DISCOVERY OF A METAL-LINE ABSORBER ASSOCIATED WITH A LOCAL DWARF STARBURST GALAXY

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ABSTRACT

We present optical and near-infrared images, H i 21 cm emission maps, optical spectroscopy, and Hubble Space Telescope Space Telescope Imaging Spectrograph ultraviolet spectroscopy of the QSO/galaxy pair SBS 1122+594/IC 691. The QSO sight line lies at a position angle of 27° from the minor axis of the nearby dwarf starburst galaxy IC 691 (cz_{gal} = 1204 ± 3 km s^{-1}, L_B ∼ 0.09L^∗), current star formation rate = 0.08–0.24 h_70^{-1} M_☉ yr^{-1}) and 33 h_70 kpc (6.6) from its nucleus. We find that IC 691 has an H i mass of M_{HI} = (3.6 ± 0.1) × 10^8 M_☉ and a dynamical mass of M_{dyn} = (3.1 ± 0.5) × 10^{10} h_70^{-3} M_☉. The UV spectrum of SBS 1122+594 shows a metal-line ([Lα]+[C IV]) absorber near the redshift of IC 691 at cz_{abs} = 1110 ± 30 km s^{-1}. Since IC 691 is a dwarf starburst and the SBS 1122+594 sight line lies in the expected location for an outflowing wind, we propose that the best model for producing this metal-line absorber is a starburst wind from IC 691. We place consistent metallicity limits on IC 691 ([Z/Z_☉] ∼ −0.7) and the metal-line absorber ([Z/Z_☉] < −0.3). We also find that the galaxy’s escape velocity at the absorber location is v_{esc} = 80 ± 10 km s^{-1} and derive a wind velocity of v_w = 160 ± 50 km s^{-1}. Thus, the evidence suggests that IC 691 produces an unbound starburst wind that escapes from its gravitational potential to transport metals and energy to the surrounding intergalactic medium.

Key words: galaxies: dwarf — galaxies: individual (IC 691) — galaxies: starburst — quasars: absorption lines — quasars: individual (SBS 1122+594)

1. INTRODUCTION

Metals have been distributed throughout much of the intergalactic medium (IGM) at all observed redshifts. Transport by galactic starburst winds is a leading theory for explaining the existence of these IGM metals, which are often found far (several hundred kiloparsecs; Stocke et al. 2006b) from any sites of ongoing star formation. However, it is not clear whether starbursts associated with luminous massive galaxies or smaller but more numerous dwarf galaxies produce the winds that are primarily responsible for enriching the IGM with metals and energy. Statistically, it appears that 0.1% of galaxies must contribute to IGM enrichment unless L^∗ galaxies can enrich regions up to ∼1 Mpc in radius (Tumlinson & Fang 2005).

Starburst winds have been studied around nearby galaxies in emission using narrowband nebular emission-line (e.g., Hα) and thermal X-ray continuum images (Watson et al. 1984; Martin 1999; Martin et al. 2002), as well as ultraviolet and optical absorption-line spectroscopy (Heckman et al. 2000, 2001; Rupke et al. 2005a, 2005b; Martin 2005, 2006; Keeney et al. 2005, 2006). Both imaging and absorption-line spectroscopy have limitations, but the two techniques are complementary in many ways. Emission-line studies can address the extent and morphology of the outflow, but only in its densest regions. These studies cannot measure the velocity or temperature of the outflow in the diffuse halo, so they are incapable of determining whether ejecta in the halo are bound to the galaxy. Thus, emission-line studies alone cannot determine which galaxies produce outflows that enrich the surrounding IGM. Absorption-line studies, on the other hand, are much more sensitive to diffuse gas and therefore can determine whether ejecta in the halo are bound to the galaxy, but only along one line of sight (LOS), so they are unable to study the outflow morphology.

Most absorption-line studies also introduce an ambiguity in the distance between the background source and the absorbing gas since they typically use the stellar continuum of the starburst itself as their source (e.g., Heckman et al. 2000, 2001; Rupke et al. 2005a, 2005b; Martin 2005, 2006). Consequently, they cannot distinguish a high-velocity outflow in the galactic halo from one in the starburst region itself. Using outflow velocities measured in the galactic disk to predict whether the absorbing gas is gravitationally bound to the galaxy is problematic because ejecta within several kiloparsecs of the starburst region will decelerate under the combined effects of gravity and mass loading (e.g., Suchkov et al. 1996; Martin et al. 2002; Strickland et al. 2004). This problem can be circumvented by probing the outflow well away from the starburst region, which is only feasible if there is a bright background QSO projected near the galaxy of interest (e.g., Stocke et al. 2004; Keeney et al. 2005, 2006).

Massive galaxies have high rates of metal production and thus large amounts of potential fuel for IGM enrichment. Luminous low-redshift starbursts have star formation rates (SFRs) in the range 1–10 M_☉ yr^{-1}, although rates of ∼100–1000 M_☉ yr^{-1} can be triggered by mergers (Heckman et al. 1990; Martin 2003; Rupke et al. 2005a, 2005b). These galaxies generate winds with average outflow velocities of 300–400 km s^{-1}, but wind speeds of ≥1000 km s^{-1} are not unheard of (Heckman et al. 2000; Filippenko & Sargent 1992; Veilleux et al. 1994, 2005). Only the most luminous galaxies can be detected at high redshift, so studies of the earliest epochs of star formation and metal enrichment are inherently biased toward the most massive starbursts (Steidel et al. 1996a, 1996b, 1999, 2001; Pettini et al. 2001, 2002; Adelberger et al. 2003).
Dwarf galaxies produce fewer metals per galaxy than their massive counterparts, but they are much more numerous, and their cumulative effects could dominate IGM enrichment (Stocke et al. 2004; Tumlinson & Fang 2005). Dwarf starburst galaxies have typical SFRs of 0.1–1 M⊙ yr⁻¹ (Martin 2003) and produce winds with outflow velocities of ~50–200 km s⁻¹ (Marlowe et al. 1995; Martin 1998; Schwartz & Martin 2004). However, starbursts of all luminosities have the same maximum areal SFR (~45 M⊙ kpc⁻² yr⁻¹; Meurer et al. 1997) and produce winds with the same X-ray temperature (Martin 1999). These results indicate that dwarf starbursts may be more efficient than their massive counterparts at transporting the metals entrained in their winds to the IGM due to their shallower gravitational potentials with lower escape velocities.

Recent wind studies that use nearby QSOs to probe starburst winds several kiloparsecs from the host galaxy find that luminous galaxies produce bound winds, while dwarf galaxies produce unbound winds. Keeney et al. (2005) found that the nearby luminous starburst galaxy NGC 3067 (L \( \sim \) 0.5 L* and SFR \( \sim 1.4 M_\odot \) yr⁻¹) produces a bound wind along the LOS to 3C 232, which is located near the minor axis of NGC 3067 and 11 h⁻¹ kpc from the galactic plane. The Milky Way also produces a bound starburst wind along the LOSs to two high-latitude active galactic nuclei (AGNs) (Mrk 1383 and PKS 2005–489) at \( l \sim 350° \) that probe the regions on either side of the Galactic center at heights up to 12.5 kpc (Keeney et al. 2006). On the other hand, Stocke et al. (2004) found that a dwarf poststarburst galaxy produced an unbound wind \( \sim 3.5 \) Gyr ago that is now observed as the 1586 km s⁻¹ metal-line absorber in the spectrum of 3C 273, which is 71 h⁻¹ kpc away in projection on the sky.

In our ongoing study to determine what types of galaxies enrich the IGM, this paper presents an ultraviolet spectrum of the QSO SBS 1122+594, as well as optical and near-infrared images, an H i 21 cm emission map, and an optical spectrum of the blue compact galaxy IC 691, which is 6.6 away on the sky. These observations will be used to study whether the starburst wind produced by IC 691 can escape its gravitational potential to enrich the surrounding IGM. In § 2 we describe the acquisition and reduction of our multiwavelength observations. The connection between the metal-line absorber in the spectrum of SBS 1122+594 and IC 691 is discussed in § 3. In § 4 we examine whether the starburst wind produced by IC 691 can escape from its gravitational potential. We summarize our results and discuss their implications for IGM enrichment in § 5.

2. OBSERVATIONS AND DATA REDUCTION

We have obtained images and spectra of the QSO/galaxy pair SBS 1122+594/IC 691 at several wavelengths. Our data set includes ultraviolet and optical spectra of SBS 1122+594, as well as optical, near-infrared, and H i 21 cm images and a long-slit optical spectrum of IC 691. The acquisition and reduction of these data are described below in §§ 2.1–2.4. Broadband optical images and fiber spectra of SBS 1122+594 and IC 691 are also available from the Sloan Digital Sky Survey (SDSS; York et al. 2000; Abazajian et al. 2005). SBS 1122+594 is located 6.6 from IC 691, which corresponds to an impact parameter of \( 33 h_{70}^{-1} \) kpc at the redshift of IC 691 assuming a distance of \( cz_{\text{gal}}/H_0 = 17.2 h_{70}^{-1} \) Mpc (\( cz_{\text{gal}} = 1204 \pm 3 \) km s⁻¹; see § 2.4).

2.1. Ultraviolet and Spectrum of SBS 1122+594

SBS 1122+594 was observed by the Hubble Space Telescope (HST) with the G140L grating of the Space Telescope Imaging Spectrograph (STIS) for 1320 s on 2004 April 6 as part of GO program 9874 (principal investigator: J. Tumlinson). Despite the short exposure time of this snapshot spectrum, an intergalactic Ly\( \alpha \) + C IV absorber is evident near the redshift of IC 691. Figure 1 shows the associated Ly\( \alpha \) and C IV absorption features, as well as an intergalactic Ly\( \alpha \) line at \( cz \approx 2350 \) km s⁻¹ that can be seen in the top panel. Information about other features in this spectrum, which covers wavelengths of \( \sim 1120–1720 \) Å, can be found in the Appendix.

The continuum near the associated Ly\( \alpha \) and C IV absorption lines was normalized with Legendre polynomials, and the Ly\( \alpha \) and C IV features in the normalized spectra were fitted with Voigt profiles using a \( \chi^2 \) minimization routine developed by B. A. K. Rest wavelengths, oscillator strengths, and transition rates for the Voigt profile fits were taken from Morton (2003). The fit to the C IV data was constrained such that both lines in the doublet (rest wavelengths of 1548.2 and 1550.8 Å; Morton 2003) were fitted with the same velocity, Doppler b-value, and ionic column density, resulting in a best fit with a velocity of \( cz_{\text{abs}} = 1110 \pm 30 \) km s⁻¹ and a rest-frame equivalent width in the stronger, bluer line of 800 \( \pm 200 \) mÅ. The best fit to the intergalactic Ly\( \alpha \) absorber found a velocity of \( 1250 \pm 70 \) km s⁻¹ and a rest-frame equivalent width of 1700 \( \pm 200 \) mÅ. However, this absorber is located on the wing of the Galactic Ly\( \alpha \) line and is further blended with another intergalactic Ly\( \alpha \) absorber at \( cz \approx 2350 \) km s⁻¹ at the low resolution of STIS with the G140L grating (see Fig. 1). We believe that this blending and the poorer resolution in the Ly\( \alpha \) region (\( \approx 430 \) km s⁻¹) as compared to the C IV region (\( \approx 340 \) km s⁻¹) make the best-fit Ly\( \alpha \) velocity untrustworthy. Therefore, we adopt the best-fit C IV velocity of \( cz_{\text{abs}} = 1110 \pm 30 \) km s⁻¹ as the velocity of the Ly\( \alpha \)+C IV absorber. This velocity is indicated by a vertical gray bar in Figure 1.

We have estimated the Ly\( \alpha \) and C IV column densities for this absorber using the apparent optical depth (AOD) method (Savage & Sembach 1991). This method predicts an H i column density of \( N_{\text{H}1} = 10^{14.6 \pm 0.1} \) cm⁻² for this absorber, which we treat as a lower limit to the true column density since the AOD method underpredicts the column density of saturated lines. Unresolved saturation is likely in this Ly\( \alpha \) absorber due to the low velocity resolution of our G140L spectrum (e.g., the trough of the Galactic Ly\( \alpha \) absorption feature in Fig. 1 is well above zero). Both lines of the C IV doublet yield AOD column densities that agree to within the combined errors. We adopt the column density predicted by the weaker line of the doublet, \( N_{\text{C}\ IV} = 10^{14.7 \pm 0.2} \) cm⁻², since it is less susceptible to unresolved saturation. These column densities are used to estimate the absorber metallicity in § 3.

2.2. Optical and Near-Infrared Images of IC 691

Broadband optical and H\( \alpha \) images of IC 691 were obtained with the T2KA CCD at the Kitt Peak National Observatory (KPNO) 2.1 m telescope on 2003 March 4 and March 6. IC 691 was observed for a total exposure time of 480 s in the B band, 1680 s in the R band, and 2400 s each in the H\( \alpha \) on- and off-band filters. A mosaic of the R-band images showing both IC 691 and SBS 1122+594 is shown in Figure 2. Relative photometry with in-field standard stars yields an apparent B-band magnitude for IC 691, integrated to the 25 mag arcsec⁻² isophote (\( r_{25} = 39'' = 3.3 h_{70}^{-1} \) kpc), of \( m_{B,25} = 14.1 \pm 0.1 \), which corresponds to an absolute magnitude of \( M_B = -17.1 \pm 0.1 \) and a luminosity of \( L_B \approx 0.09L^* \) (using \( M_B^* \) from Marzke et al. 1994).

The inset to Figure 2 is a pure H\( \alpha \) image of IC 691 and shows ongoing star formation in the nucleus of the galaxy. The stellar continuum was subtracted from our H\( \alpha \) on-band image using a slightly bluer narrowband image. The resulting emission-line image of IC 691 contains flux not only from H\( \alpha \) but also from the nearby [N II] \( \lambda 6584 \) line (the stronger [N II] \( \lambda 6548 \) line is redshifted
out of our H$\alpha$ on-band filter. We have subtracted the [N ii] flux from our emission-line image by assuming that the entire galaxy has a constant $F(\text{H}$<sub>α</sub>$)/F([\text{N} \text{ ii}] \, \lambda 6548)$ ratio of 12, as found in our optical spectrum of IC 691 (see § 2.3 and Fig. 4). This pure H$\alpha$ image yields a total H$\alpha$ flux (corrected for Galactic extinction but not intrinsic extinction from IC 691) of $(2.9 \pm 0.1) \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$ for IC 691, which corresponds to an H$\alpha$ luminosity of $(1.03 \pm 0.04) \times 10^{40}$ $h_{70}^{-2}$ ergs s$^{-1}$ at the assumed distance to IC 691 of $17.2 \, h_{70}^{-1}$ Mpc. Using the conversion of Kennicutt (1998) this H$\alpha$ luminosity indicates a current SFR of $0.08 \pm 0.01 \, h_{70}^{-2} \, M_\odot$ yr$^{-1}$ for IC 691. After using the Balmer decrement in our optical spectrum of IC 691 (see § 2.3, Fig. 4, Table 1) to correct for the intrinsic extinction in IC 691, we find that its SFR is $0.24 \pm 0.03 \, h_{70}^{-2} \, M_\odot$ yr$^{-1}$. We treat this value as

![Figure 1](image-url)
an upper limit on the SFR because we have most likely overestimated the intrinsic extinction in IC 691 by applying an extinction correction derived from the densest region of the galaxy (i.e., the nuclear region where the Balmer decrement was measured) to our entire Hα image. Thus, we have bounded the SFR of IC 691 to lie in the range 0.08–0.24 $h_7^2 M_\odot$ yr$^{-1}$, which is comparable to the values of 0.1–1 $M_\odot$ yr$^{-1}$ typically found in nearby dwarf starburst galaxies (Martin 2003).

Near-infrared H- and K-band images of IC 691 were obtained with the Near Infrared Camera (NIC) at the Apache Point Observatory ARC 3.5 m telescope on 2005 April 20. IC 691 was observed for a total exposure time of 100 s in both H and K band. We determined the surface brightness profile of the H-band images to find the photometric properties of the stellar distribution of IC 691 since the other broadband images were contaminated by nebular emission lines associated with star formation ([O ii] in the B band, Hα in the R band, and Brγ in the K band). Figure 3 shows the H-band surface brightness profile of IC 691, generated with the IRAF tasks ellipse and bmodel, with a best-fit de Vaucouleurs (1948) $R^{1/4}$ profile overlaid. The dotted vertical line indicates the seeing of 0.7 in our image. Due to the small field of view of NIC, there were no in-field standard stars, so the photometric zero point of $C_H = 23.93 \pm 0.03$ mag was determined.
by comparing the Two Micron All Sky Survey $H$-band magnitudes of IC 691 at several apertures to the instrumental isophotal magnitudes at the same apertures. With this calibration, IC 691 has an $H$-band magnitude, integrated to the radius of the 20 mag arcsec$^{-2}$ $K$-band isophote ($R_{K20} = 13'' = 1.1 h_{70}$ kpc), of $m_H(R_{K20}) = 11.36 \pm 0.03$, and the best-fit $R^{1/4}$ profile has an effective radius of $r_e = 400 \pm 10 h_{70}$ pc and a fiducial surface brightness of $\mu_H(r_e) = 17.49 \pm 0.07$ mag arcsec$^{-2}$. The ellipticity of the isophotes varies smoothly from $e = 0$ in the center of the galaxy to $e = 0.3$ at a semimajor axis of $1.1''$ ($\sim 90 h_{70}$ pc), and stabilizes at this value for larger radii. Thus, IC 691 has an observed axial ratio of 0.7 in the $H$ band, implying that it is at an inclination of $i = 54^\circ \pm 2^\circ$ using the distribution of intrinsic dwarf galaxy shapes derived by Staveley-Smith et al. (1992). Subtracting the model galaxy from our original $H$-band image reveals a residual stream of material to the north that we interpret as a tidal tail caused by an interaction with a nearby galaxy (see § 2.4).

2.3. Optical Spectrum of IC 691

An optical spectrum of IC 691 that covers 3600–9700 Å at $\sim 6$ Å resolution was obtained on 2003 May 2 with the Dual Imaging Spectrograph (DIS) at the Apache Point Observatory 3.5 m telescope. The spectrum is split by a dichroic onto two CCDs with reduced sensitivity from 5200 to 5600 Å. The galaxy spectrum was acquired through a 1.5 slit rotated to a position angle of $90^\circ$ and was extracted using a 12'' wide aperture. All of the emission lines listed in Table 1 are labeled.

Table 1 lists the rest-frame equivalent widths for all emission lines detected in our optical spectrum of IC 691. This spectrum is displayed in Figure 4, with all emission lines from Table 1 labeled. The total H$\alpha$ flux in the spectrum is $2.3 \times 10^{-11}$ ergs s$^{-1}$ cm$^{-2}$, or $\sim 80\%$ of the flux in the H$\alpha$ image (§ 2.2). The emission lines in Table 1 are observed at an average velocity of $\langle \ddot{cz} \rangle = 1200 \pm 30$ km s$^{-1}$, which agrees with the $H\alpha$ velocity of $cz_{\text{gal}} = 1204 \pm 3$ km s$^{-1}$ found in § 2.4. We adopt the latter value as the best redshift of IC 691 due to its smaller error bars.

2.4. H $\alpha$ 21 cm Emission Map of IC 691

IC 691 was observed in the Very Large Array (VLA) D configuration on 2003 April 21 with a bandwidth of 3.125 MHz centered at 1.422 GHz ($cz = 1200$ km s$^{-1}$) and a channel width of 48.8 kHz (10.4 km s$^{-1}$). The data were reduced using standard AIPS procedures: 3C 286 was used as a flux calibrator while 1035+564 (J2000.0) was used for the bandpass calibration. The data were then imaged using uniform weighting with the parameter ROBUST = 0. After imaging, the data were continuum subtracted using IMLIN. In order to mask the noise in the cube before moment maps were constructed, the cube was first convolved with a Gaussian to a resolution of 100'' $\times$ 100''. This lower resolution cube was then blanked at the $\sigma$ level (1.8 mJy beam$^{-1}$), followed by blanking of the cube by hand to remove features that were not correlated from one channel to the next. This smoothed, blanked cube was then applied as a mask to the original data. The resulting cube was then used to create moment maps and spectra.

Figure 5 shows $H\alpha$ 21 cm intensity contours overlaid on a SDSS $g'$-band image of IC 691, which indicate that it is interacting with a low surface brightness (LSB) galaxy to the north, SDSS J112625.96+591737.5 (hereafter SDSS J1126+593). The SDSS spectrum of the LSB galaxy shows no emission lines and places it at a redshift of $cz = 1340 \pm 50$ km s$^{-1}$. Interestingly, if we separate the $H\alpha$ 21 cm emission from IC 691 and SDSS J1126+593 by placing a cut at a declination of $59^\circ 14'$, we find a much lower redshift for SDSS J1126+593 of $cz = 1180 \pm 20$ km s$^{-1}$. This same cut indicates that the $H\alpha$ 21 cm emission from SDSS J1126+593 has a FWHM of $26 \pm 6$ km s$^{-1}$ and an H $\mathord{\alpha}$ mass of $M_{H\alpha} = (4.6 \pm 0.5) \times 10^7 M_{\odot}$, and the $H\alpha$ around IC 691 has a velocity of $cz_{\text{gal}} = 1204 \pm 3$ km s$^{-1}$, a FWHM of 116 \pm 3 km s$^{-1}$, and an H $\mathord{\alpha}$ mass of $M_{H\alpha} = (3.6 \pm 0.1) \times 10^7 M_{\odot}$.

A tilted ring model was fitted to the $H\alpha$ 21 cm velocity profile of IC 691, with the ring inclination fixed at the value ($i = 54^\circ$) predicted by the axial ratio of the optical and near-infrared images (§ 2.2). The approaching (northern) and receding (southern) sides of the galaxy were fitted separately to search for evidence of tidal effects and agree to within errors for radii $< 14.2 h_{70}$ kpc.
(170'). At larger radii the two sides of the galaxy become more and more discrepant, indicating that tidal effects are becoming increasingly important. Our B-band images of IC 691 (§ 2.2) indicate that its Holmberg radius is 66″ = 5.5 h−1 70 kpc, so our 14.2 h−1 70 kpc cutoff corresponds to a radius of ~2.5 Holmberg radii. Figure 6 shows our final rotation curve for IC 691, which was fitted to both the approaching and receding sides of the galaxy simultaneously with a fixed inclination of i = 54° and is truncated at a radius of 14.2 h−1 70 kpc. This rotation curve is used to derive the dynamical mass of IC 691 in § 4.1.

3. GALAXY-ABSORBER CONNECTION

Statistically, low column density (NHI ≤ 1017.3 cm−2) intergalactic Lyα absorbers are associated with overdense IGM filaments rather than individual luminous (L > 0.1L*) galaxies (Morris et al. 1993; Tripp et al. 1998; Impey et al. 1999; Penton et al. 2002, 2004). Existing HST and Far Ultraviolet Spectroscopic Explorer (FUSE) spectra of QSO sight lines with low-redshift intergalactic Lyα absorbers are not generally sensitive enough to detect metals (C II, C III, C IV, Si II, Si III, Si IV, and O VI) in these absorbers except at NHI > 1014 cm−2 (Stoke et al. 2006a), where metallicities of 5%–10% solar are found (but see Aracil et al. [2006] and Prochaska et al. [2004] for individual absorber metallicities that may approach solar values; Sembach et al. 2001; Tripp et al. 2002; Shull et al. 1998, 2003; Tumlinson et al. 2005; Danforth & Shull 2005; Danforth et al. 2006). Weak metal-line systems are found to have smaller impact parameters from nearby galaxies than typical Lyα absorbers without associated metal lines (e.g., Stocke et al. 2006b), and the average QSO-galaxy impact parameter decreases with increasing column density. Thus, damped Lyα absorbers, the highest column density systems (NHI > 1020.3 cm−2), are plausibly associated with galactic disks (although see York et al. [2006] for a different hypothesis), and Lyman limit systems (LLSs; NHI = 1017.3–1020.3 cm−2) are likely associated with galactic halos (e.g., Steidel 1995, 1998), whereas lower column density metal-line absorbers (NHI = 1014–1017.3 cm−2) could be associated with outflowing galactic winds (see, e.g., Stocke et al. 2004, 2006a, 2006b). These statistical results suggest that the Lyα + C IV absorber at czabs = 1110 ± 30 km s−1 in the spectrum of SBS 1122+594 could be associated with a nearby galaxy.

Figure 7 shows the positions of all galaxies with cz < 1600 km s−1 that are within 500 h−1 70 kpc of SBS 1122+594 (100' at...
\(cz = 1200 \text{ km s}^{-1}\), as compiled by SDSS and the NASA/IPAC Extragalactic Database (NED). The position of SBS 1122+594 is indicated by the filled star in the center of the plot. The circles represent galaxies with \(cz < 1300 \text{ km s}^{-1}\) and the diamonds represent galaxies with \(cz = 1300-1600 \text{ km s}^{-1}\). Symbol size is proportional to the SDSS \(r^\prime\)-band luminosity of the galaxy. While no obvious groups of galaxies are evident, there is a large-scale “filament” of galaxies present in Figure 7 in which both IC 691 and the absorber are embedded. This absorber environment is similar to the filamentary environments of the 1586 km s\(^{-1}\) absorber toward 3C 273 and the 1685 km s\(^{-1}\) absorber toward RX J1230.8+0115 studied previously by Stocke et al. (2004) and Rosenberg et al. (2003). Any galaxies with unknown redshifts near SBS 1122+594 are fainter than the SDSS spectroscopic completeness limit of \(m_r = 17.8\). At \(cz_{\text{gal}} \approx cz_{\text{abs}}\) this limit implies that Figure 7 is complete to an absolute magnitude of \(M_r \leq -5\) log 70 kpc \(-13.2\), or \(L_r \geq 0.001 L^\odot\) h\(^{-2}\) (Blanton et al. 2001).

With impact parameters of 33 and 42 h\(^{-1}\) kpc, respectively, IC 691 and SDSS J1126+593 are by far the closest galaxies in Figure 7 to the SBS 1122+594 sight line. While the redshift of SDSS J1126+593 as derived from the centroid of its H\(i\) 21 cm emission is marginally closer to the absorber velocity than that of IC 691, IC 691 is \(\pm 20\) times more luminous in the SDSS \(r^\prime\) band than SDSS J1126+593. This luminosity difference, combined with the facts that IC 691 is currently forming stars while SDSS J1126+593 is not and IC 691 is closer to the SBS 1122+594 sight line, indicate that IC 691 is more likely to have created the metal-line absorber.

The closest luminous galaxy to SBS 1122+594 is NGC 3642 at \(cz_{\text{gal}} = 1598 \text{ km s}^{-1}\), which is \(130 h_{70}^{-1}\) kpc away (28\% at \(cz_{\text{abs}}\)), and it is \(\sim 10\) times more luminous than IC 691. We consider IC 691 to be the more likely source of the metal-line absorber, however, since NGC 3642 is both 4 times farther from SBS 1122+594 in projection and 5 times more discrepant in redshift. Other than NGC 3642, the only galaxies in Figure 7 that are more luminous than IC 691 are NGC 3795B and NGC 3619, which are 452 h\(^{-1}\) kpc (97\% at \(cz_{\text{abs}}\)) and 458 h\(^{-1}\) kpc (99\% at \(cz_{\text{abs}}\)) away from SBS 1122+594, respectively. NGC 3795B is at a redshift of \(cz = 1257 \text{ km s}^{-1}\) and is twice as luminous as IC 691, and NGC 3619 is at a redshift of \(cz = 1553 \text{ km s}^{-1}\) and is \(\sim 6\) times more luminous than IC 691. Neither of these galaxies are as luminous as NGC 3642 nor as close to the SBS 1122+594 sight line, so they are not likely candidates for the origin of the metal-line absorber.

Several circumstantial lines of reasoning also point to a connection between IC 691 and the metal-line absorber. The \(33 h_{70}^{-1}\) kpc impact parameter between SBS 1122+594 and IC 691 is much less than the median nearest-neighbor distance of 180 h\(^{-1}\) kpc between low-metallicity (10% \(\pm 5\%\) solar) O \(vi\) and C \(m\) absorbers detected with FUSE and galaxies of any luminosity detected in regions where galaxy surveys are complete to at least 0.1L\(^\odot\) (Stocke et al. 2006b). The SBS 1122+594 sight line also lies at a position angle \(\theta = 27^\circ\) from the minor axis of IC 691, which is the expected direction for an outflowing starburst wind since nearby starburst galaxies often show biconic outflows with opening angles above the disk of \(20^\circ \approx 45^\circ-100^\circ\) (values of \(20^\circ \sim 65^\circ\) are typical; Heckman et al. 1990; Veilleux et al. 2005). Furthermore, the H\(21\) cm emission along the major axis of IC 691 extends to distances comparable to the SBS 1122+594/IC 691 separation (see Fig. 5). While some of this material is affected by tidal interactions between IC 691 and SDSS J1126+593, the large extent of the H\(i\) envelope of IC 691 with respect to the angular distance between IC 691 and SBS 1122+594 indicates that gas associated with IC 691 can plausibly reach the location of SBS 1122+594 on the sky.

The H\(i\) emission map in Figure 5 suggests that the metal-line absorber could be due to the recent interaction between IC 691 and SDSS J1126+593. However, the extended H\(i\) is in a plane nearly perpendicular to the direction of SBS 1122+594 from IC 691, and while tidal tails are often strongly curved (e.g., NGC 520; Hibbard & van Gorkom 1996; Norman et al. 1996), the H\(21\) cm emission of IC 691 shows no evidence of such curvature. Also, the H\(i\) velocities of the tidal border between these two galaxies is never less than \(1180 \pm 20 \text{ km s}^{-1}\) at any location. Therefore, any tidal debris in the direction of SBS 1122+594 must be more diffuse and/or more highly ionized and have different kinematics from the tidal material seen in Figure 5. The absence of velocity overlap between the H\(i\) tidal debris and the absorber argue against a tidal origin for the absorbing gas. So, while we cannot rule out tidal debris as the origin of the metal-line absorber, we believe that the outflowing gas from a starburst superwind triggered by the recent interaction is more likely. This model naturally explains why absorption is seen near the minor axis of IC 691, which is far from the plane of the galaxy interaction (although outflows from dwarf galaxies may have less of a preferred direction than in more massive starbursts; e.g., Ott et al. 2003).

Table 1 lists the rest-frame equivalent widths for the emission lines detected in the IC 691 starburst with optical spectrum (§ 2.3). The [O \(iii\)]-derived mean temperature of \(\sim 14,000 \text{ K}\) is uncertain due to the weakness of the [O \(iii\)] \(\lambda4363\) line in our spectrum but is similar to [O \(iii\)]-derived temperatures for hotter H\(\eta\) regions in the LMC (Oey & Shields 2000). Likewise, the relatively reddening-free line ratios [O \(iii\)] \(\lambda5007)/H\beta\) and [N \(ii\)] \(\lambda6584)/H\alpha\) in IC 691 are also similar to values found for LMC H\(\eta\) regions by Oey et al. (2000). Because the Balmer decrement listed in Table 1 is only slightly larger than case B, there is only quite modest reddening present in the H\(\eta\) region spectrum of IC 691, which should not affect these line ratios significantly. Since the detailed position-resolved abundance study of LMC H\(\eta\) regions by Oey & Shields (2000) found oxygen and nitrogen abundances of 20\%–30\% solar, the mean metal abundances in the IC 691 starburst are comparable to those values based on our long-slit spectrum. Therefore, the metal abundance in this dwarf starburst is significantly subsolar, as expected for such a small galaxy.

Our STIS spectrum of SBS 1122+594 (see § 2.1 and Fig. 1) limits the H\(\eta\) and C \(iv\) column densities to \(N_{H\eta} \geq 10^{14.6} \text{ cm}^{-2}\) and \(N_{CIV} = 10^{14.7 \pm 0.2} \text{ cm}^{-2}\), respectively. A standard photoionization model can be employed to estimate the metallicity of this absorber by assuming an extragalactic photoionizing flux of \(L_{\gamma} = 10^{23} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ Hz}^{-1}\) and a gas overdensity for this absorber of 10–100 based on estimates from numerical simulations for the observed \(N_{H\eta}\), lower limit (i.e., log \(U = -0.5\) to \(-1.5\)). In this case the C \(iv\) equivalent width of 800 mA yields \([Z/Z_{\odot}] < -0.3\) and a particle density of \(\sim 10^{-5} \text{ cm}^{-3}\), implying a scale size along the LOS of \(>10\) pc. It is quite unlikely that this absorber is either hotter, collisionally ionized gas or diffuse, photoionized gas because of the strength of the C \(iv\) absorption; however, searches for O \(vi\) in the far-UV and lower ions in the HST band should be conducted if better UV spectra become available to discriminate between these two possibilities. Our estimated absorber metallicity is broadly consistent with our metallicity estimate of \([Z/Z_{\odot}] \sim -0.7\) for IC 691, although the absorber metallicity could be less than that of IC 691, since there is only a lower limit on the absorber \(N_{H\eta}\). However, the upper limit on the absorber metallicity is still significantly subsolar, as expected from an outflow associated with a dwarf galaxy.
While the inferred LOS size for this absorber may seem quite small, it is comparable to the LOS scale size for the 1586 km s$^{-1}$ absorber in the 3C 273 sight line (Tripp et al. 2002), as well as many “weak-Mg ii” absorbers studied by Charlton et al. (2002) at higher redshifts. Stocke et al. (2004) argued that the small LOS sizes reported for weak metal-line absorbers coupled with their relative frequency (which requires a scale size on the sky of $\sim$100 kpc) were naturally explained by the thin-shell geometry produced by a galactic superwind. Recent hydrodynamic simulations of dense clouds entrained in an outflowing galactic superwind by Marcolini et al. (2005) modeled these clouds as spheres with a radius of 15 pc, which is comparable to the LOS sizes of the 3C 273 and SBS 1122+594 absorbers discussed above. Therefore, both the subsolar metallicity of the metal-line absorber and its small size are suggestive of an origin in a dwarf galaxy superwind from IC 691.

4. DOES THE STARBURST WIND ESCAPE?

In this section we assume that the Ly$\alpha$+C iv absorber in SBS 1122+594 is gas entrained in a starburst superwind from IC 691. Since galactic winds are a leading mechanism for transporting metals and energy from galaxies into the IGM, we use the Ly$\alpha$+C iv absorber in SBS 1122+594 to determine whether the starburst wind from IC 691 can escape from its gravitational potential to enrich large regions of intergalactic space. The total mass of IC 691 is calculated in § 4.1. In § 4.2 we use this mass to derive various properties of the starburst wind.

4.1. Total Mass of IC 691

The H i 21 cm rotation curve discussed in § 2.4 is shown in Figure 6. These data are truncated at a radius of 14.2 $h^{-1}_{70}$ kpc (170$''$) because the interaction of IC 691 with SDSS J1126+593 (the LSB galaxy to the north; see Fig. 5) precludes us from extending the rotation curve to larger radii. However, the last data point in Figure 6 suggests that the H i 21 cm rotation curve has begun to flatten at radii $>$ 9.2 $h^{-1}_{70}$ kpc (110$''$). In order to estimate the total mass of IC 691, we have assumed that the rotation curve has flattened at these radii and remains flat to a radius of 24.6 $h^{-1}_{70}$ kpc (295$''$; $-$4.5 Holmberg radii), the maximum radial extent of IC 691 (using the cut at a declination of 59$''$14′′ to separate the H i emission from IC 691 and SDSS J1126+593; see § 2.4). Under this assumption, the rotation curve was fitted with an isothermal halo truncated at 24.6 $h^{-1}_{70}$ kpc. The best-fit model (reduced $\chi^2 = 1.0$) is overlaid on the data points in Figure 6 and has a central density of $0.005 \pm 0.002 M_{\odot}$ pc$^{-3}$ and a core radius of $6 \pm 2 h^{-1}_{70}$ kpc. The escape velocity as a function of radius predicted by the best-fit model is shown in Figure 6 by the solid line above the data points, and the open triangle indicates the observed wind velocity and absorber location. These quantities are discussed further in § 4.2.

Assuming that the rotation curve of IC 691 is flat at a velocity of $74 \pm 9$ km s$^{-1}$ to a radius of 24.6 $h^{-1}_{70}$ kpc and declines thereafter implies that IC 691 has a total mass of $M_{\text{dyn}} = (3.1 \pm 0.5) \times 10^{10} h^{-1}_{70} M_{\odot}$. This dynamical mass predicts a total mass-to-light ratio of $M_{\text{dyn}}/L_B = 28 \pm 5 h_{70}$ and a gas mass fraction of $f_{\text{gas}} = M_{\text{gas}}/M_{\text{dyn}} = 0.012 \pm 0.002 h_{70}$ for IC 691. These values are consistent with the mass-to-light ratios and gas mass fractions found for nearby blue compact galaxies and dwarf irregular galaxies (Begum et al. 2005; Pisano et al. 2001; Roberts & Haynes 1994).

It is quite possible that this dynamical mass is an overestimate. Figure 5 shows that IC 691 is interacting with a nearby galaxy to the north, which should act to increase the turbulent motions in IC 691, and thus its velocity dispersion. Therefore, one would expect that only part of the velocity in Figure 6 is caused by galactic rotation, with the remainder caused by the interaction. If this is correct it implies that the true dynamical mass of IC 691 is lower than our estimate. IC 691 is also well fitted by a de Vaucouleurs (1948) $R^{1/4}$ profile (Fig. 3), making it photometrically similar to elliptical galaxies rather than spiral galaxies, further implying that it may not be dominated by rotation. However, since our dynamical mass estimate of $M_{\text{dyn}} = (3.1 \pm 0.5) \times 10^{10} h^{-1}_{70} M_{\odot}$ predicts a mass-to-light ratio and gas mass fraction for IC 691 that are consistent with the range of values found for similar nearby galaxies, we assume that it is valid for all subsequent calculations.

4.2. Starburst Wind Properties

We assume that the Ly$\alpha$+C iv absorber is entrained in a radial outflow emanating from the galactic center of IC 691, that the galaxy’s mass distribution is spherically symmetric, and that all of the mass is located interior to the SBS 1122+594 sight line. Under these assumptions, IC 691 can be treated as a point mass when calculating the escape velocity at the absorber location:

$$v_{\text{esc}} = 93 \text{ km s}^{-1} \left( \frac{M_{\text{dyn}}}{10^9 M_{\odot}} \right)^{1/2} \left( \frac{r}{1 \text{ kpc}} \right)^{-1/2}.$$  

If IC 691 is at an inclination $i$ then $M_{\text{dyn}} = [(2.0 \pm 0.3) \times 10^{10} h^{-1}_{70} M_{\odot}]/\sin^i (which corresponds to the value from § 4.1 for $i = 54^o$), $r = (33 h^{-1}_{70} \text{ kpc})/\sin i$, and $v_{\text{esc}} = (72 \pm 8 \text{ km s}^{-1})/\sin^i$. The starburst wind has a LOS velocity of $v_{\text{los}} = |cz_{\text{abs}} - cz_{\text{gal}}| = 95 \pm 30 \text{ km s}^{-1}$ at the absorber location, which corresponds to an outflow speed perpendicular to the disk of IC 691 of $v_{\text{w}} = v_{\text{los}}/\cos i$. The wind will escape the gravitational potential of IC 691 if $v_{\text{w}}/v_{\text{esc}} > 1$, which will occur at inclinations $i > 26^o \pm 10^o$. The H-band axial ratio ($\beta 2.2$) predicts an inclination of $i = 54^o \pm 2^o$ for IC 691. Thus, under our set of assumptions, IC 691 produces an unbound starburst wind.

With our assumed geometry and a galaxy inclination of $i = 54^o$, the escape velocity at the absorber location of $r = (33 h^{-1}_{70} \text{ kpc})/\sin i = 41 h^{-1}_{70} \text{ kpc}$ is $v_{\text{esc}} = (72 \pm 8 \text{ km s}^{-1})(\sin^i)^{1/2} = 80 \pm 10 \text{ km s}^{-1}$, and the starburst wind is moving at a speed of $v_{\text{w}} = v_{\text{los}}/\cos i = 160 \pm 50 \text{ km s}^{-1}$. This outflow velocity places an upper limit on the time since the absorbing gas was ejected of $t_{\text{ej}} = w/v_{\text{w}} = 250 \pm 80 h^{-1}_{70}$ Myr, assuming that the wind has been moving at a constant velocity. This timescale is an upper limit since the ejecta would likely decelerate due to gravity and mass loading, and indicates that the metal-line absorber is associated with the current star formation episode in IC 691 or a burst immediately preceding it.

It is interesting to consider how much mass the current burst in IC 691 could eject as wind material. If the burst that created the metal-line absorber lasted for $10^8$ yr at the current SFR of IC 691 (uncorrected for intrinsic extinction), then $\sim 8 \times 10^9 M_{\odot}$ of stars would have been formed. A Salpeter initial mass function predicts that a burst of this size would create $\sim 10^5$ stars with $M > 8 M_{\odot}$, each of which would eventually become a supernova. If each supernova has $10^{52}$ ergs of energy available, which is converted to bulk motions with an efficiency of $3\%-30\%$ (Cioffi & Shull 1991; Koo & McKee 1992a, 1992b), then the burst would produce $3 \times 10^{53}-10^{55}$ ergs that could be used to generate a wind. This energy could accelerate up to $6 \times 10^{50} M_{\odot}$ of material to a velocity of $\sim 160 \text{ km s}^{-1}$ after escaping the gravitational potential well of IC 691. Thus, the production of the metal-line absorber toward SBS 1122+594 by the IC 691 starburst is plausible energetically.

If IC 691 continues to form stars at its current rate of $0.08 \pm 0.01 h^{-1}_{70} M_{\odot} \text{ yr}^{-1}$, then it will run out of available material for...
additional star formation in the gas depletion timescale of $\tau_{\text{gas}} \equiv M_{\text{H}_2}/\text{SFR} = 4.5 \pm 0.6 \, h_{70}^{-1} \text{Gyr}$ (Kennicutt 1983). This timescale is longer than the duration of a typical star formation episode, so IC 691 will likely experience further star formation episodes once the current burst ceases. Complicated, episodic star formation histories are not uncommon for dwarf starbursts, as evidenced by the Local Group dwarf elliptical and spheroidal galaxies (Mateo 1998).

5. CONCLUSIONS

We have used HST to detect Ly$\alpha$ and C iv absorption ($cz_{\text{abs}} = 1110 \pm 30 \, \text{km s}^{-1}$) from the nearby dwarf starburst galaxy IC 691 ($cz_{\text{gal}} = 1204 \pm 3 \, \text{km s}^{-1}$) in the spectrum of the QSO SBS 1122+594. Narrowband H$\alpha$ images show that IC 691 is currently forming stars at a rate of $0.08-0.24 \, h_{70}^{-2} \, M_\odot \, \text{yr}^{-1}$, which is comparable to the SFRs found in other nearby dwarf starburst galaxies (Martin 2003). A long-slit optical spectrum of IC 691 has distributed metals. A & Charlot 1993; Bruzual & Charlot 2003; Babul & Ferguson 1996). While the cloud has no velocity structure, the rotation curve of IC 691 when it was forming stars at its current rate in a burst lasting $\sim 10^8 \, \text{yr}$, then it could accelerate $\gtrsim 10^7 \, M_\odot$ of material to the current absorber velocity. A rough estimate of a subsolar metallicity ($Z/Z_\odot < -0.3$) for this absorber is also consistent with the metallicity limit of $Z/Z_\odot \sim -0.7$ found for IC 691.

Our conclusion that IC 691 produces an unbound starburst wind agrees with the results of Stocke et al. (2004), who found that an unbound wind from a dwarf poststarburst galaxy could be responsible for the $cz_{\text{abs}} = 1586 \, \text{km s}^{-1}$ metal-line system in the 3C 273 sight line $71 \, h_{70}^{-1} \, \text{kpc}$ away. This dwarf poststarburst galaxy could be representative of a later stage in the evolution of the SBS 1122+594/IC 691 system. Once all of the H$\text{I}$ in IC 691 has been exhausted via star formation and ejection, it will develop a poststarburst spectrum and fade in luminosity as envisioned by Babul & Rees (1992) to the current brightness of the 3C 273 dwarf ($M_B = -13.9$) within $\sim 1 \, \text{Gyr}$ after the H$\text{I}$ is exhausted (Bruzual A. & Charlot 1993; Bruzual & Charlot 2003; Babul & Ferguson 1996). Meanwhile, the unbound wind will continue to propagate into the surrounding IGM and increase the distance to which IC 691 has distributed metals.

On the other hand, more luminous galaxies appear to produce bound winds. Keeney et al. (2005) found that the nearby luminous (0.5$L^*$) starburst galaxy NGC 3067 (SFR $\approx 1.4 \, M_\odot \, \text{yr}^{-1}$) produces a bound wind along the 3C 232 sight line, which probes the halo of NGC 3067 near its minor axis and $11 \, h_{70}^{-1} \, \text{kpc}$ from the plane. Similarly, Keeney et al. (2006) found that the Milky Way produces a bound wind toward two high-latitude AGN sight lines near $l = 0^\circ$ (Mrk 1383 and PKS 2005–489) that probe regions directly to the north and south of the Galactic center at heights of up to 12.5 kpc. In both NGC 3067 and the Milky Way, the bound winds have the same spectral signature as high-velocity clouds and share many of their properties.

Statistical studies of QSO-absorber pairs in large samples of low-$z$ Ly$\alpha$+metal line absorbers, for example, Stocke et al. (2006) also suggest that IGM metals are spread primarily by dwarf galaxies. For example, Tumlinson & Fang (2005) found that enriched regions of gas must extend $\sim 1 \, \text{Mpc}$ from $L^*$ galaxies to be due to $>L^*$ galaxy superwinds. Enrichment regions of 100–150 kpc are much more plausible based on observed absorber-galaxy distances (Stocke et al. 2006b), but require that enrichment be due primarily to dwarf ($<0.1 L^*$) galaxies (Tumlinson & Fang 2005). The SBS 1122+594/IC 691 system supports this conclusion.

IC 691 is not the only blue compact galaxy that shows evidence for an outflowing wind. The Fornax Cluster galaxy FCC 35 shows strong H$\text{I}$ and [O ii] emission and an unusual single-dish H$\text{I}$ 21 cm profile in which a rotationally supported H$\text{I}$ disk is superposed with an irregularly shaped H$\text{I}$ cloud with no optical counterpart (Putman et al. 1998). The disk and the cloud have roughly the same H$\text{I}$ mass ($M_{\text{HI}} = 2.2 \times 10^8 M_\odot$) and overlap spatially but not in velocity, with the cloud blueshifted by $\sim 150 \, \text{km s}^{-1}$ with respect to the systemic velocity of the disk. While the cloud has no velocity structure, the rotation curve of the disk indicates that it has a truncated mass distribution. Putman et al. (1998) suggest that the H$\text{I}$ cloud is triggering the current burst of star formation in FCC 35, but by analogy with IC 691 the H$\text{I}$ cloud could also be ejecta from the starburst wind of FCC 35, which would explain the truncated mass distribution of its disk. FCC 35 has an H$\text{I}$ mass comparable to the galaxies with the lowest gas masses and smallest gas depletion timescales in the Pisano et al. (2001) sample of nearby blue compact galaxies. These low-mass galaxies may be undergoing their last star formation event and will likely fade in luminosity as envisioned by Babul & Rees (1992) once their current star formation ceases (Pisano et al. 2001).

Collectively, these results imply that starburst winds escape more easily from dwarf starburst galaxies than from their more massive counterparts. This is to be expected since Meurer et al. (1997) found a maximum areal SFR of $\sim 45 \, M_\odot \, \text{pc}^{-2} \, \text{yr}^{-1}$ for starbursts of all luminosities, and Martin (1999) found that the temperature of starburst winds is nearly constant as a function of galaxy mass, both of which imply that the strength of a starburst wind is independent of galaxy size. Thus, there is growing evidence that the metals and energy expelled by massive galaxies are retained in their bound halos and that the weaker but more numerous dwarfs are primarily responsible for enriching the IGM.

We have argued that an outflowing unbound starburst wind from IC 691 is the best model for explaining the origin of the metal-line absorber in the spectrum of SBS 1122+594 due to (1) the proximity of the QSO sight line to the galaxy’s minor axis, (2) the ongoing star formation in IC 691, (3) the energetic ability of the current IC 691 starburst to eject $\sim 10^7 M_\odot$ of material to the observed wind velocity after escaping the galaxy’s gravitational potential well, and (4) the consistent subsolar metallicities derived for IC 691 and the metal-line absorber. However, plausible models for the absorber origin exist. In particular, we cannot rule out the possibility that the absorber is caused by diffuse tidal debris from the recent interaction of IC 691 and SDSS J1126+593, although the observed geometry of the H$\text{I}$ 21 cm-emitting gas does not obviously support this hypothesis. Future observations of SBS 1122+594, as well as of fainter AGNs near
IC 691, with the Cosmic Origins Spectrograph would allow us to
distinguish between these models and to sensitively search for ab-
sorption in other ions at \(c_z \approx 1110 \text{ km s}^{-1}\).

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APPENDIX

The full STIS G140L snapshot spectrum of SBS 1122+594 is
displayed in Figure 8. This spectrum shows a ~30% continuum
decrement blueward of ~1435 Å, which suggests the presence of a
partial Lyman limit system (LLS) at \(z \approx 0.58\). A search for
other absorption lines at this redshift revealed \(\text{Ly}\beta, \text{C\,\,n}/\text{C\,\,n}^*,\) and \(\text{O\,\,i}\) absorption at \(z = 0.583\). The apparent optical depth (Savage &
Sembach 1991) of the \(\text{Ly}\beta\) line places a lower limit on the \(\text{H}\,\,i\)
column density of the LLS of \(N_{\text{H}}/C = 10^{15.4} \text{ cm}^{-2}\). LLSs have
column densities of \(N_{\text{H}}/C = 10^{17.3}-10^{20.3} \text{ cm}^{-2}\) and an optical
depth at the Lyman limit of \(\tau_{\text{LL}} \approx 1\). The 28% ± 13% continuum
decrement in our spectrum of SBS 1122+594 implies an optical
depth at the Lyman limit of \(\tau_{\text{LL}} = 0.3 ± 0.2\), which requires an
\(\text{H}\,\,i\) column density of \(N_{\text{H}}/C = (5 ± 3) \times 10^{16} \text{ cm}^{-2}\).

The positions of Galactic lines in Figure 8 are indicated with
tick marks below the spectrum, and the positions of interga-
lactic absorption lines are indicated with tick marks above the
spectrum. The \(\text{Ly}\alpha\) and \(\text{C\,\,iv}\) lines at \(cz_{\text{abs}} = 1110 ± 30 \text{ km s}^{-1}\)
(see Fig. 1) are shown with dotted tick marks, lines associated
with the LLS at \(z = 0.583\) are shown with dashed tick marks,
and intergalactic \(\text{Ly}\alpha\) lines at other redshifts are shown with
solid tick marks. We have not searched for associated metal
lines at the redshifts of the \(\text{Ly}\alpha\) absorbers indicated with solid
tick marks. The broad feature at \(z \approx 1460 \text{ Å}\) is likely intrinsic \(\text{O\,\,iv}\)
\(\lambda 787\) emission at \(z = 0.852\). The signal-to-noise ratio of the
spectrum ranges from ~10 per resolution element near Galactic Ly\(\alpha\)
to ~5 per resolution element near Galactic \(\text{Al}\,\,ii}\).

Neither the SDSS spectrum of SBS 1122+594 nor a DIS spec-
trum taken on 2003 May 2 show \(\text{Mg}\,\,ii\) absorption at \(z = 0.58\)
with an equivalent width \(\approx 50 \text{ mA}\). Luminous \([L > (0.1-0.3)L']\)
galaxies are typically found within a projected distance of
\(50 h_{70}^{-1}\) kpc of LLSs with strong \(\text{Mg}\,\,ii\) absorption (Steidel
1995, 1998). Our R-band image of IC 691 (see § 2.2) does not show a
L > 0.3L' \((mg \approx 21.0\) Brown et al. 2001) galaxy within \(50 h_{70}^{-1}\)
(\(6''\) at \(z = 0.58\) of SBS 1122+594 that could be responsible for this LLS
(the SDSS plates show no galaxy within \(50 h_{70}^{-1}\) kpc of
SBS 1122+594 with L > 0.7L' in the \(i'\) band or L > 3L' in the \(z'\)
band; Blanton et al. 2001). Our \(R\)-band and near-infrared
images of IC 691 cannot be used to search for the galaxy responsible
for this LLS because they do not have a large enough field of view
to cover the SBS 1122+594 sight line. Since the LLS seen in
the STIS spectrum of SBS 1122+594 does not produce a strong \(\text{Mg}\,\,ii\)
absorber, it is not surprising that our images do not show a lu-
mious galaxy within a projected distance of \(50 h_{70}^{-1}\) kpc from the
sight line.

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