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PROBING THE GALACTIC DISK AND HALO: METAL ABUNDANCES IN THE MAGELLANIC STREAM[1]

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ABSTRACT

We derive metal abundance limits for two clouds in the Magellanic Stream using Goddard High Resolution Spectrograph medium resolution spectra of the Seyfert galaxy Fairall 9. We find Si/H ≥ 0.2 solar and S/H ≤ 0.9 solar for the $+170$ km s^{-1} cloud with a N(H I) $= 2 \times 10^{19}$ cm^{-2}, and Si/H ≥ 0.07 solar and S/H ≤ 0.3 solar for the $+210$ km s^{-1} cloud with a N(H I) $= 6 \times 10^{19}$ cm^{-2}. These abundance limits rule out the Magellanic Stream as primordial gas. The metal abundance limits are consistent with the Magellanic Cloud abundances. *If* the two Magellanic Stream clouds have the same metal abundances, then Si/H ≥ 0.2 solar and S/H ≤ 0.3 solar for the gas. The ratio Si/S is then ≥ 0.6 of the solar ratio, suggesting that dust depletion is probably not very significant in the Magellanic Stream.

Subject headings: galaxies: individual (Fairall 9) — galaxies: Seyfert — Galaxy: halo — Magellanic Clouds

1. INTRODUCTION

The Magellanic Stream (MS) is a narrow band of neutral hydrogen subtending a 180° arc from the Magellanic Clouds to the south Galactic pole and beyond (Wannier & Wrixon 1972; van Kuilemberg 1972; Mathewson, Clearly, & Murray 1974). Suggestions for the origin of the MS include infalling primordial gas, tidally disrupted gas from the LMC/SMC system due to a close encounter with the Galaxy, and ram pressure–stripped gas from the inter-Cloud region of the LMC/SMC system (see Wayte 1990a for a review). Knowledge of the chemical composition of the MS gas is extremely important for understanding its origin. Songaila (1981) reported Ca II absorption from the MS at $v_{\rm LSR} \sim +193$ km s^{-1} in the spectrum of the Seyfert galaxy Fairall 9, which is projected onto the part of the MS closest to the Magellanic Clouds (named MSI by Mathewson, Schwartz, & Murray 1977; also see Fig. 1 of Songaila 1981). The Ca abundance limits deduced by Songaila, $0.01 \leq$ Ca/H ≤ 1.8 times the solar value, ruled out the MS being primordial (zero-metallicity) gas, but could not distinguish among other possibilities for the origin of the MS.

In a survey to study the distribution and physical conditions of gas in the Galactic outer halo (Lu, Savage, & Sembach 1994; Sembach, Savage, & Lu 1995; Savage, Sembach, & Lu 1994), we obtained *HST* Goddard High Resolution Spectrograph (GHRS) spectra of Fairall 9. In this *Letter*, we report observations of UV absorption lines from the MS gas in the direction of Fairall 9. We derive metal abundance limits for the MS and discuss their implications.

2. DATA ACQUISITION AND MEASUREMENTS

GHRS spectra of Fairall 9 were obtained on 1994 April 9 with the G160M grating and the large science aperture in the regions 1233–1268 and 1522–1556 Å. The data are preserved in the *HST* archieve under the identifications Z26O0208N and Z26O020B5. The species covered are listed in Table 1. Standard comb-addition and the FP-split scanning sequence were used to reduce the effects of detector/photocathode fixed pattern noise. The spectra have two samples per diode width, and the on-spectrum integration time is 7168 s for each setup. The data reduction techniques are identical to those described in Lu et al. (1994). Because these spectra were obtained after the installation of COSTAR, the line spread functions can be adequately described by Gaussian functions with FWHM = 19 and 15 km s^{-1} at 1250 and 1550 Å, respectively. The signal-to-noise ratio (S/N) in the continuum of the spectrum varies with wavelength, with S/N per diode ~5:1 (1526 Å), 7:1 (1550 Å), 10:1 (1240 Å), 15:1 (1250 Å), and 21:1 (1260 Å). The rapid increase in S/N from 1240 to 1260 Å is the result of the elevated flux from the broad Lyα emission line of the Seyfert galaxy.

Figure 1 shows the continuum-normalized profiles of selected absorption lines plotted against local standard of rest (LSR) velocity. In the direction of Fairall 9 ($l = 295.1$, $b = -57.8$), $v_{\rm LSR} - v_{\rm helio} = -10$ km s^{-1}. Absorption at $v_{\rm LSR} <$ 100 km s^{-1} is assumed to originate from the Milky Way disk and halo. The good velocity agreement between the zero-velocity component of Si II λ1526 and the S II absorption suggests that the *relative* velocity scales of the two G160M spectra are consistent with each other. We also detect absorption at $+170$ and $+210$ km s^{-1} in the Si II lines (blended in Si II λ1260), which we identify as absorption from the Magellanic Stream. The MS was initially discovered through 21 cm emission (Mathewson et al. 1974). The higher resolution (34′ beam with a velocity resolution of 2 km s^{-1}) 21 cm map of Morras (1983) reveals two 21 cm components from the MS in the direction of Fairall 9: $v_{\rm LSR} \sim +160$ km s^{-1} with N(H I) $\sim 2 \times 10^{19}$ cm^{-2}, and $v_{\rm LSR} \sim +200$ km s^{-1} with N(H I) $\sim 6 \times 10^{19}$ cm^{-2}. The velocity offset of ~10 km s^{-1} between the 21 cm and UV data could be partly attributed to uncertainties in the *absolute* velocity scale of the UV data and partly to beam smearing in the 21 cm data. It is thus reasonable to identify the two Si II components with the two radio components.

There are some indications that S II λ1253 absorption from the MS may be present near $+200$ km s^{-1}, but the absorption

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TABLE 1

EQUIVALENT WIDTH MEASUREMENTS[a]

Ion	λ[b]	f[b]	$v = +170$ km s^{-1} [+100, +190][c]	$v = +210$ km s^{-1} [+190, +250][c]
C IV......	1548.195	0.1908	≤138	≤123
C IV......	1550.770	0.09522	≤132	≤111
N V......	1238.821	0.1570	≤93	≤66
N V......	1242.804	0.07823	≤81	≤60
Si II......	1260.422	1.007	544 ± 12[d]	...[d]
Si II......	1526.707	0.11	211 ± 46	238 ± 27
S II.......	1250.584	0.005453	≤63	≤42
S II.......	1253.811	0.01088	≤48	≤39
S II.......	1259.519	0.01624	...[e]	...[e]

[a] Equivalent widths and 1 σ error (in mÅ) of absorption lines from the Magellanic Stream at $v_{LSR} = +170$ and $+210$ km s^{-1} are listed. Upper limits are 3 σ estimates.

[b] Rest frame vacuum wavelength and oscillator strength from Morton 1991, except for Si II λ1526.707 for which we dopt the f-value recommended by Spitzer & Fitzpatrick 1993.

[c] The velocities in square brackets give the LSR velocity range within which the equivalent width is measured.

[d] The absorptions from the $+170$ and $+210$ km s^{-1} components are blended. The value listed is the total equivalent width obtained within the velocity range [+100, +300] km s^{-1}.

[e] The absorption is blended with the Si II λ1260.422 absorption (see Fig. 1).

($w_r = 28 \pm 13$ mÅ) is only at the 2 σ level (Fig. 1). We note that the absorption near $v_{LSR} = +100$ km s^{-1} in the S II λ1253 panel is not likely S II absorption because the intrinsically stronger S II λ1259 line does not show the same absorption. This absorption is likely due to intergalactic H I Lyα at $z = 0.03173$ and will not be discussed further in this *Letter*. There are also indications for MS absorption in both members of the C IV doublet (at the 2 σ level). The lower right-hand corner panel of Figure 1 shows the mean of the two C IV profiles. The measured equivalent width within the velocity interval [100, 200] km s^{-1} is 95 ± 35 mÅ from the mean C IV profile, suggesting that there probably is some C IV absorption at velocities near the $+170$ km s^{-1} component.

In Table 1 we list the equivalent widths of lines covered by our spectra for the two MS clouds (the analysis of Galactic disk and near-halo absorption will be presented elsewhere). The first three columns of Table 1 list the ion name, vacuum wavelength, and oscillator strength from Morton (1991), except for the Si II λ1526 line for which we adopt the value $f = 0.11$ (rather than Morton's 0.23) recommended by Spitzer & Fitzpatrick (1993). Equivalent widths are measured from direct integration of the normalized line profile within the specified LSR velocity range given in Table 1. To separate the two MS components, we split the absorption at the velocity of $+190$ km s^{-1} where the Si II λ1526 absorption from the MS reaches a local minimum. Equivalent width uncertainties are calculated including both the contributions from photon-counting noise and from continuum-placement uncertainty (cf. Savage et al. 1993, and references therein). Upper limits are 3 σ estimates using the same velocity ranges.

3. RESULTS

Absorption from the MS is detected unambiguously only for the Si II lines. Both the Si II $\lambda\lambda$1260 and 1526 absorption are saturated (especially for the $+210$ km s^{-1} component), so they cannot be used to derive accurate column densities. We use apparent column density profiles [$N_a(v)$] to derive lower limits of the Si II column density for the two clouds. Briefly, the observed absorption profile is converted into apparent optical depth per unit velocity, $\tau_a(v)$, through $\tau_a(v) = \ln[I_c(v)/I_{obs}(v)]$, where $I_c(v)$ is the estimated intensity in the continuum and $I_{obs}(v)$ is the observed intensity in the absorption line as a function of velocity. The measures of $\tau_a(v)$ are then converted into measures of apparent column density per unit velocity,

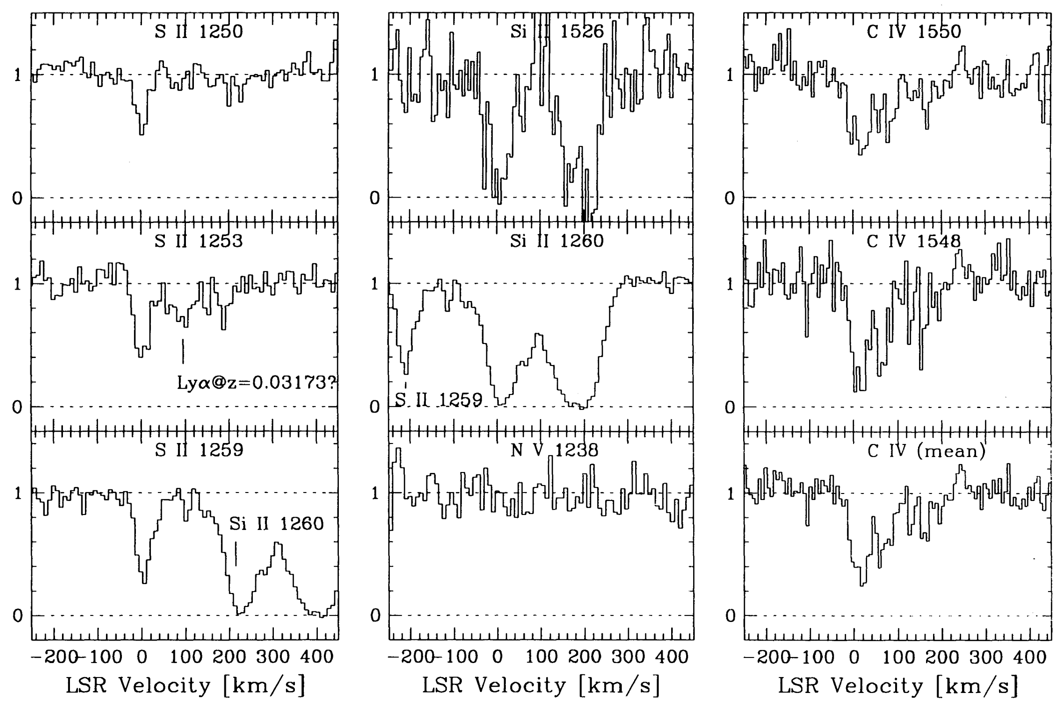

FIG. 1.—Normalized profiles of absorption lines in the spectrum of Fairall 9 plotted against LSR velocity. Absorption from the Magellanic Stream is detected in the Si II lines at $v_{LSR} = +170$ and $+210$ km s^{-1}. The absorption near $+100$ km s^{-1} in the S II λ1253 panel is probably intergalactic H I Lyα at $z = 0.03173$. The lower right-hand corner panel shows the average profile of the C IV doublet.

$N_a(v)$, in units of atoms cm^{-2} $(km\ s^{-1})^{-1}$ through the relation

$$\log N_a(v) = \log \tau_a(v) - \log (f\lambda) + 14.576 ,$$

where λ is in Å. The total column density, estimated by integrating $N_a(v)$ over the entire velocity profile, should represent the true column density to within the measurement uncertainty if the absorption contains no unresolved saturated components (Savage & Sembach 1991). We find N(Si II) $\geq 1.5 \times 10^{14}$ cm^{-2} for each of the two components by applying the $N_a(v)$ method to the Si II λ1526 absorption. The values are lower limits because (1) the Si II λ1526 absorption may contain unresolved, saturated absorption that cannot be recognized with the existing data, and (2) in calculating the $N_a(v)$'s we have replaced the observed flux values in the absorption with the $+1\ \sigma$ error values of the flux for those data points whose observed flux values are indistinguishable from zero to within the $\pm 1\ \sigma$ error. The error spectrum was calculated from the photon-counting statistics and radiation background noise during the data reduction stages. Taking the N(H I) values of 2×10^{19} and 6×10^{19} cm^{-2} for the two components from Morras (1983), and adopting the solar abundance of $(Si/H)_\odot = 3.55 \times 10^{-5}$ (Anders & Grevesse 1989), we then find Si/H $\geq$ 0.2 and $\geq$0.07 times solar for the +170 and +210 km s^{-1} components, respectively.

S II absorption from the MS is not detected. Taking the 3 σ upper limits on S II λ1253 absorption from Table 1 (the stronger S II λ1259 absorption is blended with the Si II λ1260 at these velocities), and assuming the absorption lines are unsaturated, we find N(S II) $\leq 3.3 \times 10^{14}$ cm^{-2} for the +170 km s^{-1} component, and N(S II) $\leq 2.7 \times 10^{14}$ cm^{-2} for the +210 km s^{-1} component. Adopting the solar abundance of $(S/H)_\odot = 1.86 \times 10^{-5}$ from Anders & Grevesse (1989), we find S/H $\leq$ 0.9 and $\leq$0.3 times solar for the +170 km s^{-1} and +210 km s^{-1} components, respectively. In deriving these abundance limits, we have made the traditional assumption that S II and Si II are the dominant ionization stages of the two elements in the gas.

4. DISCUSSION

4.1. *Metal Abundances*

Prior to this work, there have been several observations of Fairall 9 with the *IUE* satellite (Penston 1982; York et al. 1982; and Kinney et al. 1991) and with ground-based telescopes (Songaila & York 1980; Songaila 1981; Morton & Blades 1986). Songaila (1981) obtained Ca abundance limits for the MS of between 0.01 and 1.8 times solar, using N(H I) = 2×10^{20} cm^{-2} derived from the 21 cm map of Mathewson et al. (1974). These limits indicate that the MS is not composed of primordial (zero-metallicity) gas. However, the limits are consistent with the values for metal-poor globular clusters (~0.01 solar), the Magellanic Clouds (~0.2–0.5 solar), or the Galactic ISM (~solar). Penston (1982) reported *IUE* high-dispersion (FWHM ~ 25 km s^{-1}) observations of Fairall 9 in a number of species and deduced metal abundances for the MS that are broadly consistent with those in the Magellanic Clouds. Details of the analysis were not given.

Our abundance limits suggest the MS has metallicities that are incompatible with the metal-poor globular cluster value (especially for the +170 km s^{-1} component) or with the solar value (for the +210 km s^{-1} component). The limits, however, are consistent with values for the Magellanic Clouds. Studies of young stars in the LMC/SMC by Russell & Bessel (1989), Spite, Spite, & Francois (1989), and Spite, Barbuy, & Spite (1989) indicate that the LMC and the SMC have Fe abundances of ~0.5 and ~0.2 times the solar value, respectively. Direct metal abundance studies of the ISM in the Magellanic Clouds using absorption lines (de Boer 1990; Blades et al. 1988) suggest that the LMC and the SMC have metal abundances of ~0.3 and ~0.1 times the solar value, but the uncertainties are large (at least a factor of 2). Our metal abundance limits for the MS are consistent with these metal abundance estimates for the Magellanic Clouds, providing further evidence that the MS is closely related to the Magellanic Clouds.

It is of some interest to compare the Fairall 9 sight line with the NGC 3783 sight line (l = 287.46, b = 22.95). NGC 3783 is projected on to a high-velocity cloud (HVC) complex HVC 287.5+22.5+240 at +240 km s^{-1}, which is on the opposite side of the MS with respect to the Magellanic Clouds, and which was suggested to be possibly related to the MS by Mathewson et al. (1974). In Lu et al. (1994), we obtained a S abundance for this HVC of S/H = 0.15 $\pm$ 0.05 solar, and Si/H $\geq$ 0.006 solar. Based on the available evidence we concluded that HVC 287.5+22.5 + 240 is most likely gas stripped away from a Local Group object (either the Magellanic Clouds or another member of the Local Group) due to interactions with the Milky Way. It is interesting that the S abundance obtained for this HVC is close to the limits we derive here for the MS. In particular, if the +170 and +210 km s^{-1} components toward Fairall 9 have identical origins (metal abundances), which seems likely, then we find Si/H $\geq$ 0.2 times solar, and S/H $\leq$ 0.3 times solar. The S abundance for the HVC toward NGC 3783 is close to this narrow range, supporting the suggestion that the HVC is part of the MS. However, this agreement could be fortuitous: The greatest uncertainty in abundance studies of HVCs (the MS included) undoubtedly is associated with the sampling differences between the absorption line data (infinitesimal solid angle) and the H I 21 cm data (large beam). Wakker & Schwarz (1991) found that the H I column density of HVCs can vary by a factor of 5 over arc minute scales. If the same is true of the MS, then the true metallicity of the MS can differ from the estimated values by a factor of several. Clearly new measurements of N(H I) should be obtained with high spatial resolution (1′) 21 cm mapping of the two sight lines.

4.2. *Dust*

Since S is essentially unaffected by dust in the ISM, while Si can be easily depleted onto dust grains (in the diffuse ISM, Si is typically depleted by a factor of 10; see Sofia, Cardelli, & Savage 1994), the abundance ratio of Si/S in a cloud relative to their solar ratio gives some indication of the presence or absence of dust in the cloud (assuming the intrinsic Si/S ratio in the cloud is the same as in the Sun). For the +170 and +210 km s^{-1} clouds toward Fairall 9, Si/S $\geq$ 0.4, while the solar ratio is Si/S = 1.9. The Si/S ratio in the MS is then within a factor of 5 of the solar ratio. If one makes the reasonable assumption that the +170 and +210 km s^{-1} clouds have the same intrinsic metal abundances, then Si/H $\geq$ 0.2 times solar and S/H $\leq$ 0.3 times solar for the clouds. The corresponding Si/S ratio is then $\geq$0.6 of the solar ratio, suggesting that dust depletion is probably not very significant in the MS. This seems to be consistent with the lack of significant extinction or infrared emission from the MS (Fong et al. 1987).

4.3. *Ionization*

Finally we briefly discuss the significance of the possible detection of C IV absorption near +170 km s^{-1} (§ 2). If the absorption is real, the implied column density is N(C IV) $\sim 3 \times 10^{13}$ cm^{-2} for the +170 km s^{-1} component assuming no line saturation. Note that this N(C IV) value constitutes <3% of all carbon in the cloud for a metal abundance ≥0.2 solar. There are several reasons that one might expect highly ionized gas such as C IV to exist in the MS. The process which created the MS may have involved collisions between the inter-Cloud region gas (the bridge gas between the LMC and SMC, which accounts for nearly half of the total gas in the system) with HVCs in the Galactic halo (Mathewson et al. 1987), in which case hot, collisionally ionized gas may have been created by shocks. The MS may also have been formed through ram pressure sweeping of the inter-Cloud region gas by a hot Galactic corona (Wayte 1990b), in which case the MS should contain a mix of hot and warm gas. The C IV might then be associated with hot and warm gas interface phenomena. In either scenario, the dust may have been destroyed by sputtering, thus explaining the absence of significant amounts of dust in the MS. Alternatively, ionized gas in the MS may be produced through photoionization by extragalactic radiation if the gas density is low enough. Simple photoionization calculations using the computer code CLOUDY (Ferland 1991) suggest that for an AGN-type (i.e., power-law) photon energy distribution, photoionization can produce the observed column densities (or limits) of C IV, Si II, and S II for the following range of parameters: gas density $\sim$0.007–0.011 cm^{-3}, cloud dimension $\sim$1.8–4.8 kpc, metallicity $\sim$0.08–0.5 times solar, and $J_\nu \sim 10^{-22}$ ergs^{-1} s^{-1} cm^{-2} Hz^{-1} sr^{-1}, where J_ν is the mean intensity of the radiation background at the Lyman limit. We note that the width of the MS in the general direction of Fairall 9 is $\sim$20° (Mathewson et al. 1974; Morras 1983), corresponding to a linear size of $\sim$18 kpc at the distances of the Magellanic Clouds ($\sim$50 kpc). Absorption from N V is probably not expected to be detectable given the weakness of the (possible) C IV absorption from the MS. If C IV is present, however, the metallicity estimates given above for the MS may be subject to (uncertain) ionization corrections. In addition, the lack of C IV absorption from the +210 km s^{-1} component, perhaps due to a higher gas density, could mean that the ionization corrections for the two components may be different. Higher S/N observations would be quite useful to confirm or refute the suggested C IV absorption from the +170 km s^{-1} component.

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