THE ABSENCE OF DIFFUSE GAS AROUND THE DWARF SPHEROIDAL GALAXY LEO I[1]

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ABSTRACT

We have obtained spectra of three QSO/AGNs with the GHRS aboard the *Hubble Space Telescope* to search for absorption from low column density gas in the halo of the dwarf spheroidal (dSph) galaxy Leo I. The probe sight lines pass 2.1, 3.7, and 8.1 kpc from the center of the galaxy, but no C IV, Si II, or Si IV absorption is found at the velocity of Leo I. The absence of low-ionization species suggests that the column density of neutral hydrogen that exists within 2–4 kpc of the galaxy is $N(\text{H I}) \lesssim 10^{17}$ cm^{-2}; assuming that the high-ionization lines of Si IV and C IV dominate the ionization fraction of silicon and carbon, the limit to the total hydrogen column is $N(\text{H}) \lesssim 10^{18}$ cm^{-2}.

Our results demonstrate that there are no dense flows of gas in or out of Leo I and that there is no evidence for tidally disrupted gas that might have accompanied the galaxy's formation or evolution. However, our detection limits are insufficient to rule out the existence of a sphere or shell of ionized gas around the dSph, with a mass up to that constituting the entire galaxy. Our models show that dSph galaxies similar to Leo I are not massive enough to have halos that can contribute significantly to the metal line absorption cross section of QSO absorbers seen at high redshift.

Subject headings: galaxies: halos — galaxies: individual (Leo I) — galaxies: structure — quasars: absorption lines

1. INTRODUCTION

That there is still no consensus as to how dwarf galaxies form is demonstrated by the number of theories that exist to explain their origin. The dwarf spheroidal (dSph) galaxies, in particular, present a challenge—and indeed a constraint—to our understanding of galaxy formation and evolution. The properties of these galaxies, and the theories that are advanced to explain their origin and evolution, are summarized in detail by Gallagher & Wyse (1994). Notably, many of the hypothesized mechanisms imply that the dSph galaxies we see today could be surrounded by extended gaseous halos. In this paper we present the results of a search for such a halo around Leo I, using UV absorption lines to expose the existence of any low-density gas around the galaxy that cannot be detected in any other way.

How might the formation and evolution of dwarf galaxies influence the distribution of gas around them? Dwarf galaxies may collapse and evolve almost independently from massive galaxies, forming in large numbers at early epochs from primordial density fluctuations (Ferguson 1994).

Dwarf irregular galaxies may evolve from dwarf ellipticals by accreting gas cooling from the intergalactic medium (Silk, Wyse, & Shields 1987). Alternatively, dwarf galaxies may act as the basic building blocks of all galaxies, merging at higher redshift to form the distribution of galaxies we see today. Dwarfs seen at the present epoch would then be the few remnants from this earlier period of galaxy formation. With more massive galaxies in place, dwarf spheroidals may form as the result of interactions between galaxies (Gerola, Carnevali, & Salpeter 1983; Hunsberger, Charlton, & Zaritsky 1996), or they may evolve from more massive elliptical galaxies suffering substantial gas loss through SN-driven winds (Vader 1986).

Similarly, dSph galaxies may form and evolve as a result of mass loss from the cumulative effect of supernovae and stellar winds in more gas-rich systems. Such processes would be highly effective in redistributing gas away from the center of the galaxy. Supernovae may drive gas out of low-mass (proto-) galaxies before most of the initial gas reservoir is converted into stars (Larson 1974; Saito 1979; Dekel & Silk 1986; Ferrara & Tolstoy 1997). Bursts of star formation lasting more than 10^8 yr would then deposit large amounts of energy into the surrounding interstellar medium, imparting enough momentum for the (metal-enriched) gas to become unbound. The gas then escapes the galaxy and mixes with the intergalactic medium (e.g., De Young & Gallagher 1990; De Young & Heckman 1994). Though these processes may be at work in all types of dwarf galaxies, extensive mass loss may weaken the potential well of the lowest mass galaxies, producing relatively round, low surface brightness and low-metallicity remnants similar to the dwarf spheroidals seen in the Local Group (Saito 1979), such as Leo I.

If the galaxy mass is high enough, it is possible that the flow breaking out of the main body of the galaxy will remain bound to it. This "dwarf galactic fountain" could then eventually fall back to the center of the galaxy causing

subsequent bursts of star formation. Recent analysis of color-magnitude diagrams of the stellar populations of Carina and Leo I suggest that they have undergone more than one discrete burst of star formation (Smecker-Hane et al. 1994; Lee et al. 1993), which would support this theory. Clearly, such evolution should produce multiple shells of gas spread over many kpc that ought to be detectable through UV absorption lines.

Thus, discriminating between different theories of dSph galaxy evolution has important implications for our general understanding of galaxy formation. Importantly, most of these scenarios suggest that interstellar gas will be substantially disrupted, leading to its redistribution away from the stellar population. Such gas is likely to be of low column density, however, and susceptible to ionization by the intergalactic UV background, making it difficult to observe. Gas that is shocked due to its expulsion from a galaxy will also remain highly ionized. The only way to detect the gas is to search for the weak UV absorption lines it produces in the spectra of background sources. In this paper, we report on a search for C IV, Si IV, and Si II absorption toward three QSO/AGNs that lie 2.1, 3.7, and 8.1 kpc from the center of Leo I. Leo I is particularly interesting because it contains a relatively young stellar population, with an age measured to be 1.5 Gyr (Caputo, Castellani, & Degl'Innocenti 1996), 3 Gyr (Lee et al. 1993), and 5 ± 2 Gyr (Demers, Irwin, & Gambu 1994). These first two estimates would place the stellar population's formation at redshifts of $z < 0.5$ for any value of h and Ω_b in the usually accepted range $h = 0.5-1.0$ and $\Omega_b < 0.2$ (Ω_b is the baryonic density parameter and $H_0 = 100$ h km s^{-1} Mpc^{-1}, where H_0 is the Hubble constant). Around Leo I, therefore, there may still exist some evidence of an extended gas envelope which formed during the galaxy's evolution.

In § 2 of this paper we outline the observations made with *HST* and present the spectra obtained of the three probes, which show no absorption lines from Leo I. In § 3 we list the equivalent width limits obtained and their conversion to column densities. We calculate a limit to the total gas column density in § 4.1, along with estimates of the gas volume density and mass within the inner radius of the halo, assuming two different models for the distribution of gas around the galaxy. Finally, in § 4.2, we briefly explore the implications of our results for the hypotheses of galaxy formation and evolution discussed above.

2. OBSERVATIONS AND DATA REDUCTION

Observations of Q1004+1303, Q1008+1319, and Q0957+1317 were made 1995 May 17, June 3, and May 29, respectively, with the Large Science Aperture (LSA) of the

GHRS and the G140L grating centered at 1416 Å. Q0957+1317 is actually NGC 3080, a bright Seyfert 1 AGN galaxy also identified as Mrk 1243. The V-band magnitudes, and the redshifts of the probes, are given in Table 1, along with the observed flux, F_λ at 1400 Å, the separation between the QSO/AGN and the center of Leo I on the plane of the sky in arcmin, ρ, and the corresponding separation, s, at Leo I's distance from us of 210 kpc. Also listed are the separations in terms of the tidal radius, r_c. Q1004+1303 and Q1008+1319 are the closest objects to Leo I on the plane of the sky, within $\simeq 1°$. We reproduce in Figure 1 (Plate 10) a region of the sky around the galaxy taken with the UK Schmidt Telescope showing the positions of these two objects relative to Leo I.

Exposure times were the same for each object, 1.63 hr, (three orbits). The data were taken with an FP-SPLIT of two, and quarter-stepped, giving a dispersion of 0.14 Å pixel^{-1}. Time spent measuring the background was 11% of the total exposure time. The spectra were calibrated using the standard pipeline software. Data sets taken at different carousel positions were co-added, wavelength calibrated, and resampled to a linear dispersion using the calibration wavelength files. The offsets in wavelength between the two FP-split data were then calculated with the STSDAS IRAF routine "poffsets" and a correction applied. For the Q1008+1319 spectra, the peak of the cross-correlation function was poorly determined because of the low signal-to-noise ratio of the data; however, for these, and for the two other data sets, careful comparison was made between the wavelengths of features in the FP-SPLIT data to ensure that the co-addition of the two halves of the data was correct. Error arrays were constructed in the same manner using the pipeline error files.

To obtain an exact zero point for the wavelength calibration of the final co-added data, we compared the velocity of O I $\lambda 1302$ and Si II $\lambda 1526$ absorption lines in the QSO/AGN spectra from the Milky Way, with the velocity of H I emission along the line of sight to Leo I taken from the Leiden/Dwingeloo 21 cm H I survey (Hartmann 1994). For Q1004+1303 and Q0957+1317, shifts of -0.4 and -0.2 Å (0.7 and 0.4 diodes) were required, respectively.

For Q1008+1319, the data were of too low a signal-to-noise to accurately measure the centers of the O I $\lambda 1302$ and Si II $\lambda 1526$ absorption lines, but their positions are consistent with that expected from the 21 cm measurement, and no correction was applied.

Plots of the normalized spectra around the position of the Si IV lines are shown in Figure 2, while portions of the spectra around C IV are shown in Figure 3. The figures mark the rest wavelengths of the absorption expected from

TABLE 1

PROBES BACKGROUND TO LEO I

| QSO/AGN PROBE | ALIAS | V | F_λ[b] | z_{em} | PROBE-GALAXY SEPARATIONS[a] | | |
					ρ (arcmin)	s[c] (kpc)	ρ/r_c
Q1004+1303......	4C+13.41	15.2	1.0	0.240	34.0	2.1	0.6
Q1008+1319......	...	16.3	0.1	1.287	60.7	3.7	1.1
Q0957+1317......	NCG 3080	15.0	0.4	0.035	132.4	8.1	2.5

[a] Assuming the center of Leo I is at $\alpha = 10:08:27.39$, $\delta = 12:18:27$ (J2000.0).
[b] Flux at 1400 Å, in units of 10^{-14} ergs cm^{-2} s^{-1} Å^{-1}
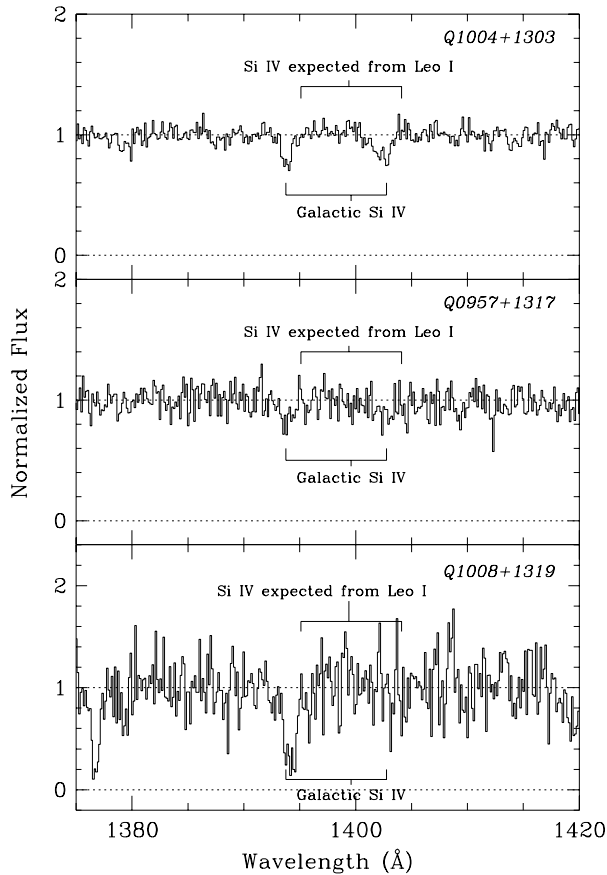[c] Assuming a distance to Leo I of 210 kpc (Demers et al. 1994).

FIG. 2.—Portions of the normalized G140L spectra of the three QSO/AGNs observed at the wavelength region expected for Si IV absorption from Leo I. Absorption is seen from gas in our own Milky Way, but no absorption is detected from Leo I at or near a heliocentric velocity of 285 km s^{-1}.
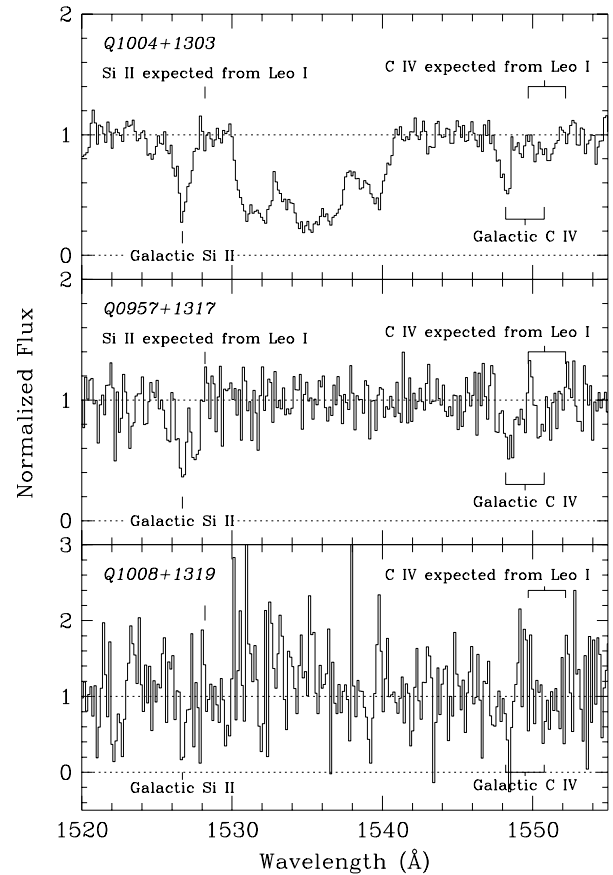
FIG. 3.—Same as Fig. 2, except the wavelength region covers that expected for C IV and Si II absorption. For Q1004 + 1303, complex absorption between 1530 and 1540 Å arises from N V absorption close the emission redshift of the QSO. C IV and Si II absorption are detected from our own Galaxy, but none is detected from Leo I.

our own Galaxy, as well as the wavelengths of any absorption arising from Leo I. In this case we take the velocity of Leo I to be 285 km s^{-1} (Zaritsky et al. 1989).

3. RESULTS

As Figures 2 and 3 show, there is no evidence for Si IV or C IV absorption from Leo I. 2 σ equivalent width limits, 2 $\sigma(W)$, to the absorption are given in Table 2A. The quantity $\sigma(W)$ is calculated from $\sigma(W)^2 = \delta\lambda^2 \sum N\sigma_i^2$, where σ_i is the error in the measurement of the flux at the ith pixel (measured from the calibrated error arrays), N is the number of pixels the line is measured over, and $\delta\lambda$ is the dispersion. The Line Spread Function for the GHRS taken after the installation of "COSTAR" is approximately Gaussian with a width of 1.4 diodes FWHM, or for the data discussed herein, 5.6 pixels. We have therefore taken N to be 11. Table 2B lists the equivalent widths, W, of the Milky

Way absorption lines. Figure 2 shows that the Si IV λ1392 line seen in the spectrum of Q1008 + 1319 is extremely strong and resolved, considerably stronger than the absorption seen toward the other two lines of sight. Yet the corresponding Si IV λ1402 line is absent. Either the Galactic Si IV λ1392 has an equivalent width several $\sigma(W)$ from its correct value, or it is actually blended with a stronger higher redshift absorption line (possibly Lyα at $z = 0.146$) and does not represent Si IV absorption from our own Galaxy.

To calculate limits to the column densities of the gas, we assume that any gas that has not been detected would give rise to absorption lines with equivalents widths derived from the linear part of the curve of growth. For the limits listed in Table 2A, lines are independent of the Doppler parameter, b, for $b \gtrsim 15$–20 km s^{-1}.

For sight lines through our own Galaxy toward extragalactic sources, or in high-redshift QSO absorption-line

TABLE 2A

EQUIVALENT WIDTHS OF LINES IN THE HALO OF LEO I[a]

QSO/AGN Probe	Si IV λ1392 (Å)	Si IV λ1402 (Å)	C IV λ1548 (Å)	C IV λ1550 (Å)
Q1004 + 1303	<0.07	<0.07	<0.10	<0.12
Q0957 + 1317	<0.11	<0.11	<0.22	<0.24
Q1008 + 1319	<0.37	<0.42	<1.23	<1.61

[a] All limits are 2 $\sigma(W)$.

TABLE 2B

EQUIVALENT WIDTHS OF LINES IN THE MILKY WAY HALO[a]

QSO/AGN Probe	Si IV λ1392 (Å)	Si IV λ1402 (Å)	C IV λ1548 (Å)	C IV λ1550 (Å)
Q1004 + 1303	0.24 ± 0.03	0.24 ± 0.03	0.40 ± 0.05	0.23 ± 0.06
Q0957 + 1317	0.21 ± 0.05	0.16 ± 0.05	0.40 ± 0.10	0.21 ± 0.11
Q1008 + 1319	Blended?	<0.41	<1.18	<1.37

[a] All limits are 2 $\sigma(W)$.

TABLE 3

COLUMN DENSITY LIMITS TOWARD
Q1004+1303

Ion	$\log N$	$\log N(H)$
Si II	<13.6	<19.0
Si IV........	<13.1	<18.5
C IV	<13.6	<18.0
Mg II......	<12.0	<17.4

NOTE.—$\log N(H)$ is the value deduced assuming that the particular ion dominates the ionization fraction of the element.

systems, b-values of 10–20 km s^{-1} are measured for most C IV and Si IV lines (e.g., Savage, Sembach, & Lu 1995, and references therein; Fan & Tytler 1994; Lu et al. 1994). These lines are observed at 10–20 km s^{-1} resolution and may be comprised of several components. The few observations of C IV and Si IV absorption lines taken at the highest resolution (~ 3.5 km s^{-1}, with the echelle of the GHRS), where individual components might be observed, are along sight lines through the Milky Way, for which values of b between 5–12 km s^{-1} for Si IV and 10–27 km s^{-1} for C IV are found (Savage, Sembach, & Cardelli 1994a; Sembach, Savage, & Jenkins 1994b). These lines may themselves be comprised of components that are not resolved even at this high resolution, but since single, isolated lines with small b-values are rarely seen, a limit of $b \gtrsim 15$–20 km s^{-1} is probably adequate to characterize any absorption close to our equivalent width limit.

Table 2A lists the equivalent width limits to the Si IV and C IV absorption lines. No useful limits can be obtained for the absorption toward Q1008+1319 due to the low signal-to-noise of the data, but for the remaining two sight lines, we can derive column density limits for the following ions:

Si IV.—Toward Q1004+1303 and Q0957+1317 the limit to the column density of N(Si IV) is almost the same, $\log N$(Si IV) < 12.9 and < 13.1.

C IV.—The limit to N(C IV) toward Q1004+1303 is $\log N$(C IV) < 13.4; toward Q0957+1317, $\log N$(C IV) < 13.8.

Si II.—We can also derive a limit to the Si II column density from the lack of the Si II $\lambda 1526$ line, since the limit to the equivalent width is the same as that for the C IV line: toward Q1004+1303, $\log N$(Si II) < 13.4, while for Q0957+1317, $\log N$(Si II) < 13.8.

Mg II.—The GHRS spectrum taken by Bowen, Blades, & Pettini (1995, hereafter BBP) allows us to place a tight constraint on the Mg II column density toward Q1004+1303. BBP set an equivalent width of 40 mÅ, which corresponds to $\log N$(Mg II) < 12.0.

The sight line toward Q1004+1303 provides the lowest column density limits at the closest impact parameter, as well as an additional measurement of N(Mg II) from BBP. We therefore collate and summarize these limits in Table 3, although as can be seen from the results above, the limits to the column densities toward Q0957+1317 are similar (although no search for Mg II absorption has been made along this sight line).

4. DISCUSSION

4.1. Limits to the Gas Mass and Gas Density around Leo I

To understand whether the lack of absorption in the halo of Leo I is significant, we need to estimate the limit to the total column density of gas along the QSO/AGN lines of sight. To convert to total column densities of carbon and silicon (summed over all ionization stages) we need to know the ionization state of the gas. That is, we need to know whether C IV or Si IV was not detected because the majority of the gas lies in a different ionization stage.

The absence of Si II, and particularly Mg II absorption toward Q1004+1303 to good column density limits, suggests that any gas that is undetected is probably optically thin at the Lyman limit, so that the H I column density, N(H I), is less than 2×10^{17} cm^{-2}. For example, simple ionization models show that Mg II disappears rapidly as H I becomes optically thin at the Lyman limit, (e.g., Bergeron & Stasińska 1986; Steidel & Sargent 1992), falling below 10^{12} cm^{-2}—the limit we measure toward Q1004+1303—as N(H I) drops below 2×10^{17} cm^{-2}. Also, the lack of any detectable H I around Leo I from 21 cm measurements (Knapp, Kerr, & Bowers 1978) to a limit of $M_{H I} < 7.2 \times 10^3$ $M_\odot$ also strongly suggests that there is no optically thick gas anywhere near the lines of sight.

Thus, to calculate limits to the total column densities of carbon and silicon, N(C) and N(Si), along the lines of sight, we assume that undetected gas is highly ionized, and that a significant fraction of it is in the form of C IV or Si IV. This need not be so: models of the fractional ionization of different metals photoionized by a UV background by Donahue & Shull (1991) show that C IV and Si IV rarely dominate the ionization fractions in the gas. However, they remain significant over several dex in the ionization parameter, $U = n_\gamma / n_H$, where n_γ and n_H are the ionizing photon and hydrogen densities, respectively. Further, if the gas was collisionally ionized alone, Si IV would cease to contribute more than 30% of the ionization fraction at temperatures of $\log T \gtrsim 5.5$ (Shull & Van Steenberg 1982). If a significant fraction of the gas is *not* in the form of C IV and Si IV, the implication is that gas around Leo I is extremely hot and highly ionized, and that N(H) derived below is underestimated.

We also note that Donahue & Shull (1991) conclude that the resulting limit on U for the narrow metal line systems observed at redshifts of $z > 2$ is $-3.1 \leq U \leq -2.1$. At these redshifts the ionizing flux—and hence U—is expected to be larger than the present-day value. Yet C IV and Si IV only fail to contribute significantly to the ionization fraction of C and Si for $\log U > -1$. Hence, if any (undetected) gas around Leo I was similar to that observed in higher redshift QSO absorption-line systems, the possibility of ionization stages higher than C IV and Si IV contributing more significantly to the total amount of gas appears to be ruled out.

The total hydrogen column density, N(H), is related to the metal line column densities by

$$\log N(H) = \log N(X) - D_X - A_X , \qquad (1)$$

where $\log N(X)$ is the column density of a particular element X, D_X is the gas phase abundance of element X compared to its solar value, defined as $\log N(X/H) - \log N(X/H)_\odot$, or, equivalently, $\log N(X/H) - A_X$, with $A_X = \log N(X/H)_\odot$ the solar abundance of X. So if C IV and Si IV contribute significantly to the ionization fractions of carbon and silicon, N(C) $\approx N$(C IV), and N(Si) $\approx N$(Si IV), we can calculate a limit to $\log N$(H). We take $(A_X + 12.00)$ to be 8.65 and 7.57 for carbon and silicon, respectively (Morton, York, & Jenkins 1988). D_X is not known for interstellar gas in or around Leo I; gas around the galaxy is unlikely to be

more metal rich than the stellar population, but again, the metallicity of the stars in not well determined. Values of [Fe/H] = −1.6, (Demers, Irwin, & Gambu 1994), −2.0 (Lee et al. 1993) and −(0.7–0.3) (Reid & Mould 1991) have been measured; for our estimate of log N(H), we adopt a value of 1/10 solar, $D_X = -1.0$.

Values of log N(H) for Q1004+1303 are given in Table 3, and are less than 18.5 derived from the limit to the Si IV absorption, and less than 18.0 from C IV. As noted in § 3, the values for Q0957+1317 are similar. The table also includes the values that would be derived from Mg and Si assuming Mg II and Si II dominated their respective ionization stages, for comparison. (We take $A_X + 12.00 = 7.60$ for magnesium). These values would give N(H) if our assumption that the gas was optically thin was incorrect, and lower ionization species dominated. We note that the absence of Mg II absorption lines would give log N(H) < 17.4.

Although we can obtain little information on the column densities toward Q1008+1319, 8.1 kpc from the center of Leo I, the two brighter objects allow us to quantify the column density of gas closer in. We conclude that for Leo I, the lack of low-ionization absorption lines suggest log N(H I) < 17, and that the total hydrogen column is log N(H) < 18, at separations of 2–4 kpc from the center of the galaxy. This limit to N(H) is too small if the gas is hotter and more highly ionized, or the gas phase abundance, D_X, is less than −1.

To calculate a limit to the mean density of hydrogen around Leo I, ρ, and the mass of hydrogen, M_H, we consider two possible geometries for the distribution of any gas that may remain around the galaxy. We consider (1) that the gas resides in a spherical halo of radius R_s, or (2) that the gas resides in a shell of thickness ℓ and outer radius R_s. Physically, the two models are important because they could plausibly arise from outflows of gas as a result of processes within the ISM of the galaxy. Figure 4 shows the limits to ρ and M_H, for log N(H) = 18 and a QSO/AGN-galaxy separation of 2 kpc (although the results are practically independent on this latter value) as a function of the assumed outer radius of the gaseous halo, R_s. Values of ρ

and M_H can be read off the figure from the lines marked ρ and M for any adopted value of R_s.

In the case where the gas resides in a shell, it is necessary to make an extra assumption about its thickness. The cooling length behind the radiative shock leading to the shell formation is $\ell \sim v_s t_{cool}$, where v_s is the shock velocity, and $t_{cool} = kT/\rho_{IGM} \Lambda(T)$ is the cooling time for the shocked gas at temperature T; ρ_{IGM} is the density of the ambient (i.e., intergalactic) medium (Giroux & Shapiro 1996), which we take to be $8.6 \times 10^{-6} \Omega_b (1 + z)^3$ h^2 cm^{-3} or 7.7×10^{-8} cm^{-3} for $\Omega_b = 0.009$ and $h = 1$ (this is the lower limit to $\Omega_b h^2$ given by Copi, Schramm, & Turner 1995, $0.009 \leq \Omega_b h^2 \leq 0.02$; adopting the upper limit does not change our results). $\Lambda(T)$ is the cooling rate. If $v_s \simeq v_e$, where $v_e = 15$ km s^{-1} is the escape velocity from the galaxy, then $\ell = 4.4$ kpc.

Figure 4 shows that for log N(H) = 18 the upper limit to ρ is ~ 0.7–5×10^{-4} cm^{-3} for both models, for $R_s = 5$–50 kpc, while the upper limits to M_H reach, for example, 6×10^8–1×10^9 $M_\odot$ for the spherical and shell case, respectively, for $R_s = 50$ kpc.

4.2. Has the Gas Gone?

Figure 4 shows that the total mass of gas around Leo I is not well constrained by our observations since a shell or sphere of gas could exist over a wide range of radii (R_s). In fact, the total mass of Leo I is known from derivations of the global and central M/L ratios by Irwin & Hatzidimitriou (1995), who found $M/L \simeq 1$, and therefore $M \simeq 3 \times 10^6$ $M_\odot$ for $L \sim 3.4 \times 10^6$ $L_\odot$. From Figure 4, it can be seen that this much mass could only give rise to a column density of N(H) = 10^{18} cm^{-2} if $R_s \simeq 7$ kpc and $\rho \simeq 10^{-5}$ cm^{-3} (there is no solution for a shell since its thickness, ℓ, is comparable to R_s). With $M_{HI} < 7 \times 10^3$ $M_\odot$ (Knapp et al. 1978), this sphere would be highly ionized and would account for all the observed dynamical mass. For N(H) $\ll 10^{18}$ cm^{-2}, the same—or less—gas mass can be distributed over larger spheres (or shells). For example, at log N(H) = 15, a strong constraint on R_s exists because ρ is comparable to ρ_{IGM}. Since $\rho > \rho_{IGM}$ for a shell or sphere to exist, it is possible to show that R_s must be less than 5 kpc and that the mass of gas would be 10^4 $M_\odot$ and 10^3 $M_\odot$ for a shell and halo, respectively. Unfortunately, the metal absorption-line column densities required to obtain these limits to N(H) are very low. For example, log N(C IV) would have to be ~ 11 for gas with 1/10 solar metallicity to reach log N(H) = 15, a column density unattainable with current instrumentation. A more suitable probe of low column density H I would be the Lyα line, since the transition is sensitive to H I column densities several dex less than the metal absorption lines. Unfortunately, at the velocity of Leo I, Lyα absorption would be lost in the strong absorption from the Milky Way.

The idea that dwarf galaxies may be responsible for both metal-line and Lyα QSO absorption systems at high redshift has been widely discussed (York et al. 1986; Tyson 1988; Impey & Bothun 1989; Rauch et al. 1996). Our models show that low-luminosity dSph galaxies like Leo I are simply not massive enough to have halos that can be detected from metal absorption lines, even if all their mass resides in an ionized halo. This does not mean that more massive/luminous dwarfs, including gas-rich dwarfs, do not give rise to absorption lines at high redshift. Nor does it imply that dSphs could not give rise to Lyα absorption
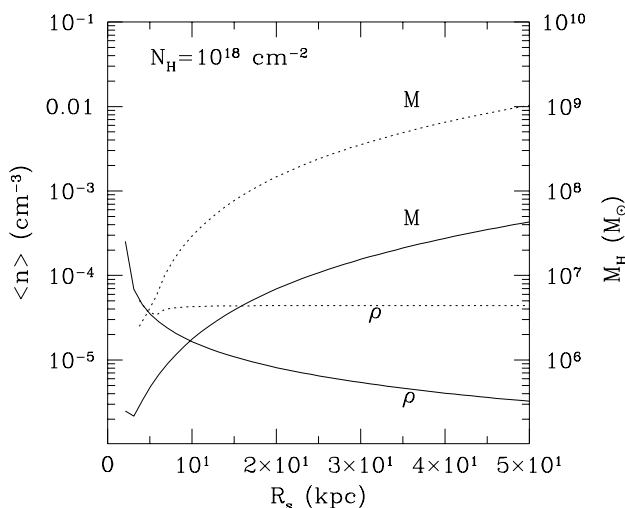

FIG. 4.—Upper limits for the mean hydrogen density, ρ, and total mass M_H, in the halo of Leo I for a spherical (*solid lines*) and shell (*dotted line*) distribution as a function of the total extent of the halo, R_s. The figure assumes a limiting column density of log N(H) = 18.

lines. It does suggest, however, that the population of dSphs, which can be so prevalent in environments like the Virgo Cluster (Sandage et al. 1985), contribute little to the absorption cross section of metal absorption lines such as C IV, Si IV, Mg II, etc.

Despite the fact that we cannot rule out the presence of diffuse, ionized shells or spheres around Leo I, we note that the lack of absorption could also be because gas has been removed via dynamical processes. The absence of high-ionization lines is consistent with the conclusion that there are no inflows or outflows of dense gas intercepting the QSO lines of sight, as might be expected, for example, from concentrated galactic fountains or dense inflows destined to re-ignite star formation. If the galaxy underwent a transient period of intense star formation in which most of the gas was ejected (Larson 1974; Saito 1979; Dekel & Silk 1986), the gas could have merged with the IGM for it now to be undetectable. Assuming that when blowout occurred, the shell moved to an escape velocity of v_e after a short initial transient, the merging time would be $t_m \sim R_s/v_e$, where R_s is the size of the shell when $\rho = \rho_{IGM}$. For $R_s = 5-50$ kpc and $v_e = 15$ km s^{-1}, $t_m \sim 3 \times 10^{8-9}$ yr. This is less than or comparable to the age of the stellar population measured for Leo I (see § 1) so it is possible that gas has been removed this way.

Gas that has existed around Leo I may have been stripped via interactions with neighboring galaxies. Indeed, similar hypotheses have been suggested to account for the *origin* of dSph galaxies (e.g., Gerola, Carnevali, & Salpeter 1983). It is impossible to generalize about the ability of interstellar gas to survive such encounters, its physical state, or its distribution around the parent dSph. In more massive galaxies, however, interactions occur such that tidal debris remains optically thick at the Lyman limit, with column densities high enough to be detected at 21 cm. Indeed, such debris offer some of the best material in which to cause absorption lines in nearby galaxies (BBP; Bowen et al. 1994; Carilli, van Gorkom, & Stocke 1989). If Leo I was

formed from a more massive, gas-rich galaxy, one might expect the remains of the stripped gas to still be detectable. The lack of absorption suggests that any stripping that has occurred could not have taken place recently.

5. SUMMARY

We have searched for absorption lines of C IV, Si II, and Si IV arising in gas around Leo I, toward three QSOs whose lines of sight pass within $\simeq 2-8$ kpc of the galaxy. We have found no absorption, and we conclude that between 2 and 4 kpc from the center of the galaxy the column density of neutral hydrogen is log $N(H\ I) \lesssim 17$, while the total hydrogen column density is log $N(H) \lesssim 18$, assuming the gas has 1/10 solar metallicity and that most of the gas is in an ionization state, whereby C IV and Si IV dominate the ionization fractions. Our results are consistent with the conclusion that there are no dense flows of gas in or out of the galaxy, and there is no evidence for tidally disrupted gas that might have accompanied Leo I's formation or evolution. We cannot rule out the possibility, however, of a sphere or shell of ionized gas around the dSph, with a mass as high as the entire galaxy's dynamical mass. The fact that our detection limits are insufficient to reveal such a gaseous halo demonstrates that dSph galaxies similar to Leo I are not massive enough to have halos that can contribute significantly to the metal line absorption cross section of QSO absorbers seen at high redshift.

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