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A SEARCH FOR IONIZED GAS IN THE DRACO AND URSA MINOR DWARF SPHEROIDAL GALAXIES

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ABSTRACT

The Wisconsin Hα Mapper has been used to set the first deep upper limits on the intensity of diffuse Hα emission from warm ionized gas in the Draco and Ursa Minor dwarf spheroidal galaxies (dSphs). Assuming a velocity dispersion of 15 km s^{-1} for the ionized gas, we set limits of $I_{\mathrm{H}\alpha} \leq 0.024$ R and $I_{\mathrm{H}\alpha} \leq 0.021$ R for the Draco and Ursa Minor dSphs, respectively, averaged over our 1° circular beam. Adopting a simple model for the ionized interstellar medium, these limits translate to upper bounds on the mass of ionized gas of $\lesssim$10% of the stellar mass, or $\sim$10 times the upper limits for the mass of neutral hydrogen. Note that the Draco and Ursa Minor dSphs could contain substantial amounts of interstellar gas, equivalent to all of the gas injected by dying stars since the end of their main star-forming episodes $\gtrsim$8 Gyr in the past, without violating these limits on the mass of ionized gas.

Subject headings: galaxies: dwarf — galaxies: individual (Draco, Ursa Minor) — galaxies: ISM

1. INTRODUCTION

Among the unusual characteristics of dwarf spheroidal (dSph) galaxies is the apparent lack of any interstellar gas, even in systems such as Fornax or Carina, where star formation occurred in the last 1 to 3 Gyr (Skillman & Bender 1995; also see reviews by Gallagher & Wyse 1994, Mateo 1998, and Grebel 1999). Stetson, Hesser, & Smecker-Hane (1998) find a sequence of stars in the color-magnitude diagram of the Fornax dSph that appears to be only a few times 10^8 yr old. The major exception to this trend may be the Sculptor dSph, where an H I cloud could be associated with the galaxy (Carignan et al. 1998; Carignan 1999). Recent sensitive 21 cm H I observations by Young (1999, 2000) yielded upper limits on any diffuse neutral gas at column densities of $<10^{18}$ cm^{-2}, implying that any distributed gas would have low mean volume density and therefore could be ionized. Bowen et al. (1997) searched for a hot ionized ISM in the outskirts of the Leo I dSph by seeking interstellar ultraviolet lines with no detection, thereby setting ionized gas column density limits along two sight lines to background QSOs similar to those of the H I surveys. Gizis, Mould, & Djorgovsky (1993) studied the Fornax dSph with *ROSAT* and found no extended component that could be associated with very hot gas and set a limit of $\leq 10^5\ M_\odot$.

The limits on interstellar gas column densities from the ultraviolet and H I observations correspond to gas masses of $<10^4\ M_\odot$ or $\lesssim$1% of the estimated stellar mass (see Grebel, Gallagher, & Harbeck 2003). As noted by Young (2000), even if gas were initially removed from a dSph at the time that its star formation ceased, mass loss from stars should have replenished the interstellar medium to detectable levels. Evidently, dSphs either lose essentially all their interstellar gas or their interstellar gas lies in a form that has yet to be detected. For example, their gas could reside in dense, cold clumps or be nearly fully ionized but at a moderate temperature $\sim 10^4$ K that can be sustained by photoionization. In either case, substantial amounts of gas could escape detection by previous H I, X-ray, and ultraviolet absorption line studies. In this paper we report results from observations with the highly sensitive Wisconsin Hα Mapper (WHAM) with the goal of detecting Hα emission from ionized interstellar matter in the Draco and Ursa Minor dSphs. No emission is found to sensitive limits, and we discuss the implications of these results.

2. OBSERVATIONS

We have used WHAM to search for the Hα emission from the Draco and Ursa Minor dSphs. The WHAM instrument is a spectrometer located at the Kitt Peak National Observatory and is remotely operated from Madison, Wisconsin. WHAM consists of a 0.6 m siderostat coupled with a 15 cm dual-etalon Fabry-Perot system (Tufte 1997; Reynolds et al. 1998). It produces an optical spectrum integrated over its circular, 1° diameter field of view within a 200 km s^{-1} wide spectral window, centered on any wavelength between 4800 and 7400 Å, with a resolution of 12 km s^{-1}. WHAM was designed to detect very faint emission lines from the diffuse interstellar medium and is capable of detecting Hα emission down to an emission measure of ~0.02 cm^{-6} pc. Its capabilities are well matched to surveys for faint diffuse Hα emission from extended sources, such as the Galactic satellite dSph galaxies.

We chose to study the Draco and Ursa Minor dSphs because they are the closest northern examples of these systems. Our WHAM observations were all taken on the night of 2002 May 6 and employed an "ON minus OFF" technique. In order to accurately remove the contamination

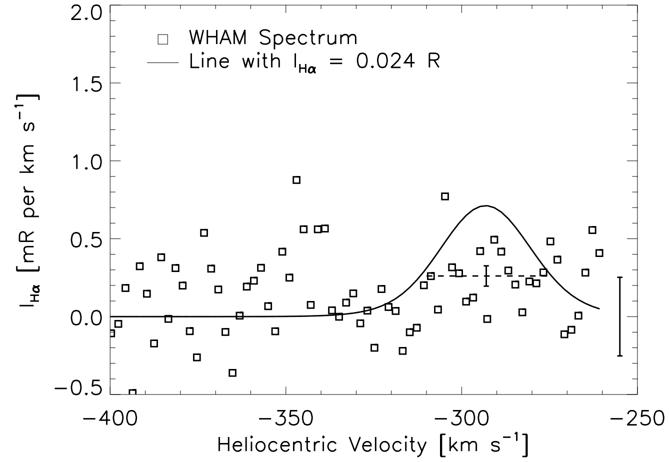

FIG. 1.—WHAM Hα spectrum toward the Draco dwarf spheroidal galaxy. The average of 34 OFF spectra were subtracted from the average of 34 ON spectra to produce this spectrum (see text). The x-axis is heliocentric velocity in km s^{-1}. The y-axis is Hα intensity in milli-Rayleighs per km s^{-1}. A characteristic 2 $\sigma_{\rm data}$ error bar for each data point is shown at the far right near −250 km s^{-1}. The solid line through the spectrum is a 3 σ upper limit to an Hα emission line, placed at the velocity of Draco with line width (b-value) of 15 km s^{-1} and intensity $I_{\rm H\alpha} = 0.024$ R. The dashed line through middle of the Hα emission line is an average of all the data points that lie within the full width at half-maximum of the superimposed Hα line. The error bar in the middle of this dashed line, $\sigma_{\rm ave}$, is the average deviation of those data points from this line. The dashed line lies 3 $\sigma_{\rm ave}$ below the peak of the Hα line.

of the spectra by faint atmospheric lines (Madsen et al. 2001; Hausen et al. 2002), the observations were alternated between the galaxies (ONs) and a couple of directions (OFFs) a few degrees away from the ONs. The OFF directions were checked to ensure that no potential systematic contaminants, i.e., bright stars or high-velocity H I gas, were present within the 200 km s^{-1} spectral window. Each individual observation was 120 s, and the total integration time toward each ON direction was 78 minutes. The average of the OFF spectra was subtracted from the average of the corresponding ON spectra to yield spectra of the galaxies that minimized the contamination by atmospheric lines.

Figures 1 and 2 show the resultant Hα spectra toward the Draco and Ursa Minor dSphs, respectively. The spectra were corrected for atmospheric and internal transmission effects, and their intensities calibrated using synoptic observations of a portion of the North America Nebula, which has an intensity$I_{\rm H\alpha} = 800$ R[1] (Scherb 1981). The velocity scales were calibrated using a bright atmospheric OH line near −420 km s^{-1} with respect to Hα. The x-axis of each plot is heliocentric velocity, and the y-axis is milli-Rayleighs per km s^{-1}.

3. RESULTS

3.1. *Upper Limits on* Hα *Intensities*

The spectra in Figures 1 and 2 show no statistically significant emission lines, providing only upper limits to the Hα emission from these galaxies. To estimate these upper limits, we assume an emission line exists at the heliocentric velocities of each of the dSph systems, −293 km s^{-1} for Draco and −248 km s^{-1} for Ursa Minor (Armandroff, Olszewski, & Pryor 1995). In order to set a limit on the expected width of an Hα line, we assume that the gas would have a velocity dispersion close to that of the stars, which have line-of-sight dispersions of about 10 km s^{-1} (e.g., Olszewski, Aaronson, & Hill 1995; Armandroff et al. 1995; Hargreaves et al. 1996; Kleyna et al. 2002). However, it is likely that the velocity dispersion of the ionized gas would be larger than that of the stars, as the gas receives additional energy input from the host stars as they evolve. Furthermore, if we impose the condition that a significant amount of ionized gas is actually present in these galaxies, we cannot use a dispersion that is larger than is allowed in order to keep the gas bound in the system ($V_{\rm esc} \gtrsim 15$ km s^{-1}). We therefore adopt a dispersion of 15 km s^{-1} for the Hα emission line that we attribute to ionized gas bound to the Draco and Ursa Minor dSph galaxies.

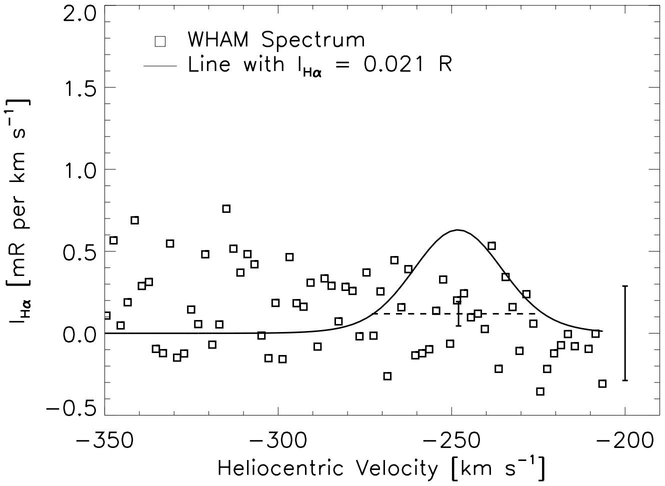

FIG. 2.—Same as Fig. 1, but for the Ursa Minor dwarf spheroidal galaxy. The average of 16 OFF spectra were subtracted from the average of 32 ON spectra to produce this spectrum. A characteristic 2 $\sigma_{\rm data}$ error bar for each data point is shown at the far right near −200 km s^{-1}. The solid line through the spectrum is a 3 σ upper limit to an Hα emission line, placed at the velocity of Ursa Minor with line width (b-value) of 15 km s^{-1} and intensity $I_{\rm H\alpha} = 0.021$ R.

Adopting the above heliocentric velocities and 15 km s^{-1} dispersion, we use the observed spectra to constrain the maximum area (intensity) of an undetected Hα line with these parameters. In particular, we increase the area of the imposed spectra line until the average value of the observed spectra within the FWHM of the line is more than 3 σ below the peak of the imposed line (see Figs. 1 and 2). In this sense, we consider the limits to the strengths of the imposed emission lines to be 3 σ upper limits. We find upper limits of $I_{\rm H\alpha} \leq 0.024$ R and $I_{\rm H\alpha} \leq 0.021$ R for the Draco and Ursa Minor dSphs, respectively, averaged over the 1° circular WHAM beam. These limits are factors of 20–50 below the Hα intensity limits obtained for external galaxies from deep, conventional narrowband filter imaging or spectroscopy (e.g., Ferguson et al. 1996; Hoopes, Walterbos, & Rand 1999), albeit at the price of the low angular resolution required to increase our sensitivity, but with the advantage of precision radial velocity information.

We note that these results were derived using uncertainties arising only from the random errors (i.e., photon statistics), whereas the systematic uncertainties from the

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[1] 1 R = $10^6/4\pi$ photons cm^{-2} s^{-1} sr^{-1}.

incomplete subtraction of atmospheric lines may also contribute to the overall error measurements, particularly with the location of the continuum. However, we have little understanding of the origin and variability of these lines. Given that these random errors account for point-to-point variation in the data, and that a straight line fit to the spectra, i.e., a spectrum with no features, yields a $\chi^2_\nu = 1$, we conclude that the contribution of systematic errors to our upper limits is minimal. However, it is not clear if significantly deeper observations can be obtained with WHAM, as systematic errors are likely to become important for longer observations.

An additional consideration regarding these upper limits is extinction of the Hα emission by interstellar dust in the Galaxy. However, according to the NASA Extragalactic Database, the predicted Galactic extinction at Hα toward the Draco ($b^{\rm II} = 86°$) and Ursa Minor ($b^{\rm II} = 45°$) dSphs is less than 10%. Furthermore, the variation in Galactic extinction across the projected angular extent of the Draco dSph is negligible (Odenkirchen et al. 2001). We do not make any correction for Galactic extinction.

Another possible systematic error could be photospheric Hα absorption by the stars in the host galaxies themselves. This dip in the background stellar continuum would tend to reduce the measured intensity of any Hα emission feature from the ionized gas. To estimate the magnitude of this effect, we consider a completely saturated Hα absorption line at the velocity of the host galaxy. The strength of such a saturated line, as observed by WHAM, is at most equal to the surface brightness, or continuum level, of the galaxy. The apparent total V magnitudes of the Draco and Ursa Minor dSphs, m_V, are 10.1 and 10.3, respectively (Grebel et al. 2003). In the limit where this light uniformly fills the WHAM 1° beam, we derive surface brightnesses of 0.7 S_{10}[2] and 0.5 S_{10}. Using a line width of 50 km s^{-1} (1 Å), we find conservative upper limits of 0.003 and 0.002 R for the strength of an Hα absorption line. Given that such a line is not likely to be completely saturated in these systems, and that the line width at the core may be overestimated, it is likely that any absorption line would be even weaker than these limits. We therefore have not taken into account any correction for an internal stellar Hα absorption feature.

3.2. *Limits on the Mass of Ionized Gas*

With these upper limits of $I_{{\rm H}\alpha}$ in hand, we estimate the total mass of ionized gas in these galaxies. At a temperature of $T = 8000$ K, 1 R of Hα emission corresponds to an emission measure of 2.5 cm^{-6} pc. If we assume that the gas uniformly fills a fraction f of a cylinder of length L along the line of sight, we use the definition of emission measure EM:

$$\mathrm{EM} = f n_e^2 L \approx 2.5 I_{{\rm H}\alpha} \epsilon_{\rm beam}^{-1} , \qquad (1)$$

where the beam efficiency $\epsilon_{\rm beam}$ is given by the ratio of the circular 1° diameter WHAM field to the solid angle subtended by the source. The electron density is

$$n_e = \mathrm{EM}^{1/2} f^{-1/2} L^{-1/2} . \qquad (2)$$

If we further assume that the gas only fills a sphere of radius $R = L/2$ within this cylinder, then the geometric filling factor is $f_g = \frac{2}{3}$, so that with an internal gas filling factor on small spatial scales of f_i, then the total filling factor is $f = f_i f_g$.

The mass of ionized gas $M_{\rm ion}$ within a volume V is given by

$$M_{\rm ion} = n_e m_{\rm H} f C_Y V , \qquad (3)$$

with the mass of the hydrogen atom $m_{\rm H}$, and the correction factor to include helium $C_Y = 1.33$. Placing the emission within a sphere with $f_g = \frac{2}{3}$ and combining the above relations then yields

$$\begin{aligned} M_{\rm ion} &= 2\pi \sqrt{\frac{5}{6}}\, m_{\rm H} \left(f_i\, \mathrm{EM}\right)^{1/2} R^{5/2} \\ &= 0.059 \left(\frac{f_i}{0.1}\, I_{{\rm H}\alpha}\, \epsilon_{\rm beam}^{-1}\right)^{1/2} R^{5/2}\, M_\odot , \qquad (4) \end{aligned}$$

where the radius R is measured in parsecs.

To compute conservative limits we assume that the ionized gas, if present, has a spherical distribution with radius equal to the tidal radius and an internal volume filling factor of $f_i = 0.1$ by analogy to conditions in the Galactic diffuse ionized gas (Reynolds 1977). This model is based on the assumption that any gas beyond the tidal radius would be lost (see Blitz & Robishaw 2000). We adopt a tidal radius of $R_T = 34'$ and a distance $D = 72$ kpc for Ursa Minor (Kleyna et al. 1998; see also Carrera et al. 2002), and $R_T = 40'$ with $D = 80$ kpc for Draco (Odenkirchen et al. 2001). We then have $\epsilon_{\rm beam} = 1$ for both galaxies and $R_T =$ 710 pc and 930 pc, respectively for the Ursa Minor and Draco dSphs. Since we do not detect any emission, we do not correct for the elliptical shapes of these two galaxies, which could reduce $\epsilon_{\rm beam}$ and increase in the upper mass limits by 20%–25%, if the gas had the same projected distribution as the stars but with uniform intensity.

Incorporating these data into equation (4) results in 3 σ upper limits to the ionized gas mass in Ursa Minor of $\leq 1 \times 10^5 M_\odot$ and in Draco of $\leq 2 \times 10^5 M_\odot$. If we instead assumed that the ionized gas is confined to the galaxies' core regions, these values would be reduced by about a factor of 5.

3.3. *Sources of Ionizing Radiation*

If Hα emission is present at its upper limit, we can assume ionization equilibrium to estimate the flux of ionizing photons required to produce this amount of Hα emission. For a given $I_{{\rm H}\alpha}$ in Rayleighs, the corresponding flux of Lyman continuum photons ϕ incident on the surface of the galaxies is given by

$$\phi = 2.05 \times 10^6\, I_{{\rm H}\alpha} \left(\text{photons cm}^{-2}\ \text{s}^{-1}\right) , \qquad (5)$$

where the factor of 2.05 comes from the number of Lyman continuum photons need to produce one Hα photon via photoionization (Osterbrock 1989). The upper limit on $I_{{\rm H}\alpha}$ derived for these two dSph galaxies would thus correspond to $\phi \approx 10^4$ photons cm^2 s^{-1}. The total rate of Lyman continuum photons Q incident upon a galaxy having a projected area A is then

$$Q = \phi A \left(\text{photons s}^{-1}\right) . \qquad (6)$$

For the projected areas (πR_T^2) of these galaxies, we thus find Lyman continuum photon rates of 1.3×10^{48} and 0.6×10^{48} photons s^{-1} for the Draco and Ursa Minor dSphs, respectively.

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[2] 1 S_{10} = One 10th mag A0 star deg^{-2} = 0.0044 R Å^{-1} at Hα.

The hot stellar populations in the Draco and Ursa Minor dSphs, unfortunately, are poorly known. Given their dominant old stellar populations, hot stars arise from evolved low-mass stars. For example, Ursa Minor has a predominantly blue horizontal branch (e.g., Kleyna et al. 1998; Bellazzini et al. 2002) while that in Draco the red horizontal branch is much stronger (Odenkirchen et al. 2001; Aparicio, Carrera, & Martínez-Delgado 2001), and both galaxies should be producing white dwarfs. It is also possible that the Milky Way could ionize gas in these nearby dSphs. However, at the 70–80 kpc distances of these galaxies, it is unclear what the Milky Way's ionizing flux is. Detections of Hα emission from H I clouds at distances of 10–50 kpc within the Galactic halo suggest an escaping flux $\phi \approx 2 \times 10^5$ photons $\mathrm{cm}^2\ \mathrm{s}^{-1}$ (Tufte, Reynolds, & Haffner 1998; Bland-Hawthorne & Maloney 1999). Even the cosmic background may be sufficient to maintain ionization near our observed limit. From WHAM Hα observations of the outer H I disk of M31, Madsen et al. (2001) set an upper limit of $\phi \leq 6 \times 10^4$ photons $\mathrm{cm}^2\ \mathrm{s}^{-1}$ for the cosmic background in the Local Group. Note that assuming the galaxies are spheres, ϕ as defined in our paper is 4 times larger than the Φ_0 definition adopted by Madsen et al. Therefore, the cosmic background radiation field is sufficient to maintain an ionized ISM of substantial mass in the Draco and Ursa Minor dSphs even in the absence of stellar photoionization from the galaxies themselves or from the Milky Way.

4. DISCUSSION AND CONCLUSIONS

Table 1 lists the estimated stellar masses and limits on gas masses for the Draco and Ursa Minor dSphs. These results show that the H I limits now are at the level of <1% of the stellar mass, while our new H II results place limits of order $\lesssim$10% of the stellar mass. Furthermore, we find that current estimates of the background ionization rate would allow gas masses near our limits to be maintained in an ionized state even without additional energy inputs from the dSph stellar populations, which are unlikely to be completely negligible (e.g., Burkert & Ruiz-Lapuente 1997).

Therefore, the old and extremely dim Ursa Minor and Draco dSphs could harbor considerable amounts of ionized interstellar matter. It is interesting to compare our limits with theoretical expectations. Unfortunately, it is unclear how much gas should be left over after early epochs of star formation in a small dwarf galaxy. Several possibilities exist for the evolution of interstellar matter in dwarf galaxies (e.g., Skillman & Bender 1995). Currently available theoretical models suggest that populations of cool gas in clouds can survive star formation and associated supernovae over cosmic time spans in dwarf galaxies, where galaxies with more dark matter should be better able to retain their gas (e.g., Hirashita 1999; Andersen & Burkert 2000; Ferrara & Tolstoy 2000). These models suggest that >10% of the baryonic mass remaining in low-mass dwarfs that evolve over ~10 Gyr in isolation could be in the form of interstellar gas (Lia, Carraro, & Salucci 2000; Carraro et al. 2001). In this regard it is interesting to note that Ursa Minor and Draco may have different dark matter properties. Odenkirchen et al. (2001) find that the outer regions of the Draco dSph have a regular structure, suggesting that perturbations induced by the Milky Way's tidal force are small, leading to the conclusion that Draco is dominated by its dark matter halo. The Ursa Minor dSph, on the other hand, shows evidence for tidal disturbances (Martínez-Delgado et al. 2001) and may have less dark matter, but also appears to be free of interstellar matter.

TABLE 1

Baryonic Mass in the Draco and Ursa Minor Dwarf Spheroidal Galaxies in Solar Masses

Galaxy	$M_* = 3L_V$	H I Mass	H II Mass
Draco	1.4×10^6	<8000	$\leq 2 \times 10^5$
Ursa Minor	9×10^5	<7000	$\leq 1 \times 10^5$

Notes.—Stellar luminosities and H I masses from literature, as given by Grebel et al. (2003). Ionized gas mass, M (H II), from this paper.

A second option is that gas is removed via external processes. This may happen early on if reionization of the universe cuts off gas supplies to small galaxies, as suggested by some (Barkana & Loeb 1999; Bullock, Kravtsov, & Weinberg 2000; see also review by Loeb & Barkana 2001) but not all models (e.g., Ricotti, Gnedin, & Shull 2002). Evolution near giant galaxies provides additional opportunities for gas to be removed from dwarfs through ram pressure stripping or tidal effects (e.g., Sofue 1994; Grebel et al. 2003). Since the Ursa Minor and Draco dSphs are near the Milky Way, they probably experienced gas stripping.

Our observations in combination with the H I data appear to rule out the possibility of a massive residual interstellar medium in either the Ursa Minor or Draco dSphs. We therefore consider how much gas might collect in these systems under the less strict assumption that they were cleaned of gas when their star formation ceased. Evolving stars are the most likely sources of interstellar gas for dSphs orbiting near the Milky Way. In an old stellar population the mass-loss rate from stars is $\dot{M} \approx 10^{-2}[(5\ \mathrm{Gyr})/t]$ (e.g., Schulz, Fritze-von Alvensleben, & Fricke 2002). Over an $\gtrsim$8 Gyr span appropriate to the time since star formation stopped in these two dwarfs (Carrera et al. 2002; Ikuta & Arimoto 2002), we expect about 5% of the stellar mass to return to the interstellar medium. A significant fraction of the gas returned by stars therefore cannot be in the form of H I, but even with our new limits, this material could remain hidden in a diffuse ionized interstellar medium.

Of course, not all of the gas ejected by stars into the very empty interstellar space of a dwarf spheroidal system necessarily will remain in the galaxy. Ram pressure stripping can be highly effective if the orbits of dSphs take them within <50 kpc of the Milky Way (Sofue 1994; Grebel et al. 2003). Thus the possibility remains that dSphs close to giants, like Ursa Minor and Draco, are nearly gas-free systems; our new observations do not disprove this option.

In summary, we obtained 1° angular resolution WHAM observations of the integrated Hα line fluxes from the Draco and Ursa Minor dSph companions of the Milky Way at their optical radial velocities. Our limits of $I_{\mathrm{H}\alpha} < 0.024$ R for Draco and <0.021 R for Ursa Minor are the most sensitive Hα emission line measurements for dSph galaxies to date. However, they still allow for the presence of a diffuse ionized interstellar medium with mass approaching 10% of that of the stars, or ~10 times that set by the H I 21 cm line limits. It is possible that even dSphs with dominant old stellar populations, like Draco and Ursa Minor, could contain the bulk of material lost by stars after star formation activity halted, or they may be periodically cleaned of gas during close encounters with the Milky Way. Searches for diffuse ionized gas in denser dSphs and dwarf galaxies further from the Milky Way will help to illuminate solutions to this long standing mystery. To this end we recently obtained WHAM observations of the Fornax dSph, a system that supported star formation, and we will report these results in a subsequent paper.

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REFERENCES

Andersen, R.-P., & Burkert, A. 2000, ApJ, 531, 296
Aparicio, A., Carrera, R., & Martínez-Delgado, D. 2001, AJ, 122, 2524
Armandroff, T. E., Olszewski, E. W., & Pryor, C. E. 1995, AJ, 110, 2131
Barkana, R., & Loeb, A. 1999, ApJ, 523, 54
Bellazzini, M., Ferraro, F. R., Origlia, L., Pancino, E., Monaco, L., & Oliva, E. 2002, AJ, 124, 3222
Bland-Hawthorn, J., & Maloney, P. R. 1999, ApJ, 510, L33
Blitz, L., & Robishaw, T. 2000, ApJ, 541, 675
Bowen, D. V., Tolstoy, E., Ferrara, A., Blades, J. C., & Brinks, E. 1997, ApJ, 478, 530
Bullock, J. S., Kratsov, A. V., & Weinberg, D. A. 2000, ApJ, 539, 517
Burkert, A., & Ruiz-Lapuente, P. 1997, ApJ, 480, 297
Carignan, C. 1999, Publ. Astron. Soc. Australia, 16, 18
Carignan, C., Beulieu, S., Côté, S., Demers, S., & Mateo, M. 1998, AJ, 116, 1690
Carraro, G., Chiosi, C., Girardi, L., & Lia, C. 2001, MNRAS, 327, 69
Carrera, R., Aparico, A., Martínez-Delgado, D., & Alonso-García, J. 2002, AJ, 123, 3199
Ferguson, A. M. N., Wyse, R. F. G., Gallagher, J. S., & Hunter, D. A. 1996, AJ, 111, 2265
Ferrara, A., & Tolstoy, E. 2000, MNRAS, 313, 291
Gallagher, J., & Wyse, R. 1994, PASP, 106, 1225
Gizis, J. E., Mould, J. R., & Djorgovsky, S. 1993, PASP, 105, 871
Grebel, E. K. 1999, in IAU Symp. 192, The Stellar Content of the Local Group, ed. P. Whitelock & R. Cannon (San Francisco: ASP), 17
Grebel, E. K., Gallagher, J. S., & Harbeck, D. 2003, AJ, submitted
Hargreaves, J. C., Gilmore, G., Irwin, M. J., & Carter, D. 1996, MNRAS, 282, 305
Hausen, W. R., Reynolds, R. J., Haffner, L. M., & Tufte, S. L. 2002, ApJ, 565, 1060
Hirashita, J. 1999, ApJ, 520, 607
Hoopes, C. G., Walterbos, R. A. M., & Rand, R. J. 1999, ApJ, 522, 669
Ikuta, C., & Arimoto, N. 2002, A&A, 391, 55
Kleyna, J., Wilkinson, M. I., Evans, N. W., Gilmore, G., & Frayn, C. 2002, MNRAS, 330, 792
Kleyna, J. T., Geller, M. J., Kenyon, S. J., Kurtz, M. J., & Thorstensen, J. R. 1998, AJ, 115, 2359
Lia, C., Carraro, G., & Salucci, P. 2000, A&A, 360, 76
Loeb, A., & Barkana, R. 2001, ARA&A, 39, 19
Madsen, G. J., Reynolds, R. J., Haffner, L. M., Tufte, S. L., & Maloney, P. R. 2001, ApJ, 560, L135
Martínez-Delgado, D., Alonso-García, J., Aparicio, A., & Gómez-Flechso, M. A. 2001, ApJ, 549, L63
Mateo, M. 1998, ARA&A, 36, 435
Odenkirchen, M., et al. 2001, AJ, 122, 2538
Olszewski, E. W., Aaronson, M., & Hill, J. M. 1995, AJ, 110, 2120
Osterbrock, D. E. 1989, Astrophysics of Gaseous Nebulae and Active Galactic Nuclei (Mill Valley: University Science Books)
Reynolds, R. J. 1977, ApJ, 216, 433
Reynolds, R. J., Tufte, S. L., Haffner, L. M., Jaehnig, K., & Percival, J. W. 1998, Publ. Astron. Soc. Australia, 15, 14
Ricotti, M., Gnedin, N. Y., & Shull, J. M. 2002, ApJ, 575, 49
Scherb, F. 1981, ApJ, 243, 644
Schulz, J., Fritze-von Alvensleben, U., Möller, C. S., & Fricke, K. J. 2002, A&A, 392, 1
Skillman, E. D., & Bender, R. 1995, Rev. Mexicana Astron. Astrofis. Ser. Conf., 3, 25
Sofue, Y. 1994, ApJ, 423, 207
Stetson, P. B., Hesser, J. E., & Smecker-Hane, T. A. 1998, PASP, 110, 533
Tufte, S. L. 1997, Ph.D. thesis, Univ. Wisconsin—Madison
Tufte, S. L., Reynolds, R. J., & Haffner, L. M. 1998, ApJ, 504, 773
Young, L. M. 1999, AJ, 117, 1758
———. 2000, AJ, 119, 188