ABUNDANCES IN THE H i ENVELOPE OF THE EXTREMELY LOW METALLICITY BLUE COMPACT DWARF GALAXY SBS 0335—052 FROM FAR ULTRAVIOLET SPECTROSCOPIC EXPLORER OBSERVATIONS1

TRINH X. THUAN
Astronomy Department, University of Virginia, P.O. Box 3818, University Station, Charlottesville, VA 22903; txt@virginia.edu

ALAIN LECAVELIER DES ETANGS
Institut d’Astrophysique de Paris, CNRS, 98 bis Boulevard Arago, 75014 Paris, France; lecaveli@iap.fr

YURI I. IZOTOV
Main Astronomical Observatory, National Academy of Sciences, 27 Zabolotnoho, 03680 Kiev, Ukraine; izotov@mao.kiev.ua

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ABSTRACT

We present Far Ultraviolet Spectroscopic Explorer spectroscopy of SBS 0335—052, the second most metal-deficient blue compact dwarf (BCD) galaxy known [log (O/H) = −4.70]. In addition to the H i Lyman series, we detect C ii, N i, N ii, O i, Si ii, Ar i, and Fe ii absorption lines, mainly arising from the extended H i envelope in which SBS 0335—052 is embedded. No H2 absorption lines are seen. The absence of diffuse H2 implies that the warm H2 detected through infrared emission must be very clumpy and associated with the star-forming regions. The clumps should be denser than ∼1000 cm−3 and hotter than ∼1000 K and account for ≥5% of the total H i mass. Although SBS 0335—052 is a probable young galaxy, its neutral gas is not pristine. The metallicity of its neutral gas is similar to that of its ionized gas and is equal to log (O/H) ∼ −5. This metallicity is comparable to that found in the H i envelopes of four other BCDs with ionized gas metallicities spanning the wide range from log (O/H) = −4.8 to −3.8, and in Ly α absorbers, fueling the speculation that there may have been previous enrichment of the primordial neutral gas to a common metallicity level of log (O/H) ∼ −5, possibly by Population III stars.

Subject headings: galaxies: abundances — galaxies: individual (SBS 0335—052) — galaxies: irregular — galaxies: ISM

1. INTRODUCTION

The blue compact dwarf (BCD) galaxy SBS 0335—052 (Izotov et al. 1990), with an ionized gas oxygen abundance of 12 + log (O/H) = 7.30 [Melnick et al. 1992; Izotov et al. 1997, 1999; Z0/23, if the recent lower determination of the Oxygen abundance of the Sun 12 + log (O/H) = 8.66 by Asplund et al. (2004) is adopted], is one of the most metal-deficient star-forming galaxies known, just after its dwarf irregular companion SBS 0335—052W [12 + log (O/H) = 7.22 or Z0/28; Lipovetsky et al. 1999] and the BCD I Zw 18 [12 + log (O/H) = 7.17 or Z0/31; Izotov et al. 1999]. Because of its extremely low metallicity and its high neutral hydrogen content (Pustilnik et al. 2001), SBS 0335—052 is an excellent candidate for being a young galaxy, just like I Zw 18. The latter has been shown by Izotov & Thuan (2004) to be a bona fide young galaxy. Resolving I Zw 18 into stars with deep Hubble Space Telescope (HST) Advanced Camera for Survey images and constructing its color-magnitude diagram (CMD), Izotov & Thuan (2004) have shown that the galaxy does not contain red giant stars and that the most evolved stars in it are not older than 500 Myr. Because of its larger distance (54.3 Mpc [Thuan et al. 1997, hereafter TIL97]), instead of 15 Mpc for I Zw 18, SBS 0335—052 cannot be resolved into stars by HST, so its age cannot be determined directly by CMD analysis. However, using optical colors of the low surface brightness component together with evolutionary synthesis models, TIL97 and Papaderos et al. (1998) have constrained the age of the underlying stellar population to be less than ∼100 Myr. Near-infrared (NIR) colors after correction for gaseous emission are consistent with a stellar population not older than 4 Myr, with a possible contribution to the NIR light from an evolved stellar population not exceeding ∼15% (Vanzi et al. 2000). Östlin & Kunth (2001) have derived from surface photometry considerably larger ages for SBS 0335—052. However, these large ages may be the consequence of their not subtracting out the large ionized gas contamination from the surface brightness profiles used. Recently, Pustilnik et al. (2004) have also found a young age for SBS 0335—052. Depending on the adopted star formation history of the BCD, they derive an age between 100 and 400 Myr. In any case, SBS 0335—052 constitutes an excellent nearby laboratory for studying massive star formation and its interaction with the ambient interstellar medium (ISM) in a very metal-deficient environment. Most of the star formation in SBS 0335—052 occurs in six super star clusters, roughly aligned in the southeast-northeast direction, with ages ≤ 25 Myr, within a region of ∼2′′ or 520 pc in size (TIL97).

Very Large Array (VLA)2 observations have shown the presence of a massive (2.2 × 109 M⊙) and extended (66 × 22 kpc)

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2 The VLA is operated by the National Radio Astronomy Observatory, which is a facility of the National Science Foundation, operated under cooperative agreement by Associated Universities, Inc.
neutral hydrogen gas envelope around SBS 0335−052 (Pustilnik et al. 2001). This H i envelope absorbs all the Lyα photons emitted by the young massive stars. Thuan & Izotov (1997) have obtained an HST Goddard High Resolution Spectrograph (GHRS) spectrum of SBS 0335−052 that reveals a broad damped Lyα absorption with a high H i column density $N(H) = (7.0 \pm 0.5) \times 10^{14} \text{cm}^{-2}$, the largest known in a BCD. The HST GHRS spectrum also shows absorption lines of several heavy elements such as O i, Si ii, and S ii. Assuming that these absorption lines are not saturated, Thuan & Izotov (1997) found the derived heavy element abundance in the neutral gas to be considerably lower than that of the ionized gas. Furthermore, using infrared spectrophotometry Vanzì et al. (2000) have detected molecular hydrogen in emission in SBS 0335−052. The presence of a neutral gas envelope around SBS 0335−052 and the detection of molecular hydrogen in emission make this galaxy an ideal target for Far Ultraviolet Spectroscopic Explorer (FUSE) spectroscopy. Using SBS 0335−052 as a source of UV light shining through the H i envelope, a FUSE absorption spectrum will allow us to independently determine the heavy element abundances in the neutral gas of the galaxy and check for the presence of H$_2$ in it.

We describe the FUSE observations in § 2. In § 3 we set upper limits on the amount of diffuse H$_2$. In § 4 we show that the warm H$_2$ detected through infrared emission must be very clumpy. We derive the column densities of the interstellar ionic species in the H i gas, and we compare the heavy element abundances in the neutral and ionized gas in § 5. We summarize our findings in § 6.

2. OBSERVATIONS AND DATA ANALYSIS

SBS 0335−052 has been observed with FUSE (Moos et al. 2000) through the $30^{11} \times 30^{10}$ LWRS large-entrance aperture on 2001 September 26 for a total integration time of 24.4 ks. The data have been processed with version 1.8.7 of the CALFUSE pipeline. The eight separate exposures have been aligned and co-added. This results in a set of four independent spectra, two spectra for the two long wavelength LiF channels covering the wavelength range $\sim$1000–1187 Å, and two spectra for the two short wavelength SiC channels, covering the wavelength range $\sim$900–1100 Å. After co-addition, the signal-to-noise ratio (S/N) per resolution element and per channel is estimated to be $\sim$2 below 1000 Å and $\sim$4 above 1000 Å.

To derive the spectrum, special attention was paid to the background residual, which is not negligible for this faint target. The background has been estimated both on spectra obtained off-target through other apertures and at the bottom of wide saturated lines. The background level is found to be between 0 and $3 \times 10^{-15}$ ergs cm$^{-2}$ s$^{-1}$ Å$^{-1}$. The line-spread function has been estimated with the unresolved Galactic H$_2$ absorption lines.

The resolution is found to be $R = \Delta \lambda / \lambda \approx 12,000$.

The resulting spectrum of SBS 0335−052 shifted to its rest frame is shown in Figure 1. It exhibits two absorption-line systems at two different radial velocities. The first system at nearly zero radial velocity is attributed to the interstellar clouds in the Milky Way. The second system at $\sim$4050 km s$^{-1}$ is attributed to the ISM in SBS 0335−052, as the H i velocity of the BCD is 4057 $\pm$ 5 km s$^{-1}$ (Pustilnik et al. 2001), in good agreement with the optical velocity obtained by Izotov et al. (1997). Absorption lines from the atomic and ionic species N i, P ii, Fe ii, and Ni ii are observed in the Milky Way, while in addition to the H i Lyman series, absorption lines from the atoms and ions C ii, N i, N ii, O i, Si ii, Ar i, and Fe ii are seen for SBS 0335−052. In Figure 1, the lines arising from SBS 0335−052 are labeled, while those belonging to the Milky Way are indicated by tick marks below the FUSE spectrum. For the characteristics of the electronic transitions of H$_2$, we have used the wavelengths and oscillator strengths tabulated by Abgrall et al. (1993a, 1993b) for the Lyman and the Werner systems and the inverses of the total radiative lifetimes tabulated by Abgrall et al. (2000). For atomic lines, we have used the data for resonance absorption lines tabulated by Morton (2004).

3. UPPER LIMITS ON THE DIFFUSE H$_2$ CONTENT OF SBS 0335−052

Molecular hydrogen is known to be present in SBS 0335−052, since Vanzì et al. (2000) have detected several H$_2$ emission lines in their low-resolution NIR spectrum of the star-forming region. These lines observed in the $K$ band are generally consistent, within the errors, with both thermal and fluorescent excitation by the strong UV field. It is thus of great interest to check whether there are H$_2$ absorption lines in the FUSE spectrum of SBS 0335−052. We found no H$_2$ line at the radial velocity of the BCD (Fig. 1). We obtained the following $3 \sigma$ upper limits for the H$_2$ column density: $1.2 \times 10^{17}, 1.4 \times 10^{17}, 7.9 \times 10^{16}, 3.4 \times 10^{17},$ and $1.5 \times 10^{17}$ cm$^{-2}$, respectively, for the $J = 0, 1, 2, 3,$ and 4 levels. To set an upper limit on the total H$_2$ column density, we followed the procedure of Aloisi et al. (2003). We added the two upper limits for the $J = 0$ and 1 levels. For the higher $J$ levels, we assumed a temperature ($T = 500$ and 1000 K) that determines the level populations and then normalized the level populations so as to be consistent with the measured upper limits. We obtained upper limits for the total H$_2$ column density of $3.7 \times 10^{17}$ cm$^{-2}$ for $T = 500$ K and $5.5 \times 10^{16}$ cm$^{-2}$ for $T = 1000$ K. These upper limits for H$_2$ are more than 2 orders of magnitude larger than those established for the BCDs I Zw 18 (Aloisi et al. 2003; Lecavelier des Etangs et al. 2004) and Mrk 59 (Thuan & Izotov 2002) because of the larger distance of SBS 0335−052, its fainter apparent magnitude, and its lower S/N FUSE spectrum. They correspond to column densities above which the damping wings start to broaden appreciably the H$_2$ absorption lines.

With a H i column density of $7.0 \times 10^{21}$ cm$^{-2}$ as determined by the HST/GHRS damped Lyα profile (Thuan & Izotov 1997), this corresponds to a fraction of H$_2$ molecules $f(H_2) = 1.1 \times 10^{-4}$ ($T = 500$ K) and $f(H_2) = 1.6 \times 10^{-4}$ ($T = 1000$ K), where the fraction is defined as $f(H_2) = 2n(H_2)/[2n(H_2) + n(H \iota)]$ and where $n(H_2)$ and $n(H \iota)$ are the number densities of H$_2$ and H i.

Are the H$_2$ upper limits established by FUSE consistent with the expected fraction of H$_2$ molecules in SBS 0335−052? This fraction can be estimated in the following manner. As discussed by Vidal-Madjar et al. (2000), at equilibrium, when the formation of H$_2$ on dust equals its destruction rate by UV photons, then

$$f(H_2) = 1.6 \times 10^{-34} \frac{Z}{Z_\odot} \left( \frac{F_{R_0}}{\text{ergs s}^{-1} \text{cm}^{-2} \text{Å}^{-1}} \right)^{-1} \times \left( \frac{R_0}{\text{kpc}} \right)^{-1} \frac{N(H \iota)}{\text{cm}^{-2}}.$$  

(1)

Here $F_{R_0}$ is the flux at 1000 Å of UV H$_2$ dissociating radiation at radius $R_0$ from the central ionizing clusters in SBS 0335−052, $Z$ is the metallicity equal to ZZ/23, and $N(H \iota)$ is the H i column density. From the H i map of Pustilnik et al. (2001), we estimate $R_0 = 10^8$, or 2.5 kpc, for a H i column density
level of $7.2 \times 10^{20}$ cm$^{-2}$. This corresponds to a H i number density $n$(H i) $\sim 0.1$ cm$^{-3}$. Since the density of the H i is increasing inward, we adopt for our calculations a mean value of $n$(H i) $= 1$ cm$^{-3}$.

The observed UV flux at 1000 Å is $1.7 \times 10^{-14}$ ergs s$^{-1}$ cm$^{-2}$ Å$^{-1}$ (Thuan & Izotov 1997). Correcting for interstellar Galactic extinction using $A_{1000}$ Å $= 5.742$ $A_V$ (Cardelli et al. 1989) and $A_V = 0.155$ mag (Schlegel et al. 1998), we obtain $F_{\text{cor}} = 3.8 \times 10^{-14}$ ergs s$^{-1}$ cm$^{-2}$ Å$^{-1}$. Then

$$F_{R_0} = F_{\text{cor}} \left(\frac{D}{R_0}\right)^2 = 1.7 \times 10^{-3} \text{ ergs s}^{-1} \text{ cm}^{-2} \text{ Å}^{-1},$$

where $D = 54.3$ Mpc is the distance of SBS 0335–052. Finally, from equation (1) we derive $f$(H$_2$) $= 1.1 \times 10^{-10}$, more than 6 orders of magnitude below and fully consistent with the upper limits derived from the FUSE spectrum.

4. A CLUMPY INTERSTELLAR MEDIUM

Is such a low fraction of H$_2$ consistent with the Vanzi et al. (2000) detection of NIR H$_2$ emission lines in the star-forming region of SBS 0335–052? We note that such a question has also arisen in the context of a circumstellar disk observed by Lecavelier des Etangs et al. (2001), where H$_2$ is detected in the infrared but no UV absorption lines are seen. To address the

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**Fig. 1.—**FUSE spectrum in the rest frame of SBS 0335–052 (shifted by 4050 km s$^{-1}$). Here the data have been rebinned to a resolution of 0.2 Å. Prominent interstellar absorption lines are indicated. The lines arising in SBS 0335–052 are marked on top, and those in the Milky Way are indicated at the bottom. In addition to the H i Lyman series in SBS 0335–052, there are also strong interstellar absorption lines from C ii, N i, N ii, O i, Si ii, and Fe ii.
question for SBS 0335–052, we have carried out calculations specifically for the $H_2(1, 0) S(0)$ line with a wavelength of 2.223 $\mu m$. The results for the other detected $H_2$ lines should not be too different. Vanzi et al. (2000) have obtained a flux of $1.4 \times 10^{-16}$ ergs s$^{-1}$ cm$^{-2}$ for the 2.223 $\mu m$ line in SBS 0335–052. Assuming that the NIR emission is the result of fluorescent excitation, the luminosity of the $H_2$ (1, 0) $S(0)$ line from the region with radius $R_0$ is

$$L_{tot} = n(H) f(H_2) Q h \nu V,$$

where $h \nu = 9 \times 10^{-13}$ ergs is the energy of the photon with wavelength 2.223 $\mu m$, and $V = 4 \pi R_0^2 / 3 = 1.92 \times 10^{66}$ cm$^{-3}$ is the volume of the region with radius $R_0$. Following Black & Dalgarno (1976) and using the UV flux $F_{HI}$ given by equation (2), we calculate a cascade entry rate $Q = 1.55 \times 10^{-11}$ cm$^{-3}$ s$^{-1}$. From equation (3) we obtain the luminosity of the 2.223 $\mu m$ line to be $L_{tot} = 1.82 \times 10^{33}$ ergs s$^{-1}$. The spectrum of Vanzi et al. (2000) was obtained through a 1'' x 1.5 aperture, which corresponds to a volume of $V_{\text{aperture}} = 1.38 \times 10^{66}$ cm$^{-3}$. Thus, $V_{\text{aperture}}/V = 7.2 \times 10^{-2}$, and we predict $L_{predicted} = 1.31 \times 10^{33}$ ergs s$^{-1}$, corresponding to a flux at Earth of $2.4 \times 10^{-23}$ ergs s$^{-1}$ cm$^{-2}$. This is $\sim 10^5$ times lower than the observed flux.

The large flux discrepancy very probably comes from our assumption that the ISM of SBS 0335–052 is uniform. In all likelihood, the NIR $H_2$ emission comes not from a uniform low-density neutral medium but from dense clumps.

For such dense clumps, self-shielding of electronic transitions, which becomes important starting at $N(H_2) \sim 10^{14}$ cm$^{-2}$ (Black & van Dishoeck 1987), further increases $f(H_2)$. Although the UV pumping decreases, thermal excitation of the $H_2$ vibrational states becomes important, since it scales as $n(H) n(H_2)/H_2$. Following Black & van Dishoeck (1987), we find that we can reproduce well the observed flux of the $H_2(1, 0) S(0)$ 2.223 $\mu m$ line if it comes from an ensemble of clumps with a total mass $\sim 10^8 M_\odot$, or about 5% of the total $H$ line mass in SBS 0335–052 of $2.1 \times 10^5 M_\odot$ (Pustilnik et al. 2001). If each clump has a number density $n(H_2) = 5 \times 10^{3}$ cm$^{-3}$ and a temperature $T = 10^3 K$. For such a clump to be stable against gravitational collapse, its mass has to be less than its Jeans mass, which is $\sim 5 \times 10^4 M_\odot$. This means that there should be at least $\sim 2000$ of these clumps. The fraction of $H_2$ molecules in such clumps is $f(H_2) = (5 \times 10^{-3}) (6.8 \times 10^{-11}) = 3.4 \times 10^{-7}$. The total number of $H_2$ molecules in such clumps is $N_{tot} = f(H_2) M / m_{H_2} = 4.1 \times 10^{38}$, where $m_{H_2} = 1.673 \times 10^{-24}$ g is the mass of the hydrogen atom. Then the luminosity emitted in the $H_2(1, 0) S(0)$ line is $L = N_{tot} n(H_2) Q h \nu V = 4.5 \times 10^{37}$ ergs s$^{-1}$, where $q \sim 10^{-10} \exp (-6000/T)$ cm$^{-3}$ s$^{-1}$ is the rate of collisional excitation. The flux at Earth is then $1.4 \times 10^{-16}$ ergs s$^{-1}$ cm$^{-2}$, in very good agreement with the observed flux for the $H_2(1, 0) S(0)$ line at 2.223 $\mu m$. Because of the exponential temperature dependence of the rate of collisional excitation, the above estimate is very sensitive to the adopted temperature for the gaseous clumps. This temperature cannot be lower than $\sim 1000 K$, since for lower temperatures, the total mass of the clumps needed to account for the observed $H_2(1, 0) S(0)$ 2.223 $\mu m$ flux would exceed the $H$ line mass of SBS 0335–052.

Our FUSE observations are not sensitive to such a clumpy $H_2$ distribution. They can only probe diffuse $H_2$ along the lines of sight to the several thousands of UV-bright massive stars in SBS 0335–052. As in the cases of the BCDs I Zw 18 (Aloisi et al. 2003;LECavelier des Etangs et al. 2004) and Mrk 59 (Thuan et al. 2002), the absence of diffuse $H_2$ in SBS 0335–052 can be explained by the combined effects of a low $H$ density, a scarcity of dust grains on which $H_2$ molecules can form, and a large UV flux that destroys molecules.

### 5. Heavy Element Abundances
#### 5.1. Column Densities

We now derive the column densities of the heavy elements in the neutral $H$ envelope of SBS 0335–052 by fitting the profiles of the metal absorption lines. Column densities have been calculated by profile fitting using the Owens.f procedure developed by Martin Lemoine and the FUSE French team. This code returns the most likely values of many free parameters like the Doppler widths and column densities through a $\chi^2$ minimization of the difference between the observed and computed profiles. The latest version of this code is particularly suited to the characteristics of FUSE spectra. For example, it allows for a variation of the background level, for an adjustable line-spread function as a function of the wavelength domain, and for shifts in wavelength scale. These are taken as free parameters that depend on the wavelength region and are determined by a $\chi^2$ minimization.

The derived column densities with their error bars are given in Table 1. We will be quoting 1 $\sigma$ error bars throughout the paper. These have been estimated as usual by considering the $\Delta \chi^2$ increase of the $\chi^2$ of the fit (see Hébrard et al. [2002] for a full discussion of the fitting method and error estimation with the Owens.f code). These error bars include the uncertainties in the continuum, the intrinsic line widths ($b$), the background residual, and the instrumental line-spread function. It is important to note that the use of different lines with different oscillator strengths of the same species allows us to constrain reasonably well all these quantities. In particular, the line width is well constrained by strongly saturated lines. On the other hand, the instrumental line-spread function is mainly constrained by the very narrow lines from $H_2$ in the Milky Way. The final results are obtained from a simultaneous self-consistent fit to all the data. In this final fit, the continuum, the background residual, the instrumental line-spread function, and the physical parameters of the absorption lines are free parameters. They are estimated by determining the best $\chi^2$ in the parameters’ space.

For each wavelength domain, we use the data from two different channels simultaneously: the SiC 1 and SiC 2 channels.
for wavelengths between 940 and 990 Å, and the LiF 1 and LiF 2 channels for wavelengths above ~990 Å (see Sahnow et al. [2000] for a description of the FUSE channels). Because of the low S/N of the SBS 0335–052 FUSE spectrum, only lines that are more or less saturated are clearly detected. This explains the relatively large error bars on the estimated column densities. However, for most species detected in SBS 0335–052, we have for each species several absorption lines from different transitions with different oscillator strengths. This allows us to obtain reliable column densities despite the saturation of the lines. For example, several O i lines are detected. The O i column density is mainly constrained by the profiles of four strong transitions with rest wavelengths $\lambda_0 = 929.5, 950.9, 988.8,$ and 1039.2 Å. For N i, we detect the well-known triplet at 1034–1035 Å. The ions N ii and N iii* have transitions in the wavelength region around 1084–1085 Å, which is usually unusable because of its location in the hole between the two LiF detectors (see, e.g., Lecavelier des Etangs et al. [2004], in the case of I Zw 18). However, here the large redshift of SBS 0335–052 moves that region out of the hole and allows clear detections of these transitions in the LiF 1b and LiF 2a channels. Si ii is detected only in the $\lambda_0 = 1020.7$ Å transition, the line at $\lambda_0 = 989.9$ Å being blended with a strong N iii line. However, with an optical depth of ~2, this line does not suffer from much saturation and allows a reliable column density determination, albeit with large error bars. On the other hand, C ii, which is also detected in only one transition at $\lambda_0 = 1036.3$ Å, is strongly saturated. This makes its column density determination very sensitive to systematic errors and can explain its deviation from the abundance pattern found for other species (see § 5.2).

With the exception of H i, for which the strong damping wings in the Ly/β line allow a very accurate determination of the column density, Fe ii is the species for which we have obtained the highest precision (Table 1). Fe ii indeed has nine clearly detected lines at $\lambda_0 = 1055, 1063, 1064, 1082, 1097, 1122, 1125, 1143,$ and 1145 Å. Those lines have optical depths ranging from ~2 to ~30, which allow a good determination of the Fe ii column density by co-adding the nine separate profiles to improve the S/N. Figure 2 shows the fit to the co-added continuum and Fe ii line profile.

To better constrain the column densities, we have also used, in addition to the FUSE data, the low-resolution HST spectra obtained with the GHR5 spectrograph and the G160M and G140L gratings by Thuan & Izotov (1997). These spectra show absorption lines of C ii (1334.5 Å), O i (1302.2 Å), and Si ii (1190.4, 1193.3, 1260.4, and 1304.4 Å).

For the species that are detected in both FUSE and HST spectra (O i, C ii, and Si ii), the column densities given in Table 1 are derived from a simultaneous fit of both spectra. This assumes that both instruments cover the same spatial regions in the BCD, although the observations have been obtained through very different aperture sizes, 30'' in the case of FUSE and 2'' for HST. This assumption is reasonable as the brightest star-forming clusters in SBS 0335–052 are confined within a very compact region ($\leq 2''$; TIL97), and this region is fully sampled by both FUSE and HST apertures. That is this indeed the case is confirmed by the fact that the H i column densities derived independently from the FUSE and HST spectra are very similar: the FUSE column density is $\log N(H i) = 21.86^{+0.08}_{-0.05}$ while the HST column density is $\log N(H i) = 21.85 \pm 0.05$. The heavy element column densities derived from the FUSE spectra alone and from the FUSE+HST spectra are consistent with each other within the errors. But by using the FUSE and HST spectra together, we are able to decrease the error bars by a factor of ~2.

For example, the derived column density of C ii using only the FUSE spectrum is $\log N(C ii)(FUSE) = 17.68^{+0.23}_{-1.6}$ as compared to $\log N(C ii)(HST + FUSE) = 17.59^{+0.23}_{-0.65}$. The simultaneous fit of a large set of lines with different oscillator strengths for the same species, and of many different species with the same intrinsic line width, allows us to constrain the line-broadening parameter (or Doppler width) b. In other words, a single b-value is derived that gives the best simultaneous fit to the profile of every detected line of each species. As an example, Figure 3 shows the fit to the O i at 1039 line. From the FUSE spectrum alone, we obtain $b = 12.0^{+2.2}_{-1.2}$ km s$^{-1}$. The error bar on the b-value includes the uncertainties in the continuum level, the background residual, the instrumental line-spread function, and the column densities of the different species detected at the redshift of SBS 0335–052. If the FUSE and HST spectra are taken together, we obtain $b = 11.3^{+1.2}_{-1.2}$ km s$^{-1}$. The two b-values are in good agreement, and thus b is well constrained.

A b-value of 12 km s$^{-1}$ would correspond to a velocity dispersion $\sigma$ of only $b/\sqrt{2} = 8.5$ km s$^{-1}$, somewhat smaller than the value of ~15 km s$^{-1}$ derived from the H i VLA map of SBS 0335–052 (Pustilnik et al. 2001), although the two values are not directly comparable. The radio observations measure the velocity dispersion within a region equal to the VLA beam size of 20'' × 15'', while the FUSE observations probe only the star-forming region of ~2'' in size. Note that if b is underestimated, the column densities derived from very saturated lines would be overestimated. For instance, we estimate that if the real value of the b-parameter is 16 km s$^{-1}$, the column density of O i would be overestimated by ~1 dex. As for C ii, the species for which the column density estimate is most sensitive to the b-value, it would be overestimated by ~1.3 dex. Other species are less sensitive to the exact value of b, making the determination of their column densities more robust.
5.2. Modeling

We use the CLOUDY code (Ferland 1996; Ferland et al. 1998, ver. c90.05) to construct a photoionized H ii region model that best reproduces the optical nebular emission-line intensities observed in SBS 0335–052 (Izotov et al. 1997). By comparing the H ii column densities predicted by CLOUDY with the (H i + H ii) column densities observed by FUSE, we will be able to deduce the relative amounts of heavy elements in the H i and H ii gas.

We consider a spherically symmetric, ionization-bounded H ii region model. The calculations are stopped in the zone away from the ionizing stars where the temperature drops to 2000 K. The ionization in this zone is very low, and it is taken to be the outer edge of the H ii region. Several input parameters need to be set. For a distance of 54.3 Mpc, using the aperture-corrected Hβ flux from Izotov et al. (1997), we set the Hβ luminosity to be \( L(H/\beta) = 7.9 \times 10^{40} \, \text{ergs s}^{-1} \) and the number of ionizing photons to be \( N(L_{\text{Ly}c}) = 1.7 \times 10^{53} \, \text{s}^{-1} \). We use the Kurucz (1991) stellar atmosphere models and assume the effective temperature of the ionizing stellar radiation to be \( T_{\text{eff}} = 50,000 \, \text{K} \), a typical value for low-metallicity high-excitation H ii regions. For the inner radius of the H ii region, we adopt \( R_{\text{in}} = 1.0 \times 10^{19} \, \text{cm} \). The chemical composition of the H ii region is set by the observed element abundances derived from optical spectroscopy of SBS 0335–052 (Izotov et al. 1997), except for the carbon, silicon, and phosphorus abundances. For carbon we adopt \( \log(C/O) = -0.83 \) and for silicon \( \log(Si/O) = -1.60 \) (Izotov & Thuan 1999). As for phosphorus, we adopt the solar log \( \log(P/O) = -3.42 \) of Grevesse & Noels (1996). The adopted abundances are shown in Table 2.

We run the CLOUDY code varying the filling factor \( f \) and the electron number density \( N_e \) in order to obtain the best agreement between the predicted and observed [O ii] and [O iii] emission lines. We find that if \( N_e \) varies in the range 7–13 cm\(^{-3} \) and \( f \) in the range 0.17–0.29, then we have adequate agreement between the observed and model line intensities. The best model is found for a filling factor of \( f = 0.22 \) and an electron number density of \( N_e = 10 \, \text{cm}^{-3} \). The optical line intensities of the best model are shown in Table 3, where we compare them with the observed ones (Izotov et al. 1997). The error bars of the model line intensities (and those of the model parameters in Tables 1 and 4) correspond to the maximum range of their values. There is good general agreement between the observed and model line intensities, giving us confidence that the photoionization model is correct. The predicted total hydrogen (neutral and ionized) column density in the H ii region is \( N(H_1 + H_\text{ii}) = 4.93 \times 10^{21} \, \text{cm}^{-2} \), or log \( N(H_1 + H_\text{ii}) = 21.69 \). As expected for a H ii region model, most of the hydrogen is ionized: \( N(H_\text{ii}) = 4.89 \times 10^{21} \, \text{cm}^{-2} \). The column density of the neutral hydrogen is 2 orders of magnitude lower. The model

\[ \text{TABLE 2} \]

| Species       | \( \log[N(X)/N(H)] \) |
|---------------|-----------------------|
| He            | -1.0915             |
| C             | -5.50                |
| N             | -6.26                |
| O             | -4.67                |
| Ne            | -5.48                |
| Si            | -6.27                |
| P             | -8.05                |
| S             | -6.23                |
| Ar            | -6.93                |
| Fe            | -6.10                |

\[ ^a \text{From Izotov et al. (1997).} \]
\[ ^b \text{From Izotov \\& Thuan (1999).} \]
\[ ^c \text{Adopting solar log (P/O) = -3.42 from Grevesse \\& Noels (1996).} \]

\[ \text{TABLE 3} \]

| Ion          | Observed\(^a\) | CLOUDY                      |
|--------------|---------------|-----------------------------|
| [O ii]       | 0.233         | 0.217 ± 0.04                |
| [O ii]       | 0.079         | 0.079 ± 0.00                |
| [Ne ii]      | 0.239         | 0.253 ± 0.014               |
| [Ne ii] + H\( ^\text{II} \)| 0.172 | 0.194 ± 0.002                     |
| [Ne ii] + H\( ^\text{II} \)| 0.239 | 0.239 ± 0.004                     |
| H\( ^\text{I} \) | 0.255         | 0.264 ± 0.000               |
| H\( ^\text{II} \)| 0.476 | 0.474 ± 0.000                     |
| H\( ^\text{II} \)| 0.109 | 0.102 ± 0.000                     |
| He\( ^\text{I} \) | 0.035         | 0.035 ± 0.001               |
| He\( ^\text{I} \) | 0.003         | 0.002 ± 0.001               |
| He\( ^\text{I} \) | 0.010         | 0.009 ± 0.001               |
| He\( ^\text{I} \) | 1.000 | 1.000 ± 0.000                     |
| He\( ^\text{I} \) | 1.054 | 1.099 ± 0.001                     |
| He\( ^\text{I} \) | 3.155 | 3.173 ± 0.172                      |
| He\( ^\text{I} \) | 0.100         | 0.095 ± 0.000               |
| He\( ^\text{I} \) | 0.007         | 0.002 ± 0.000               |
| [S ii]       | 0.006         | 0.013 ± 0.001               |
| [S ii]       | 2.745         | 2.840 ± 0.07                |
| [N ii]       | 0.007         | 0.004 ± 0.000               |
| [N ii]       | 0.027         | 0.027 ± 0.000               |
| [Si ii]      | 0.019         | 0.013 ± 0.003               |
| [Si ii]      | 0.017         | 0.009 ± 0.002               |
| [Ar iv]      | 0.039         | 0.024 ± 0.001               |
| [Ar iv]      | 0.014         | 0.029 ± 0.001               |

\[ ^a \text{From Izotov et al. (1997).} \]
TABLE 4
CLOUDY PREDICTED COLUMN DENSITIES IN THE H II REGION

| Ion     | log N(a) | log N(b) |
|---------|----------|----------|
| C ii    | −1.64±0.09 | 14.55±0.02 |
| N ii    | −2.95±0.14 | 13.13±0.03 |
| N a     | −1.70±0.09 | 13.73±0.02 |
| N iii   | −0.14±0.01 | 15.29±0.10 |
| O i     | −2.16±0.08 | 14.86±0.04 |
| Si ii   | −2.16±0.07 | 13.96±0.01 |
| P ii    | −1.58±0.06 | 12.06±0.01 |
| Ar i    | −2.43±0.10 | 12.32±0.01 |
| Fe ii   | −1.99±0.03 | 13.60±0.01 |

a Radially averaged ratio of the ion number to the total number of the element.
b Column density.

Also predicts a column density of molecular hydrogen made via H− N(H2) = 1.91 × 1011 cm−2, more than 6 orders of magnitude lower than our observational upper limit.

We now compare the column densities of heavy elements predicted by CLOUDY with those derived from the FUSE and HST spectra. The CLOUDY predicted column densities are given in Table 4. Those relevant to the FUSE observations are also repeated in column (3) of Table 1. In Table 4, x is the radially averaged ratio of the ion number to the total number of a particular element, for example, N(Fe+) / N(Fe). The predicted log N(X) of species X is then derived as log N(X) = log  N(H i + H ii) + (log X+ / H) − log (X+). The column densities listed in Table 1 are plotted with their 1 σ error bars as filled circles in Figure 4. For comparison, the corresponding CLOUDY predicted column densities are plotted as open circles. There are two features that should be noted. First, the observed and calculated relative variations from ion element to ionic element show the same pattern. While this simply reflects the relative cosmic abundances of the considered species, retrieving that pattern from the data does show the consistency of the derived column densities for different species despite the low S/N of our FUSE spectra.

Second, the majority of the calculated H ii column densities are systematically smaller by more than 1 order of magnitude than the observed column densities. This implies that the FUSE column densities arise mainly in the neutral hydrogen envelope as well as in the gas ionized by young stars.

Figure 5 shows the ratio of the column densities of all ions relative to that of O i. As for the column density of O i, it is given relative to that of H i. There is general good agreement between the ratios of the FUSE column densities (filled circles) and the ratios of the elements abundances in the H ii region (stars). The only exception is the N(C ii) / N(O i) ratio, which is a factor of 30 larger than the C/O ratio in the H ii region. As discussed in § 5.1, the C ii column density is derived from a single strongly saturated line and is probably overestimated.

Of special interest is the N(O i) / N(H i) ratio. The ionization potential of O i is very similar to that of H i, and there is an efficient charge exchange between O ii and H i. Hence, there is a strong coupling between the oxygen and hydrogen ionization fractions. In the neutral gas, the O i / H i ratio can therefore be considered a very good proxy for the O/H ratio, and hence it is a very good tracer of metallicity. We obtain log N(O i) / N(H i) = −5.04 ± 0.55, or [O i / H i] = −1.70.

This is to be compared with log (O / H) = −4.70 ± 0.01 for the ionized gas in SBS 0335−052 (Izotov et al. 1999). Thus, within the errors, the metallicity of the neutral gas in SBS 0335−052 is comparable to that of its ionized gas. The much lower metallicity of the neutral gas of SBS 0335−052 obtained by Thuan & Izotov (1997) from HST observations is not correct.
since it is based on the erroneous assumption that the O i, Si ii, and S ii lines are not saturated.

How does the metallicity of the H i gas in SBS 0335–052 compare with those determined in the neutral ISM of other BCDs? Such a determination has been made for four other BCDs. For the most metal-deficient BCD known, I Zw 18 with a log (O/H) of the ionized gas equal to $-4.82 \pm 0.01$ (Izotov & Thuan 1999), Aloisi et al. (2003) have obtained log (O/H)$_n$ of the neutral gas $= -5.37 \pm 0.28$, while Lecavelier des Etangs et al. (2004) derived the higher value log (O/H)$_n = -4.7 \pm 0.35$. The discrepancy between the two values may be due to the fact that, to derive O/H, Aloisi et al. (2003) used the strongly saturated O i line at $\lambda_0 = 1039 \text{ Å}$, which, at the redshift of I Zw 18, is blended with terrestrial air glow. For I Zw 36 $\equiv$ Mrk 209 with log (O/H)$_i = -4.23 \pm 0.01$ (Izotov & Thuan 1999), Lebouteiller et al. (2004) derived log (O/H)$_i = -4.5^{+0.6}_{-0.5}$. For the BCD Mrk 59 with log (O/H)$_i = -4.01 \pm 0.01$ (Izotov & Thuan 1999), Thuan et al. (2002) derived log (O/H)$_n = -5.0 \pm 0.3$. As for the BCD NGC 1705 with log (O/H)$_i = -3.79 \pm 0.05$ (Lee & Skillman 2004), Heckman et al. (2001) derived log (O/H)$_n = -4.6 \pm 0.3$. Thus, if we disregard the low value of Aloisi et al. (2003), the ionized gas metallicity of the five different BCDs observed by FUSE span a log (O/H)$_i$ range from $-4.82$ to $-3.79$, i.e., a 1.03 dex spread. On the other hand, the metal content in their H i envelopes varies in the range log (O/H)$_n = -5.0$ to $-4.5$, or (O/H)$_n^i = -1.7$ to $-1.2$, using the revised solar abundance (O/H)$_S$ = $3.34$ of Asplund et al. (2004), i.e., a 0.5 dex spread.

At first glance, the metallicity spread of the neutral gas component appears to be only slightly lower than that of the ionized gas component. However, a real difference appears once the error bars of the metallicity measurements are considered. The metallicities of the ionized gas, log (O/H)$_i$, are determined from emission-line spectra with a precision of $0.01$ dex (0.05 dex for NGC 1705), while those of the neutral gas, log (O/H)$_n$, derived from absorption spectra, have considerably larger error bars varying from 0.3 dex for Mrk 59 and NGC 1705 to 1.0 dex for I Zw 36. These large error bars are in fact responsible for the apparent large-metallicity spread of the neutral gas. If we take into account the error bars, the log (O/H)$_i$ values do vary over a 1.0 dex range, while the log (O/H)$_n$ measurements are consistent with a single constant value. The spread of the log (O/H)$_n$ measurements around their mean value $\langle \log (O/H)_n \rangle = -4.8$ can be evaluated by the sum of their squared normalized differences, which, for five measurements, follow a $\chi^2$ law with 4 degrees of freedom. We obtain a very low dispersion $\sum (\log (O/H)_n - \langle \log (O/H)_n \rangle)^2 = 1.40$. There is more than an 84% chance that $\chi^2$ is larger than this value, supporting our contention that all five measurements are consistent with a single value of log (O/H)$_n$.

The fact that the most metal-deficient BCD (I Zw 18) has approximately the same log (O/H)$_n$ as the most metal-rich BCD (NGC 1705) studied by FUSE thus far suggests that the metallicities of the neutral and ionized gas are unrelatable. As discussed in § 1, the two most metal-deficient BCDs known, I Zw 18 and SBS 0335–052, have been suggested to be bona fide young galaxies, with ages not exceeding 500 Myr (see Izotov & Thuan [2004] for a discussion of the age of I Zw 18 and TIL97, Papaderos et al. [1998], and Pustilnik et al. [2004] for a discussion of the age of SBS 0335–052). Thus, the H i envelopes that surround these two BCDs may be expected to be truly primordial, i.e., not to contain heavy elements. Our study here of SBS 0335–052 and previous work on I Zw 18 show that this is clearly not the case, that the H i envelopes in these two BCDs have been previously enriched to a level of [O/H]$_n = -1.7$ to $-1.4$, perhaps by Population III stars. This speculation appears to be supported by the oxygen abundances derived by Telfer et al. (2002) for the intergalactic medium using ultraviolet absorption lines in Ly$\alpha$ absorbers. Those authors derive a [O/H] range of $-2.0$ to $-1.1$ (we have corrected their values using the O solar abundance of Asplund et al. [2004]), which overlaps well with that derived thus far for the neutral ISM in five BCDs.

6. CONCLUSIONS

We present FUSE far-UV spectra of the second most metal-deficient BCD galaxy known, SBS 0335–052, with an ionized gas oxygen abundance log (O/H) = $-4.70 \pm 0.01$. Because this galaxy is one of the best candidates for being a young galaxy in the local universe, with an age not exceeding $\sim 100$ Myr, the study of the abundances in its neutral hydrogen envelope is of special interest because it can shed light on the possible metal enrichment of the intergalactic medium by Population III stars. This speculation appears to be supported by observations of Ly$\alpha$ absorbers which give similar oxygen abundances in the intergalactic medium.

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