HEAVY-ELEMENT ABUNDANCES IN BLUE COMPACT GALAXIES
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ABSTRACT
We present high-quality ground-based spectroscopic observations of 54 supergiant H II regions in 50 low-metallicity blue compact galaxies with oxygen abundances \(12 + \log O/H\) between 7.1 and 8.3. We use the data to determine abundances for the elements N, O, Ne, S, Ar, and Fe. We also analyze Hubble Space Telescope (HST) Faint Object Spectrograph archival spectra of 10 supergiant H II regions to derive C and Si abundances in a subsample of seven BCGs. The main result of the present study is that none of the heavy element-to-oxygen abundance ratios studied here \((C/O, N/O, Ne/O, Si/O, S/O, Ar/O, Fe/O)\) depend on oxygen abundance for BCGs with \(12 + \log O/H \leq 7.6\) \((Z \leq Z_\odot/20)\). This constancy implies that all of these heavy elements have a primary origin and are produced by the same massive \((M \geq 10 M_\odot)\) stars responsible for O production. The dispersion of the ratios C/O and N/O in these galaxies is found to be remarkably small, being only \(+0.03\) and \(+0.02\) dex, respectively. This very small dispersion is strong evidence against any time-delayed production of C and primary N in the lowest metallicity BCGs (secondary N production is negligible at these low metallicities). The absence of a time-delayed production of C and N is consistent with the scenario that galaxies with \(12 + \log O/H \leq 7.6\) are now undergoing their first burst of star formation, and that they are therefore young, with ages not exceeding 40 Myr. If very low metallicity BCGs are indeed young, this would argue against the commonly held belief that C and N are produced by intermediate-mass \((3 M_\odot \leq M \leq 9 M_\odot)\) stars at very low metallicities, as these stars would not have yet completed their evolution in these lowest metallicity galaxies. In higher metallicity BCGs \((7.6 < 12 + \log O/H < 8.2)\), the abundance ratios Ne/O, Si/O, S/O, Ar/O, and Fe/O retain the same constant value they had at lower metallicities. By contrast, there is an increase of C/O and N/O along with their dispersions at a given O. We interpret this increase as due to the additional contribution of C and primary N production in intermediate-mass stars, on top of that by high-mass stars. The above results lead to the following timeline for galaxy evolution: (1) all objects with \(12 + \log O/H \leq 7.6\) began to form stars less than 40 Myr ago; (2) after 40 Myr, all galaxies have evolved so that \(12 + \log O/H > 7.6\); (3) by the time intermediate-mass stars have evolved and released their nucleosynthetic products \((100-500\) Myr), all galaxies have become enriched to \(7.6 < 12 + \log O/H < 8.2\). The delayed release of primary N at these metallicities greatly increases the scatter in N/O; (4) later, when galaxies get enriched to \(12 + \log O/H > 8.2\), secondary N production becomes important. BCGs show the same O/Fe overabundance with respect to the Sun \((\sim 0.4\) dex) as Galactic halo stars, suggesting the same chemical enrichment history. We compare heavy elements yields derived from the observed abundance ratios with theoretical yields for massive stars and find general good agreement. However, the theoretical models are unable to reproduce the observed N/O and Fe/O. Further theoretical developments are necessary, in particular to solve the problem of primary nitrogen production in low-metallicity massive stars. We discuss the apparent discrepancy between abundance ratios N/O measured in BCGs and those in high-redshift damped Ly\(\alpha\) galaxies, which are up to 1 order of magnitude smaller. We argue that this large discrepancy may arise from the unknown physical conditions of the gas responsible for the metallic absorption lines in high-redshift damped Ly\(\alpha\) systems. While it is widely assumed that the absorbing gas is neutral, we propose that it could be ionized. In this case, ionization correction factors can boost N/O in damped Ly\(\alpha\) galaxies into the range of those measured in BCGs.

Subject headings: galaxies: abundances — galaxies: compact — galaxies: ISM

1. INTRODUCTION
The study of the variations of one chemical element relative to another is crucial for our understanding of the chemical evolution of galaxies and for constraining models of stellar nucleosynthesis and the shape of the initial mass function. Blue compact galaxies (BCGs) are ideal objects in which to carry out such a study. They are low-luminosity \((M_B > -18)\) dwarf systems each undergoing an intense burst of star formation that gives birth to a large number \((10^3-10^4)\) of massive stars in a compact region, which ionize the interstellar medium, producing high-excitation supergiant H II regions and enriching it with heavy elements (see Thuan 1991 for a review). The optical spectra of these H II regions show strong narrow emission lines superposed on a stellar continuum that is rising toward the blue, allowing abundance determinations of such heavy elements as nitrogen, oxygen, neon, sulfur, argon, and iron. Recently, the Hubble Space Telescope (HST) has permitted the determination of carbon and silicon abundances from emission lines in the UV range (Garnett et al. 1995a, 1995b, 1997; Thuan, Izotov, & Lipovetsky 1996; Kobulnicky et al. 1997; Kobulnicky & Skillman 1998; Thuan, Izotov, & Foltz 1999).
These studies are particularly important for understanding the evolutionary status of extremely low-metallicity BCGs. The debate has been raging for decades, ever since the discovery paper by Sargent & Searle (1970), on whether BCGs are truly nearby young dwarf galaxies each undergoing one of its first bursts of star formation or the present starburst is occurring within an older galaxy. The abundances of heavy elements in these galaxies ranging between $Z_{/50}$ and $Z_{/3}$ make them among the least chemically evolved galaxies in the universe. However, subsequent photometric studies have shown that the majority of blue compact galaxies possess old stellar populations. Hence they have experienced star formation episodes in the past and are not young. Loose & Thuan (1985) found that $\sim 95\%$ of the BCGs in their sample exhibit an underlying extended red low surface brightness component, on which are superposed the high surface brightness blue star-forming regions. Later CCD surveys of BCGs have confirmed and strengthened that initial result (Kunth, Maurogordato, & Vigroux 1988; Papaderos et al. 1996; Telles & Terlevich 1997). However, there are at least two known objects with extremely young stellar populations. They are the two most metal-deficient galaxies known, I Zw 18 ($Z_{/50}$; Searle & Sargent 1972) and SBS 0335$-052$. HST imaging of I Zw 18 to $V \sim 26$ mag by Hunter & Thronson (1995) suggests that the stellar population is dominated by young stars and that the colors of the underlying diffuse component are consistent with those from a sea of unresolved B or early A stars, with no evidence for stars older than $\sim 10^7$ yr. The BCG SBS 0335$-052$ was first shown by Izotov et al. (1990) to possess an extraordinarily low metallicity, equal to $1/41$ of the Sun’s metallicity (Melnick, Heydari-Malayeri, & Leisy 1992). HST $V$ and $I$ imaging of this galaxy (Thuan, Izotov, & Lipovetsky 1997) reveals extraordinarily blue ($V-I$) colors (between 0.0 and 0.2), not only in the region of current star formation but also in the extended ($\sim 4$ kpc in size) low surface brightness underlying component. The blue low-intensity emission has been shown by Izotov et al. (1997b) and Papaderos et al. (1998) to be the combined effect of emission from ionized gas (contributing $\sim 1/3$ of the total flux) and from a very young stellar population (contributing the remaining $\sim 2/3$ of the emission), not older than $\sim 10^8$ yr. There is further observational evidence for the extremely young age of SBS 0335$-052$. Thuan & Izotov (1997) have argued from HST UV spectrophotometry that the large (some 64 kpc in size) and massive ($\sim 10^9 M_\odot$) H I cloud associated with the BCG (Pustilnik et al. 1999) is made of pristine gas, unpolluted by metals.

The above observational evidence thus strongly suggests that there exists in our local volume of space a few young dwarf galaxies in which the first star formation did not occur until $\sim 100$ Myr ago. Somehow the H I clouds with which they are associated have not undergone gravitational collapse for a whole Hubble time. The detailed studies of these young dwarf galaxies are not only important for understanding their intrinsic properties but are also crucial for galaxy formation studies. The proximity of these young dwarfs allows studies of their structures, metal contents, and stellar populations, and star formation processes in a nearly pristine environment with a sensitivity, precision, and spatial resolution that faint, small angular size, distant high-redshift galaxies do not allow. We focus here on the analysis of heavy-element abundance ratios in BCGs. We shall show that some of these ratios are very good indicators of the BCG age.

It is now well established that the oxygen seen in H II regions is a primary element produced by massive stars with $M \geq 10 M_\odot$ (see the review by Weaver & Wooley 1993). As for the other $\alpha$-process elements seen in the spectra of H II regions, such as neon, silicon, sulfur, and argon, they are generally thought to be also primary (for references, see Thuan, Izotov & Lipovetsky 1995; hereafter TIL95).

Carbon is also a primary element, believed to be produced by both massive and intermediate-mass ($3 M_\odot \leq M \leq 9 M_\odot$) stars. However, because carbon has its strong nebular emission lines not in the optical but the UV range, it has not been possible until recently, with the advent of HST, to obtain precise measurements of its abundance. Garnett et al. (1995b) found C/O in BCGs to increase with increasing oxygen abundance and its value in the lowest metallicity galaxies to be below that predicted by stellar nucleosynthesis theory. However, a subsequent study by Garnett et al. (1997) found C/O in I Zw 18 to be much larger (by a factor of $\sim 2$) than the mean value for other metal-deficient galaxies. This led those authors to conclude that I Zw 18 is not a young galaxy and that it has experienced carbon-enriching episodes of star formation in the past.

The situation for nitrogen is even more complex. Spectral observations of H II regions in spiral galaxies with high metallicities ($Z \sim Z_\odot$) show that N/O increases with O/H (Pagel & Edmunds 1981; Serrano & Peimbert 1983; Torres-Peimbert, Peimbert, & Fierro 1989; Vila-Costas & Edmunds 1993). This implies that a large part of the nitrogen in these high-metallicity spiral galaxies is produced as a secondary element in the CNO cycle, i.e., its synthesis is controlled by carbon seed atoms already present in the main-sequence or red-giant stars (which can be of any mass). However, in low-metallicity ($Z_{/50} \leq Z \leq Z_{/3}$) environments such as in irregular and blue compact galaxies, N/O is found to be constant and independent of O/H (Lequeux et al. 1979; French 1980; Kinman & Davidson 1981; Kunth & Sargent 1983; Campbell, Terlevich, & Melnick 1986; TIL95). This implies that nitrogen is mainly a primary element when O/H is small. Stellar nucleosynthesis models predict that primary nitrogen is produced mainly in intermediate-mass stars by hot-bottom carbon burning undergoing a third dredge-up episode that brings carbon-rich material from the core into the hydrogen-burning shell (Renzini & Voli 1981, hereafter RV81; van den Hoek & Groenewegen 1997, hereafter HG97). The spread of N/O at a fixed O/H in early spectral observations is seen to be large and has been attributed to observational uncertainties and/or to the time delays ($\tau \leq 5 \times 10^8$ yr) between the production of oxygen by short-lived massive stars and that of nitrogen by longer lived intermediate-mass stars (Matteucci & Tosi 1985; Garnett 1990; Pilyugin 1992, 1993; Vila-Costas & Edmunds 1993; Marconi, Matteucci, & Tosi 1994). However, TIL95 have shown subsequently that a large part of the scatter is due to observational uncertainties. High signal-to-noise ratio observations show a very small dispersion of $\log N/O (\pm 0.02$ dex) at low metallicities, which favors primary nitrogen production not in intermediate-mass stars but in massive ones.

The optical spectra of BCGs also contain iron lines, which allow one to derive abundances for that element, as was first done by TIL95. Iron is a primary element produc-
ed by explosive nucleosynthesis either in Type I supernovae (SNe I) with low-mass progenitors or in Type II supernovae (SNe II) with more massive progenitors (Weaver & Woosley 1993; Woosley & Weaver 1995, hereafter WW95). During the collapse of the Galaxy, while O and other \( Z \)-elements are mainly produced in massive stars and restored to the interstellar medium (ISM) through SNe II, iron is thought to come mainly from SNe I. Therefore, because of the different evolution timescales of stars with different masses, oxygen is injected sooner than iron into the ISM, resulting in an oxygen overabundance relative to iron in the halo population. It is well established that halo Population II stars with [Fe/H] < −1 (where [X] = log X − log X⊙) have a constant overabundance [O/Fe] ~ 0.3−0.5. As for disk stars with higher metallicities ([Fe/H] ≥ −1), they show a progressive decrease of O/Fe toward the solar ratio ([O/Fe] ~ 0) (Lambert, Sneden, & Ries 1974; Spite & Spite 1981; Gratton & Ortolani 1986; Barbuy 1988; Barbuy & Erdelyi-Mendes 1989; Edvardsson et al. 1993).

In order to constrain models of stellar nucleosynthesis and chemical evolution of the heavy elements discussed above in a metal-deficient environment, we present in this paper high signal-to-noise ratio spectrophotometric observations of 54 H II regions in 50 low-metallicity (\( Z/Z⊙\leq Z/Z⊙/50 \)) BCGs. This paper is a continuation of the study by ITL95, based on a substantially larger observational sample (more than triple the size of the old sample). We found the enlarged sample to confirm and considerably strengthen the main results obtained by ITL95. In § 2 we discuss the properties of the sample. The methods used for heavy-element abundance determinations are discussed in § 3. In § 4 we discuss how the behavior of various heavy element abundance ratios as a function of metallicity can constrain the origin of these elements. We discuss in § 5 how these data can put limits on the age of BCGs. We show that BCGs with metallicities below a certain value are likely to be young systems that are making stars for the first time at the present epoch. In § 6 we compare our results for heavy-element abundances in BCGs with those in another highly metal-deficient environment: that of high-redshift damped Ly\( \alpha \) galaxies. We summarize our results in § 7.

2. The Sample

We choose for analysis the sample of low-metallicity BCGs for which we have obtained optical spectrophotometry to derive the primordial helium abundance. Because the requirements for an accurate helium abundance determination are very strict (the precision has to be better than a few percent), the spectra have been obtained at the 4 m and 2.1 m Kitt Peak telescopes with the very highest signal-to-noise ratio, typically ~20−40 in the continuum. The sample includes mainly BCGs from the First Byurakan (or Markarian) and Second Byurakan surveys. Additionally, UGC 4483, VII Zw 403 and several BCGs from the University of Michigan (UM) survey have been included. All galaxies have been observed with nearly the same observational settings (slit width ~2", spectral resolution of 6 Å, and spectral range covered during a single exposure 3600−7500 Å), and the data reduction has been done in a homogeneous way. The results of the spectrophotometric observations and the details of the data reduction are presented in Izotov, Thuan, & Lipovetsky (1994, 1997c; hereafter ITL94, ITL97), TIL95, and Izotov & Thuan (1998a, 1998b). The total sample consists of 54 supergiant H II regions observed in 50 BCGs. All observed H II regions are of high excitation, with equivalent widths of H\( \beta \) generally larger than 100 Å.

For the majority of the BCGs in the sample, high-order H\( \alpha \)−H\( \beta \) Balmer emission lines are detected, which permits correction of the observed line intensities for both extinction and underlying hydrogen stellar absorption with a very high precision over the whole optical spectral range. This is most important as uncertainties in these corrections will introduce uncertainties in the derived abundances, resulting in an artificial scatter in the data. In particular, it is especially important that these corrections are done correctly for the [O II] 3727 Å line at the blue end of the spectrum. This line is used for the determination of the O\( ^+ \) abundance and for the correction of nitrogen and iron abundances for unseen stages of ionization. Ignoring, for example, stellar hydrogen absorption will lead to an overestimate of the extinction and of the intensity of [O II] 3372 Å and to an underestimate of nitrogen and iron abundances. In all cases therefore, we have made sure that the Balmer hydrogen emission-line intensity ratios are in agreement with the theoretical recombination ratios after correction for both these effects.

Another important feature of the sample is that the auroral [O III] 4363 Å line is detected with a high signal-to-noise ratio. This allows derivation of electron temperatures and element abundances with much higher precision than could be achieved with the use of empirical statistical methods based, for instance, on the total intensity of oxygen lines. The precision of these empirical methods is not better than 0.2−0.3 dex in the determination of the oxygen abundance.

Our sample includes nearly all of the most metal-deficient BCGs known. Among the cataloged BCGs with heavy element abundances less than 1/20 solar, only three galaxies (CG 1116 + 51, Tol 65, and Tol 1214−277) are missing. The other six are present, including the two most metal-deficient galaxies known, I Zw 18 and SBS 0335−052. We have purposely not included galaxies observed by other authors in the optical range so as to preserve the homogeneity of a data set obtained and reduced by us in a uniform way. This allows us to minimize the scatter that would be inevitably and artificially introduced were we to assemble different authors’ data, with varying quality, which differ by their reduction methods, line intensity measurements, corrections for extinction and underlying stellar absorption, the formulae used for abundances calculations, etc.

For the derivation of carbon and silicon abundances, we have assembled a sample of BCGs observed in the UV with the \( HST \) Faint Object Spectrograph (FOS) by Garnett et al. (1995a, 1995b, 1997), Kobulnicky et al. (1997), Kobulnicky & Skillman (1998), and Thuan et al. (1999). In total, this sample includes 15 supergiant H II regions in 11 galaxies. Again, in an effort to treat the data in a homogeneous way, we have reanalyzed all the UV data in the same manner, supplementing it for some galaxies with our most recent ground-based observations.

3. Heavy Element Abundance Determination

3.1. Ground-based Optical Observations

To derive element abundances from the optical spectra, we have followed the procedure detailed in ITL94 and ITL97. We adopt photoionized H II region model
have used the emission lines \([\text{O III}] \lambda(4959 + 5007)\) in the FOS spectra (these are used instead of higher signal-to-noise ratio ground-based spectra to ensure that exactly the same region is observed as in the UV) to determine C/O. This approach is subject to uncertainties in the extinction curve, but fortunately, at least in some of the galaxies, the extinction is small. (2) Because of the uncertainties in the atomic data, different authors have used different analytical expressions for the determination of carbon and silicon abundances. As this may introduce systematic shifts, we have reanalyzed all spectra in the same manner, using the same expressions, to insure the homogeneity of our data set. (3) The abundance ratio C/O is dependent on several physical parameters, and in particular on the electron temperature, which needs to be determined with relatively high precision. Because of the poorer signal-to-noise ratio of the FOS spectra in the optical range, Garnett et al. (1997) and Kobulnicky & Skillman (1998) have used electron temperatures derived from higher signal-to-noise ratio ground-based observations. We use here our own new ground-based observations with very high signal-to-noise ratios to better constrain the electron temperature for some of the most metal-deficient galaxies in our sample. (4) In deriving silicon abundances, Kobulnicky et al. (1997) have not corrected for unseen stages of ionization. We have taken into account here the ionization correction factor for Si, which can be large.

We derive the C\(^{2+}\) abundance from the relation (Aller 1984)

\[
\frac{C^{2+}}{O^{2+}} = 0.093 \exp \left( \frac{4.656}{t} \right) \frac{I(\text{C III}] \lambda1906 + \lambda1909)}{I(\text{[O III]} \lambda4959 + \lambda5007)},
\]

where \(t = T_e/10^4\). Following Garnett et al. (1995b), we adopt the temperature in equation (3) the \(T_e(\text{O III})\) value in the \(O^{++}\) zone. Then

\[
\frac{C}{O} = \text{ICF}(C/O) \frac{C^{2+}}{O^{2+}}.
\]

The correction factor ICF(C/O) in equation (4) for unseen ionization stages of carbon is taken from Garnett et al. (1995b). In the majority of cases, the correction factor is small, i.e., ICF(C/O) = 1.0–1.1. However, it is evident from equation (3) that the abundance ratio C/O is critically dependent on the electron temperature. To derive as precise a temperature as possible, we have used, when available, very high signal-to-noise ratio ground-based observations obtained within apertures nearly matching the circular or square 0.86 FOS aperture.

The abundance of silicon is derived following Garnett et al. (1995a) from the relation

\[
\frac{\text{Si}}{C} = \text{ICF}(\text{Si/C}) \frac{\text{Si}^{2+}}{C^{2+}},
\]

where

\[
\frac{\text{Si}^{2+}}{C^{2+}} = 0.188t^{0.2} \exp \left( \frac{0.08}{t} \right) \frac{I(\text{Si II]} \lambda1883 + \lambda1892)}{I(\text{C III}] \lambda1906 + \lambda1909)}.
\]

For the determination of the silicon abundance, we again adopt the temperature \(T_e(\text{O III})\). The correction factor ICF(Si/C) is given by Garnett et al. (1995a) and is larger than that for carbon. One of the main uncertainties in the
determination of the silicon abundance comes from the Si II] 1892 Å emission line. It is not seen in some galaxies (such as in the northwest component of I Zw 18), although atomic theory predicts that this line should be present, given the signal-to-noise ratio and intensity of the neighboring Si II] 1883 Å emission line. In those cases, we assume $I(\text{Si II}] 1883 + 1892) = 1.67 \times I(\text{Si II}] 1883)$, as expected in the low-density limit.

Next, we discuss in more detail the carbon and silicon abundance determinations in a few BCGs of special interest. The heavy-element abundance ratios derived from the HST FOS observations are given in Table 5.

3.2.1. I Zw 18

Both the northwest and southeast components of this BCG, the most metal-deficient galaxy known, have been

| Object          | $12 + \log O/H$ | $\log N/O$ | $\log Ne/O$ | $\log S/O$ | $\log Ar/O$ | $[O/Fe]$ | Other Name | Reference  |
|-----------------|----------------|------------|-------------|------------|-------------|----------|------------|------------|
| UM 461 A        | 7.40           | 0.06       |             |            |             |          |            |            |
| Mrk 930         | 0.04 0.34      |            |             |            |             |          |            |            |
| I Zw 18         | 0.12           | 0.02 0.42  |             |            |             |          |            |            |
| Mrk 750         | 0.03 0.38      |            |             |            |             |          |            |            |
| Mrk 22          | 0.12           | 0.02 0.47  |             |            |             |          |            |            |
| Mrk 416         | 0.03 0.34      |            |             |            |             |          |            |            |
| Mrk 1450        | 0.04 0.32      |            |             |            |             |          |            |            |
| Mrk 1434        | 0.04 0.30      |            |             |            |             |          |            |            |
| Mrk 1271        | 0.04 0.25      |            |             |            |             |          |            |            |
| CG 798          | 0.03 0.11      |            |             |            |             |          |            |            |
| Mrk 361         | 0.04 0.22      |            |             |            |             |          |            |            |
| Mrk 162         | 0.05 0.10      |            |             |            |             |          |            |            |
| VII Zw 403      | 0.04 0.27      |            |             |            |             |          |            |            |
| Mrk 1450        | 0.04 0.32      |            |             |            |             |          |            |            |
| Mrk 1434        | 0.04 0.30      |            |             |            |             |          |            |            |
| Mrk 1271        | 0.04 0.25      |            |             |            |             |          |            |            |
| CG 798          | 0.03 0.11      |            |             |            |             |          |            |            |
| Mrk 361         | 0.04 0.22      |            |             |            |             |          |            |            |
| Mrk 162         | 0.05 0.10      |            |             |            |             |          |            |            |
| VII Zw 403      | 0.04 0.27      |            |             |            |             |          |            |            |

References.—(1) Izotov & Thuan 1998b; (2) ITL97; (3) ITL94; (4) TIL95.
observed in the UV and optical with the HST FOS by Garnett et al. (1997). Adopting \( T_e (\text{O} \text{~m}) = 19,600 \) and 17,200 K, respectively, for the northwest and southeast components (Skillman & Kennicutt 1993) and using the emission lines \( \text{C ~m} \) \( \lambda (1906 + 1909) \) and \( \text{[O ~m]} \) \( \lambda 4959 + 5007 \), those authors derived very high C/O for both components, \(-0.63 \pm 0.10 \) and \(-0.56 \pm 0.09 \), as compared to \(-0.8 \) in other metal-deficient galaxies and predictions from massive stellar nucleosynthesis theory (Weaver & Woosley 1993; WW95). This led Garnett et al. (1997) to conclude that I Zw 18 is not a young galaxy and has experienced star formation episodes in the past that have enhanced C/O through the evolution of intermediate-mass stars.

As the adopted value for the electron temperature is crucial for the determination of C/O, we have redetermined it using new data by Izotov et al. (1997a). Those authors have obtained with the Multiple Mirror Telescope (MMT) a spectrum of both the northwest and southeast components during a 3 hr exposure with excellent seeing conditions (FWHM \( \approx 0.7 \)). The much higher signal-to-noise ratio of this spectrum as compared to that by Skillman & Kennicutt (1993) has resulted in the discovery of a Wolf-Rayet stellar population in the northwest component of I Zw 18 (Izotov et al. 1997a). We have extracted from this two-dimensional spectrum two one-dimensional spectra at the location of the brightest parts of the northwest and southeast components, within the smallest aperture allowed by the MMT observations, 0.6 \( \times \) 1.5. This provides a fairly good match to the round 0.86 FOS aperture, as the ratio of the area of the former to that of the latter is \( \approx 1.54 \). The observed and corrected emission-line fluxes relative to H\( \beta \) for both components are shown in Table 2, and the extinction coefficients \( \text{C(H} \beta \text{)}, \) observed H\( \beta \) fluxes and equivalent widths, and equivalent widths of the underlying stellar Balmer absorption lines are shown in Table 3. The errors of the line intensities listed in Table 2 take into account the noise statistics in the continuum and the errors in placing the continuum and fitting the line profiles with Gaussian profiles. We also retrieved the FOS spectra from the HST archives and remeasured the emission-line fluxes. Comparison of the MMT and FOS H\( \beta \) fluxes in the southeast component shows very good agreement: \( 3.5 \times 10^{-15} \) ergs cm\(^{-2} \) s\(^{-1} \) in the MMT spectrum as compared to \( 3.2 \times 10^{-15} \) ergs cm\(^{-2} \) s\(^{-1} \) in the HST spectrum. The H\( \beta \) emission equivalent widths are also in good agreement: 144 Å in the MMT spectrum as compared to 127 Å in the HST spectrum. There is not such good agreement, however, for the northwest component. The ratio of the observed H\( \beta \) flux in the MMT spectrum of \( 2.9 \times 10^{-15} \) ergs cm\(^{-2} \) s\(^{-1} \) to that of \( 5.0 \times 10^{-15} \) ergs cm\(^{-2} \) s\(^{-1} \) in the HST spectrum is \( \approx 0.6 \), just the ratio of the measured emission equivalent width of H\( \beta \) of 34 Å from the MMT spectrum to that of 55 Å from the HST spectrum. These differences are probably due to a slight positioning shift between the MMT and HST apertures on the northwest component. The electron temperatures and oxygen abundances derived from the MMT

| LINE | I Zw 18 NW | I Zw 18 SE | SBS 0335—052 |
|------|------------|------------|--------------|
| 1883 + 1892 Si \text{[m]} | ... | ... | 0.121 \pm 0.010 |
| 1907 C \text{[m]} | ... | ... | 0.300 \pm 0.015 |
| 3727 [O \text{[n]}] | 0.153 \pm 0.007 | 0.158 \pm 0.008 | 0.497 \pm 0.008 |
| 3835 H\( \beta \) | 0.083 \pm 0.007 | 0.208 \pm 0.023 | 0.041 \pm 0.004 |
| 3868 [Ne \text{[m]}] | 0.138 \pm 0.007 | 0.140 \pm 0.008 | 0.152 \pm 0.005 |
| 3899 He \text{"} + H\( \beta \) | 0.094 \pm 0.007 | 0.215 \pm 0.021 | 0.172 \pm 0.005 |
| 3968 [Ne \text{[m]}] + H\( \alpha \) | 0.177 \pm 0.007 | 0.264 \pm 0.015 | 0.231 \pm 0.005 |
| 4101 H\( \alpha \) | 0.383 \pm 0.008 | 0.467 \pm 0.012 | 0.450 \pm 0.007 |
| 4340 H\( \alpha \) | 0.078 \pm 0.007 | 0.076 \pm 0.008 | 0.059 \pm 0.004 |
| 4656 He \text{"} | 0.012 \pm 0.005 | 0.011 \pm 0.006 | 0.034 \pm 0.004 |
| 4711 He \text{"} | 0.038 \pm 0.006 | 0.036 \pm 0.006 | ... |
| 4861 H\( \beta \) | 1.000 \pm 0.012 | 1.000 \pm 0.014 | 1.000 \pm 0.011 |
| 4959 [O \text{[m]}] | 0.729 \pm 0.010 | 0.675 \pm 0.010 | 0.620 \pm 0.008 |
| 5007 [O \text{[m]}] | 2.173 \pm 0.022 | 2.003 \pm 0.022 | 1.850 \pm 0.018 |
| 5876 He \text{"} | 0.063 \pm 0.004 | 0.055 \pm 0.004 | 0.095 \pm 0.003 |
| 6563 H\( \alpha \) | 3.235 \pm 0.030 | 2.727 \pm 0.030 | 2.832 \pm 0.026 |
| 6717 [S \text{[ii]}] | 0.027 \pm 0.004 | 0.023 \pm 0.003 | 0.030 \pm 0.002 |
| 6731 [S \text{[ii]}] | 0.021 \pm 0.004 | 0.017 \pm 0.003 | 0.043 \pm 0.003 |

| Property | I Zw 18 NW | I Zw 18 SE | SBS 0335—052 |
|----------|------------|------------|--------------|
| C(H\( \beta \)) (dex) | 0.145 | 0.015 | 0.130 |
| \( F(H\beta) \times 10^{-14} \) ergs cm\(^{-2} \) s\(^{-1} \) | 0.29 | 0.35 | 1.91 |
| \( EW(H\beta) \) (Å) | 34 | 144 | 237 |
| \( EW(\text{absolute}) \) (Å) | 2.5 | 3.9 | 5.4 |
spectra for both the northwest and southeast components are shown in Table 4. In deriving these quantities, we have neglected temperature fluctuations. While there is evidence for large temperature fluctuations in planetary nebulae and perhaps in high-metallicity H II regions, we believed that there is, until now, no such convincing evidence for low-metallicity H II regions like the ones considered here (see a detailed discussion of this issue in Izotov & Thuan 1998b).

The electron temperatures $T_e$(O III) are much higher than those obtained by Skillman & Kennicutt (1993) through a larger aperture ($2' \times 5'$ for the southeast component and $2' \times 7.55'$ for the northwest component), by 1900 K in the northwest component, and by 2300 K in the southeast component. They are also higher by 1800 and 700 K, respectively, than the temperatures obtained by Izotov & Thuan (1998a) within an aperture of $2' \times 5'$. There are evidently temperature gradients at the centers of both the northwest and southeast components (see also Martin 1996), and large apertures invariably give lower electron temperatures. Matching the small HST FOS aperture as closely as possible is essential to derive appropriate abundances. The higher electron temperatures lead to lower oxygen abundances than those derived by Skillman & Kennicutt (1993) and Izotov & Thuan (1998a) for larger regions. Note that the oxygen abundance derived for the northwest component is lower than that derived for the southeast component by a factor of $\sim 1.2$. This is again because there is a gradient toward higher temperatures in the central part of the northwest component, which leads to lower abundances. In larger apertures, the derived oxygen abundances are the same within the errors for both components, suggesting good mixing (Skillman & Kennicutt 1993; Izotov & Thuan 1998a). The new C/O derived using emission-line fluxes from Garnett et al. (1997) is also lower than the value derived by those authors, implying C/O abundance gradients. We have also measured the fluxes of the Si iii] 1883 Å and 1992 Å emission lines and derived silicon abundances in both components.

3.2.3. SBS 1415 + 437

This galaxy, with a heavy-element abundance $Z_0/21$ (Izotov & Thuan 1998b), has been observed with the HST FOS in the UV and optical ranges (Thuan et al. 1999). As in I Zw 18 NW, the Si iii] 1892 Å emission line is not seen. Instead, at the location of this line, a deep absorption is observed. Therefore, the total flux of the Si iii] emission lines has been derived by multiplying the Si iii] 1883 Å emission-line flux by a factor of 1.67. The UV emission-line fluxes have been corrected for extinction using the reddening law for the Small Magellanic Cloud (Prévote et al. 1984). The electron temperature is derived from a high signal-to-noise ratio MMT spectrum in a $1.5' \times 0.6'$ aperture (Thuan et al. 1999).

3.2.4. UM 469, NGC 4861, and T1345 – 420

We use for these galaxies the corrected emission-line fluxes derived by Kobulnicky & Skillman (1998) to calculate C/O and Si/O with equations (3)–(6). We also correct the abundance ratio C++/O++ for unseen stages of ionization, whereas Kobulnicky & Skillman (1998) decided not to apply a correction factor.

3.2.5. NGC 5253

Kobulnicky et al. (1997) have derived C/O and Si/O in three H II regions of this galaxy. Our measurements of the emission-line fluxes in the same FOS spectra retrieved from the HST archives are in fair agreement with theirs, except for the Si iii] (1883 Å + 1992 Å) emission-line flux in the H II – 2 region, for which we derive a higher value. We have also corrected Si++/C++ for unseen stages of ionization, which was not done by Kobulnicky et al. (1997). This correction factor can be as high as $\sim 1.4$.

4. HEAVY ELEMENT ABUNDANCES

Our main goal here is to use the large homogeneous BCG sample described above to extend the work of TIL95 and study in more detail and with more statistics the relationship between different heavy elements in a very low-metallicity environment. Some of the very low-metallicity galaxies are most likely young nearby dwarf galaxies each having undergone its first burst of star formation not more than 100 Myr ago (Thuan et al. 1997, 1999; Thuan & Izotov 1997). Therefore, the relationships between different heavy-element abundances will not only put constraints on the

| Table 4: Electron Temperatures and Oxygen Abundances Derived from the MMT Spectra |
|----------------------------------|-----------------|-----------------|-----------------|
| Property                        | I Zw 18 NW      | I Zw 18 SE      | SBS 0335 – 052  |
| $T_e$(O iii) (K)                 | 21500 ± 1400    | 19500 ± 800     | 19300 ± 100     |
| $T_e$(O iii) (K)                 | 16100 ± 900     | 15500 ± 600     | 15500 ± 100     |
| $T_e$(O iii) (K)                 | 19500 ± 1100    | 17900 ± 600     | 17700 ± 100     |
| $O^+/H^+ (\times 10^3)$          | 0.11 ± 0.02     | 0.38 ± 0.04     | 0.15 ± 0.01     |
| $O^+/H^+ (\times 10^3)$          | 1.00 ± 0.14     | 1.09 ± 0.10     | 1.90 ± 0.01     |
| $O^+/H^+ (\times 10^3)$          | 0.05 ± 0.01     | 0.04 ± 0.01     | 0.04 ± 0.01     |
| $O/H (\times 10^4)$              | 1.17 ± 0.15     | 1.48 ± 0.10     | 2.09 ± 0.01     |
| $12 + \log(O/H)$                | 7.07 ± 0.05     | 7.17 ± 0.06     | 7.32 ± 0.01     |

We again use new high signal-to-noise ratio MMT spectral observations (Izotov et al. 1997b) in an effort to improve the situation. We extracted a one-dimensional spectrum of the brightest part of the SBS 0335 – 052 within a $1' \times 0.6'$ aperture to best match the FOS aperture. We use the MMT spectrum to derive the electron temperature and the oxygen abundance and combine it with the HST UV spectrum to derive C/O and Si/O. Emission-line fluxes are shown in Table 2, and the electron temperature $T_e$(O iii) and oxygen abundance are given in Table 4. The observed emission C iii] $\lambda$(1906 + 1909) and Si iii] $\lambda$(1882 + 1893) fluxes are corrected for extinction using the reddening law for the Small Magellanic Cloud, as parameterized by Prévote et al. (1984). The carbon and silicon abundances are shown in Table 5. We derive higher log C/O = $-0.83 \pm 0.08$ and log Si/O = $-1.60 \pm 0.21$ values than do Garnett et al. (1995a, 1995b), although the values are consistent within the errors.
## TABLE 5
**Carbon and Silicon Abundances**

| Property | I Zw 18NW | I Zw 18SE | 0335 – 052 | 1415 + 437 | UM 469 | NGC 4861 | T1345 – 420 | N5253 H i–1 | N5253 UV–1 | N5253 H i–2 |
|----------|-----------|-----------|-------------|-------------|---------|-----------|-------------|-------------|-------------|-------------|
| $F(\text{Si} \\text{iii}) 1853 + 1892^a$ | 0.32 ± 0.06$^a$ | 0.26 ± 0.06$^a$ | 0.20 ± 0.02 | 0.37 ± 0.05$^b$ | ... | 0.64 ± 0.05 | ... | 0.11 ± 0.04 | 0.12 ± 0.05 | 0.12 ± 0.06$^b$ |
| $F(\text{C} \\text{iii}) 1906 + 1909^a$ | 0.55 ± 0.09 | 0.50 ± 0.07 | 0.49 ± 0.03 | 0.51 ± 0.05 | 0.55 ± 0.09 | 1.40 ± 0.36 | 0.47 ± 0.01 | 0.34 ± 0.05 | 0.35 ± 0.05 | 0.28 ± 0.05 |
| $T_e (K)$ | 7.02 ± 0.05 | 7.17 ± 0.06 | 7.32 ± 0.01 | 7.60 ± 0.01 | 7.97 ± 0.05 | 8.03 ± 0.02 | 8.11 ± 0.05 | 8.12 ± 0.05 | 8.16 ± 0.12 | 8.19 ± 0.06 |

$^a$ Emission line flux corrected for extinction, relative to the flux in H$\beta$.

$^b$ The $\text{Si} \\text{ii}$ 1892 was not detected. We adopt $F(\lambda 1883 + 1892) = 1.67F(\lambda 1883)$, as expected in the low-density limit.
star formation history of BCGs, they will also be useful for understanding the early chemical evolution of galaxies. Furthermore, a precise determination of heavy-element abundances in BCGs can put constraints on stellar nucleosynthesis models, as theoretical predictions for the yields of some elements are not yet very firm. The best-studied and most easily observed element in BCGs is oxygen. Nucleosynthesis theory predicts it to be produced only by massive stars. We shall use it as the reference chemical element and consider the behavior of heavy-element abundance ratios as a function of oxygen abundance.

4.1. Neon, Silicon, Sulfur, and Argon

The elements neon, silicon, sulfur, and argon are all products of $\alpha$-processes during both hydrostatic and explosive nucleosynthesis in the same massive stars that make oxygen. Therefore, $\text{Ne/O}$, $\text{Si/O}$, $\text{S/O}$, and $\text{Ar/O}$ should be constant and show no dependence on the oxygen abundance. In Figure 1 we show the abundance ratios for these elements as a function of $12 + \log O/H$ (filled circles). For $\text{Si/O}$, we have also shown for comparison the data from Garnett et al. (1995a) for those galaxies that we have not reanalyzed for lack of necessary data (open circles). These galaxies are not included in the computation of the mean abundance ratios listed in Table 6. The mean values of these element abundance ratios are directly related to the stellar yields and thus provide strong constraints on the theory of massive stellar nucleosynthesis. Note that, while silicon and sulfur abundances can be measured in a wide variety of astrophysical settings (stars, H II regions, high-redshift damped Ly$\alpha$ clouds), neon and argon abundances can be measured with good precision at low metallicities only in BCGs. Table 6 gives the mean values of $\text{Ne/O}$, $\text{Si/O}$, $\text{S/O}$, and $\text{Ar/O}$ calculated for the total sample, as well as for two subsamples: a low-metallicity subsample containing galaxies with $12 + \log O/H \leq 7.6$ and a high-metallicity subsample containing galaxies with $12 + \log O/H > 7.6$. For comparison, we also list the solar ratios taken from Anders & Grevesse (1989). Generally, the dispersion about the mean of the points in the low-metallicity subsample is smaller than that in the high-metallicity subsample and the total sample, although the differences are not statistically significant. Examination of Figure 1 and Table 6 shows that, as predicted by stellar nucleosynthesis theory, no dependence on oxygen abundance is found for any of the abundance ratios $\text{Ne/O}$, $\text{Si/O}$, $\text{S/O}$, and $\text{Ar/O}$.

Independently of the subsample, $\text{Ne/O}$, $\text{Si/O}$, $\text{S/O}$, and $\text{Ar/O}$ are all very close to the corresponding solar values

**Table 6: Mean Heavy-Element Abundance Ratios**

| Quantity   | Total Sample | Low-Metallicity Subsample | High-Metallicity Subsample | Sun    |
|------------|--------------|----------------------------|---------------------------|--------|
| $\log C/O$ | $-0.63 \pm 0.14$ (10) | $-0.78 \pm 0.03$ (4)       | $-0.52 \pm 0.08$ (6)      | $-0.38$ |
| $\log N/O$ | $-1.47 \pm 0.14$ (53) | $-1.60 \pm 0.02$ (6)       | $-1.46 \pm 0.14$ (47)     | $-0.88$ |
| $\log Ne/O$ | $-0.72 \pm 0.06$ (54) | $-0.75 \pm 0.03$ (6)       | $-0.72 \pm 0.06$ (48)     | $-0.84$ |
| $\log Si/O$ | $-1.48 \pm 0.11$ (8)  | $-1.50 \pm 0.06$ (4)       | $-1.45 \pm 0.13$ (4)      | $-1.37$ |
| $\log S/O$  | $-1.56 \pm 0.06$ (49) | $-1.59 \pm 0.04$ (6)       | $-1.55 \pm 0.06$ (43)     | $-1.66$ |
| $\log Ar/O$ | $-2.26 \pm 0.09$ (53) | $-2.22 \pm 0.07$ (6)       | $-2.27 \pm 0.10$ (47)     | $-2.37$ |
| $\text{[O/Fe]}$ | $0.40 \pm 0.14$ (38) | $0.32 \pm 0.11$ (4)       | $0.42 \pm 0.12$ (33)      | $0.00$  |

**Note:** The number of H II regions entering in the mean is shown in parentheses.

* Galaxies with $12 + \log O/H \leq 7.6$.
* Galaxies with $12 + \log O/H > 7.6$.
* Solar abundance ratios are from Anders & Grevesse 1989.
* The SBS 0335–052 deviant point is excluded. Its inclusion would have given $\langle \text{[O/Fe]} \rangle = 0.23 \pm 0.20$. 

**(Fig. 1, dotted lines).** There may be a hint that the mean $\text{Si/O}$ in BCGs is slightly lower than the solar value, but the difference is again not statistically significant. We thus conclude that there is no significant depletion of silicon into dust grains in BCGs. By contrast, Garnett et al. (1995a) have found a weighted mean $\log \text{Si/O} = -1.59 \pm 0.07$ for their sample of low-metallicity galaxies, lower by a factor of $\sim 1.6$
than the solar value. This led them to conclude that about 50% of the silicon is incorporated into dust grains. The number of galaxies with measured silicon abundances is not large, and more observations are needed for a more definite conclusion.

The mean values of the abundance ratios for the other elements are in very good agreement with those derived by TIL95 for a smaller sample of BCGs. TIL95 have made detailed comparisons of their results with those of previous studies, so we shall not repeat the discussion here. We shall mention only the more recent work of van Zee, Haynes, & Salzer (1997), who have studied heavy element abundance ratios in the H II regions of 28 gas-rich, quiescent dwarf galaxies. Their mean values of Ne/O, S/O, and Ar/O are consistent within the errors with the results of TIL95 and those obtained here, although in many of their galaxies, the abundance measurements are more uncertain because the [O III] 4363 Å emission line is not detected and the electron temperature is derived from an empirical method.

4.2. Carbon

Carbon is produced by both intermediate and high-mass stars. Since C is a product of hydrostatic burning, the contributions of SNe Ia and SNe II are small. Therefore, C/O is sensitive to the particular star formation history of the galaxy. It is expected that, in the earliest stages of galaxy evolution, carbon is mainly produced by massive stars, so that C/O is independent of the oxygen abundance, as both C and O are primary elements. At later stages, intermediate-mass stars add their carbon production, so that an increase in C/O is expected with increasing oxygen abundance.

The results of the study by Garnett et al. (1995b) did not conform to these expectations. Those authors found a continuous increase of log C/O with increasing log O/H in their sample of metal-deficient galaxies, an increase that could be fitted by a power law with slope 0.43. Because log C/O is fairly constant at −0.9 for halo stars in the Galaxy (Tomkin et al. 1992), Garnett et al. (1995b) suggested there may be a difference between the abundance patterns seen in the Galaxy and in dwarf galaxies. Subsequent HST FOS observations of I Zw 18 by Garnett et al. (1997) yielded abundances that complicated the situation even more. It was found that I Zw 18 bucks the trend shown by the other low-metallicity objects. Although it has the lowest metallicity known, it shows a rather high log C/O, equal to −0.63 ± 0.10 and −0.56 ± 0.09 in the northwest and southeast components, respectively. These values are significantly higher than those predicted by massive stellar nucleosynthesis theory. This led Garnett et al. (1997) to conclude that carbon in I Zw 18 has been enhanced by an earlier population of lower mass stars, and, hence, despite its very low metallicity, I Zw 18 is not a "primeval" galaxy. Garnett et al. (1997) considered and dismissed the possibility that the high value of C/O in I Zw 18 may be due to errors in the electron temperature. We have revisited the problem here for I Zw 18 with our own data and conclude that it is indeed a too-low adopted electron temperature that is responsible for the too-high value of C/O in both components of I Zw 18. The temperatures adopted by Garnett et al. (1997) for I Zw 18 are derived from optical observations in an aperture larger than the FOS aperture and are too low because of a temperature gradient. In Figure 2a we have plotted with filled circles log C/O against 12 + log O/H for all the galaxies that we have reanalyzed. Great care was taken to derive electron temperatures in apertures matching as closely as possible the FOS aperture. Open circles show galaxies from Garnett et al. (1995b), Kobulnicky et al. (1997), and Kobulnicky & Skillman (1998) and our optical data obtained with the Multiple Mirror Telescope. Other data from Garnett et al. (1995b), Kobulnicky et al. (1997), and Kobulnicky & Skillman (1998) are shown by open circles. Note the very small dispersion of C/O and N/O for BCGs with 12 + log O/H ≤ 7.6 (labeled points). (a) For C/O, the two solid horizontal lines show abundance ratios predicted by theoretical models by WW95 with Z = 0 and Z = 0.01 Z⊙, in the case of C production by high-mass stars only. The value of C/O predicted in the case of C production by both high- and intermediate-mass stars is shown by the horizontal dashed line. The stellar yields for the latter are from RV81. (b) For N/O, the solid line shows the mean observed value for high-mass stars, as there is no model for primary N production by high-mass stars as yet. The dashed line shows the expected N/O when primary N is produced by both high and intermediate-mass stars. The stellar yields for the latter are from RV81. The dotted lines in (a) and (b) show the solar ratios.
Z = 0.01 Z⊙ are shown by horizontal lines in Figure 2a. They are in good agreement with the observations. At higher metallicities (12 + log O/H > 7.6), there is an increase in log C/O with log O/H and also more scatter at a given O/H, which we attribute to the carbon contribution of intermediate-mass stars in addition to that of massive stars.

4.3. Nitrogen

The origin of nitrogen has been a subject of debate for some years. The basic nucleosynthesis process is well understood—nitrogen results from CNO processing of oxygen and carbon during hydrogen burning—however, the nature of the stars mainly responsible for the production of nitrogen remains uncertain. If oxygen and carbon are produced not in a previous generation of stars but in the same stars prior to the CNO cycle, then the amount of nitrogen produced is independent of the initial heavy-element abundance of the star and its synthesis is said to be primary. On the other hand, if the “seed” oxygen and carbon are produced in previous-generation stars and incorporated into a star at its formation and a constant mass fraction is processed, then the amount of nitrogen produced is proportional to the initial heavy-element abundance and the nitrogen synthesis is said to be secondary. Secondary nitrogen synthesis can occur in stars of all masses, while primary nitrogen synthesis is usually (but not universally) thought to occur mainly in intermediate-mass stars (RV81; WW95). In the case of secondary nitrogen production, it is expected that massive stars with decreasing metallicity will produce decreasing amounts of 14N (WW95). There is, however, a caveat: there is the possibility that in some massive stars the convective helium shell penetrates into the hydrogen layer, with the consequent production of large amounts of primary nitrogen.

The behavior of the abundance ratio N/O as a function of O/H has provided the main observational constraint to this debate. In low-metallicity Galactic halo stars, N/O is nearly independent of O/H, implying that nitrogen has a strong primary component that can be explained by primary nitrogen production in massive stars with large amounts of convective overshoot (Timmes, Woosley, & Weaver 1995). Several studies of low-metallicity (12 + log O/H ≤ 8.3) H II regions in dwarf galaxies have also revealed that N/O is independent of O/H implying again a primary origin of nitrogen (Garnett 1990; Vila-Costas & Edmunds 1993; TIL95; van Zee et al. 1997; van Zee, Salzer & Haynes 1998). It is generally believed that primary nitrogen in BCGs is produced by intermediate-mass stars by carbon dredge-up (RV81). For high-metallicity H II regions in spiral galaxies (12 + log O/H > 8.3), N/O increases linearly with the O abundance, indicating that, in this metallicity regime, N is primarily a secondary element. We shall not be concerned with secondary N here and shall discuss mainly primary N since all our BCGs have 12 + log O/H < 8.3.

A problem in interpreting the data in the vast majority of studies is the existence of a considerable scatter (±0.3 dex) in N/O at a given O/H. The large scatter has been attributed to the delayed release of N produced in intermediate-mass long-lived stars, compared to O produced in massive short-lived stars (Matteucci & Tosi 1985; Matteucci 1986; Garnett 1990; Pilyugin 1992, 1993; Marconi et al. 1994; Kobulnicky & Skillman 1996, 1998). In contrast to these studies, TIL95 found the scatter in N/O at a given O/H to be large only when the metallicity exceeds a certain value, i.e., 12 + log O/H > 7.6. At lower O abundances, the scatter is extremely small. It is difficult to improve much the statistics by adding more galaxies in this very low-metallicity range to the TIL95 sample because the known objects having such a low heavy-element content are very scarce and extremely difficult to discover. We have added only SBS 0335−052 with Z⊙/41, the second most metal-deficient BCG known after I Zw 18 (Fig. 2b). As for the latter, we have used our own data instead of that of Skillman & Kennicutt (1993). The result is the same. The scatter of the points is very small: ⟨log N/O⟩ = −1.60 ± 0.02 (Table 6). We do not believe that this very small scatter is the result of some unknown selection effect that would invariably pick out low-metallicity BCGs at the same stage of their evolutionary history. This is for two reasons. First, we have plotted all the data we have, without any selection. Second, as discussed later, the scatter does increase substantially for higher metallicity BCGs. There is no obvious reason why a selection effect would operate only on low-metallicity objects and not on higher metallicity ones.

As discussed by TIL95, the very small dispersion of N/O puts very severe constraints on time-delay models. A time delay between the primary production of oxygen by massive stars and that of nitrogen by intermediate-mass stars can be as large as 5 × 10^8 yr, the lifetime of a 2−3 M⊙ star. This would introduce a significant (≥0.2 dex) scatter in N/O, as chemical evolution models by Pilyugin (1993) and Marconi et al. (1994) show. We reiterate the conclusion of TIL95, that the small scatter of N/O in the most metal-deficient galaxies in our sample can be best understood if primary N in these galaxies is produced by massive stars (M > 9 M⊙) only. As we shall see in § 5, intermediate-mass stars have not yet returned their nucleosynthesis products to the interstellar medium in these most metal-poor galaxies, because they have not had enough time to evolve. There is a further data point that we did not include in our sample but that strengthens our results even more. It comes from the western companion of SBS 0335−052, the BCG SBS 0335−052 W, located in a common H I envelope with the former object. This BCG was observed by Lipovetsky et al. (1999) with the MMT and Keck telescopes to have oxygen abundances in its two knots of 12 + log O/H = 7.22 ± 0.03 and 7.13 ± 0.07, respectively, with corresponding log N/O = −1.54 ± 0.06 and −1.53 ± 0.19, consistent with our mean derived value of log N/O (Table 6).

We have compared our results with those of other authors for BCGs in the range 12 + log O/H ≤ 7.6, using the compilation of Kobulnicky & Skillman (1996) of the existing data for element abundances in BCGs. Two galaxies in their compilation show values of N/O that are significantly lower than our mean value, by many times the dispersion of our sample. The first one is Tol 65, with 12 + log O/H = 7.56, which has a very low log N/O = −1.79 ± 0.20. This galaxy was observed nearly two decades ago (in 1980) by Kunth & Sargent (1983). Its N/O has large errors and should be redetermined more precisely. The second galaxy, CG 1116+51 with 12 + log O/H = 7.53, has log N/O = −1.68 ± 0.11. However, Izotov & Foltz (1999) have recently reobserved this galaxy with the MMT and found log N/O = −1.57 ± 0.09, consistent with the mean value and small dispersion about the mean found here and in TIL95. Studies of southern BCGs by Campbell et al. (1986) and Masegosa, Moles, & Campos-Aquilar...
(1994) also show a lower envelope for log N/O at around $-1.6$ to $-1.7$. The very few galaxies with N/O below the envelope all have large observational uncertainties.

The situation changes appreciably for BCGs with $12 + \log O/H > 7.6$. The scatter of the C/O and N/O values increases significantly at a given O abundance. This increase in the dispersion is best explained if, in addition to the production of carbon and primary nitrogen by massive stars during the starburst phase, there is an additional production of both these elements by intermediate-mass stars during the interburst quiescent phase. Within the framework of current nucleosynthesis theory (RV81; WW95), primary nitrogen is produced only by intermediate-mass stars, not by massive stars. In this case the production of nitrogen would be decoupled from that of oxygen, and in principle very low N/O values could be observed. However, our observations do not confirm these expectations. Instead, Figure 2\textsuperscript{b} shows a definite lower envelope for the N/O at the level set by primary nitrogen production in low-metallicity massive stars.

To summarize, we have arrived at the following important conclusions concerning the origin of nitrogen: (1) in very low-metallicity BCGs with $12 + \log O/H \leq 7.6$, nitrogen is produced as a primary element by massive stars only. Intermediate-mass stars have not had the time to evolve and release their nucleosynthesis products to the interstellar medium. The massive stars set the level of log N/O at $\sim -1.60$. This picture is the most reasonable one to account for the extremely small dispersion in log N/O ($\pm 0.02$ dex) at a given O abundance.

(2) The values of log N/O increases above $-1.60$ along with the scatter at a given O abundance in BCGs with $7.6 < 12 + \log O/H < 8.2$. We interpret this increase in log N/O and its larger scatter as due to the additional contribution of primary nitrogen produced by intermediate-mass stars, on top of the primary nitrogen produced by massive stars.

Finally, we check whether N/O values observed in more quiescent dwarf galaxies with less active star formation (van Zee et al. 1997, 1998) are consistent with the scenario outlined above. The H II regions in the latter have much lower excitation than those in BCGs, and the [O III] 4363 Å emission line is not seen in many galaxies. In the framework of a time-delayed nitrogen production model, we would expect lower values of N/O in quiescent dwarf galaxies than in BCGs as the bursts in the former are older (the Hβ emission equivalent widths are smaller) and more oxygen has been released relative to nitrogen. Van Zee et al. (1997, 1998) do find some galaxies with very low log N/O $\leq -1.7$. However, these low values are suspect and may be subject to systematic errors. There are several odd features concerning the galaxies with low N/O in the sample of van Zee et al. (1997, 1998). First, they were all observed in the same run, the mean value of their log N/O in 9 H II regions being $-1.84$, while that for the rest of the sample observed during four other runs is $-1.52$, in good agreement with the mean value found for BCGs. Second, the derived extinctions for the low-N/O galaxies are either zero or systematically lower than those of other galaxies observed in different runs. The H II region UGC 5764-3 with the lowest log N/O = $-2.02$ has an intensity ratio Hα/Hβ of only 2.3, much lower than the theoretical recombination value of 2.7–2.8. We conclude therefore that there is no strong evidence in the quiescent dwarf galaxy data against a scenario of primary nitrogen production by high-mass stars in the galaxy metallicity range $12 + \log O/H \leq 7.6$.

### 4.4. Iron

The abundance ratio Fe/O also provides a very important constraint on the chemical-evolution history of galaxies. TIL95 first discussed the iron abundance in BCGs. From their small sample of seven low-metallicity BCGs, they found that oxygen in these galaxies is overproduced relative to iron, as compared to the Sun: $[\text{O/Fe}] = \log (\text{Fe/O})_\odot - \log (\text{Fe/O}) \approx 0.34 \pm 0.10$. This value is in very good agreement with the $[\text{O/Fe}]$ observed for Galactic halo stars (Barbuy 1988), implying that the origin of iron in low-metallicity BCGs and in the Galaxy prior the formation of halo stars is similar and supporting the scenario of an early chemical enrichment of the Galactic halo by massive stars.

We have considerably increased the size of the sample of BCGs with iron abundance measurements. In Figure 2c we show [O/Fe] versus $12 + \log O/H$ for a total of 38 BCGs. It can be seen that, for all BCGs except one, [O/Fe] is above the solar value, reinforcing the conclusion of TIL95. The mean value of [O/Fe] for the whole sample is $0.40 \pm 0.14$ (Table 6). The only exception is the BCG SBS 0335$-$052, which has a negative [O/Fe]; i.e., oxygen is underabundant with respect to iron as compared to the Sun. These odd abundances are not the result of observational errors, as Izotov et al. (1997b) derived a similar result from independent MMT observations. The low value of [O/Fe] is more probably caused by the contamination and hence artificial enhancement of the nebular [Fe III] 4658 Å emission line by the narrow stellar C IV 4658 Å emission line produced in hot stars with stellar winds. The presence of these stars in SBS 0335$-$052 is demonstrated by the detection of stellar Si IV 1394 and 1403 Å lines with P Cygni profiles (Thuan & Izotov 1997). A case in point that supports this contamination hypothesis is that of the northwest component of I Zw 18. Izotov et al. (1997a) and Legrand et al. (1997) have discovered a Wolf-Rayet population in this northwest component, with a significant contribution from WC4 stars to the C IV λ4658 emission. The spectrum by Izotov et al. (1997a) shows that a narrow emission line at 4658 Å superposed on top of the broad C IV λ4658 bump produced by the WR stars. The use of this narrow emission line to derive Fe abundance results in an artificially low [O/Fe] $\approx -0.4$ for the northwest component of I Zw 18. On the other hand, the southeast component, which does not possess Wolf-Rayet stars and hence has a nebular [Fe III] 4658 Å emission line uncontaminated by narrow stellar C IV λ4658 emission, has a normal [O/Fe] $\approx 0.3$, consistent with the value derived by ITL97 and with the mean value for the BCGs in our sample. We have plotted in Figure 2c the [O/Fe] value for the southeast component of I Zw 18. Another possible explanation for the abnormally low [O/Fe] in SBS 0335$-$052 is the enhancement of the [Fe III] lines by supernova shocks. Disregarding SBS 0335$-$052, Figure 2c shows that O/Fe in BCGs is nearly constant, irrespective of the oxygen abundance, at a value $\sim 2.5$ higher than in the solar neighborhood.

### 4.5. Comparison of Observational and Theoretical Nucleosynthetic Yields

#### 4.5.1. Heavy-Element Enrichment by Massive Stars

The remarkable constancy and small scatter of C/O and
N/O for the BCGs with oxygen abundance $12 + \log O/H \leq 7.6$, and the similar behavior of Ne/O, Si/O, S/O, Ar/O and [O/Fe] with respect to the O abundance for all the BCGs in our sample, provide a unique opportunity to compare the observed yields of massive stars with theoretical predictions and put stringent constraints on nucleosynthetic models of low-metallicity massive stars. This comparison has generally been made for stars in the Galaxy (Timmes et al. 1995; Samland 1998). However, the Galaxy is a complex evolved stellar system with a juxtaposition of many generations of stars. While its study allows the possibility of testing models for a wide range of metallicities, the task is complex because the chemical enrichment is made not only by massive but also by intermediate- and low-mass stars. Additionally, heavy-element abundance ratios in the Galaxy may be modified by dynamical effects such as gas infall or outflow. BCGs are simple systems by comparison. Since, in the lowest metallicity BCGs, all heavy elements are made by massive stars only, the chemical enrichment of BCGs is insensitive to infall or outflow of material and is dependent only on the characteristics of the initial mass function (IMF) and stellar yields.

A first comparison of observed stellar yields by massive stars with theoretical calculations has been made by TIL95. Since our observational sample is much increased and new calculations (WW95) have appeared that cover a wider metallicity range (TIL95 had only solar metallicity models to compare with), we revisit the problem here. Table 7 shows the heavy element–oxygen yield ratios as derived from the observed abundance ratios. Since intermediate-mass stars contribute significantly to the synthesis of C and N in BCGs with $12 + \log O/H > 7.6$, the observed yield ratios $M(C)/M(O)$ and $M(N)/M(O)$ were derived using BCGs with $12 + \log O/H \leq 7.6$, so that only the contribution from massive stars is taken into account. For each of the other elements, the derived yield is simply the mean value of the abundance ratio for the whole sample. As for the theoretical yields given in Table 7, they are taken from WW95 and averaged over an IMF with a Salpeter slope in the stellar mass range 1–100 $M_\odot$, for a heavy-element mass fraction ranging from $Z = 0$ to $Z_\odot$. The two horizontal solid lines in Figures 1 and 2 show, for all elements except N and Fe, the range of theoretical yield ratios predicted by WW95 as determined by their models with metallicities of 0 and 0.01 $Z_\odot$.

Inspection of Table 7 and Figures 1 and 2 shows that the heavy-element yield ratios calculated by WW95 are generally not too far off from the yield ratios inferred from the observations. The model that fits best the observed Ne/O and Si/O (Figs. 1a and 1b) has $Z = 0$. Models with $Z > 0$ predict a Ne abundance too low by a factor of ~2, while the predicted Si abundance is too high by about the same factor. This anticorrelation can be explained by the fact that part of the Ne produced is consumed in the later stages of hydrostatic burning, synthesizing Si in particular. The observed S/O and Ar/O (Figs. 1c and 1d) are best fitted by the $Z = 0.01 Z_\odot$ and $Z = 0.1 Z_\odot$ models that give nearly identical yields. The $Z = 0$ model predicts yields too low by a factor of ~1.3. As for C/O (Fig. 2a), the $Z = 0$ and $Z = 0.01 Z_\odot$ models, in which C is produced only by massive stars and not by intermediate-mass stars, nicely bracket the data for BCGs with $12 + \log O/H < 7.6$. It may seem surprising that the models that best fit elements such as Ne and Si have $Z = 0$, considering that the BCGs in our sample all have $Z \geq 0.02 Z_\odot$. However, these heavy-element abundances characterize the ionized gas, not the stars, which can have much lower metallicities.

Because the most abundant Ne isotope, $^{20}$Ne, is synthesized during hydrostatic carbon burning, it is not sensitive to uncertainties in explosive nucleosynthesis models. Si, S, and Ar yields in massive stars are, on the other hand, sensitive to the treatment of the explosion. Additionally, the production of these elements is sensitive to a variety of uncertain factors, such as the rate of the $^{12}$C$(x, y)^{16}$O process, the treatment of semiconvection, the treatment of convection and convective overshoot mixing during the last stages of shell oxygen burning, the density structure near the iron core, the initial location of the mass cut, and the amount of mass that falls back in the explosion (WW95). Given all these uncertainties, it is not so much the small discrepancies between theoretical and observational yield ratios that should be emphasized but the overall good general agreement: it is remarkable that the abundance ratios inferred from the stellar yields by WW95 do not differ from those observed in BCGs by large factors, being invariably in the ballpark.

The calculated N and Fe yields constitute exceptions: they do not agree well with the data. TIL95 have already discussed the problem of iron, for which the theoretical yields are ~2 times greater than those inferred from the theoretical observation.

### TABLE 7

| Quantity  | Observations | $Z = 0$ | $Z = 10^{-4} Z_\odot$ | $Z = 10^{-2} Z_\odot$ | $Z = 10^{-1} Z_\odot$ | $Z = Z_\odot$ |
|-----------|--------------|---------|-------------------------|-------------------------|-------------------------|------------------|
| $M(O)/M_\odot$          | ...          | 3.59E−2 | 3.59E−2                  | 3.78E−2                  | 3.96E−2                  | 4.48E−2          |
| $M(C)/M(O)$           | 1.24E−1b     | 1.39E−1 | 1.34E−1                  | 1.22E−1                  | 1.16E−1                  | 1.17E−1          |
| $M(N)/M(O)$           | 2.19E−2      | 2.64E−4 | 4.67E−5                  | 4.77E−4                  | 3.77E−3                  | 3.82E−2          |
| $M(Fe)/M(O)$          | 2.38E−1      | 2.48E−1 | 1.08E−1                  | 9.73E−2                  | 1.11E−1                  | 1.33E−1          |
| $M(Fe)/M(O)$          | 5.79E−2      | 7.19E−2 | 9.98E−2                  | 1.02E−1                  | 1.01E−1                  | 1.15E−1          |
| $M(Fe)/M(O)$          | 5.15E−2      | 3.56E−2 | 4.69E−2                  | 4.89E−2                  | 4.83E−2                  | 5.41E−2          |
| $M(Fe)/M(O)$          | 1.23E−2      | 7.32E−3 | 9.54E−3                  | 1.05E−2                  | 1.01E−2                  | 1.12E−2          |
| $M(Fe)/M(O)$          | 5.55E−2      | 1.31E−1 | 9.99E−2                  | 1.17E−1                  | 1.18E−1                  | 9.55E−2          |

*a* IMF-averaged yield ratios. The Salpeter IMF with slope $\alpha = -2.35$ is adopted. The lower and upper mass limits are 1 and 100 $M_\odot$, respectively. The stellar yields are from WW95.

*b* Mean value for the BCGs with $12 + \log O/H \leq 7.6$.

*c* Mean value for the total sample.
observations. Theoretical calculations predict that iron is produced during explosive nucleosynthesis by supernovae of both Types I and II in nearly equal quantities. However, the progenitors of SNe II are short-lived massive stars while the progenitors of SNe Ia are low-mass stars that explode only after 1 Gyr. Therefore, \([O/Fe]\) is a good estimator of the galaxy’s age. The constancy of \([O/Fe]\) and its high value in BCGs as compared to the Sun (Fig. 2c) implies that iron in BCGs was produced only by massive stars in Type II supernovae. Because explosive nucleosynthesis models are sensitively dependent on the initial conditions of the explosion, the observed iron-to-oxygen abundance ratio can serve as a good discriminator between different models. TIL95 found that the models fit the observations best when the mass of the central collapsing core in the explosive synthesis is \(\sim 10\%\) larger than the mass of the iron core. Since the mean value of \([O/Fe]\) has not changed with the larger sample as compared to that found by TIL95, this conclusion still holds with the new data.

The discrepancy between theory and observation is much more important for N. The N yield inferred from observations is 1 to more than 2 orders of magnitude larger than the theoretical yields of models with subsolar metallicities (Table 7). This is because conventional low-metallicity massive star models do not produce primary nitrogen. However, as noted by WW95, it is possible that in some massive stars, the convective helium shell penetrates into the hydrogen layer with the consequent production of large amounts of primary nitrogen. In fact, Timmes et al. (1995) have found that the theoretical predictions for primary N production in massive stars with a large amount of convective overshoot are much more consistent with the observed \([N/Fe]\) in low-metallicity halo stars as compared to conventional models, in which nitrogen is produced only as a secondary element, despite the unknown details of convective overshoot.

### 4.5.2. The Role of Intermediate-Mass Stars in Heavy Element Production

While a picture in which all heavy elements in BCGs with \(12 + \log O/H \leq 7.6\) are produced only in high-mass stars (HMS) is consistent with the observations, the additional production of carbon and nitrogen by intermediate-mass stars (IMS) needs to be taken into account in BCGs with oxygen abundances \(12 + \log O/H > 7.6\).

As already discussed, it is commonly thought that primary nitrogen in low-metallicity BCGs is produced only by intermediate-mass stars (RV81; WW95). Additionally, some nitrogen is produced as a secondary element in both intermediately- and high-mass stars. However, because production of secondary nitrogen drops as metallicity decreases, it is expected that the amount of secondary nitrogen is negligible compared to that of primary nitrogen in low-metallicity BCGs. As for carbon, it is believed to be produced as a primary element in all stars more massive than \(1.5 M_\odot\) (RV81; WW95).

We compare in Table 8 the observed C/O and N/O values with theoretical predictions, taking into account the contributions of both high- and intermediate-mass stars. As before, all theoretical ratios are IMF-averaged values with Salpeter slopes of \(-2.35\) and lower and upper mass limits of 1 and \(100 M_\odot\), respectively. Theoretical yields for massive stars in the mass range 12–40 \(M_\odot\) with heavy-element mass fractions \(Z = 0.0002\) are taken from WW95. Since production of primary nitrogen by massive stars is not considered by these authors, we adopt as the primary N yield by massive stars that which is consistent with the observed \(\langle \log N/O \rangle = -1.60\) for low-metallicity BCGs (Table 8 and solid horizontal line in Fig. 2b). As for the C and N yields for intermediate-mass stars, they are taken from two different sets of models. The first set of models is from RV81. They are characterized by stellar masses in the range 3.5–7 \(M_\odot\), a mass-loss efficiency parameter on the asymptotic giant branch of \(\eta = 0.33\), and a mixing length parameter \(\alpha = 1.5\). The other set of models is from HG97. They are characterized by \(Z = 0.001\) and a standard scaling parameter related to the efficiency of mass loss on the asymptotic giant branch of \(\eta = 1\). We shall argue in §5 that the high value of \([O/Fe]\) with respect to the Sun in the BCGs studied here implies that they are not older than \(\sim 1–2\) Gyr. Therefore, we have considered only yields from HG97 for stars with lifetimes less than 1 Gyr, i.e., with masses \(\geq 2 M_\odot\). We assume furthermore that oxygen is produced by massive stars only. We do not give in Table 8 the value of C/O in the case of C production by intermediate-mass stars only, as this situation is not realistic: C produced by longer lived intermediate-mass stars is always accompanied by C produced by shorter lived massive stars.

It is evident from Table 8 that there is general good agreement between observations and theory for C/O. We

### Table 8

**Comparison of Observed and Theoretical Abundance Ratios**

| Quantity       | Observations       | RV81          | HG97          |
|----------------|--------------------|---------------|---------------|
|                | 12 + \log O/H \leq 7.6 | 12 + \log O/H > 7.6 |                |
| \(\log (C/O)\) | \(-0.78 \pm 0.03\) | \(-0.52 \pm 0.08\) | \(-0.75\) \(\pm 0.31\) |
| \(\log (N/O)\) | \(-1.60 \pm 0.02\) | \(-1.46 \pm 0.14\) | \(-1.60^b\) \(\pm 0.11\) |
| \(dY/d\log(O/H)\) | \(\pm 45 \pm 19\) | \(17\) \(\pm 30\) | \(17\) \(\pm 83\) |
| \(dY/d\log(C/H)\) | \(\pm 2.4 \pm 1.0\) | \(129\) \(\pm 83\) | \(129\) \(\pm 133\) |
| \(dY/dZ\) | \(\pm 0.94 \pm 1.66\) | \(0.94\) \(\pm 1.54\) |

* IMF-averaged abundance ratios. The Salpeter IMF with slope \(\alpha = -2.35\) is adopted. The lower and upper mass limits are 1 and \(100 M_\odot\), respectively. The yields for the high-mass stars (HMS) with \(Z = 0.0002\) are from WW95. The yields for the intermediate-mass stars (IMS) are from RV81 for \(Z = 0.004\) and a mixing length parameter \(\alpha = 1.5\) and from HG97 for \(Z = 0.001\) and a mass-loss efficiency parameter \(\eta = 1\). In the latter case, stellar masses range from 2 to \(7 M_\odot\).

* Value adopted from the observations.

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have already discussed the agreement for low-metallicity BCGs with oxygen abundance $12 + \log O/H \leq 7.6$ in which C is produced by massive stars only. The agreement is as good for higher metallicity BCGs with $12 + \log O/H > 7.6$, if C is produced in both massive and intermediate-mass stars. We have plotted in Figure 2a the theoretical C/O value calculated with models by WW95 for high mass stars and by RV81 for intermediate-mass stars \((\text{horizontal dashed line})\). This value should be considered an upper limit as the production of oxygen by massive stars in the current burst of star formation lowers the observed C/O. The latter should lie between a lower limit set by primary C production by massive stars alone, and whose possible range is shown by the two horizontal solid lines in Figure 2a, and that upper limit. The data points for BCGs with $12 + \log O/H > 7.6$ do indeed scatter between these two limits as expected. Using the HG97 models would give a lower upper limit (by a factor of 1.6), but this is still consistent with the data given the observational uncertainties.

The situation for nitrogen is more complex. If nitrogen is produced only by intermediate-mass stars (and oxygen only by massive stars), then the RV81 and HG97 models predict, respectively, $\log N/O = -1.27$ and $-0.84$. While these values are consistent with the largest values of N/O observed for the BCGs in our sample with $12 + \log O/H > 7.6$ (Fig. 2b), N production by intermediate-mass stars alone cannot explain, as discussed before, the very small dispersion of N/O values in BCGs with lower metallicities, so we do not consider this scenario further. We examine therefore the picture where nitrogen is produced by both high- and intermediate-mass stars. If nitrogen is produced only as a secondary element in massive stars, then the predicted $\log N/O$ is too small, $\leq -2.37$ for massive star models with $Z \leq 0.1 Z_\odot$ (Table 7). We thus have to consider the situation in which the nitrogen produced in massive stars is primary. In this case, the combined \((\text{HMS} + \text{IMS})\) nitrogen and oxygen production gives $\log N/O = -1.11$ and $-0.77$ for the RV81 and HG97 models, respectively. As in the case of C/O, these values should be considered upper limits. We have shown in Figure 2b the upper limit corresponding to the RV81 model \((\text{horizontal dashed line})\). The data are completely consistent with the latter model: all the BCGs points fall within the dashed line and the lower limit set by primary N production in massive stars only \((\text{solid line})\). It is important to stress here that, in this picture, no BCG can have an N/O (or C/O) value below the value set by massive star evolution, as indicated by the solid lines in Figure 2b (and Fig. 2a). We have already discussed in §§ 4.2 and 4.3 that we know of no reliable data that contradict that statement.

In summary, the comparison of observational and theoretical yields shows a remarkably good general agreement in spite many uncertain parameters in the models. With the presently available data, the RV81 yields appear to give a slightly better fit to the data than the HG97 yields, although both sets are consistent with it within the observational uncertainties. It is also clear that further development of massive-star nucleosynthesis theory is needed, especially concerning nitrogen and iron production. Because the theoretical yields of some elements are still so uncertain, we feel it is best to use, in computing chemical-evolution models, the empirical yields derived from observations of low-metallicity BCGs, as summarized in Table 7.

### 4.6. Evolution of the He Abundance in BCGs

The analysis of the behavior of the heavy-element abundance ratios as a function of oxygen abundance has shown that chemical enrichment proceeds differently in BCGs with low and high oxygen abundances. In BCGs with $12 + \log O/H \leq 7.6$, high-mass stars are the main agents of chemical enrichment, the very small dispersion of the abundance ratios ruling out the time-delayed production of carbon and nitrogen by intermediate-mass stars. On the other hand, in higher metallicity BCGs with $7.6 < 12 + \log O/H < 8.2$, the contribution of intermediate-mass stars to heavy-element enrichment is significant, as evidenced by an increase in the values and dispersions of C/O and N/O. One might expect therefore that the He enrichment history is also different in these two ranges of oxygen abundances, as helium is produced in different proportions by high and intermediate-mass stars.

In Figure 3 we show the helium mass fraction $Y$ as a function of oxygen abundance for the galaxies in our sample. All of them possess accurate He abundance determinations, as the present sample is precisely the one used by Izotov & Thuan (1998b) to derive the primordial helium abundance $Y_p$. It is the usual practice to extrapolate the $Y$ versus O/H and $Y$ versus N/H linear regressions to $O/H = N/H = 0$ to derive $Y_p$ (Peimbert & Torres-Peimbert 1974, 1976; Pagel, Terlevich, & Melnick 1986). The $Y$ versus O/H regression line is described by

$$Y = Y_p + \frac{dY}{d(O/H)} \cdot (O/H). \quad (7)$$

The dotted line in Figure 3 represents the best-fit regression line as derived by Izotov & Thuan (1998b), with $dY/dZ = 2.4$, which corresponds to $dY/d(O/H) = 45$.

We now compare this best-fit slope with those predicted in various models. In the scenario of element production in high-mass stars only for BCGs with $12 + \log O/H \leq 7.6$ or $O/H \leq 4 \times 10^{-5}$, the predicted slope (WW95) is much shal-
lower, \(\frac{dY}{dZ} = 0.94\) (Table 8). The solid line in Figure 3 has this slope (we adopt \(Y_p = 0.244\); Izotov & Thuan 1998b). It can be seen that it fits the lowest metallicity points quite well and is in fact nearly indistinguishable from the best-fit line. At higher oxygen abundances, the slope steepens because of the additional production of helium in intermediate-mass stars and takes the values \(\frac{dY}{dZ} = 1.66\) and 1.54 for the RV81 and HG97 yields, respectively (Table 8). These values are lower than the best-fit slope, \(\frac{dY}{dZ} = 2.4 \pm 1.0\), but are consistent with it within the errors. The dashed line in Figure 3 shows the slope derived with the RV81 yields. Taking into account the error bars, it fits the observations quite well. We shall need to supplement our BCG sample with more high-metallicity BCGs to determine \(dY/dZ\) better and reduce the observational uncertainties in the individual He determinations before we can ascertain whether there is any difference between the best-fit slope and the one derived from theory. Given the present data, we conclude that our proposed scenario—He production in only high-mass stars for galaxies with \(12 + \log O/H < 7.6\), and He production by both high- and intermediate-mass stars for higher metallicity galaxies—is in good agreement with the observations. If we assume that 25% of the oxygen produced is lost by a galaxy because of supernova-driven winds, then \(dY/dZ\) is nearly unchanged at low metallicities because both oxygen and helium are produced in massive stars. However, when intermediate-mass stars play a role in producing He (but not O), the slope steepens, becoming 1.89 instead of 1.66.

The above analysis implies that a slope change may be expected for the \(Y\) versus O/H linear regression at \(12 + \log O/H \sim 7.6\), and that fitting both the low- and high-metallicity ranges with the same slope may introduce some systematic underestimation of \(Y_p\). If this is the case, it is perhaps best to derive \(Y_p\) not by a regression fit but by taking the mean \(Y\) of the most metal-deficient galaxies. TTL97 and Izotov & Thuan (1998b) did indeed find that the mean \(Y\) of the two most metal-deficient BCGs known, I Zw 18 and SBS 0335–052, is higher by 0.001 than the value derived from a linear regression fit to the whole sample \((<Y> = 0.245 \pm 0.004\) instead of \(Y_p = 0.244 \pm 0.002\)). However, as shown in Figure 3, the difference between the regression line derived by fitting the data with the same slope over the whole metallicity range and that expected for He production by only massive stars is small and far below the observational uncertainties. We conclude therefore that, given the present quality of the data, the method of using a single linear regression (eq. [7]) with the same \(dY/dZ\) slope over the whole metallicity range is perfectly adequate for the determination of the primordial helium abundance.

We next examine the behavior of He with respect to C in the context of our favored model: He and heavy-element production by only high-mass stars in BCGs with \(12 + \log O/H < 7.6\) and by both high-mass and intermediate-mass stars in higher metallicity BCGs. In Figure 4 we show the dependence of the helium mass fraction \(Y\) on the carbon abundance C/H for those BCGs in our sample for which both of these quantities are known. Admittedly, the total number of such galaxies is very small (only four), too small to draw any definite conclusion on the slope of the \(Y\)-C/H relation. The solid line shows the expected relation when He and C are produced only by high-mass stars, and the dashed line that expected when both high- and intermediate-mass stars contribute. The theoretical IMF-averaged yields are taken from WW95 for high-mass stars and from RV81 for intermediate-mass stars. Despite the very small number of data points, it can be seen that the theoretical predictions agree well with the observational data. We give in Table 8 the theoretical slopes \(dY/d(C/H)\) in both situations (HMS and IMS+HMS). The theoretical yields for HMs are IMF-averaged yields for massive-star models with \(Z = 10^{-4} Z \odot\) (WW95). The theoretical yields for intermediate-mass stars are IMF-averaged yields from RV81 for the models with heavy-element mass fraction \(Z = 0.004\) and mixing scale parameter \(\alpha = 1.5\). The Salpeter slope \(-2.35\) and lower and higher mass limits of \(1 M \odot\) and \(100 M \odot\), respectively, have been adopted for the IMF.

![Figure 4](image-url)

**Figure 4**—Helium mass fraction \(Y\) vs. the carbon abundance C/H for four BCGs from the Izotov & Thuan (1998b) sample. The theoretical dependences are shown by the solid line for helium and carbon enrichment by high-mass stars (HMS) only and by the dashed line when He and C are produced by both high- and intermediate-mass stars (HMS+IMS). The theoretical yields for HMS are IMF-averaged yields for massive-star models with \(Z = 10^{-4} Z \odot\) (WW95). The theoretical yields for intermediate-mass stars are IMF-averaged yields from RV81 for the models with heavy-element mass fraction \(Z = 0.004\) and mixing scale parameter \(\alpha = 1.5\). The Salpeter slope \(-2.35\) and lower and higher mass limits of \(1 M \odot\) and \(100 M \odot\), respectively, have been adopted for the IMF.

5. CHEMICAL CONSTRAINTS ON THE AGE OF BCGS

Because O, Ne, Si, S, and Ar are made in the same high-mass stars, their abundance ratios with respect to O are constant and not sensitive to the age of the galaxy. By contrast, C, N, and Fe can be produced by both high- and lower mass stars, and their abundance ratios with respect to O can give important information on the evolutionary status of BCGs.

The constancy of [O/Fe] for the BCGs in our sample and its high value compared to the Sun (Fig. 2c) suggest that all iron was produced by massive stars, i.e., in SNe II only. Since the time delay between iron production from SNe II and SNe Ia is about 1–2 Gyr, it is likely that BCGs with oxygen abundances less than \(12 + \log O/H < 8.2\) are younger than 1–2 Gyr, assuming that abundances measured in the supergiant H II regions are representative of the whole galaxy. We cannot put more stringent constraints on the star formation history of BCGs with [O/Fe] because intermediate-mass stars do not produce oxygen and iron.

We next use the behavior of C/O and N/O as a function of oxygen abundance to constrain the age of BCGs. As discussed previously, this behavior is very different depend-
ing on whether the BCG has $12 + \log O/H$ smaller or greater than 7.6. The abundance ratios C/O and N/O in BCGs with $12 + \log O/H \leq 7.6$ are independent of the oxygen abundance and show very small scatter about the mean value. We have argued that this small scatter rules out any time-delay model, in which O is produced first by massive stars and C and N are produced later by intermediate-mass stars, and supports a common origin of C, N, and O in the same first-generation massive stars. Thus, it is very likely that the presently observed episode of star formation in BCGs with $12 + \log O/H \leq 7.6$ is the first one in the history of the galaxy and that the age of the oldest stars in it do not exceed $\sim 40$ Myr, the lifetime of a 9 $M_\odot$ star.

The conclusion that BCGs with $Z \leq Z_\odot/20$ are young is supported by the analysis of HST WFPC2 images of some of these galaxies. Hunter & Thronson (1995) have concluded that the blue colors of the underlying diffuse extended emission in I Zw 18 ($Z_\odot/50$) are consistent with those from a sea of unresolved B and early A stars, with no evidence for stars older than $\sim 10^7$ yr. Izotov et al. (1997b) and Thuan et al. (1997) have also found in SBS 0335−052 ($Z_\odot/41$), after removal of the gaseous emission, an extremely blue extended underlying stellar component with an age of less than 100 Myr. In the same manner, SBS 1415+437 ($Z_\odot/21$; Thuan et al. 1999), T1214−277, and Tol 65 (respectively, $Z_\odot/21$ and $Z_\odot/22$; Izotov, Thuan, & Papaderos 1999) show, after subtraction of the gaseous emission, a very blue extended emission consistent with an underlying stellar population not older than 100 Myr.

The situation changes for BCGs with $Z > Z_\odot/20$. The scatter of C/O and N/O increases significantly at a given O abundance, which we interpret as due to the additional production of primary N by intermediate-mass stars, on top of the primary N production by high-mass stars. Thus, since it takes at least 500 Myr (the lifetime of a 2−3 $M_\odot$ star) for C and N to be produced by intermediate-mass stars, BCGs with $12 + \log O/H > 7.6$ must have had several episodes of star formation before the present one and they must be at least older than $\sim 100$ Myr. This conclusion is in agreement with photometric studies of these higher metallicity BCGs that, unlike their very low-metallicity counterparts, have an old red instead of a young blue underlying stellar component (Loose & Thuan 1985; Papaderos et al. 1996; Telles & Terlevich 1997).

In summary, the study of heavy element abundances in BCGs leads us to the following timeline for galaxy evolution: (1) all objects with $12 + \log O/H \leq 7.6$ began to form stars less than 40 Myr ago; (2) after 40 Myr, all galaxies have evolved so that $12 + \log O/H > 7.6$; (3) by the time intermediate-mass stars have evolved and released their nucleosynthetic products (100−500 Myr), all galaxies have become enriched to $7.6 < 12 + \log O/H < 8.2$—the delayed release of primary N at these metallicities greatly increases the scatter in the N/O; (4) later, when galaxies get enriched to $12 + \log O/H > 8.2$, secondary N production becomes important.

6. COMPARISON WITH DAMPED Lyα SYSTEMS

Damped Lyα systems are believed to be young disk galaxies in their early stages of evolution. They are extremely metal deficient, their heavy-element abundances ranging between $Z_\odot/300$ and $Z_\odot/10$ (Pettini et al. 1994; Wolfe et al. 1994; Lu et al. 1996). The large light-gathering power of the 10 m Keck telescope has made it possible to study their elemental abundance ratios (Lu et al. 1996), thus revealing many similarities between these ratios and those found in BCGs. A direct comparison, however, is not always possible. The Ne and Ar emission lines are present in the spectra of BCGs, but the absorption lines of the same noble elements are absent in the spectra of Lyα galaxies. On the other hand, the abundances of several elements in the iron-peak group have been measured in damped Lyα galaxies, but only iron abundance measurements are available for BCGs. There exist only lower limits for the carbon and oxygen abundances in damped Lyα systems as the O i 1302 Å and C ii 1334 Å absorption lines are strongly saturated. In the case of the elements for which a direct comparison can be made, Lu et al. (1996) have shown that some z-elements such as Si and S are overabundant with respect to iron as compared to the Sun. This is true as well for BCGs (and for halo stars) since, in these objects, Si and S are normal with respect to O while O is overabundant with respect to Fe, by comparison with the Sun. On the other hand, the iron-peak element abundance ratios are nearly solar, as expected.

The values of N/O seem at first glance to constitute the major difference. N/O in damped Lyα systems appears to be significantly lower than that measured in our low-metallicity BCGs. Pettini, Lipman, & Hunstead (1995) have found in one damped Lyα galaxy an upper limit of $\log N/O \leq -2.12, -0.52$ dex lower than the mean log N/O = −1.60 for the most metal-deficient BCGs in our sample, a value that, we have argued, is set by primary N production in massive stars and constitutes a lower limit to log N/O in BCGs. Lu, Sargent, & Barlow (1998) have measured N/Si in 15 damped Lyα galaxies and have set upper limits for log N/O ranging from −1.2 to −2.1. Until now, nearly all log N/O measurements lower than the BCG lower limit of −1.60 in damped Lyα systems are upper limits. There is, however, one exception, the 1946+7658 system, in which Lu et al. (1998) did measure an actual value, $[N/Si] = -1.70$, which translates to $\log N/O = -2.6$, or 1.0 dex lower than the BCG lower limit. From the N/O and N/Si measurements, Pettini et al. (1995) concluded that both primary and secondary nitrogen production are important over the whole range of metallicity measured in damped Lyα systems, while Lu et al. (1998) favor time-delayed primary nitrogen production by intermediate-mass stars.

We find such a large difference between N/O measured in BCGs and in damped Lyα galaxies to be very puzzling. If we believe the physics of star formation, the stellar IMF and the nucleosynthesis processes in stars at a given metallicity, to be universal and independent of cosmic epoch, then there must be some systematic differences in the way in which N/O is derived in damped Lyα systems from how it is derived in BCGs. The derivation of N/O in BCGs is straightforward enough. The photoionized H ii region models are simple and well defined, the nebular emission lines are strong, and their intensities can be measured with precision. There is no hidden assumption in the path from line intensities to N and O abundances. On the other hand, there is a basic assumption in the derivation of N/O in damped Lyα systems that we would like to discuss. It is generally assumed that absorption lines in damped Lyα systems originate in the H i clouds in the disk of the galaxy. In this case, only low-ionization species are expected and
correction factors for unseen stages of ionization are close to unity (Viegas 1995). We suggest here that this basic assumption may not be valid. We may expect that in high-redshift gas-rich disks there is ongoing star formation giving birth to massive stars that ionize the H I gas and create H II regions and diffuse ionized gas. There is thus a nonzero probability for the line of sight to cross diffuse ionized gas that is ubiquitous and has a large covering factor in gas-rich galaxies and/or H II regions, so that absorption lines would originate not in neutral but in ionized gas. Supporting this hypothesis is the fact that many of the spectra of Lu et al. (1996) do show absorption lines of high-ionization species such as Al III, C IV, and Si IV, which are usually present in ionized gas regions.

Lu et al. (1996) have dismissed the ionized gas hypothesis with the following two arguments. First, the absorption profile of the high-ionization species Al III is similar to those of lower ionization species, and hence both types of species must be produced in the same physical region. The latter must be mostly neutral because of the large observed H I column densities. In that case, Al III comes from an ionized shell surrounding the H I gas. Second, the Al II lines are always much stronger than the Al III lines, so that N(Al III) > N(Al II), implying that most of the gas where the absorption arises is neutral. The last argument is not airtight. Supposing that all absorption lines originate not in H I but H II gas, we have constructed with the radiative-collisional equilibrium code CLOUDY (Ferland 1993) a series of spherically symmetric H II region models with the ionization parameter log U in the range −0.4−0, which is typical for H II regions, and ionizing stars with effective temperatures between 40,000 and 50,000 K and metallicities of 1/10 solar. For these models, typical radially averaged column densities are N(H II) = 10^{19}−10^{21} cm^{-2} and N(Al II) = 10^{12}−10^{14} cm^{-2}. The models give invariably N(Al II) > N(Al III) even when the hydrogen gas is totally ionized. The profile similarities noted by Lu et al. (1996) between Al III and Al II can indeed be explained by the formation of absorption lines in the same physical region, but the latter can be H II rather than H I gas. If the gas is ionized, the correction factors for unseen stages of ionization are dependent on the parameters of the particular H II region model, and will be higher than for those in a H I cloud. The determination of abundances is more uncertain because of the lack of information on the column density of ionized hydrogen. However, the abundance ratios for some elements will not change greatly when the absorption lines are assumed to originate in the H II instead of the H I gas. This is because the abundances of these elements are derived from column densities of singly ionized ions, e.g., C^+, Si^+, S^+, Fe^+. Photoionized H II region models (Stasińska 1990) predict for these ions similar correction factors, so that their ratios are close to unity and the element abundance ratios are roughly equal to the singly ionized ion abundance ratios. However, the situation changes dramatically when we compare abundances of elements derived from column densities of ions in different stages of ionization. In those cases, the ratio of the ionization correction factors for different elements can be very far from unity, and the abundance ratios very different from the ion abundance ratios. Such is the case for N/Si. While the silicon column density is derived from the Si^+ absorption-line equivalent widths, the nitrogen column density is derived from the N^0 absorption lines. In the H I cloud model,

$$\frac{N}{Si} = \frac{N^0}{Si^+}.$$

(8)

The situation is however totally different if the H II region model is adopted. In Figure 5 we show the correction factors ICF(N/Si) as a function of the fraction of O^+ ions x(O^+) = O^+ / O, for the set of H II region models of Stasinska (1990). The correction factors ICF(N/Si) are weakly dependent on x(O^+) and have a lower envelope at a value ~ 10. Hence, for the H II region model,

$$\frac{N}{Si} = \frac{ICF(N)}{Si^+} \frac{N^0}{Si^+} \geq 10 \frac{N^0}{Si^+}.$$

(9)

This factor of ~ 10 is just about that needed to bring N/O measured in the 1946 + 7658 damped Lyα system to the mean value of N/O obtained for low-metallicity BCGs.

Instead of N/Si, Pettini et al. (1994) have measured N/O in the damped Lyα systems directly. This method is in principle subject to fewer uncertainties because the abundances of both elements in the H II region are derived from column densities of neutral species. We have run the CLOUDY code for several spherically symmetric H II region models, varying the ionization parameter and the temperature of the ionizing radiation. These calculations show that the fractions of neutral nitrogen and neutral oxygen in the H II region along the line of sight are nearly the same, i.e.,

$$\frac{N}{O} \approx \frac{N^0}{O^+}.$$

(10)

However, the O abundance is not known with good precision. The O I 1302 Å absorption line is saturated, and the O abundances derived by Pettini et al. (1995) by fitting the saturated O I profiles have errors so large that they span 3 orders of magnitude. Furthermore, the very method of using saturated absorption lines to derive column densities and abundances is questionable (Pettini & Lipman 1995; Lu et al. 1998).

We stress therefore that there is a great uncertainty in the derived N/O in damped Lyα absorption systems. This uncertainty comes in large part from our ignorance of the nature of the absorbing medium, whether it is neutral or

![Fig. 5. Correction factor ICF(N/Si) as defined in eq. (9) vs. the ion fraction x(O^+) = O^+ / O as derived from photoionized H II region models by Stasinska (1990).](image-url)
ionized gas. If the absorbing system is an H II region instead of an H I cloud, the derived value of N/O may increase by a factor of 10 or more if the Si\(^+\) lines instead of neutral oxygen lines are used, which would bring N/O derived in damped Ly\(\alpha\) systems in closer agreement with those found in low-metallicity BCGs. Another large source of uncertainty comes from the derivation of abundances from saturated O I 1302 Å absorption lines. If, in the future, there is evidence that the absorption lines do come from a neutral medium, and better O determinations in damped Ly\(\alpha\) systems still give a value of N/O a whole order of magnitude lower than the value found in low-metallicity BCGs, then we would have to conclude that star formation and metal-dispersion histories in damped Ly\(\alpha\) galaxies are very different from those in BCGs.

7. SUMMARY AND CONCLUSIONS

The present study is a continuation and extension of the one by TIL95 on heavy-element abundances in very metal-deficient environments, with considerably more data. We derive here the abundances of N, O, Ne, S, Ar, and Fe in a sample of 54 supergiant H II regions in 50 low-metallicity blue compact galaxies with oxygen abundances in the range 7.1 < 12 + log O/H < 8.3. The objects in this sample all possess very high signal-to-noise ratio spectra that have been obtained for the determination of the primordial helium abundance. This allows us to measure line intensities with high precision and properly correct them for interstellar extinction and underlying stellar hydrogen Balmer absorption. In addition, we redetermine the carbon and silicon abundances in some BCGs with the use of HST UV and optical archival spectra, supplemented in a few cases by ground-based optical spectroscopic observations to derive accurate electron temperatures.

We have obtained the following results.

1. As in TIL95, the x-elements–oxygen abundance ratios Ne/O, Si/O, S/O and Ar/O show no dependence on oxygen abundance over the whole range of metallicities studied here. Furthermore, these ratios are about the same as those found in halo stars and high-redshift damped Ly\(\alpha\) galaxies, and they have approximately solar values. This result is to be expected from stellar nucleosynthesis theory as oxygen and all x-elements are produced by the same massive stars.

2. We rederive the carbon-to-oxygen abundance ratio in both the northwest and southeast components of I Zw 18, the most metal-deficient galaxy known. Our values of log C/O = −0.77 ± 0.10 for the northwest component and −0.74 ± 0.09 for the southeast component are in excellent agreement with those predicted by the theory of massive-star nucleosynthesis but are significantly lower (by ~0.2 dex) than those derived by Garnett et al. (1997). The main source of the differences comes from the adopted electron temperatures. We use higher electron temperatures (by 1900 and 2300 K, respectively, for the northwest and southeast components), as derived from recent MMT spectral observations (Izotov et al. 1997a) in apertures that match more closely those of the HST FOS observations used to obtain C abundances. With these lower C/O values, I Zw 18 no longer stands apart from the other low-metallicity BCGs. An earlier lower mass carbon-producing stellar population need not be invoked, and I Zw 18 can still be a “primeval” galaxy undergoing its first burst of star formation.

3. The abundance ratio C/O is constant, independent of the O abundance in BCGs with 12 + log O/H ≤ 7.6 (Z ≤ Z\(_\odot\)/20), with a mean value log C/O = −0.78 ± 0.03 and a very small dispersion about the mean. This result is based on a small sample of four data points in three galaxies and needs to be strengthened by more C/O measurements in extremely metal-deficient galaxies. The constancy of C/O suggests that carbon in these galaxies is produced in the same stars that make O, i.e., only in massive stars (M > 9 M\(_\odot\)). By contrast, C/O in BCGs with higher oxygen abundance (12 + log O/H > 7.6) is significantly higher, with a mean value log C/O = −0.52 ± 0.08 and a larger dispersion about the mean. This enhanced C/O and the larger scatter at a given O/H are likely the result of additional carbon production by intermediate-mass stars (3 M\(_\odot\) ≤ M ≤ 9 M\(_\odot\)) stars, on top of the carbon production by high-mass stars.

4. TIL95 showed that N/O has a very small scatter in BCGs with 12 + log O/H ≤ 7.6, with a mean value log N/O = −1.58 ± 0.02. We have added here a very low-metallicity object, SBS 0335−052 with Z\(_\odot\)/41, and the results do not change. As discussed by TIL95, such a small dispersion of N/O is not consistent a time-delayed production of primary nitrogen by longer lived intermediate-mass stars in these extremely metal-deficient galaxies. The small dispersion at very low metallicities can be explained only by primary nitrogen production in short-lived massive stars. As in the case of C, galaxies with 12 + log O/H > 7.6 show a considerably larger scatter of N/O, with a mean value log N/O = −1.46 ± 0.14. Again, the larger scatter can be explained by the addition of primary nitrogen production in intermediate-mass stars, on top of that in massive stars. None of our galaxies has log N/O below −1.67, implying that the lower envelope of the N/O distribution is set by the production of primary nitrogen in massive stars over the whole range of metallicities studied here, 7.1 < 12 + log O/H < 8.3. While a detailed scenario of primary nitrogen production by massive stars is yet to be developed, the mean log N/O obtained here for the most metal-deficient BCGs will put strong constraints on any future theory.

5. Fe/O in our BCGs is ~2.5 times lower than in the Sun, with a mean [O/Fe] = 0.40 ± 0.14. Again, it does not show any dependence on oxygen abundance, in agreement with the findings of TIL95. This implies that iron in BCGs was synthesized during the explosive nucleosynthesis of SNe II. Only one BCG bucks the trend: SBS 0335−052 has a higher Fe/O than the Sun. We argue that the high abundance of Fe in this BCG may not be real and may be caused by the contamination of the nebular [Fe III] 4658 Å emission line by narrow stellar C IV 4658 produced in expanding envelopes of hot massive stars.

6. Comparison of theoretical heavy element yields for low-metallicity massive stars (WW95) with those inferred from observations of BCGs shows that the theory of massive star nucleosynthesis is generally in good shape. The major problems are with iron and nitrogen yields. The predicted iron-to-oxygen yield ratio is a factor of ~2 larger than the observed ratio. Models of primary nitrogen production by intermediate-mass stars cannot reproduce the N/O observed in very low-metallicity BCGs, and conventional models of low-metallicity massive stars do not allow for primary nitrogen production. Until further developments of the theory of massive-star nucleosynthesis resolve
these disagreements, it is best to use the observed yields given in Table 7 for studies of the early chemical evolution of galaxies.

7. Helium follows the same pattern as carbon and nitrogen. The helium abundance is constant within the observational uncertainties for BCGs with \(12 + \log O/H \leq 7.6\). Again we interpret this constancy by He being produced in high-mass stars only. At higher oxygen abundances, the mean and dispersion increase, and we again interpret this increase as the addition of helium production by intermediate-mass stars to that by massive stars. Although the sources of helium production appear to be different in low- and high-metallicity BCGs, implying slightly different dependences of the helium mass fraction \(Y\) on oxygen abundance and below \(12 + \log O/H = 7.6\), we find that the commonly used \(Y\) versus \(O/H\) linear regression over a large range of oxygen abundances to determine the primordial helium abundance is a good approximation.

8. The constancy of C/O, N/O, and \([O/Fe]\) in BCGs with \(12 + \log O/H \leq 7.6\) argues strongly for the production in the most metal-deficient galaxies of these elements by massive stars only. Intermediate-mass stars have not yet returned their nucleosynthesis products to the interstellar medium in these most metal-poor galaxies because they have not had enough time to evolve. This allows us to date these galaxies. Galaxies with \(12 + \log O/H \leq 7.6\) are young, in the sense that they have experienced their first episode of star formation not more than \(\approx 40\) Myr ago, the lifetime of a \(9 M_\odot\) star. This derived young age is in agreement with the results obtained by recent photometric studies with \(HST\) images of some of the most metal-deficient galaxies discussed here.

9. The study of heavy element abundances in BCGs leads us to the following timeline for galaxy evolution: (1) all objects with \(12 + \log O/H \leq 7.6\) began to form stars less than \(40\) Myr ago; (2) after \(40\) Myr, all galaxies have evolved so that \(12 + \log O/H > 7.6\); (3) by the time intermediate-mass stars have evolved and released their nucleosynthetic products (100–500 Myr), all galaxies have become enriched to \(7.6 < 12 + \log O/H < 8.2\) — the delayed release of primary N at these metallicities greatly increase the scatter in \(O/H\); (4) later, when galaxies get enriched to \(12 + \log O/H > 8.2\), secondary N production becomes important.

10. Values of N/O derived for BCGs are apparently larger by factors of up to \(\approx 10\) than those obtained for high-redshift damped Ly\(\alpha\) galaxies (Lu et al. 1996). We suggest here that this discrepancy may not be real. Contrary to the situation for BCGs, in which N/O values are very well determined, N/O values derived for damped Ly\(\alpha\) systems are highly uncertain because of the unknown physical conditions in the interstellar medium of high-redshift systems. It is generally assumed that the absorption lines in these systems originate in the H I gas. In that case, the ionization correction factors for the low-ionization species used for abundance determination are close to unity. However, if we assume that the absorption lines originate not in neutral but in ionized gas, the correction factors can be \(\geq 10\), and the derived values of N/O in the damped Ly\(\alpha\) systems can be as high as those derived in BCGs.

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