of the three nearby starbursts NGC 4670, NGC 3690, and NGC 7552 are plotted in Fig. 1. The metallicity of the three objects ranges from $\sim 1/4 Z_{\odot}$ to almost $3 Z_{\odot}$ (Robert et al. 1999). Both the narrow interstellar lines (e.g., C II $\lambda 1335$) and the broad stellar-wind lines (Si IV $\lambda 1400$ and C IV $\lambda 1550$) increase with increasing Z — despite being saturated. The continuum slope is metallicity-dependent as well: NGC 4670 has a rather blue continuum, whereas NGC 7552 is essentially flat in F_{λ} . This be-

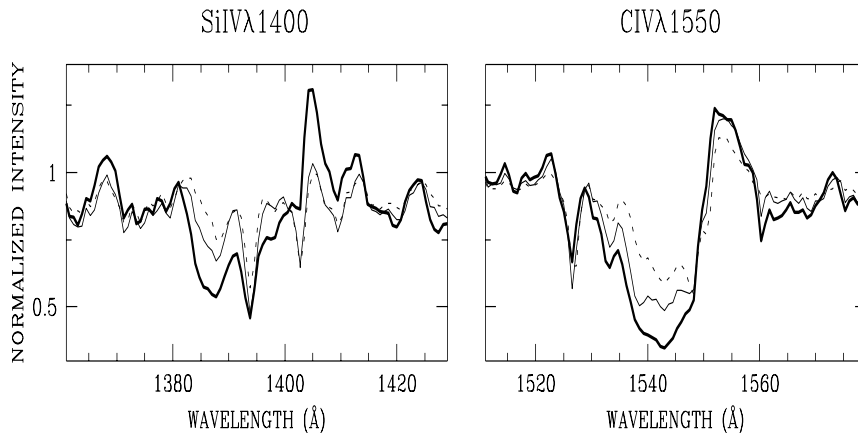


Fig. 2. Si IV $\lambda 1400$ and C IV $\lambda 1550$ for instantaneous burst populations with metallicities Z_{\odot} (thick solid line), $1/4 Z_{\odot}$ (thin solid), and $1/10 Z_{\odot}$ (dashed); age: 3 Myr; Salpeter IMF. From Robert et al. (1999).

havior gives rise to the hope to model the UV properties of star-forming galaxies with the goal of deriving the metallicity.

A first attempt to model the UV spectra of star-forming galaxies with significantly sub-solar metallicity was made by Robert et al. (1999). They extended the spectral synthesis models of Robert et al. (1993) and Leitherer et al. (1995) to lower metallicities by compiling a UV spectral library of O stars in the LMC and SMC. An example is shown in Fig. 2. The two panels are a snapshot of the Si IV $\lambda 1400$ and C IV $\lambda 1550$ profiles predicted for 3 Myr old burst populations with different metallicities. Lower Z results in weaker wind lines. The effect is much more pronounced in Si IV, which is predicted to be essentially absent for SMC-like composition, whereas C IV, due to its higher opacity should still show a P Cygni profile even for metallicities as low as $\sim 1/10 Z_{\odot}$. These results should be considered a first, pioneering effort, with the need for improvement. Most importantly, the stellar library employed is rather sparse (only 25 stars for all spectral types and metallicities) and not of very high S/N (typically only 10 to 20 due to the short FOS snapshot exposures). This should improve in the future with the availability of an HST STIS library compiled by D. Lennon (Cycle 7 Program 7437).

An alternative approach has been taken by Heap & de Koter (1995), who computed fully theoretical UV spectra of starburst populations. This eliminates uncertainties due to insufficient spectral-type coverage in the available UV libraries but rests on still somewhat experimental model atmospheres. Nevertheless, calculated spectra for a burst population over the range $0.2 Z_{\odot} < Z < 2 Z_{\odot}$ are in quite reasonable agreement with the empirical models of Robert et al. (1999). Si IV $\lambda 1400$ from stellar winds is predicted to become unobservable in a population with $Z < 1/4 Z_{\odot}$, whereas C IV $\lambda 1550$ should still be a strong line at

this metallicity. Comparison with the restframe UV spectrum of cB58 suggests that this galaxy should have abundances somewhat above those of the LMC.

3 Interstellar Lines: Comparison With a Local Sample

Synthesis models for stellar-wind lines of massive-star populations are reasonably advanced to allow tailored analyses of *individual* local star-forming galaxies if high-quality HST UV spectra are available (e.g., Leitherer et al. 1996; Johnson et al. 1999). On the other hand, the physics of the interstellar lines observed in these galaxies is rather complex so that a *statistical* approach is the method of choice. Heckman et al. (1998) have performed a systematic study of 45 nearby starburst galaxies with available IUE UV spectra. The advantage of IUE over HST is the larger projected aperture, which matches the projected aperture sizes used for the high- z observations, and the much larger data set in the IUE archive. Limitations of the IUE data are the low S/N and the spectral resolution of only 6 \AA or about 10^3 km s^{-1} . This resolution is often insufficient to distinguish between stellar-wind and interstellar lines.

The choice of galaxies was driven by S/N considerations, and the sample is by no means rigorously defined. All selected galaxies are included in the atlas of Kinney et al. (1993). The most pertinent parameters are:

- luminosity: $10^7 L_{\odot} < L < 4 \times 10^{11} L_{\odot}$,
- metallicity: $1/50 Z_{\odot} < Z < 3 Z_{\odot}$,
- H I rotation speed: $35 \text{ km s}^{-1} < \sigma_{\text{HI}} < 275 \text{ km s}^{-1}$.

The galaxies cover a variety of morphological types and activity classes, like blue compact dwarfs, irregulars, H II galaxies, and nuclear starbursts. Since this is a UV-selected sample, luminous IR-bright are underrepresented. A typical object in the sample has a blue luminosity comparable to that of the LMC.

The measured UV continuum slopes, defined as $F_{\lambda} \propto \lambda^{\beta}$, are plotted in the left panel of Fig. 3. The UV continuum of an OB-star dominated population is rather insensitive to age and IMF effects but is mostly a reddening indicator (Calzetti et al. 1994). Therefore the correlation between β and Z in Fig. 3 suggests that more metal-rich galaxies are more reddened. The right panel of this figure shows the correlation between the ratio of the IR over UV luminosities (a measure of the escape fraction of UV radiation) and Z . The interpretation of Fig. 3 is that the observed UV continuum is subject to lower reddening and extinction in more metal-poor systems as the dust-to-gas ratio decreases for lower metallicity.

Equivalent widths of all strong UV lines in the IUE sample were measured. Rather than studying individual lines, two groups of lines were constructed due to S/N considerations. The mean equivalent width of the wind lines is defined as $W_{\text{W}} = [W(1400) + W(1550)]/2$. Although Si IV $\lambda 1400$ and C IV $\lambda 1550$ often show conspicuous stellar-wind profiles in high-resolution HST spectra, they also have a substantial interstellar component which cannot be resolved and subtracted in IUE low-dispersion data. Therefore W_{W} , as defined above, measures

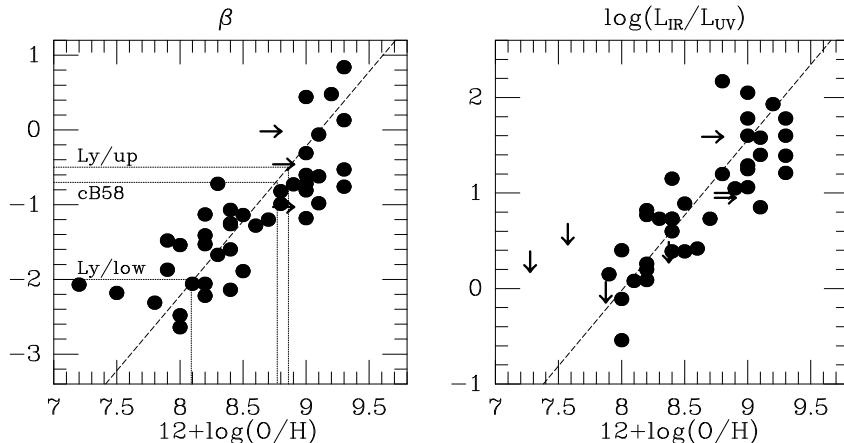


Fig. 3. Left: Correlation of the UV continuum slope β , where $F_\lambda \propto \lambda^\beta$, with metallicity. Full circles: measurements for the local IUE sample; arrows: upper limits; dashed line: least squares fit to the data points; dotted lines: observed slopes of cB58 and the Lyman-break sample (upper and lower limits) and corresponding metallicities. Right: Ratio of IR over UV luminosities of the local IUE sample versus metallicity. The two panels demonstrate the strong correlation of the dust indicators β and $L_{\text{IR}}/L_{\text{UV}}$ with galaxy metallicity. From Heckman et al. (1998).

both stellar and interstellar properties of the galaxy sample. W_{W} is plotted versus Z in Fig. 4 (left). The strong correlation is expected from the discussion in Section 2: The stellar mass-loss rates and wind velocities decrease with decreasing metal-content, and the wind lines become weaker. The three galaxies shown in Fig. 1 are included in the IUE sample as well and follow the general correlations in Figs. 3 and 4.

We can define the mean equivalent width of the interstellar lines as $W_{\text{IS}} = [W(1260) + W(1303) + W(1335)]/3$. The Si II $\lambda 1260$, O I $\lambda 1302$ + Si II $\lambda 1304$, and C II $\lambda 1335$ lines were chosen because of their strengths and location in uncrowded spectral regions. As shown in the right panel of Fig. 4, W_{IS} correlates well with metallicity, although not as tightly as W_{W} with Z . Since the strong interstellar lines in star-forming galaxies are saturated (e.g., Pettini & Lipman 1995; González-Delgado et al. 1998), eq. (1) suggests that the cause of the correlation in Fig. 4 is a *correlation between velocity dispersion and metallicity*.

The sequence along metallicity in Figs. 3 and 4 is also a progression in terms of galaxy size: metal-rich galaxies tend to be more luminous and more massive than metal-poor objects. Could the underlying cause of the correlation between Z and velocity dispersion be that the interstellar lines are broadened by galactic rotation? Heckman et al. (1998) demonstrate that W_{IS} correlates with the rotation velocity derived from the H I 21 cm line width. However, the correlation is much weaker than that between W_{IS} and Z , suggesting that rotation is not the prime mechanism responsible for the line broadening. This is also clear from

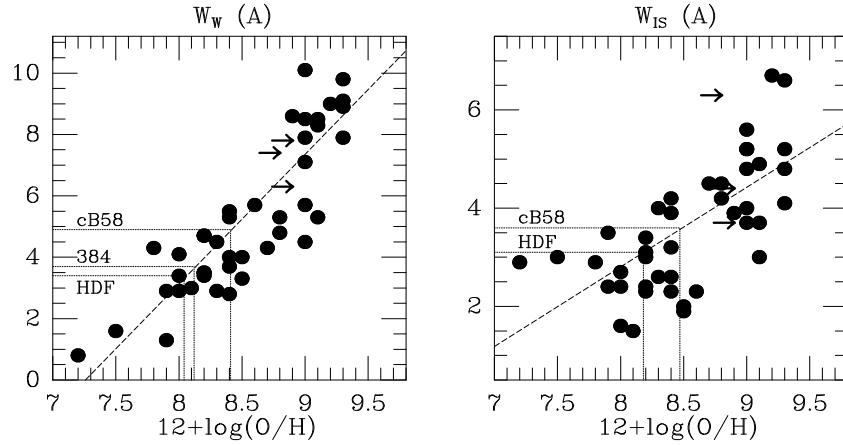


Fig. 4. Correlation of the mean stellar-wind (left) and interstellar (right) line equivalent widths with metallicity. Full circles: measurements for the local IUE sample; arrows: upper limits; dashed line: least squares fit to the data points; dotted lines: observed equivalent widths of cB58, 384, and the HDF sample and corresponding metallicities. From Heckman et al. (1998).

the large equivalent widths, which would require rotation velocities significantly greater than those obtained from H I line widths. A more plausible interpretation is that the observed line strengths have a non-gravitational origin due to mechanical energy release from the starburst. More powerful starbursts with stronger winds and higher supernova rates are hosted by more metal-rich galaxies. While the physical reason for this correlation needs to be explored further, the relations in Figs. 3 and 4 are nevertheless useful for empirical estimates of metallicities from UV spectra of starburst galaxies.

The correlations in Figs. 3 and 4 can then be applied to UV restframe spectra of star-forming galaxies at high redshift in order to estimate metallicities. This approach is only justified if the properties of the high- z population (mass, morphology, etc.) are comparable to those of the local sample, an assumption that still needs verification. The relevant observations are:

- cB58: $\beta = -0.7$; $W_W = 4.9 \text{ \AA}$; $W_{IS} = 3.6 \text{ \AA}$ (Pettini et al. 1998; Pettini, priv. comm.)
- Arc 384: $W_W = 3.7 \text{ \AA}$ (Ebbels et al. 1996; Ellis, priv. comm.)
- 12 HDF galaxies: $W_W = 3.4 \text{ \AA}$; $W_{IS} = 3.1 \text{ \AA}$ (Lowenthal et al. 1997; Lowenthal, priv. comm.)
- 211 Lyman-break galaxies: $-2 < \beta < -0.5$ (Pettini et al. 1998)

I included these data points in Figs. 3 and 4 (dotted lines). It is encouraging that the continuum slopes and the stellar-wind and interstellar lines give consistent results: the metallicities of the high- z sample are in the range $8.0 < 12 + \log(O/H) < 8.9$, with average values close to those of the LMC and SMC.

This range is in reasonable agreement with estimates obtained from stellar-wind profiles in cB58 (Section 2).

4 Conclusions

A first attempt has been made to estimate the chemical composition of star-forming galaxies at high redshift from UV absorption lines. Constraints on Z can be obtained from stellar-wind and interstellar lines. Both line types are strong and often saturated.

The technique to derive abundances from stellar-wind lines rests on evolutionary synthesis models for massive-star population, in combination with either empirical or theoretical stellar UV spectra. The current limitation is a lack of suitable empirical UV spectra and of reliable model atmospheres. Preliminary comparison with the Si IV $\lambda 1400$ and C IV $\lambda 1550$ wind lines in cB58 suggests that the stellar wind properties in this galaxy are similar to those in the LMC.

The line strengths of interstellar absorption lines in local starbursts correlate with metallicity, most likely due to a correlation between non-thermal energy input from the starburst and Z . This correlation can be applied to high-redshift galaxies, assuming the local and the distant sample have comparable properties, in particular masses. Equivalent widths and continuum slopes observed in high- z galaxies suggests LMC/SMC-like abundances if interpreted in this way.

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