ON THE ESCAPE OF IONIZING RADIATION FROM STARBURSTS

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ABSTRACT

Far-ultraviolet spectra obtained with FUSE show that the strong C II λ1036 interstellar absorption line is essentially black in five of the UV-brightest local starburst galaxies. Because the opacity of the neutral ISM below the Lyman edge will be significantly larger than in the C II line, these data provide strong constraints on the escape of ionizing radiation from these starbursts. Interpreted as a uniform, absorbing slab, the implied optical depth at the Lyman edge is huge ($\tau_0 \geq 10^5$). Alternatively, the areal covering factor of opaque material is typically $\geq 94\%$. Thus, the fraction of ionizing stellar photons that escape the ISM of each galaxy is small: our conservative estimates typically yield $f_{\text{esc}} \leq 6\%$. Inclusion of extinction due to dust will further decrease $f_{\text{esc}}$. An analogous analysis of the rest-UV spectrum of the star-forming galaxy MS 1512-cB58 at $z = 2.7$ leads to similar constraints on $f_{\text{esc}}$. These new results agree with the constraints provided by direct observations below the Lyman edge in a few other local starbursts. However, they differ from the recently reported properties of star-forming galaxies at $z \geq 3$. We assess the idea that the strong galactic winds seen in many powerful starbursts clear channels through their neutral ISM. We show empirically that such outflows may be a necessary—but not sufficient—part of the process of creating a relatively porous ISM. We note that observations will soon document the cosmic evolution in the contribution of star-forming galaxies to the metagalactic ionizing background, with important implications for the evolution of the IGM.

Subject headings: galaxies: formation — galaxies: ISM — galaxies: starburst — intergalactic medium

1. INTRODUCTION

The intergalactic medium (IGM) contains the bulk of the baryons in the universe (see, e.g., Fukugita, Hogan, & Peebles 1998). Determining the source and strength of the metagalactic ionizing radiation field and documenting its cosmic evolution are crucial to understanding the fundamental properties of the IGM at both low and high redshift. The two prime candidates for producing the background are QSOs and star-forming galaxies. While the contribution to the ionizing background from QSOs can be estimated with reasonable accuracy, considerably less is known about the contribution from galaxies. QSOs alone appear inadequate to produce the inferred background (see, e.g., Madau, Pozzetti, & Dickinson 1998; Steidel et al. 1999; Pettini et al. 2001). This approach generally assumes that $f_{\text{esc}} \approx 1$. However, the smaller-than-predicted equivalent widths of the Balmer emission lines in starbursts could imply that this assumption is suspect (see, e.g., Moy, Roca-Volmerange, & Fio 2001; Stasinska, Schaerer, & Leitherer 2001).

An H I column of only $1.6 \times 10^{17}$ cm$^{-2}$ produces $\tau = 1$ at the Lyman edge. Mean galactic gas columns are much larger, of course, ranging from $\sim 10^{21}$ cm$^{-2}$ in normal galactic disks to $10^{24}$ cm$^{-2}$ in nuclear starbursts (see, e.g., Kennicutt 1998). Starburst-like mean gas columns are inevitable in the Lyman break galaxies (Heckman 2000), given their high star formation rates per unit area (Meurer et al. 1997). The leakage of ionizing radiation out of galaxies must then be determined by the topology of the ISM. In such a case, theory gives us scant guidance, and so direct measurements of $f_{\text{esc}}$ are required.

Leitherer et al. (1995) reported the first direct measurements of $f_{\text{esc}}$ using the Hopkins Ultraviolet Telescope to observe far-ultraviolet (far-UV) light below the rest-frame...
Lyman edge in a sample of four local starbursts, and these data were later reanalyzed by Hurwitz, Jelinsky, & Dixon (1997). The resulting upper limits on $f_{\text{esc}}$ were typically 3% to 10%. In a very surprising development, Steidel, Pettini, & Adelberger (2001, hereafter SPA) have reported the detection of escaping Lyman continuum in the combined spectrum of 29 Lyman break galaxies at a mean redshift $\langle z \rangle = 3.4$. They estimate that the ratio of $f_{\text{esc}}$ at 900 and 1500 Å ranges from 0.5 to 1 in this composite spectrum (i.e., there is no definite detection of photoelectric opacity due to H I). Haehnelt et al. (2001) reach similar conclusions, but point out that star-forming galaxies at only slightly smaller redshifts cannot be this porous without violating constraints set by the observed He II-H I opacity ratio in the Ly$\alpha$ forest.

It is clearly important to obtain more determinations of $f_{\text{esc}}$ and to use these measurements to better understand the physical processes that determine $f_{\text{esc}}$. This latter goal can be best accomplished in the local universe, where detailed, multiwavelength observations of star-forming galaxies can be made. Unfortunately, direct observations of the emerging Lyman continuum require observing galaxies at redshifts greater than a few percent, so that the foreground H I opacity of the Milky Way is not significant at the relevant wavelengths (Leitherer et al. 1995; Hurwitz et al. 1997). Given the modest sensitivity of far-UV telescopes, this has limited such investigations to rather small (and possibly unrepresentative) galaxy samples.

Against this backdrop, we describe our analysis of new far-UV data obtained with FUSE for the UV-brightest local starbursts (§ 2). We point out that the strongest interstellar lines that trace the H I phase in these starbursts are black (or very nearly black) at line center. We show that this implies low values for $f_{\text{esc}}$ (§ 3). This not only more than doubles the sample of local starbursts with good upper limits on $f_{\text{esc}}$, it also illustrates a technique that can potentially be used on a much larger sample of galaxies. Indeed, similar arguments can be applied to high-redshift galaxies (§ 4) and show that $f_{\text{esc}}$ is also low in the bright star-forming galaxy MS 1512−CB58 at $z = 2.7$ (Pettini et al. 2000). We discuss these results and their implications in § 5.

2. OBSERVATIONS

2.1. The Sample

We are carrying out a program with the Far-Ultraviolet Spectroscopic Explorer (FUSE; Moos et al. 2000) to obtain spectra of the six starburst galaxies, from the Kinney et al. (1993) ultraviolet atlas of star-forming galaxies, having the largest UV flux at 1500 Å through the IUE 10° × 20° aperture ($F_{2} > 10^{-13}$ ergs cm$^{-2}$ s$^{-1}$ Å$^{-1}$). These targets span broad ranges in (1) metallicity, from 0.125 (NGC 1705) to 2.5 times solar (M83), (2) starburst bolometric luminosity, from $\sim 3 \times 10^{10}$ (NGC 1705) to $\sim 2 \times 10^{10}$ L$_{\odot}$ (NGC 3310), (3) internal dust reddening, from $A_V \sim 0.0$ (NGC 1705) to 0.6 (NGC 3310 and M83), and (4) host galaxy properties, including dwarfs (NGC 1705 and NGC 5253), irregulars (NGC 4214 and NGC 4449), and spirals (NGC 3310 and M83). The sample therefore spans most of the multidimensional parameter space of starbursts in the local universe (Heckman et al. 1998). The selection on the basis of rest-frame UV brightness makes this an appropriate sample to compare to the UV-selected Lyman break galaxies at high redshift.

2.2. Observational Details

The observations undertaken to date are summarized in Table 1. Data have been obtained for five of the six targets (only NGC 4449 has not yet been observed). Analyses of the dynamics of the ISM in individual galaxies based on these data are being reported elsewhere (Heckman et al. 2001, Martin et al. 2001, in preparation). The large aperture (LWRS; 30° × 30°) on FUSE was used for the observations of four of the five targets, while NGC 5253 was observed with the medium aperture (MDRS; 4° × 20°). The corresponding physical sizes of the projected aperture are kiloparsec-scale in all cases but NGC 5253 (Table 1).

The starburst was centered in the aperture of the LiF1 (guiding) channel for each observation by the standard guide-star acquisition procedure. For four targets, flux was recorded through the LWRS apertures in both long wavelength (LiF, $\sim 1000$–1187 Å) channels and both short wavelength (SiC, $\sim 900$–1100 Å) channels. We obtained no useful data in the SiC channels during our MDRS observations of NGC 5253 (A0460404) because of a loss of mirror alignment. We note that while the data do extend slightly below the wavelength of the starburst’s Lyman edge in the SiC1 channel, these data do not usefully constrain $f_{\text{esc}}$. This is because the opacity of foreground Galactic H I is still significant at these wavelengths, largely as a result of the influence of the high-order Lyman series absorption lines (Hurwitz et al. 1997).

Most of the data for this program were obtained at night, which minimizes O I and N I terrestrial airglow contamination in the spectra. The percentage of night to total exposure time averaged $\sim 65\%$, except for NGC 1705, for which the ratio was $\sim 92\%$.

### Table 1

| Galaxy     | $l$ (deg) | $b$ (deg) | $F_{1050\text{Å}}$ (ergs cm$^{-2}$ s$^{-1}$ Å$^{-1}$) | Data Set | Observation Date | $T_{\text{exp}}$ (ks) | Aperture$^b$ | $L^c$ (kpc) |
|------------|-----------|-----------|-----------------------------------------------|---------|-----------------|----------------------|------------|------------|
| NGC 1705   | 261.08    | -38.74    | $\sim 4.2 \times 10^{-13}$                    | A0460102 | 2000 Feb 04    | 7.7                   | LWRS       | 0.9 × 0.9  |
| NGC 3310   | 156.01    | +54.06    | $\sim 2.6 \times 10^{-13}$                    | A0460201 | 2000 May 05    | 27.1                  | LWRS       | 2.56 × 2.56|
| NGC 4214   | 160.25    | +78.08    | $\sim 1.6 \times 10^{-13}$                    | A0460303 | 2000 May 12    | 20.7                  | LWRS       | 0.50 × 0.50|
| M83        | 314.58    | +31.97    | $\sim 3.0 \times 10^{-13}$                    | A0460505 | 2000 Jul 06    | 26.5                  | LWRS       | 0.55 × 0.55|
| NGC 5253   | 314.86    | +30.11    | $\sim 8.9 \times 10^{-14}$                    | A0460404 | 2000 Aug 07    | 27.4                  | MDRS       | 0.40 × 0.08$^d$|

$^a$ On-target exposure time in the LiF1 channel.
$^b$ Aperture sizes: 4° × 20° for MDRS, 30° × 30° for LWRS.
$^c$ Physical size of projected FUSE aperture.
$^d$ Aperture position angle = 195°87. No useful SiC data were obtained for this MDRS observation.
The velocity resolution of the data depends on how the far-UV light illuminates the FUSE apertures. The resolution for a filled MDRS aperture (NGC 5253) or for a pointlike source in the LWRS aperture (NGC 1705) is \( \sim 30 \text{ km s}^{-1} \). We estimate a resolution of \( \leq 50 \text{ km s}^{-1} \) in NGC 3310, M83, and NGC 4214 based on the widths of the narrowest Galactic (foreground) absorption lines.

### 2.3. Data Processing

The raw time-tagged photon event lists for each exposure were processed with the standard FUSE calibration software (CALFUSE v. 1.8.5) available at Johns Hopkins University as of 1 January 2001. The lists were screened for valid data, and corrections for geometric distortions, spectral motions, and Doppler shifts were applied (see Sahnow et al. 2000). The individual calibrated and extracted spectra for each channel were cross-correlated, shifted to remove residual velocity offsets due to image motion in the apertures, and combined to produce a composite spectrum. These composite spectra in the 1000–1070 Å region were then compared, and any remaining velocity offsets were removed by referencing the Galactic absorption lines to the appropriate local standard of rest velocities.

Because we are interested in measuring the fluxes in the cores of saturated lines, accurate determinations of the residual fluxes are essential. We applied the standard detector background corrections available within CALFUSE for each observation. These corrections account only for the particle event backgrounds (\( \sim 0.75 \) counts cm\(^{-2}\) s\(^{-1}\)) and do not correct for scattered Ly\( \alpha \) emission or other stray light. These additional sources of background light are negligible in the LiF1 channel at the wavelengths of \( \sim 1040 \text{ Å} \) (typically \( < 5 \times 10^{-15} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1} \), or less than \( \sim 2\% \) of the continuum flux). A description of the FUSE backgrounds can be found in the FUSE Observer's Guide (Blair & Andersson 2001).

In the following discussion we consider data from the LiF1 channel, which has the highest signal-to-noise ratio (S/N) at the wavelengths of interest for this study (\( \lambda \sim 1020–1045 \text{ Å} \)). The data for the other channels are consistent with our findings presented below.

### 3. RESULTS FROM THE FUSE DATA

In Figure 1 we show the spectral region around the Ly\( \beta \), C II λ1036.337, and O I λ1039.230 absorption lines in the five galaxies in our sample. It is immediately apparent that the cores of the C II λ1036 and Lyman lines are quite black. The residual normalized intensities in the C II line are typically \( \leq 6\% \) (Table 2). These C II residual intensity estimates account for overlying Galactic absorption due to the Milky Way O vi λ1037.617 or H\(_2\) R(1) λ1037.149 and P(1) λ1038.157 lines. There are no H\(_2\) lines within the starbursts themselves that contribute to the depth of the C II line. We modeled the Galactic absorption features using the shorter wavelength member of the O vi doublet (λ1031.926) or other H\(_2\) R(1) and P(1) lines [typically P(1) λ1030.294, 1014.326 and R(1) λ1031.435] to obtain both the velocity extents and expected depths of the overlying lines. We note that the calculation of the residual intensity is also corrected for the effect of the maximum plausible stellar contribution to the C II line. Model starburst spectra (González Delgado, Leitherer, & Heckman 1997) show that the stellar photospheric line (which is entirely due to B stars) will depress the local continuum by a factor of \( \sim 1.2 \) to 2 (primarily depending on the age of the starburst). In our sample, the stellar contribution to C II should be largest in the B star-dominated spectrum of NGC 1705. Even in this case the C II line is primarily interstellar, because it (like the other interstellar lines) is blueshifted by roughly 40 km s\(^{-1}\) relative to the galaxy systemic velocity (Heckman et al. 2001; see also Heckman & Leitherer 1997).

The O I λ1039 line shows behavior ranging from a normalized residual intensity of about 15% in NGC 1705 to \( \leq 6\% \) in NGC 5253. Overlying Galactic absorption is not an issue for the O I at the resolution of the FUSE data. Both O I and C II arise in H I regions and contain direct information about the H I column density and areal covering factor of the neutral gas.

We begin by writing the ratio of the optical depth at the Lyman edge to the optical depth at line center. Following Spitzer (1977), this is

\[
\tau_{\text{Ly} / \tau_0} = 4 \times 10^{-16} (N_{\text{HI}} / N_\text{HI}) (b / \lambda) ,
\]

where \( (N_{\text{HI}} / N_\text{HI}) \) is the ratio of the H I and ground-state ionic columns, \( b \) is the normal Doppler parameter (in centimeters per second), \( f \) is the oscillator strength, and the wavelength \( \lambda \) is measured in centimeters. Assuming that O I and C II are the dominant ionic species of their respective elements in the H I phase, this can be written as

\[
\tau_{\text{Ly} / \tau_0} = RZ_{\text{gas}} (b / 100 \text{ km s}^{-1}) ,
\]

where \( Z_{\text{gas}} \) is the gas-phase C or O abundance in solar units, \( R = 8.6 \) for C II λ1036, and \( R = 50 \) for O I λ1039 (Morton 1991). The important point is that the optical depth at the Lyman edge is much larger than the optical depth at line center for both lines for typical values of \( Z_{\text{gas}} \) and \( b \). Corrections for grain depletion will only increase the implied ratio \( \tau_{\text{Ly} / \tau_0} \). Ionization corrections are unimportant for O I.

#### TABLE 2

| Galaxy       | \( \tau_{\text{sys}} \) (km s\(^{-1}\)) | \( f_{\text{esc}} \) (C II) (%) | Notes on \( f_{\text{esc}} \) and Nearby Absorption |
|--------------|----------------------------------------|-------------------------------|--------------------------------------------------|
| NGC 1705     | 569                                    | \( \leq 5.8 \)                 | Weak Galactic high-velocity O vi λ1037.617 in red wing of profile. No H\(_2\) absorption at nearby velocities. |
| NGC 3310     | 997                                    | \( \leq 6-30 \)                | Value of \( f_{\text{esc}} \) increases along redward wing of absorption. |
| NGC 4214     | 298                                    | \( \leq 4.0 \)                 | Weak Galactic H\(_2\) R(1) λ1037.149 on blue side of profile. |
| M83          | 517                                    | \( \leq 6.0 \)                 | Weak Galactic H\(_2\) P(1) λ1038.157 on red side of profile. Galactic O vi λ1031.926 on blue side of profile. |
| NGC 5253     | 405                                    | \( \leq 6.0 \)                 | Weak Galactic H\(_2\) P(1) λ1038.157 on red side of profile. Galactic O vi λ1031.926 on blue side of profile. |

This guide (v. 3.0) can be found on-line at http://fuse.pha.jhu.edu/support/guide/guide.html.
because it is closely coupled to H I through charge-exchange reactions and will only increase the implied ratio \( \tau_{Ly}/\tau_0 \) for C II.

As an example, consider the case of NGC 1705 (Heckman et al. 2001). Based on the nebular emission lines, the gas-phase oxygen abundance is 0.125 \( \times \) solar, and this is consistent with the abundances derived in the H I gas for Si, Ar, and Fe from the FUSE spectra. The measured \( b \)-value is 40 \( \pm \) 10 km s\(^{-1}\). The residual intensity at the core of the O I \( \lambda 1039 \) line implies \( \tau_0 = 1.8 \) (for unit covering factor, see below). Equation (2) above then implies that \( \tau_{Ly} = 280 \). This is roughly consistent with the H I column we derived from fitting the Lyman series lines: \( N_{HI} = 1.5 \times 10^{20} \) cm\(^{-2}\). Thus, in the context of a homogeneous absorbing slab, the escaping fraction of ionizing photons will be almost identically zero in NGC 1705. In principle, even more severe constraints on \( \tau_{Ly} \) can be placed using weaker absorption lines [transitions having smaller values of \( \langle N_f/N_{HI} \rangle f_k \)]. We do not take this approach, because even the strong O I \( \lambda 1039 \) line already implies \( f_{esc} \sim 0 \).

Less stringent (more realistic) constraints on \( f_{esc} \) can be placed by adopting a “picket fence” model in which the areal covering factor of optically thick H I is not unity (e.g., ionizing radiation can escape through “holes” in the H I). In this case, the upper limit on the residual intensity at the center of the C II \( \lambda 1036 \) line implies that the covering factor must be \( \geq 94\% \), so that the upper bound on the escape fraction for ionizing radiation is \( f_{esc} \leq 6\% \).

We have undertaken this analysis for the other four galaxies in our sample and report the results in Table 2. In all cases, the results are similar to those for NGC 1705, with implied values for \( f_{esc} \) that are almost identically zero (for

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**Fig. 1.**—FUSE spectra (LiF1A detector segment) of the spectral region containing the interstellar Ly\( \beta \), C II \( \lambda 1036 \), and O I \( \lambda 1039 \) absorption lines in five UV-selected local starbursts. The lines due to the foreground (Galactic) and starburst ISM are indicated, as is the fitted continuum (dashed line) to which the residual intensity at the line core is referenced. Note that the Ly\( \beta \) and C II \( \lambda 1036 \) lines are effectively black in the line core, while the less saturated O I \( \lambda 1039 \) line shows a range in residual intensity. Tick marks indicate the positions (or expected positions) of \( J = 0 \sim 3 \) H\(_2\) lines in the Milky Way (upper ticks) and the starbursts (lower ticks). All of the spectra shown are a combination of data taken during both orbital day and night.
the homogeneous slab model) and \( \lesssim 6\% \) for the picket fence model. The values listed in Table 2 should be considered stringent upper limits for the following reasons:

1. We list only the limits derived from the picket fence model.
2. We measured \( f_{\text{esc}} \) at velocities where the residual flux was greatest, after accounting for possible contamination by other absorption features.
3. Scattered light may contribute at low levels (\( \lesssim 2\% \)) and only serves to strengthen the limit on \( f_{\text{esc}} \).
4. The \( \text{FUSE} \) line spread function (LSF) likely consists of two components: a narrow component accounting for \( \sim 80\% \) of the LSF area and a broad component accounting for \( \sim 20\% \) and \( \sim 2-3 \) times as wide as the narrow component. While the exact details of the LSF are presently unknown, such a model describes the shapes of the cores of the Galactic H I lines toward nearby stars more accurately than a single-component LSF. As a result, it is possible that some of the observed flux in the line cores is simply redistributed light from nearby continuum regions within \( \sim 1 \) Å of the line.
5. The continuum estimates for the interstellar lines shown in Figure 1 are conservative estimates and are unlikely to be lower than those shown.
6. The upper limits on \( f_{\text{esc}} \) can be pushed to even smaller values by including the opacity due to dust (that is, our technique measures only the contribution of the photoelectric opacity of H I). Application of the empirical starburst dust attenuation law (Calzetti 1997; Meurer, Heckman, & Calzetti 1999) to the \( \text{IUE} \) spectra of these galaxies implies an extinction due to dust at 1500 Å ranging from negligible to their own ionizing radiation. This not only confirms the results of Leitherer et al. (1995) and Hurwitz et al. (1997). It is possible in these cases that spectra with higher spectral resolution and S/N would show that the lines are in fact nearly black over narrow ranges in velocity. However, the existing data are consistent with the conclusion of SPA that the escape fraction of ionizing radiation is large in these galaxies.

4. GALAXIES AT HIGH REDSHIFT

The technique described above can be applied to galaxies at high redshift. As an application, we consider the star-forming galaxy MS 1512 – CB58 at \( z = 2.7 \) (Yee et al. 1996). Thanks to strong gravitational lensing, its flux has been amplified by a factor of \( \sim 30 \) (Seitz et al. 1998). Thus, the rest-frame UV spectrum discussed by Pettini et al. (2000) is by far the best of its kind. We display the spectral region from Ly\( \alpha \) to C II \( \lambda 1335 \) in Figure 2. The quoted spectral resolution in these data is \( \sim 200 \) km s\(^{-1}\) FWHM, while the interstellar lines are much broader (500–700 km s\(^{-1}\)) and very deep. It is instructive to note that the value for \( \beta_{\text{L}} \) (eq. [1]) for the C II \( \lambda 1335 \) (O I \( \lambda 1302 \)) line is 0.1 (0.8) dex larger than that of the C II \( \lambda 1036 \) (O I \( \lambda 1039 \)) line in our \( \text{FUSE} \) spectra. Thus, the spectrum of MS 1512 – CB58 can be straightforwardly compared with that of the local starbursts.

The measured residual intensities in the line cores in the MS 1512 – CB58 spectrum are Ly\( \alpha \) (1\%), Si II \( \lambda 1260 \) (7\%), O I \( \lambda 1302 \) (6\%), and C II \( \lambda 1335 \) (2\%). To apply equations (1) and (2), we adopt a gas-phase metallicity of 0.25× solar (Pettini et al. 2000; Leitherer et al. 2001; Tremonti et al. 2001) and \( b = 300 \) km s\(^{-1}\), based on the line widths reported by Pettini et al. (2000). The implied optical depth at the Ly\( \alpha \) edge, assuming a uniform slab, is \( \tau_{\text{Ly}\alpha} \sim 300 \). Pettini et al. (2000) derive an H I column of \( 7.5 \times 10^{20} \) cm\(^{-2}\) from the damped Ly\( \alpha \) line, yielding an even larger value for \( \tau_{\text{Ly}\alpha} \) for a uniform slab. Alternatively, the residual intensity at the core of the C II \( \lambda 1335 \) line implies an areal covering factor of optically thick gas of 98\%. The implied value for \( f_{\text{esc}} \) ranges from \( \sim 0 \) to 2\%. These values are consistent with the results for the local starbursts in § 3.

The situation is quite different in the faint Lyman break galaxies at \( z \geq 3 \). As SPA point out, the interstellar lines in their composite spectrum are far from black (the apparent residual intensities are roughly 70\% at line center). The composite spectrum of Lyman break galaxies at \( \langle z \rangle = 3.0 \) in the Hubble Deep Field (HDF) is similar (Lowenthal et al. 1997). It is possible in these cases that spectra with higher spectral resolution and S/N would show that the lines are in fact nearly black over narrow ranges in velocity. However, the existing data are consistent with the conclusion of SPA that the escape fraction of ionizing radiation is large in these galaxies.

5. DISCUSSION

The results we have reported for five of the six UV-brightest local starbursts (NGC 1705, NGC 3310, NGC 4214, NGC 5253, and M83) imply that UV-bright starburst galaxies today are highly opaque to their own ionizing radiation. This agrees with results for a small sample of more distant starbursts described by Leitherer et al. (1995) and Hurwitz et al. (1997). These results, in turn, are consistent with the estimate by Shull et al. (1999) that the strength of the local metagalactic ionizing background implies that the fraction of ionizing photons that escape from star-forming galaxies cannot exceed a global average value of about 5\%.

These results are in striking contrast to the detection of significant escaping Lyman continuum radiation from Lyman break galaxies at \( z \sim 3 \) to 4 by SPA. Our analysis shows that the star-forming galaxy MS 1512 – CB58 at \( z = 2.7 \) is similar to the local starbursts: it too must be highly opaque below the Lyman break. Taking the current results at face value, we are left with a puzzle. Why is the...
topology/structure of the neutral interstellar medium apparently so different between the galaxies studied by SPA and those in the present paper?

In some ways this is a surprising result, because local starbursts and Lyman break galaxies are remarkably similar in most respects (see, e.g., Heckman 2000). Meurer et al. (1997) showed that both have the same bolometric surface brightnesses and therefore the same star formation rates per unit area. This implies that the basic physical properties of the ISM should be similar. The surface mass densities in the stars ($\Sigma_*$) and the interstellar gas ($\Sigma_g$) that fuels the star formation must be similar. The radiant energy density in the ISM must be similar ($\sim 10^4$ times higher than in the Milky Way), as must the rate of mechanical energy deposition (supernova heating) per unit area or volume. Simple considerations of hydrostatic equilibrium imply correspondingly high total pressures in the ISM in both: $P \sim G\Sigma\Sigma_\text{out}$, or $P/k \sim a$ few times $10^7$ K cm$^{-3}$. This is several thousand times the value in the local ISM in the Milky Way. Finally, the characteristic dynamical time in the ISM will be short in both cases: $t_\text{dyn} \sim (G\rho)^{-1/2} \sim (\Sigma_\text{out}\Sigma_g)^{-1/2} \sim a$ few Myr (where $H \sim 10^2$ pc is the thickness of the disk).

Perhaps the most striking difference is the size scale: starbursts in the local universe are generally circumnuclear events (sizes of $10^2$ to $10^3$ pc) imbedded in a much larger galaxy, while the intense star formation in the Lyman break galaxies appears to be a galaxywide event (sizes of $10^4$ to $10^4$ pc). This might lead to fundamental differences in the global properties of the ISM.

Such generic arguments aside, there is any empirical evidence that the structure or dynamics in the ISM in our specific sample of local starbursts differs from that of the Lyman break galaxies? We consider two possibilities.

First, our $\text{FUSE}$ sample galaxies have considerably lower luminosities (star formation rates) than the typical Lyman break galaxies: $L_{\text{bol}} \sim 8.5$ to $10.3 L_\odot$ versus $10.7$ to $11.7 L_\odot$ (Adelberger & Steidel 2000). It seems physically plausible that the ISM might become more porous in starbursts with higher star formation (and energy deposition) rates (Lehnert & Heckman 1996). We have tested this idea by considering data on $f_\text{esc}$ for more powerful local starbursts. Two of the four starbursts observed below the Lyman break by Leitherer et al. (1995) are powerful systems with $L_{\text{bol}} \sim 10^4$ to $10^5 L_\odot$. Both are opaque in the Lyman continuum: $f_\text{esc} \leq 2\%$ and $\leq 4\%$ for Mrk 496 and IRAS 08339 + 6517, respectively (Hurtwit et al. 1997). We have also searched the $\text{HST}$ archives for UV spectra of powerful local starbursts taken with a spectral resolution comparable to our $\text{FUSE}$ data and with a projected aperture size ($\sim$ kiloparsec scale) comparable to our $\text{FUSE}$ data. There are three such starbursts in the sample investigated by Kunth et al. (1998), who used the GHR2 echelle mode to observe the Lya, O I $\lambda 1302$, and Si II $\lambda 1304$ lines with a resolution of $\sim 20$ km s$^{-1}$. These starbursts have luminosities ($L_\odot$) of $L_{\text{bol}} \sim 10.4$ (ESO 400-G043), 11.0 (IRAS 08339 + 6517), and 11.2 (ESO 350-IG038). These interstellar lines are black in two cases (ESO 400-G043 and ESO 350-IG038) and have a residual intensity of 60% to 70% in the third case (IRAS 08339 + 6517). While a large value for $f_\text{esc}$ is therefore possible in this galaxy, direct observations below the Lyman break actually show that $f_\text{esc} \leq 4\%$ in this case (Hurwit et al. 1997).

A second possibility is that large values for $f_\text{esc}$ are created by supernova-driven galactic outflows (superwinds) that clear out channels through which ionizing radiation can escape (SPA). The tracers of superwinds in Lyman break galaxies are their blueshifted interstellar absorption lines (Franx et al. 1997; Pettini et al. 1998, 2000, 2001). Indeed, the composite spectrum of the 29 Lyman break galaxies analyzed by SPA shows the clear signature of these outflows: the interstellar absorption lines are blueshifted by 400 to 500 km s$^{-1}$ with respect to the Ly$\alpha$ emission line. This outflow signature is also seen in the composite spectrum formed from the sum of the spectra of 12 Lyman break galaxies in the HDF at $z \sim 3$ (Lowenthal et al. 1997; Franx et al. 1997). As noted above, the relative shallowness of the interstellar lines in both of these composite spectra is consistent with (but does not demand) a large value for $f_\text{esc}$.

Similar outflows are seen in the UV spectra of local starbursts (Kunth et al. 1998; González Delgado et al. 1998), and Heckman et al. (2000) have shown that high-velocity outflows of neutral gas are common in powerful ($L_{\text{bol}} \geq 10^{11} L_\odot$) local starbursts. In contrast, our $\text{FUSE}$ data reveal high-velocity ($\Delta v \geq 10^2$ km s$^{-1}$) outflows in the neutral phase of the ISM in only one of our five galaxies: NGC 3310, in which the mean outflow velocity is about $-200$ km s$^{-1}$ (see Fig. 1). In the other galaxies, the neutral-phase absorption lines arise in relatively quiescent gas near the galaxy systemic velocity (Fig. 1; Martin et al. 2001, in preparation; Heckman et al. 2001). Based on the ISM dynamics, it is perhaps not surprising that NGC 1705, NGC 4214, NGC 5253, and M83 are opaque to their Lyman continuum radiation.

On the other hand, González Delgado et al. (1998) have shown that outflows at several hundred kilometers per second are present in the neutral gas in at least three of the four starbursts observed below the Lyman break by Leitherer et al. (1995). In all cases, the galaxy is opaque below the Lyman break, with $f_\text{esc}$ typically $\leq 3\%$ to 10%. Of the three powerful starbursts observed by Kunth et al. (1998), two (ESO 400-G043 and ESO 350-IG038) show black interstellar lines and outflows at $(v - v_\text{sys}) = -225$ and $-58$ km s$^{-1}$, respectively. In the third (IRAS 08339 + 6517), the lines have a residual intensity of 60% to 70% and are strongly blueshifted by $\sim -500$ km s$^{-1}$ (González Delgado et al. 1998).

We conclude that the currently available data do not demonstrate that galactic winds inevitably produce large values of $f_\text{esc}$ in local starbursts. Such outflows appear to be a necessary—but not sufficient—part of the process that creates an ISM porous to ionizing radiation.

In the near future we will use $\text{FUSE}$ to observe a more powerful starbursts ($L_{\text{bol}} = 4 \times 10^{10}$ to $4 \times 10^{11} L_\odot$). This will allow us to probe the Lyman continuum opacity in more starbursts with luminosities (and star formation rates) similar to those of typical Lyman break galaxies. At the same time, the extension of the investigation at high redshift to a wider range of Lyman break galaxies can help clarify the situation. In particular, it will be important to test the high values for $f_\text{esc}$ by obtaining data on both the Balmer recombination lines and the Lyman continuum in the same set of galaxies (to provide a consistency check). Finally, the $\text{GALEX}$ mission (Martin et al. 1999) will directly measure the escaping flux below the Lyman break for the population of star-forming galaxies in the redshift range $z \sim 0.4$ to 2 (the epoch that apparently dominates the cosmic history of star formation). Thus, over the next few years, we should be able to make the first good, direct measurement of the contribution of star-forming galaxies to the
metagalactic ionizing background as a function of cosmic epoch. This will have important implications for the history of the IGM.

We thank the members of the FUSE team for providing this superb facility to the astronomical community. We thank Max Pettini for enlightening discussions, and for kindly providing us a copy of the composite Lyman break galaxy spectrum published by SPA. This work was supported in part by NASA grants NAG 5-6400 and NAG 5-9012. K. R. S. acknowledges support from NASA Long-Term Space Astrophysics grant NAG 5-3485.

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