1. INTRODUCTION

The complex interaction between gas and stars exists in all star-forming galaxies but can perhaps be most easily studied in the extreme conditions of starbursts. The high rate of star formation in these galaxies implies that the gravitational collapse of molecular clouds is proceeding at a pace much greater than that seen in normal galaxies. Once star formation has begun, the remaining gas is exposed to the destructive UV radiation field emitted by the most massive new stars. Illuminating the details of this relationship is a crucial step toward understanding the evolution of galaxies through time.

Molecular hydrogen is the fuel for star formation, so it is natural to expect large amounts of H$_2$ to exist in starburst regions. Indeed, millimeter-wave observations using CO as a tracer of H$_2$ imply the presence of $\sim 3 \times 10^8 M_\odot$ of molecular gas in the starburst region of M82 (Weiss et al. 2001). However, observations of some starbursts reveal little or no CO emission, such as NGC 1705 (Greve et al. 1996) and I Zw 18 (e.g., Gondhalekar et al. 1998). The lack of CO detections is difficult to interpret for metal-poor galaxies because the CO to H$_2$ conversion is metallicity dependent (Wilson 1995).

It is possible to study H$_2$ directly using far-UV spectroscopy. There are numerous transitions of molecular hydrogen in the far-UV, allowing the direct measurement of H$_2$ and eliminating the uncertainty caused by the conversion from CO. Furthermore, far-UV absorption studies can probe H$_2$ in column densities much lower than can be studied through CO line emission, making it possible to study H$_2$ in the diffuse interstellar medium (ISM). CO studies typically detect molecular gas with H$_2$ column densities in the range $10^{20} - 10^{23}$ cm$^{-2}$, while absorption studies have probed lines of sight in the Milky Way and Magellanic Clouds with H$_2$ column densities from $10^{14}$ to $10^{21}$ cm$^{-2}$ (Savage et al. 1977; Dixon et al. 1998; Tumlinson et al. 2002). However, unlike radio observations, far-UV measurements are profoundly affected by extinction. In particular, absorption measurements toward extended continuum sources with inhomogeneous extinction can be very difficult to interpret (e.g., Bluhm et al. 2003). Such observations must be treated carefully to derive correct conclusions about the H$_2$ content of galaxies.

Far-UV absorption studies have shown that H$_2$ is common in the diffuse ISM when the shielding along the sight line is sufficient to prevent dissociation by the interstellar UV radiation field. In the Milky Way, the transition occurs at $E(B-V) \sim 0.08$, and sight lines with at least this much reddening almost always contain H$_2$ (Savage et al. 1977). Investigation of the relationship between $N$(H$_2$) and $E(B-V)$ in environments that differ from the Milky Way, such as the intense radiation...
environment of starbursts, can shed light on the formation and destruction mechanisms for H$_2$ and dust. Previous FUSE investigations of H$_2$ absorption in metal-poor starbursts have set low upper limits on the amount of H$_2$ in the diffuse ISM (Vidal-Madjar et al. 2000; Thuan et al. 2002; Aloisi et al. 2003), and since these galaxies have not been detected in CO it is possible that they contain very little H$_2$ in denser environments as well. It is not clear whether the low metal content or the starburst radiation environment is responsible for the lack of H$_2$. To fully understand the behavior of H$_2$ in the diffuse ISM of starbursts, the sample must be extended to galaxies with higher metal content and to those in which CO emission has been detected.

We have used FUSE (Moos et al. 2000) to search for H$_2$ absorption in five starburst galaxies: NGC 1705, NGC 3310, NGC 4214, M83 (NGC 5236), and NGC 5253. The properties of these galaxies are given in Table 1. Four of these galaxies have been detected in CO emission, while NGC 1705 has not. The FUSE observations use the OB stars in the starburst as the UV continuum source and probe absorption by gas in front of the starburst. The FUSE spectra show surprisingly little absorption from H$_2$ in the diffuse ISM, which may be a result of observational selection effects but may also indicate that the H$_2$ is destroyed in starbursts.

2. OBSERVATIONS AND DATA REDUCTION

A log of the FUSE observations is given in Table 2, and more information can be found in Heckman et al. (2001a). The FUSE mission and instrument are described by Moos et al. (2000) and Sahnow et al. (2000). The spectra were obtained through the LWRS (30'' × 30'') apertures except for NGC 5253, which was observed through the MDRS (4'' × 20'') apertures. Figures 1–5 show the location of the FUSE apertures for each galaxy.

The raw spectra were processed through the FUSE calibration pipeline (CALFUSE, ver. 2.1.6) at the Johns Hopkins University. The pipeline screens data for passage through the South Atlantic Anomaly and low Earth limb angle pointings and corrects for thermal drift of the gratings, thermally induced changes in the detector readout circuitry, and Doppler shifts due to the orbital motion of the satellite. Finally, the pipeline subtracts a constant detector background and applies wavelength and flux calibration. After the pipeline reduction the individual spectra were co-added to produce the final calibrated spectrum.

FUSE consists of four co-aligned optical channels, two optimized for longer wavelength (LiF1 and LiF2; 1000–1187 Å) and two optimized for shorter wavelengths (SiC1 and SiC2; 905–1100 Å). The data from the four channels were analyzed separately, because there are slight differences in the spectral resolution between channels that can cause problems if the channels are co-added. Treating the channels separately also provides a safeguard against detector defects. The velocity zero point of each channel was found using strong Galactic absorption lines.

3. NOTES ON THE INDIVIDUAL GALAXIES

Several of the starbursts are essentially point sources in the far-UV, and the interpretation of their spectra is fairly simple. Others, however, are extended far-UV sources with varying extinction. In these sources the morphology and extinction must be taken into account to understand the information in the FUSE spectra. In this section we describe the far-UV
morphology of each galaxy and how it may affect the results. We also review previous results of CO emission measurements to contrast them with the UV absorption measurements presented in § 4.

NGC 1705.—The strongest far-UV source in NGC 1705 is the central star cluster NGC 1705-1, although there is a significant contribution from other far-UV sources (Meurer et al. 1995). The galaxy is small enough that the entire UV-emitting region fits within the FUSE LWRS aperture. Figure 1 shows an archival Hubble Space Telescope (HST) WFPC2 U-band (F380W) image and an archival Faint Object Camera (FOC) image (F220W). The bright pointlike nature of NGC 1705-1 is illustrated by the point-spread function apparent in the pre-costar FOC image. NGC 1705 is metal-poor (Meurer et al. 1992; Storchi-Bergmann et al. 1994; Heckman et al. 1998, 2001b) and has not been detected in CO (Greve et al. 1996).

NGC 3310.—Figure 2 shows an Ultraviolet Imaging Telescope (UIT) far-UV (B1 filter: 1520 Å) image of NGC 3310 and an FOC near-UV image (F220W) of the central region. The image shows that most of the star-forming regions in this galaxy fit within the LWRS aperture. A UV-bright core is surrounded by a star-forming ring. Conselice et al. (2000) showed that the nucleus is actually quite red compared with the ring, indicating that it is either very dusty or is dominated by older stars. Using the UIT image shown in Figure 2, Smith et al. (1996) concluded that the nucleus is heavily extinguished in the far-UV and that the starburst ring is the strongest far-UV source. The far-UV light in the FUSE spectrum is a composite of all these star-forming regions, but it is weighted toward the bluer regions in the ring and the UV-bright knot in the southwest (known as the “jumbo” H II region; Balick & Heckman 1981). There is molecular gas traced by CO in this knot, but the highest

Fig. 1.—UV images of NGC 1705. Left: Archival WFPC2 U-band (F380W) image. This image is approximately 21″ × 17″, so everything in the image falls within the LWRS aperture. Right: Archival FOC near-UV (F220W) image. The galaxy is essentially a point source in the UV, so the pre-costar point-spread function of HST is apparent. North is up, and east is left in both images.

Fig. 2.—UV images of NGC 3310. Left: UIT 1520 Å (B1) image (Smith et al. 1996), showing the location of the FUSE 30″ × 30″ LWRS aperture. Right: Archival FOC near-UV (F220W) image of the starburst region. The image is approximately 28″ × 24″. The LWRS aperture is centered south of the nucleus, at approximately the position of the star-forming ring. North is up, and east is left in both images.
concentration of CO is in the northwest part of the ring (Kikumoto et al. 1993). Mulder et al. (1995) found $10^8 M_\odot$ of H$_2$, most of which is located within the region probed by the FUSE pointing.

**NGC 4214.**—Figure 3 (left) is a UIT far-UV image of NGC 4214, with the FUSE LWRS aperture located on the central starburst (NGC 4214-I). Figure 3 (right) shows an archival WFPC2 far-UV (F170W) image of the central region. The strongest far-UV emission comes from NGC 4214-I, so the FUSE spectrum is essentially a spectrum of this cluster. This source lies in an extended component of diffuse CO emission, containing $8 \times 10^5 M_\odot$ of H$_2$ (Walter et al. 2001), and is in a “hole” in the H$_2$ emission (Leitherer et al. 1996).

**M83 (NGC 5236).**—Figure 4 (left) is a UIT far-UV (1520 Å) image of M83, with the FUSE LWRS aperture located on the central starburst. Figure 4 (right) shows an archival WFPC2 U-band (F300W) image of the central region. Harris et al. (2001) used this image to show that the central region contains at least 39 star clusters less than 10 Myr old. These clusters should have strong far-UV emission, so the FUSE spectrum is a combination of many individual sight lines. Israel & Baas (2001) found that the central region (roughly coincident with the LWRS aperture) contains $10^7 M_\odot$ of H$_2$ from observations of CO emission.

**NGC 5253.**—This is the only galaxy for which the MDRS aperture was used. Figure 5 shows the placement of the aperture on a UIT far-UV image and an archival WFPC2 far-UV image. The region observed includes the brightest cluster in the far-UV (Meurer et al. 1995), but no other regions of significant star formation. Meier et al. (2002) found that this
region contains \( \sim 10^5 M_\odot \) of H\(_2\) from observations of CO emission. Soft X-ray emission is associated with the cluster, suggesting the presence of a superbubble (Strickland & Stevens 1999).

4. COLUMN DENSITY MEASUREMENTS

4.1. Molecular Hydrogen

Absorption profiles for each galaxy are shown in Figure 6. Each panel in the figure shows the Si ii \( \lambda 1020.699 \) absorption profile (which traces the neutral ISM), as well as one H\(_2\) absorption profile for each rotation level from \( J = 0 \) to 4 (except for NGC 3310, for which no suitable \( J = 4 \) line was found). The lines shown were chosen because they are the strongest lines that are not blended with any other absorption, either intrinsic or Galactic. Absorption from H\(_2\) is visible only in the \( J = 1 \) and 2 levels in NGC 5253 and in the \( J = 1 \) level of M83. The NGC 5253 detections in the LiF1 spectrum are both \( \sim 3 \sigma \) or better, but the absorption is not obvious in the less sensitive LiF2 channel, so the detections in LiF1 are tentative. There is also a possible detection in the \( J = 3 \) level for NGC 5253, but this would be at less than 2 \( \sigma \) significance and is not confirmed in the LiF2 spectrum, so we do not count it as a detection. The M83 \( J = 1 \) detection is only 1.7 \( \sigma \) in LiF1, but it is confirmed in the LiF2 spectrum, so we count it as a detection. For all the other galaxies we measured only upper limits.

For the galaxies in which we detected H\(_2\) absorption, we measured the equivalent widths of the strongest lines and transformed these to H\(_2\) column densities, assuming that the absorption is optically thin. For the other galaxies we measured the noise in the spectrum at the expected location of H\(_2\) absorption and used this to compute 3 \( \sigma \) upper limits on the amount of H\(_2\) present. All measurements were made on the LiF1 spectrum because it is the most sensitive. The measured equivalent widths of the strongest lines and the derived H\(_2\) column densities or upper limits are given in Table 3. A model H\(_2\) spectrum was created using the column densities for each \( J \) level listed in Table 3 and assuming a Doppler broadening parameter of \( b = 15 \) km s\(^{-1}\). The model is shown as the smooth line in Figure 6.

The upper limits on the total H\(_2\) column density are also shown in Table 3. These were derived by simply summing the measured upper limits (or detections) in the \( J = 0 \)–4 levels. In typical Milky Way ISM conditions most (>90\%) of the H\(_2\) is in the \( J = 0 \) and 1 states (e.g., Snow et al. 2000; Friedman et al. 2000; Sembach et al. 2001). If this is true in the starbursts as well, the upper \( J \) levels should not contribute much to the total H\(_2\) column density. However, since the conditions in the ISM of the starbursts may be different (e.g., the potentially stronger UV radiation field could populate the higher \( J \) levels), summing all five levels may be appropriate.

Table 4 lists an estimate of the upper limits on the mass of H\(_2\) detectable by FUSE within the aperture. It is important to note that this does not correspond to the total H\(_2\) mass in the aperture, because the majority of the molecular gas is too dense to be detected by FUSE (see § 5.1). To determine this limit, we first applied the measured column density upper limit to the entire aperture, or in other words we assumed that the entire aperture is filled with H\(_2\) at the column density listed in Table 3. The angular area of the aperture was converted to physical area at the assumed distance of the galaxy (see Table 1) and multiplied by the column density limit. As we discuss in detail below, these upper limits need to be treated carefully, given the strong bias in these far-UV spectra against the dustiest lines of sight.

The upper limits in Table 3 do not account for the possible presence of unresolved, saturated absorption. Cold H\(_2\) clouds with \( T = 100 \) K may have Doppler \( b \)-values \( \leq 1 \) km s\(^{-1}\). A saturated absorption line with a \( b \)-value of 1 km s\(^{-1}\) would have an equivalent width EW \( \leq 10 \) mA. Such a line could easily go undetected in the FUSE data presented here, given the typical upper limits listed in Table 3. Typical \( b \)-values measured for H\(_2\) in the Milky Way and Magellanic Clouds are much broader than this, ranging from 2.3 to 20 km s\(^{-1}\) (see Shull et al. 2000; Tumlinson et al. 2002). This broadening is most likely due to bulk motions within individual clouds and the velocity dispersion of the ensemble of clouds. If \( b = 3 \) km s\(^{-1}\), EW \( \sim 17 \) mA, which would result in a 2 \( \sigma \) detection in most cases. If unresolved, saturated absorption is present it would result in the underestimation of the upper limits on the H\(_2\) column density.

4.2. Atomic Hydrogen

Table 4 shows an estimate of (or lower limit on) the H i column density in the FUSE aperture. The H i column was
estimated in different ways for each galaxy. Heckman et al. (2001b) derived the H I abundance in NGC 1705 by fitting the Ly/\text{C}12 and higher order H I lines in the FUSE spectrum. For NGC 3310, NGC 4124, and NGC 5253 we measured the equivalent width of the Ar i k 1066.660 line and converted this to a column density by assuming that the line is optically thin. The Ar i column density was converted to H I by assuming the relative warm neutral medium abundances given by Sembach et al. (2000) and scaling down by the O/H value given in Table 1. This line was used because dust depletion is not important for Ar i (e.g., Aloisi et al. 2003). It is also a relatively weak line, so while the assumption that it is optically thin is likely invalid for most of these galaxies, it gives a better lower limit to the column density than would a stronger line. However, there can be a significant ionization correction for Ar i, and furthermore, the O/H values in H ii regions (used here) are usually higher than those in the neutral ISM (see, e.g., Thuan et al. 2002; Aloisi et al. 2003). Thus, this approach gives a conservative lower limit to \(N(\text{H I})\) for most of these sight lines. The Ar i line was not detected in the FUSE spectrum of M83, so we measured the O i 950.885 Å line and converted this to H I using the O/H value given in Table 1. This value is almost identical to the upper limit on \(N(\text{H I})\) derived from the nondetection of the Ar i line, so we treat it as an estimate of the H I column density probed by the FUSE spectrum, not a lower limit. As we show in § 5.2, there are indications that the H I column densities are actually much larger than the conservative limits derived above.

Column (3) in Table 4 lists the molecular hydrogen fractions \(f(\text{H}_2)\) for the diffuse ISM in each galaxy, defined as

\[
f(\text{H}_2) = \frac{2N(\text{H}_2)}{2N(\text{H}_2) + N(\text{H I})}.
\]

Since \(N(\text{H}_2)\) is an upper limit and \(N(\text{H I})\) is a lower limit (for three of the galaxies), this expression gives an upper limit to \(f(\text{H}_2)\). The fact that we are almost certainly underestimating \(N(\text{H I})\) implies that the true values of \(f(\text{H}_2)\) could be as low as

![Interstellar absorption line profiles from the FUSE spectra of the five starburst galaxies, showing the observed spectrum (histogram) and a model H2 spectrum based on the column densities listed in Table 3 (smooth line). For each galaxy we show the Si ii 1020.690 Å profile and the expected locations of H2 lines from rotational levels \(J = 0–4\) (except NGC 3310, for which no suitable \(J = 4\) line was found). Two channels are shown for each line, although the measurements were made on the channel with the highest signal-to-noise ratio (LiF1). The velocity scale has been set so that absorption intrinsic to the galaxy falls at 0 km s\(^{-1}\), using the velocities listed in Table 1.](image-url)
and perhaps even lower if \( N(\text{H}_2) \) is much below the upper limits in Table 3. However, it is important to note that this upper limit applies to the integrated light in the \textit{FUSE} aperture and that there certainly are regions within the aperture, such as the molecular clouds seen in CO emission, in which the molecular fraction is higher.

### 5. DISCUSSION

#### 5.1. \textit{H}_2 \textit{in the Dense ISM}

The \textit{FUSE} spectra show very little absorption from \textit{H}_2 in the starburst regions of these galaxies, with the upper limits on \textit{H}_2 masses ranging from \( \sim 31 \) to less than \( 1 \, M_\odot \) (see Table 4). Similar results were found in \textit{FUSE} data for the metal-poor starburst galaxy I Zw 18 (Vidal-Madjar et al. 2000; Aloisi et al. 2003) and for the blue compact dwarf galaxy Mrk 59 (Thuan et al. 2002). This is in stark contrast with CO observations of starbursts, which often reveal large concentrations of molecular gas in the starburst region. Published CO studies of four of the five starbursts in our sample have found many orders of magnitude more \textit{H}_2 in these galaxies than the \textit{FUSE} measurements imply (see Table 4; § 3).

The explanation for the difference between the emission and absorption results is that the absorption spectra are not sensitive to the dense clouds seen in CO emission. The combined effects of extinction and the fact that the continuum source is extended biases the far-UV observations toward the least dusty environments, because dust quickly extinguishes the far-UV light in other regions (see, e.g., Bluhm et al. 2003). Since the most efficient formation mechanism for \textit{H}_2 is formation on dust grains (Hollenbach & Salpeter 1971), molecular gas is likely concentrated in the dustiest regions. Dense molecular
clouds have many magnitudes of extinction in the far-UV, rendering them opaque to the background continuum light. Since large amounts of CO are detected in these galaxies, the lack of H$_2$ seen in absorption implies that most of the molecular gas is in the form of dense clouds. The continuum that is visible in the FUSE spectra passes through the diffuse ISM between the clouds. Since the FUSE spectra detect far-UV continuum from these starbursts, the covering factor of the dense molecular clouds in front of the UV continuum source must be less than 1.

Although it is tempting to consider the metallicity dependence of the CO–H$_2$ conversion factor to be the cause of the discrepancy between the emission and absorption results, the magnitude of this effect is not nearly large enough to account for the observed difference. Wilson (1995) found a factor of 4.6 increase in the conversion factor for a factor of 10 decrease in metallicity. The metallicity range of the sample is within a factor of 10 from solar abundances, so the discrepancy between the FUSE and CO measurements is therefore much too large to be caused by metallicity. Furthermore, metal-poor galaxies such as NGC 5253 should have more H$_2$ than the CO measurements imply, which is the opposite of that which we observe.

5.2. H$_2$ in the Diffuse ISM

Sight lines with diffuse H$_2$ column densities ranging from $10^{14}$ to $10^{21}$ cm$^{-2}$ are ubiquitous in the Milky Way and Magellanic Clouds (Savage et al. 1977; Shull et al. 2000; Tumlinson et al. 2002). Indeed, it is difficult to find a sight line that extends more than ~1 kpc that does not show absorption from H$_2$. Absorption from H$_2$ has also been detected in FUSE spectra of H ii regions in M33 (Bluhm et al. 2003). It is thus surprising to see so little H$_2$ absorption in the starburst spectra. In this section we discuss how observational biases may explain the results but also give evidence that the lack of H$_2$ absorption in the FUSE spectra points to a real difference in the diffuse ISM in starbursts.

5.2.1. Observational Selection Effects

It is possible that the biases discussed in § 4 also prevent us from detecting H$_2$ in the diffuse ISM. Simply put, if the spatially extended continuum source (the starburst) is thought of as many individual sight lines within the aperture, then those sight lines with the least extinction (and therefore the lowest H$_2$ column density) contribute most to the composite continuum.
suggests that there is a deficiency of H$_2$ outside dense clouds in sight lines in Figure 7 may be even more pronounced. Figure 7 Thus, the difference between the starbursts and the Milky Way values are correct and a Milky Way gas/dust ratio is assumed. (1977) as possibly having strong radiation fields. probably underestimation of the H$_2$ column densities and molecular fractions in the starbursts are lower than those of the Galactic sight lines for similar red- denominings (except for NGC 1705). Note that the molecular fractions for the starbursts are probably much lower than the derived upper limits due to the uncertainty in the amount of H i along the sight lines, the reddening values, measured in the UV, are well within the range of H$_2$-bearing sight lines in the Milky Way. Note that the molecular fractions (f) for the starbursts are probably much lower than the derived upper limits if the measured $E(B-V)$ values are correct and a Milky Way gas/dust ratio is assumed. Thus, the difference between the starbursts and the Milky Way sight lines in Figure 7 may be even more pronounced. Figure 7 suggests that there is a deficiency of H$_2$ outside dense clouds in starbursts compared with the Milky Way.

This interpretation is consistent with the lower limits on $N$(H i) and the measured $E(B-V)$. Indeed, if there is a Milky Way H$_2$ abundance in the starbursts, there must be a difference between the $E(B-V)$ values in the IUE and FUSE bands. It is possible to envision scenarios in which the actual extinction at 1000 Å is smaller than that measured in the 1200–1800 Å spectral range of IUE, since the rise in the extinction curve causes the most reddened sight lines to contribute proportionally less to the total flux at shorter wavelengths. However, a comparison of the entire HUT spectrum with reddened model starburst spectral energy distributions (SEDs) shows a very good match even in the 1000–1200 Å FUSE range (see Fig. 8), which would not be the case if the spectrum at 1000 Å were preferentially unreddened compared with the longer wavelength data. The generic SEDs in Figure 8 match the data very well even though we did not attempt to match the models to the metallicity or stellar content of the galaxies. This strongly suggests that there is still substantial reddening at 1000 Å, with $E(B-V) = 0.1–0.3$.

Another factor to take into account is the possibility that there is a significant amount of ionized gas along the sight lines. Heckman et al. (2001b) showed that this is true for NGC 1705. Figure 6 shows that the Si ii absorption in M83 is much weaker than in the other galaxies (except NGC 1705), implying a lower column of neutral gas. The $N$(H i) measurement is only $\sim 10^{19}$ cm$^{-2}$, 2 orders of magnitude smaller than the H i column implied by the reddening. The discrepancy between the reddening and the neutral gas column may indicate that most of the hydrogen in the diffuse ISM along the sight line is ionized. Studies of sight lines in the Galaxy have shown that the dust content of the ionized ISM is similar to that in the neutral gas (Howk & Savage 1999).

If extinction limited the FUSE spectra to only a few nearly unreddened sight lines, the continuum would contain the light of a small number of stars, and they would perhaps probe only the outer edge of the galaxy. This is ruled out by the spectra themselves. The stellar features seen in the far-UV continuum in all cases are dominated by light from a very young population of O and B stars (e.g., Leitherer et al. 2002; Robert et al. 2003; C. Leitherer et al. 2004, in preparation), and the UV fluxes imply the presence of $\sim 10^{10}$ such sources (or more if they are reddened). Furthermore, the kinematic signature of the starburst outflow is also clearly evident in the O vi lines (Heckman et al. 2001a, 2001b), which indicates that the continuum source is the starburst, rather than just a few OB stars in the outer halos of the galaxies.

To summarize, the upper limits on $N$(H$_2$) derived from the FUSE starburst spectra are consistent with the Savage et al. (1977) Milky Way relationship between $N$(H$_2$) and $N$(H i) in the diffuse ISM. They cannot rule out, however, a deficiency of $N$(H$_2$) compared with Milky Way sight lines with similar amounts of reddening in four of the galaxies. Indeed, when the IUE- and HUT-measured reddening is included in the analysis, the data point to such a deficiency. However, given the differences in the IUE, HUT, and FUSE apertures and the possibility of differences in the reddening measured at FUSE versus IUE wavelengths, the present data cannot definitively rule out a Milky Way H$_2$ abundance in the diffuse ISM of these starbursts.

5.3. Formation and Destruction of H$_2$

If the suggested lack of H$_2$ in the diffuse ISM of starbursts is real, there are implications for H$_2$ formation and destruction mechanisms. Low column densities of H$_2$ in the diffuse ISM could be caused by either inhibited formation or rapid destruction of H$_2$. Tumlinson et al. (2002) and Browning et al. (2003) calculated the effects of a stronger radiation field and a lower H$_2$ formation rate on f(H$_2$). To reproduce such low f(H$_2$) values at the observed H i column densities requires a radiation field at least 50 times stronger than the Galactic mean UV
radiation field, or a formation rate less than 1/10 that of the Milky Way, or a combination of both effects (see Fig. 4 in Browning et al. 2003).

Inhibited formation is an attractive scenario in metal-poor galaxies because of the deficiency of dust grains on which to form molecules. While the most efficient mechanism for H$_2$ formation is on the surfaces of dust grains (Hollenbach & Salpeter 1971), other mechanisms have been proposed to occur in the absence of dust (Jenkins & Peimbert 1997). However, the fact that the FUSE spectra show no H$_2$ absorption in galaxies where H$_2$ is known to exist indicates that the H$_2$ is associated with dust. This suggests that formation on the surface of grains is the dominant mechanism in these galaxies.

Vidal-Madjar et al. (2000) and Aloisi et al. (2003) used FUSE to search for H$_2$ absorption in I Zw 18, and Thuan et al. (2002) did the same for Mrk 59. These are both metal-poor galaxies undergoing star formation. They set low upper limits on the abundance of H$_2$ in the diffuse ISM, similar to those we find for our sample of starbursts. Because I Zw 18 and Mrk 59 have not been detected in CO, it is not known whether these galaxies contain any H$_2$, even in the form of dense clouds. Thus, it was not clear to what extent their low metallicity inhibited the formation of molecular gas. Our sample spans a wide range of metallicity, and the CO detections in most of the galaxies in our sample establish that large amounts of molecular gas have formed. This suggests that inhibited formation is not the only factor leading to the low H$_2$ content in the diffuse ISM. Furthermore, M83 and NGC 3310 have high metal abundances and are very bright far-infrared (FIR) sources (Calzetti et al. 1995), indicating the presence of dust. Yet we still detect very little H$_2$ outside dense molecular clouds, ruling out metallicity as the culprit for those galaxies at least.

The remaining scenario then is rapid destruction. In this scenario molecules of H$_2$ that evaporate from the surface of dense clouds are photodissociated by UV radiation (Stecher & Williams 1967). The intense UV radiation fields of starburst galaxies may create an environment where the destruction of H$_2$ would be enhanced. Browning et al. (2003) modeled the formation and destruction of H$_2$ in the Milky Way and Magellanic Clouds. They assume $I = 1 \times 10^{50}$ photons cm$^{-2}$ s$^{-1}$ Hz$^{-1}$ for the Galactic radiation field, which corresponds to a surface brightness of $1.1 \times 10^{-18}$ ergs cm$^{-2}$ s$^{-1}$ A$^{-1}$ arcsec$^{-2}$ at 1000 Å. Table 4 lists the surface brightness at 1000 Å for each galaxy, measured from the FUSE spectra by dividing the flux by the angular area of the aperture. All are more than 100 times stronger than the Galactic radiation field, before correcting for extinction. This is an average across the aperture, and since the aperture is not uniformly filled with UV continuum, the

![Figure 8](image_url)

**Fig. 8.**—HUT spectra of the four most reddened galaxies in our sample (NGC 1705 is excluded). The FUSE spectra are also shown as gray lines. The dotted line in each panel shows the SED of a 100 Myr continuous star formation model from Starburst99 (Leitherer et al. 1999). The dashed line shows the same SED reddened using the starburst extinction law as given in Leitherer et al. (2002). The reddening values applied were chosen to give the best fit (by eye) to the observed HUT spectra, and the resulting $E(B - V)$ values are all within ±0.1 of those listed in Table 1. The models match the data reasonably well, even near 1000 Å, at which the H$_2$ measurements were made. In some of the panels the attenuation at 1000 Å is underestimated, implying that there is more dust/gas along the sight line than the reddening values in Table 1 would indicate. This figure illustrates that the observed spectra are consistent with $E(B - V)$ values of at least 0.1–0.3 at 1000 Å and are not consistent with zero reddening.
radiation field is undoubtedly stronger at some locations. According to the Browning et al. (2003) models, this is more than enough to produce the low f(H2) values seen in these galaxies, even if there is no reduction in the formation rate. In addition to the effects of UV radiation, the multiple supernovae that have occurred in these galaxies produce fast shocks in the ISM, which can also enhance the dissociation of molecular gas. In such a harsh environment it would not be surprising to find that there is too little H2 in the diffuse ISM to detect. It is interesting to note that the three highly reddened Galactic sight lines marked as double circles in Figure 7 (θ1 Ori C, 29 CMa, and 30 CMa) were noted by Savage et al. (1977) for their abnormally low H2 column densities, possibly due to an unusually strong dissociating radiation field. These sight lines lie closest to the starbursts in the figure.

5.4. Dust in the Diffuse ISM

We have given arguments that there is very little H2 in the diffuse ISM of these starbursts. We have also shown that the UV radiation field in these galaxies is strong enough to destroy H2 in the diffuse ISM. However, as previously discussed, UV spectroscopy has shown that there is substantial reddening of the UV continuum, indicating the presence of dust in the diffuse ISM of these galaxies (except perhaps for NGC 1705, which is nearly unreddened). Thus, the molecular gas and dust may have different distributions in these galaxies: H2 is confined to dense clumps that are highly optically thick to the far-UV continuum, and it is absent in the diffuse ISM. However, dust grains exist in both dense and diffuse environments. If the starbursts are deficient in diffuse H2, the mechanism that dissociates H2 (UV radiation field, shocks, or both) apparently is not strong enough to destroy all the dust.

These arguments also support the idea that the covering factor of the dense clumps in front of the UV continuum source is small. Meurer et al. (1999) found an empirical relation between the spectral slope β and the ratio of FIR to UV fluxes such that galaxies with strong FIR flux relative to UV flux have shallower (redder) UV spectra. The FIR excess can be attributed to dust extinction in the UV, so their conclusion was that starbursts with high extinction are also reddened. This relationship can exist only if the covering factor of dense clumps is small, because these clumps produce FIR flux but do not redden the UV spectrum since they are opaque to UV continuum. The picture based on theoretical modeling of the Meurer et al. (1999) result by Witt & Gordon (2000), Charlot & Fall (2000), and others (see Calzetti 2001 for a recent review) is that the strong correlation between the UV color and the ratio of far-IR to UV flux can be understood only in the context of an inhomogeneous dusty medium lying in the foreground between the UV sources and observer. Our results imply that this medium (which is translucent to far-UV photons) contains substantial amounts of dust but not molecular gas.

NGC 1705 is an interesting case: its UV spectral slope is close to that of an unreddened young stellar population (Meurer et al. 1999), and, unlike the other galaxies in our sample, it is not a strong far-IR source (Calzetti et al. 1995). These facts suggest that it contains less dust than the other starbursts in the sample, similar to I Zw 18 and Mrk 59. However, we cannot yet say that these galaxies are devoid of molecular gas. Cannon et al. (2002) used narrowband imaging to map the dust content of I Zw 18. The dust mass is consistent with the low metallicity and low FIR emission, and the morphology is very clumpy. If the dense H2 is traced by dust, this clumpiness would explain the nondetection with FUSE. It seems likely that there is molecular gas in I Zw 18, even though it has not been detected in CO emission (perhaps because of low metallicity) or H2 absorption (because of the clumpy morphology). The same may hold true for NGC 1705 and Mrk 59.

5.5. Further Implications

Rigopoulou et al. (2002) carried out a survey of pure rotational emission from H2 in starbursts (including M83 and NGC 5253) using the Infrared Space Observatory. This emission traces warmer H2 (T ~ 150 K) than that typically seen in CO emission (T ≤ 100 K). At least some of the warm gas is thought to be in the photodissociation regions at the surfaces of cold clouds, although there is also evidence for an extended warm component (Valentijn & van der Werf 1999). The survey found that the warm H2 makes up 15–10% of the total H2 content derived from CO observations. This is still much higher than the limits on H2 in the diffuse ISM set with the FUSE spectra. Either the column density of an extended warm component is high enough that it is opaque to far-UV light, or the bulk of the warm gas is associated with the dense clouds of cold H2, suggesting perhaps that it is in photodissociation regions.

The low limits on f(H2) found for these starbursts are reminiscent of the measured values or upper limits measured in damped Lyc systems (DLAs) in QSO spectra (see, e.g., Levshakov et al. 2002 and references therein). The difference is that in the starbursts we know there is much more H2 than is apparent in the FUSE spectra, indicating that the spectra are not sensitive to regions in the aperture containing dense H2. A similar effect may hinder the detection of DLAs with H2 if the dust associated with the H2 in such DLAs makes the QSOs behind them invisible (e.g., Fall & Pei 1993). The known QSOs would then preferentially probe DLAs with little extinction and thus little molecular gas or systems for which the line of sight to the QSO happens to pass through a hole in a clumpy or filamentary H2/dust distribution (Hirashita et al. 2003). Ellison et al. (2001) found that the underestimate of the population of DLAs due to dust is at most a factor of 2. However, the DLAs that are missed are those with the most H2 in the line of sight. This would result in an underestimation of the typical H2 content of DLAs.

6. CONCLUSIONS

We have searched for absorption from H2 associated with the diffuse ISM in FUSE spectra of five starburst galaxies. We have tentatively detected H2 in M83 and NGC 5253 and set upper limits for NGC 1705, NGC 4214, and NGC 3310. In general there is much less H2 seen in the far-UV than implied by previous millimeter-wave CO measurements, as expected if most of the H2 is in dense clumps that FUSE cannot detect because they are opaque to far-UV light. The upper limits on N(H2) and the lower limits on N(H i) in the starbursts are consistent with the Savage et al. (1977) values for the diffuse ISM in the Milky Way. However, the substantial reddening measured in IUE spectra of four of the starbursts suggests that the amount of H2 in the diffuse ISM is much lower than for sight lines in the Milky Way or Magellanic Clouds with similar amounts of reddening. If the suggested deficiency of diffuse H2 is real, it is likely due to photodissociation of H2 molecules by UV radiation from massive stars or shocks from multiple supernovae and illustrates how the harsh environment in starbursts affects the ISM. However, the mechanism that dissociates the molecular gas apparently does not destroy the dust that reddens the UV
spectra. The FUSE observations show that the absence of H₂ absorption in the far-UV does not necessarily indicate a lack of molecular gas in an actively star-forming galaxy.

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