NO DIFFUSE H$_2$ IN THE METAL DEFICIENT GALAXY I Zw 18

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ABSTRACT

The metal deficient starburst galaxy I Zw 18 has been observed with FUSE in a search for H$_2$ molecules. The spectrum obtained with an aperture covering the full galaxy shows no absorption lines of diffuse H$_2$ at the radial velocity of the galaxy. The upper limit for the diffuse H$_2$ column density is found to be very low: $N$(H$_2$) $\lesssim$ 10$^{15}$ cm$^{-2}$ (10$\sigma$), unlike our Galaxy where H$_2$ is generally present for even low H I column densities. Although the H I column density is here as high as $N$(H I) $\approx$ 2 $\times$ 10$^{21}$cm$^{-2}$, we observe 2$N$(H$_2$)/$N$(H I) $\ll$ 10$^{-6}$. We cannot exclude the possibility that some H$_2$ could be in very dense, small and discrete clumps which cannot be detected with the present observation. However, the remarkable absence of diffuse H$_2$ in this metal-poor galaxy can be explained by the low abundance of dust grains (needed to form this molecule from H-atoms), the high ultraviolet flux and the low density of the H I cloud surrounding the star–forming regions. Thus having eliminated diffuse H$_2$ as a significant contributor to the total mass, it appears that the gas of the galaxy is dominated by H I, and that the high dynamical mass is not composed of cold and diffuse baryonic dark matter.

Subject headings: ISM: molecules — galaxies: abundances — galaxies: dwarf — galaxies: individual (I Zw 18) — galaxies: ISM — ultraviolet: galaxies

1. INTRODUCTION

I Zw 18 (Mkn 116) is a dwarf blue compact galaxy presently experiencing a strong burst of star formation which has produced a pair of bright H II regions. This galaxy has the smallest known abundance of heavy elements as derived from the ionized gaseous component. Its oxygen abundance is only $\sim$ 1/50 of that of the Sun. The distribution and kinematics of neutral hydrogen derived from aperture synthesis observations have been discussed in several works. These works have derived H I masses in the range 3—7 x 10$^7$M$_\odot$ and dynamical masses in the range 3—9 x 10$^7$M$_\odot$ (Lequeux & Viallefond 1980; Viallefond et al. 1987; van Zee et al. 1998). Van Zee et al. (1998) have emphasized the complexity of the H I velocity fields, while Martin (1996) and Petrosian et al. (1997) have discussed the ionized component. It has been suggested that objects with localized massive star formation surrounded by large H I envelopes might contain a significant reservoir of molecular hydrogen. Such material could represent a significant fraction of the dark matter (Lequeux & Viallefond 1980). Attempts to detect CO in H II galaxies have so far been unsuccessful (Combes 1986; Young et al. 1986; Arnault et al. 1988; Sage et al. 1992; Israël et al. 1995; Gondhalekar et al. 1998). This lack of detection does not necessarily imply a lack of H$_2$: the CO excitation could be lower than for molecular clouds in our Galaxy or CO might be more photodissociated than H$_2$: but perhaps most importantly, C and O are highly underabundant in these metal deficient galaxies. The lack of detectable molecular material also has other important implications for galaxies like I Zw 18. Given the chemically unevolved nature of I Zw 18 and its lack of organized gas dynamics and/or spiral arms, it is unclear where and how this galaxy formed the molecular gas thought to be required to form the current generation of young stars.

Therefore, we observed I Zw 18 with the Far Ultraviolet Spectroscopic Explorer (FUSE, Moos et al. 2000) with the aim of detecting cold molecular hydrogen lines in absorption against the stellar continuum of blue massive stellar clusters. In Sect. 2 we describe the observations and the data analysis, the results are discussed in Sect. 3.

2. DATA ANALYSIS

I Zw 18 has been observed for 31600 seconds on November 28, 1999 with FUSE through the two LiF channels ($\sim$ 980 to 1187 Å). The large entrance aperture (30$''$ x 30$''$) has been used, fully covering the galaxy. The data have been processed with the pipeline version 1.5. The spectral resolution is defined by both the instrument and the size of the galaxy (10$''$). We find a resolution of about $\lambda/\Delta\lambda$ $\sim$ 10000 with a S/N ratio of $\sim$ 10 per resolution element.

Many absorption lines are clearly detected. They correspond to three main components at different radial velocities: $-260$ km s$^{-1}$, $-100$ km s$^{-1}$, and 650 km s$^{-1}$. These can easily be identified respectively with the known high velocity cloud at $-160$ km s$^{-1}$, the clouds within the

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Galaxy expected at low radial velocity, and I Zw 18 itself with a redshift of 750 km s$^{-1}$. We thus conclude that there is a systematic wavelength shift in the whole spectrum corresponding to a bluishhift of about 100 km s$^{-1}$. This systematic wavelength shift can be explained by the preliminary wavelength calibration of FUSE and by the position of the target possibly off the center of the slit. All the velocities quoted below refer to the observed velocities corrected by this systematic effect assumed to be exactly 100 km s$^{-1}$.

The high velocity cloud at $-160$ km s$^{-1}$ is detected in C$\Pi$, Fe$\Pi$, and Si$\Pi$ lines. The second component identified with galactic clouds shows absorption lines not only from atoms and ions (e.g., C$\Pi$, O$\I$, Fe$\II$ and Si$\II$) but also from molecular hydrogen. Lines from H$_2$ at levels up to at least J$=5$ are detected. This is the only component showing the presence of these electronic transitions of H$_2$. This component shows a complex structure, suggesting the presence of several interstellar clouds separated by up to 20 km s$^{-1}$, and will not be detailed further. Finally the third component detected at 750 km s$^{-1}$ is seen in Ar$\I$, N$\I$, Fe$\II$, and Si$\II$ (Fig. 1).

In addition to these three main components, a complex structure is observed around 1032 Å and 1037 Å. This corresponds to the presence of O$\VI$ lines with radial velocities between $-100$ km s$^{-1}$ and $+150$ km s$^{-1}$ originating in the galactic halo.

No line from H$_2$ is observed at the radial velocity of I Zw 18 (Fig. 2). We calculated the upper limits of the H$_2$ column densities assuming an intrinsic width of the lines of $b = 18$ km s$^{-1}$ (van Zee et al. 1998). The limits have been estimated by calculating the difference between a simulated spectrum and the observed spectrum in 9 Lyman bands (0-0 to 8-0) and calculating the corresponding increase of the $\chi^2$ of the fit to the spectrum. The upper limits quoted in Table 1 give an increase of the $\chi^2$ larger than 100, corresponding to a non detection at the $\sim 10\sigma$ level. These limits are thus very conservative and correspond to a total column density $N_{\text{tot}}$(H$_2$) $\lesssim 10^{15}$ cm$^{-2}$. A different intrinsic width of the lines would not change the result significantly.

The H$\I$ Lyman $\beta$ line is strongly perturbed by the airglow lines. However using only the blue wing of the absorption line and assuming that this wing is due to the H$\I$ of I Zw 18 at 750 km s$^{-1}$, it is possible to obtain an estimate of the H$\I$ column density. We find N(H$\I$)$\approx 2.1 \times 10^{21}$cm$^{-2}$. This value is consistent with N(H$\I$)$\approx 3.5 \times 10^{24}$cm$^{-2}$ obtained with HST with a narrow slit (Kunth et al. 1994) and the peak column density of $3.0 \times 10^{24}$cm$^{-2}$ obtained with observations of the 21 cm emission line. Assuming a constant N(H$_2$)/N(H$\I$) ratio across the whole galaxy, we can scale the upper limit on H$_2$ column density to a limit for the total mass of diffuse H$_2$, yielding $M_{\text{H}_2} \lesssim 30 M_\odot$.

Other lines of atoms and ions are observed in the I Zw 18 system at 750 km s$^{-1}$. For instance, lines of Ar$\I$, N$\I$, Fe$\II$, and Si$\II$ are clearly detected. Neither O$\VI$ nor the electronic transitions of CO are detected at the I Zw 18 radial velocity. The lack of CO absorption lines is not surprising since, contrary to diffuse H$_2$, CO should be confined in very dense clouds opaque to UV sources. The problem of O$\VI$ will be discussed in a forthcoming paper.

3. DISCUSSION

The interpretation of the lack of absorption lines of H$_2$ in the spectrum of I Zw 18 deserves a detailed discussion. Note first that FUSE gives access to the average absorption over the full body of I Zw 18, providing $\gtrsim 10^3$ lines of sight to stars emitting in the far–UV and gathered in a central region approximately 10$''$ wide. Some of these stars are resolved by the HST (Dufour et al. 1996). Our observations are not sensitive to dense molecular clouds since: i) dust, even in minute amounts will hide the background stars in the far–UV. ii) even if such clouds were transparent to UV photons, H$_2$ absorption lines would not be detected at our S/N ratio unless the covering fraction is larger than $\sim 10\%$. On the other hand, our observations are very sensitive to diffuse H$_2$. Its absence is very unusual. Indeed in our Galaxy, H$_2$ is strongly detected for H$\I$ column densities larger than a few $10^{20}$ cm$^{-2}$, and is often detected for lower N(H$\I$) (Dixon et al. 1998). With 2N(H$_2$)/N(H$\I$)$< 10^{-6}$ and H$\I$ column density as high as N(H$\I$)$\approx 2 \times 10^{21}$cm$^{-2}$, our observation is placed in the extreme bottom right corner of Fig. 5 of Dixon et al. (1998) representing the fraction of molecular hydrogen versus N(H$\I$). Such an extreme situation has never been observed within a galaxy. Even the Magellanic Clouds, with sub-solar metallicities and high far–UV radiation fields, show detectable H$_2$ along sightlines with lower H$\I$ column densities (e.g., Friedman et al. 2000, Shull et al. 2000). We also would like to stress that this result raises an interesting similarity with what is observed in the damped Ly$\alpha$ systems in QSO lines of sight at higher redshift. Despite their high levels of H$\I$, having low metallicity, low dust content and high UV environment, they also present no detectable H$_2$ (Black et al. 1987).

We now show that the lack of H$_2$ in the diffuse ISM of I Zw 18 is a consequence of the low abundance of grains, of the high ultraviolet flux and of the low atomic density in the H$\I$ cloud surrounding I Zw 18.

There are two possible mechanisms for the formation of H$_2$ in the H$\I$ cloud: formation via $\text{H}^+$ (see e.g., Jenkins & Peimbert 1997), or combination of two H atoms on a dust grain (Hollenbach & Salpeter 1971). A third mechanism involving the production of H$_2^+$ by radiative association of H and $\text{H}^+$ is very inefficient in the present case since the reaction is slow and will not be considered further. The first mechanism for H$_2$ formation starts with the formation of a negative ion, $\text{H}^+ + e \rightarrow \text{H}^- + h\nu$, with a rate $1.0 \times 10^{-15} T_3 \exp(-T_3/7) \text{cm}^3 \text{s}^{-1}$, $T_3$ being the temperature in units of 10$^3$ K (Jenkins & Peimbert 1997). This is followed by the faster associative detachment reaction $\text{H}^- + \text{H} \rightarrow \text{H}_2 + e$. The electrons come mainly from the photoionization of carbon: $n_e = (C/\text{H}) n(H)$. We assume that the abundance of carbon in the H$\I$ cloud is the same as in the HII region: C/\text{H} = 3.5 \times 10^{-6} (Garnett et al. 1997). The rate of formation is then as low as $\sim 10^{-20} n(H)^2 \text{cm}^3 \text{s}^{-1}$ at a temperature of 10$^4$ K, the most favorable case, so that the mechanism is very inefficient unless the medium contains clumps with very high densities. 

The formation of H$_2$ on grains is a more efficient mechanism if the dust is cold enough for the H atoms to stick and remain on the grain surface long enough to combine. To estimate the grain temperature, we examine what happens at the edge of the H$\I$ cloud of I Zw 18, where the UV flux which photodissociates H$_2$ is minimal. The angular radius
of the H I cloud is approximately 30′ from the VLA map of van Zee et al. (1998), corresponding to a radius $R_0 = 1.7 \text{kpc}$ at the distance of I Zw 18, taken as 11.5 Mpc from its radial velocity of 750 km s$^{-1}$ ($H_0 = 65 \text{km s}^{-1} \text{Mpc}^{-1}$). The radiation flux from the ionizing stars of I Zw 18 around 1000 Å measured by FUSE or extrapolated from IUE observations is about $3 \times 10^{-14} \text{erg s}^{-1} \text{cm}^{-2} \text{Å}^{-1}$. Correcting for the Galactic extinction ($E(B-V) = 0.04$ mag., Kunth et al. 1994), we obtain a UV flux at the Earth of approximately $4.5 \times 10^{-14} \text{erg s}^{-1} \text{cm}^{-2} \text{Å}^{-1}$. This yields at $R_0$ a flux $F_{1000} \simeq 2 \times 10^{-6} \text{erg s}^{-1} \text{cm}^{-2} \text{Å}^{-1}$. We finally find the grain temperature at $R_0$ by solving the temperature equilibrium equation $\pi a^2 \int Q_a(\lambda)A_\lambda d\lambda = 4\pi a^2 \int Q_a(\lambda)\pi B_\lambda(T) d\lambda$, where $a$ is the radius of the grain assumed to be spherical, $Q_a(\lambda)$ its absorption efficiency, $F_\lambda$ the incoming UV flux and $B_\lambda(T)$ the Planck function at the temperature $T$ of the grain. As any kind of grain is strongly absorbing in the far-UV which dominates strongly the radiation field, we take $Q_a \simeq 1$ in the left side of the equation. In the far-IR where the grains emit, we take $Q_a(\lambda) \simeq 0.1(\lambda/100 \mu\text{m})^{-2}(a/0.1 \mu\text{m})$ (Draine & Lee 1984). It is then possible to solve the temperature equation analytically, finding at $R_0$: $T \simeq 15.5(a/0.1 \mu\text{m})^{-1/6} \text{K}$. This grain temperature is close to that in the diffuse Galactic interstellar medium and allows the formation of H$_2$. However $T$ increases as $R^{-1/3}$ closer to I Zw 18 and H$_2$ cannot form on grains in the inner parts of the H I cloud.

In the steady state, the molecular hydrogen is also destroyed through absorption in the Lyman bands, and the resulting H$_2$ column density can be estimated. We can take for the formation rate on grains $\mathcal{R}$ the canonical Galactic value of $10^{-17} \text{cm}^3 \text{s}^{-1}$ (Hollenbach & Salpeter 1971) divided by 50 since the dust-to-gas ratio is less than 1/50 of the Galactic value (Kunth et al. 1994). In the present case where the H$_2$ electronic bands are optically thin the fraction of molecular hydrogen $f(H_2) = 2n(H_2)/[2n(H_2) + n(H)]$ is (Jura 1974)

$$f(H_2) = 2\mathcal{R}n(H)/I,$$  
where $I$ is a photodissociation rate. Jura (1974) has calculated $I$ for different cases and we simply use his estimate close to the O9.5V star $\zeta$ Oph, scaled to $F_{1000}$, the flux at 1000 Å at the radius $R_0$ of I Zw 18. We will assume that the cloud is spherical and uniform, in which case its density is $n(H) = N(\text{HI})/R_0 = 0.4 \text{atom cm}^{-3}$. $N(\text{HI})$ being the column density we measure in front of I Zw 18. We obtain $f(H_2) \simeq 2 \times 10^{-9}$. The abundance of H$_2$ is still smaller closer to I Zw 18 since the UV flux is accordingly larger. Thus the calculated column density of H$_2$ is

$$N(H_2) \lesssim 1 \times 10^{-9} N(\text{HI}) \simeq 2 \times 10^{12} \text{mol cm}^{-2},$$

less than the observed upper limit by more than two orders of magnitude.

We thus conclude that our observation shows that the diffuse ISM surrounding I Zw 18 cannot be very inhomogeneous at large scales, otherwise H$_2$ would have been observed. However it cannot be excluded that this medium contains molecular clouds and in particular the kind of very dense, discrete molecular clumps proposed by Pfenniger et al. (1994) to account for the dark matter in our Galaxy. These clumps would escape detection since the associated absorption would be observed only in front of stars which, although very numerous, have a very small total surface coverage. However the suggestion of Lequeux & Viallefond (1980) that the dark matter seen dynamically in I Zw 18 is made of widespread diffuse molecular hydrogen is no longer tenable after the present observations.

**Acknowledgments.**

This work is based on data obtained for the Guaranteed Time Team by the NASA-CNES-CSA FUSE mission operated by the Johns Hopkins University. Financial support to U.S. participants has been provided by NASA contract NAS5-32985. We thank E. Roueff for providing H$_2$ transition data in electronic format.

**REFERENCES**

Arnault, P., Kunth, D., Casoli, F., & Combes, F. 1988, A&A, 205, 41
Black, J.H., Chaffee, F.H., & Foltz C.B. 1987, ApJ 317, 442
Combes, F. 1986, in “Star-forming dwarf galaxies and related objects”, Eds. Kunth, D., Thuan, T. X., & Tran Thanh Van, J., Editions Frontières, 307
Dixon, W.V.D., Hurwitz, M., & Bowyer, S. 1998, ApJ, 492, 569
Draine, B. T. & Lee, H. M. 1984, ApJ, 285, 89
Dufour, R.J., Garnett, D.R., Skillman, E.D., & Shields, G.A. 1996, in Science with the Hubble Space Telescope – II, Eds. Benvenuti, P., Macchetta, F.D., Schreier, E.J., & Payne, H., 348
Friedman, S., et al. 2000, ApJ this issue
Garnett, D. R., Skillman, E. D., Dufour, R. J., & Shields, G. A. 1997, ApJ, 481, 174
Gondhalekar, P. M., Johansson, L. E. B., Brossch, N., Glass, I. S., & Brinks, E. 1998, A&A, 335, 152
Hollenbach, D. J. & Salpeter, E. E. 1971, ApJ, 163, 155
Israel, F. P., Tacconi, L. J., & Baas, F. 1995, A&A, 293, 599
Jenkins, E. B. & Peimbert, A. 1997, ApJ, 477, 265
Jura, M. 1974, ApJ, 191, 375
Kunth, D., Lequeux, J., Sargent, W. L. W., & Viallefond, F. 1994, A&A 282, 282
Lequeux, J. & Viallefond, F. 1980, A&A, 91, 269
Martin, C. 1996, ApJ, 465, 680
Moos, H.W., et al. 2000, ApJ this issue
Petrosian, A. R., Boulesteix, J., Comte, G., Kunth, D., & LeCoarer, E. 1997, A&A, 318, 390
Pfenniger, D., Combes, F., & Martinet, L. 1994, A&A, 285, 79
Sage, L. J., Salser, J. J., Loese, H.-H., & Henkel, C. 1992, A&A, 265, 19
Shull, M., et al. 2000, ApJ this issue
Viallefond, F., Lequeux, J., & Comte, G. 1977, in “Starbursts and galaxy evolution”, Eds. Thuan T. X., Montmerle T., Tran Thanh Van J., Editions Frontières, 139
Young, J. S., Kenney, J. D., Tacconi, L., Claussen, M. J., Huang, Y.-L., Tacconi-Garman, L., Xie, S., & Schoelbro, F. P. 1986, ApJ, 311, 17
van Zee, L., Westpfahl, D., & Haynes, M.P. 1998, AJ, 115, 1000
Table 1
Upper limits on the H$_2$ content of 1 Zw 18 at $\sim$10 $\sigma$ level

| Molecule | $J$ | $N$ (cm$^{-2}$) |
|----------|-----|----------------|
| H$_2$    | 0   | $< 5 \times 10^{14}$ |
| H$_2$    | 1   | $< 6 \times 10^{14}$ |
| H$_2$    | 2   | $< 5 \times 10^{14}$ |
| H$_2$    | 3   | $< 5 \times 10^{14}$ |
| H$_2$    | 4   | $< 9 \times 10^{14}$ |
Fig. 1.— Plot of some atomic lines detected at $\sim 750 \text{ km s}^{-1}$. Absorption lines of Si\textsc{ii}, Ar\textsc{i} and Fe\textsc{ii} are from I Zw 18. The Si\textsc{ii} and Ar\textsc{i} lines are blended with Galactic H$_2$ lines. This blend is easily resolved because the Galactic H$_2$ is detected in many other lines.
Fig. 2.— Plot of the 4-0 H$_2$ Lyman bands. Although the Galactic H\textsc{i} column density ($\sim 10^{20}$ cm$^{-2}$) is lower than the one from I Zw 18 ($\sim 10^{21}$ cm$^{-2}$), the Galactic H$_2$ is easily detected ($\sim 10^{20}$ cm$^{-2}$). No line of the H$_2$ bands is detected at the radial velocity of I Zw 18. The dashed lines show the expected lines if the column density of H$_2$ had been $10^{15}$ cm$^{-2}$ in the plotted J levels.
