Metal Abundances in the Magellanic Stream

Brad K. Gibson\textsuperscript{2}, Mark L. Giroux\textsuperscript{2}, Steven V. Penton\textsuperscript{2}, Mary E. Putman\textsuperscript{3}, John T. Stocke\textsuperscript{2} and J. Michael Shull\textsuperscript{2,4}

ABSTRACT

We report on the first metallicity determination for gas in the Magellanic Stream, using archival \textit{HST} GHRS data for the background targets Fairall 9, III Zw 2, and NGC 7469. For Fairall 9, using two subsequent \textit{HST} revisits and new Parkes Multibeam Narrowband observations, we have unequivocally detected the MS I H I component of the Stream (near its head) in S II\textsubscript{λλ1250,1253} yielding a metallicity of [S II/H] = $-0.55 \pm 0.06(r)^{+0.17(s)}_{-0.21(l)}$, consistent with either an SMC or LMC origin and with the earlier upper limit set by Lu, Savage & Sembach (1994). We also detect the saturated Si II\textsubscript{λ1260} line, but set only a lower limit of [Si II/H] $\approx -1.5$. We present two \textit{HST} serendipitous detections of the Stream, seen in Mg II\textsubscript{λλ2796,2803} absorption with column densities of $(0.5-1) \times 10^{13}$ cm$^{-2}$ toward the Seyfert galaxies III Zw 2 and NGC 7469. These latter sightlines probe gas near the tip of the Stream ($\sim 15^\circ$ from the peak of the MS V H I component and $\sim 80^\circ$ down-Stream of Fairall 9). In the case of III Zw 2, the lack of an accurate H I column density determination and the uncertain Mg III ionization correction severely limit the degree to which we can constrain [Mg/H]; we found a lower limit of [Mg II/H] $\gtrsim -1.3$ for this sightline. For NGC 7469, an accurate H I column density determination exists, but the extant FOS spectrum limits our ability to constrain the Mg II column density, and we conclude that [Mg II/H] $\gtrsim -1.5$ for this sightline. Ionization corrections associated with Mg III and H II suggest that the corresponding [Mg/H] may range lower by $\sim 0.3-1.0$ dex. However, an upward revision of $\sim 0.5-1.0$ dex would be expected under the assumption that the Stream exhibits a dust depletion pattern similar to that seen in both the Large and Small Magellanic Clouds. While our abundance analysis allows us to rule out a primordial origin for the Stream, the remaining systematic uncertainties in the H I column density along the lines of sight makes it difficult to differentiate between an LMC versus SMC origin.

Subject headings: galaxies: individual (III Zw 2; Fairall 9; NGC 7469) — galaxies: Seyfert — Galaxy: halo — Magellanic Clouds

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\footnote{Center for Astrophysics & Space Astronomy, Department of Astrophysical & Planetary Sciences, Campus Box 389, University of Colorado, Boulder, CO 80309-0389}

\footnote{Research School of Astronomy & Astrophysics, Australian National University, Weston Creek Post Office, Weston, ACT, Australia 2611}

\footnote{Also at JILA, University of Colorado and National Institute of Standards and Technology}
1. Introduction

Subtending \(\sim 100^\circ\) from the Magellanic Clouds through the south Galactic pole and beyond, the Magellanic Stream is the most striking extragalactic feature in the neutral hydrogen sky (Wannier & Wrixon 1972). Despite its prominence and apparent association with the Clouds, the Stream’s origin remains somewhat controversial. Tidally-disrupted (Putman et al. 1998) or ram pressure-stripped (Moore & Davis 1994) gas from the LMC or SMC remain the most likely scenarios, although ram pressure-stripped gas from the inter-Cloud region has also been suggested (Mathewson et al. 1987).

A related question pertains to the still uncertain relationship between the Stream and the general population of Galactic High-Velocity Clouds (HVCs).\(^5\) As reviewed by Wakker & van Woerden (1997, § 6.3), several models ascribe a Magellanic Cloud origin to some of the most prominent HVC complexes (e.g., Complex C, VHVCs, Population EP), similar to that of the Stream.

The chemical composition of gas comprising the Stream and HVCs has long been recognized as a key discriminant between competing models for their respective origins. Unfortunately, the dearth of suitable background probes against which to determine abundances of intervening HVC gas has made progress in this area difficult. To date, accurate metallicities have been derived for only a few HVCs, including \([\text{S} \, \text{II}/\text{H} \, \text{I}]=-0.60 \pm 0.13\), using the background probe NGC 3783, for HVC 287+22+240 (Lu et al. 1998), and \([\text{S}/\text{H}]=-1.03 \pm 0.10\), using Mrk 290, for Complex C (Wakker et al. 1999). A detailed study of the metallicity distribution within Complex C, using five different background probes, will be reported in a future paper (Gibson et al. 2000).

A comparison of the metallicity of the Stream with these and other HVCs is hampered by this same lack of suitable background probes. All efforts to date have concentrated upon the background Seyfert galaxy Fairall 9, which intersects the MS I concentration of the Stream (see Figure 1 of Mathewson 1985 for nomenclature), \(\sim 10^\circ\) down-Stream from the SMC. Songaila (1981) detected the Stream in Ca II optical absorption, which when combined with the lack of a detection at Na I D, and subsequent ionization equilibrium arguments, led to the loose constraint that \(-2 \lesssim [\text{Ca/H}] \lesssim +0.25\). This limit was not stringent enough to differentiate between a primordial or Magellanic Cloud origin for the Stream.

More recently, Lu, Savage & Sembach (1994) examined two Stream clouds along the Fairall 9 sightline (one at +210 km s\(^{-1}\), the other at +170 km s\(^{-1}\)). They derived \([\text{S} \, \text{II}/\text{H} \, \text{I}]=-0.52\) and \([\text{S} \, \text{II}/\text{H} \, \text{I}]=-1.15\), for the +210 km s\(^{-1}\) cloud, and \([\text{S} \, \text{II}/\text{H} \, \text{I}]=-0.05\) and \([\text{S} \, \text{II}/\text{H} \, \text{I}]=-0.70\), for the +170 km s\(^{-1}\) cloud. Under the assumption that the two clouds have the same metallicity, these constraints, for the full sightline, reduce to \([\text{S} \, \text{II}/\text{H} \, \text{I}]=-0.52\) and \([\text{S} \, \text{II}/\text{H} \, \text{I}]=-0.70\). The low signal-to-noise ratio S/N in the vicinity of the sulfur lines only allowed Lu et al. to set upper limits on \([\text{S}/\text{H}]\); the saturated silicon lines allowed for only lower limits on \([\text{Si} \, \text{II}/\text{H} \, \text{I}]\).

As part of our ongoing HST Guest Observer program on the origin and physical conditions in the local Ly\(\alpha\) forest (cf. Penton, Stocke, & Shull 2000; Penton, Shull, & Stocke 2000), we revisited Fairall 9 with a similar GHRS set-up to that employed by Lu et al. (1994). Supplemented with the archival Lu et al. dataset, this has led to a four-fold increase in the effective integration time spent on this one target; the resultant increase in S/N has allowed us, for the first time, to derive an unequivocal metallicity determination for the

\(^5\)The Magellanic Stream corresponds to HVC #493 in the Wakker & van Woerden (1991) catalog of High-Velocity Clouds. In our study, we use the classical definition of the Stream - i.e., the stream of gas trailing the Magellanic Clouds. Other HVCs leading the Clouds have been ascribed a similar origin to that of the Stream (Lu et al. 1998; Putman et al. 1998; Sahu 1998), but for our purposes the conventional definition is assumed throughout.
Magellanic Stream.

In § 2.1, we describe both the GHRS and neutral hydrogen data employed in our analysis of the Fairall 9 sightline. The analysis of the Stream absorption features seen in this dataset, and the corresponding implications for [S II/H I] and [Si II/H I], are described in § 3.1. We report serendipitous detections of the Stream (but ∼80° down-Stream of Fairall 9, near the tip and adjacent to the MS V concentration) in § 2.2, 3.2, 2.3, and 3.3. These detections of the Stream, seen in Mg II absorption in the spectra of III Zw 2 and NGC 7469, represent the only other probes, to date, toward which the Stream has been detected. We discuss the implications of our detections in § 4. Our results are summarized in § 5.

2. Data

2.1. Fairall 9

The first three entries of Table 1 list the HST GHRS data employed in our analysis of the Fairall 9 sightline. A single, merged, spectrum was created by first scaling the flux levels of the two 1996 exposures z3e70404m and z3e70406t to be consistent with the initial Lu et al. (1994) exposure (z26o0208n), and then averaging the three, weighting by the flux uncertainties. A detailed description of the spectrum preparation can be found in Penton, Stocke & Shull (2000). The effective integration time of the merged Fairall 9 spectrum totals ∼7.5hrs, with a 3σ equivalent width detection limit of 6 mA at λ = 1250 Å. The S/N at λ = 1250 Å is ∼30.

The resulting merged GHRS spectrum is shown in Figure 1. The Galactic and Stream lines of S II λλ1250, 1253 and Si II λ1260 are labeled accordingly. The three Galactic lines shown are redshifted (in the mean) by 0.028 Å, with respect to their rest frame wavelengths (taken from Verner et al. 1994, and listed in Table 3), corresponding to ∼+7 km s⁻¹ at λ = 1250 Å. In contrast, the Galactic H I along this sightline (upper panel of Figure 4) peaks at vLSR ≈−1 km s⁻¹. This suggests that an a posteriori velocity shift of Δv ≈−8 km s⁻¹ might be appropriate for our merged GHRS Fairall 9 spectrum, although we have not done so here since it has no impact upon the Stream abundance analysis that follows.

The neutral hydrogen column density of the Stream in this direction is N(H I)=9.35 × 10¹⁹ cm⁻². The two-component velocity structure of the high-velocity gas (components centered at +155 km s⁻¹ and +195 km s⁻¹) has been noted before, although the spectrum shown in Figure 4 is the first to clearly show it. We will return to a discussion of the H I properties of this sightline in § 3.1.

2.2. III Zw 2

The second Stream background probe discussed here is III Zw 2. As evidenced by its entry in Table 1 (row 4), only a single 25 min HST GHRS G270M exposure is available. The corresponding 3σ equivalent width detection limit and S/N, at λ = 2800 Å, are 27 mA and 8, respectively. The spectrum itself is shown in Figure 2, with Galactic and Stream Mg II λλ2796, 2803 features identified.

The Galactic Mg II lines are blueshifted (in the mean) by 0.236 Å (i.e., ∼25 km s⁻¹ at λ = 2800 Å), with

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6This scaling was applied linearly across the region overlapping that of the initial exposure.
7Such a shift was applied by Penton, Stocke & Shull (2000) in the Lyα absorber analysis.
respect to their rest frame wavelengths (Pickering, Thorne & Webb 1998). This offset is to be expected, based upon the H I distribution along this line of sight, which shows a two-component structure (Galactic and intermediate-velocity gas) centered on $v_{\text{LSR}} \approx -30\text{ km s}^{-1}$. As was the case for our Fairall 9 spectrum (§ 2.1), we have not applied any a posteriori velocity shift to the GHRS data.

### 2.3. NGC 7469

As part of an HST FOS snapshot program, NGC 7469 was observed with the G270H grating for 5 min during 1996. The 3σ equivalent width detection limit and S/N at $\lambda = 2800\ \text{Å}$ are 162 mÅ and 29, respectively. The FOS spectrum is shown in Figure 3, with Galactic and Stream Mg II $\lambda\lambda 2796, 2803$ features identified. An a posteriori velocity shift of $-20\text{ km s}^{-1}$ has been applied to the FOS wavelength calibration, in order to reconcile a systematic offset between the Galactic and Stream Mg II $\lambda\lambda 2796, 2803$ and H I features. The NRAO 140′ H I spectrum employed in our analysis (upper panel of Figure 8) was kindly provided by Ken Sembach prior to publication (Murphy, Sembach & Lockman 2000).

### 3. Analysis

#### 3.1. Fairall 9

Figure 4 shows the velocity stack for the Galactic (G) and Stream (MS) lines ($\text{Si II} \lambda 1250$, $\text{Si II} \lambda 1253$, and $\text{Si II} \lambda 1260$) detected in our Fairall 9 GHRS spectrum, as well as an H I spectrum taken with the Parkes Narrowband Receiver (Haynes et al. 1999 - spectrum kindly provided by Lister Staveley-Smith). The $\text{Si II} \lambda 1259$ Stream line is blended with the Galactic $\text{Si II} \lambda 1260$ line in the lower panel. In Table 2, we list the centroids of the Stream and Galactic lines (column 1), velocity range over which equivalent widths were determined (column 2), and the line equivalent widths (column 3). The inferred ionic column densities are listed in columns 4 and 5 – the former ($N_{\tau=0}$) corresponds to the optically-thin assumption, while the latter ($N_{\tau_v}$) corresponds to the apparent optical depth method of Sembach & Savage (1992). For the Fairall 9 $\text{Si II}$ Stream features, $N_{\tau=0}$ and $N_{\tau_v}$ are consistent within the uncertainties. Since the $\text{Si II} \lambda 1260$ lines are clearly saturated, it is not surprising that $N_{\tau=0}$ and $N_{\tau_v}$ are discrepant. This saturation allows us only to set lower limits on the Si II column densities. In what follows, we adopt $N_{\tau_v}$ in deriving the Stream’s metallicity, and we make no attempt to treat the two components seen in the H I spectrum separately in our analysis.

In the weak-line (optically-thin) limit, the column density $N_{\tau=0}$ (in cm$^{-2}$) and equivalent width of a line $W_\lambda$ (in mÅ) are related through

$$N_{\tau=0} = 1.13 \times 10^{17} \frac{W_\lambda}{f_{\lambda 0}}$$

where $\lambda_0$ (in Å) is the rest wavelength of the line and $f$ is its oscillator strength (e.g., Savage & Sembach 1996; equation 3). For the lines considered in this paper, the relevant values of $\lambda_0$ and $f$ are provided in columns 2 and 3 of Table 3.

Under the apparent optical depth method of Sembach & Savage (1992), the apparent column density

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8Equivalent widths were derived by integrating over the line profile; Gaussian fits were also undertaken (cf. Penton, Stocke & Shull 2000), but the results here are insensitive to the measurement technique employed, and thus we only report the former.
where \( I(v_i) \) and \( I_c(v_i) \) are the observed and estimated continuum intensities at velocity \( v_i \) (equations A21 and A29 of Sembach & Savage). The statistical noise uncertainty associated with the apparent column density of equation 2 is

\[
\sigma_{N_{\tau_v}} = N_{\tau_v} \left( \frac{\sum_{i=1}^{n} \sigma^2(v_i)/I(v_i)^2 \, dv_i}{\sum_{i=1}^{n} \ln \left[ \frac{I_c(v_i)}{I(v_i)} \right] \, dv_i} \right),
\]

based upon equations A27 and A30 of Sembach & Savage. Uncertainties quoted in this analysis correspond to those of equation 3; those associated with continuum placement have not been considered here. For the high S/N Fairall 9 data, the uncertainty associated with the continuum placement is only an additional \( \sim 5\% \) beyond that of equation 3 (Penton, Stocke & Shull 2000) and is neglected here.

The equivalent width ratio of the \( \text{S\,II} \) Stream features (from Table 2) is \( W_\lambda(\text{S\,II}\lambda1253)/W_\lambda(\text{S\,II}\lambda1250) = 1.72 \pm 0.24 \), further evidence that any saturation effects are mild (the expected theoretical ratio is 2.0).

Regardless, allowing for these marginal optical depth effects, the apparent column densities of the Stream \( \text{S\,II} \) and \( \text{Si\,II} \) features seen in the Fairall 9 GHRSE spectrum are \( N_{\tau_v}(\text{S II}\lambda1250) = (5.39 \pm 0.61) \times 10^{14} \text{cm}^{-2} \), \( N_{\tau_v}(\text{S II}\lambda1253) = (4.75 \pm 0.41) \times 10^{14} \text{cm}^{-2} \), and \( N_{\tau_v}(\text{Si\,II}) = N(\text{Si\,II}) > 9.29 \times 10^{13} \text{cm}^{-2} \). The \( \text{S\,II} \)-weighted average is \( N_{\tau_v}(\text{S II}) = N(\text{S II}) = (4.95 \pm 0.34) \times 10^{14} \text{cm}^{-2} \).

Expressing the sulfur abundance in terms of the logarithmic abundance \( A_S \) with respect to that of the Sun \( A_{S_\odot} \), we can write

\[
[S/H] = \log \frac{A_S}{A_{S_\odot}} = \log N(S) - \log N(H) - \log A_{S_\odot},
\]

since \( A_S = N(S)/N(H) \), by definition. The nondetection of \( \text{S\,I}\lambda1262 \) in our Fairall 9 spectrum (\( W_\lambda < 6 \text{ m}\AA \)) implies \( N(\text{S I}) < 2.1 \times 10^{14} \text{cm}^{-2} \). With an ionization potential of only 10.36eV, \( \text{S I} \) is easily ionized by the ambient halo radiation field and likely makes a negligible contribution to \( N(S) \). We currently have no observational limits on the contribution of \( \text{S\,III} \) to \( N(S) \) but, after Wakker et al. (1999) who consider a Complex C cloud of similar \( \text{H I} \) column density, we assume that \( N(\text{S\,III}) < N(\text{S II}) \). (Also, see our discussion of corrections for \( \text{H II} \) below). With \( A_{S_\odot} = (1.862 \pm 0.215) \times 10^{-5} \) (column 4 of Table 3), and explicitly restricting ourselves to \( \text{S\,II} \) and \( \text{H I} \) (as opposed to the global \( \text{S} \) and \( \text{H} \)), equation 4 reduces to

\[
[S\,\text{II}/\text{HI}] = (19.425 \pm 0.058) - \log N(\text{HI}).
\]

During a 02/17/99-02/22/99 observing run at Parkes Observatory, the Multibeam Narrowband Facility (Haynes et al. 1999) was employed to obtain the Fairall 9 sightline \( \text{H I} \) spectrum shown in the upper panel of Figure 4. The quality of this \( \text{H I} \) data is a vast improvement over that available to Lu et al. (1994) - i.e., the McGee, Newton & Morton (1983) and Morras (1983) datasets. The \( \text{H I} \) column density for the Stream, along this sightline, is \( N(\text{H I}) = (9.35 \pm 0.47) \times 10^{19} \text{cm}^{-2} \).

In combination with equation 5, we can use this new determination of \( N(\text{H I}) \) to derive the sulfur abundance for the Stream in the Fairall 9 sightline, resulting in \( [S\,\text{II}/\text{HI}] = -0.55 \pm 0.06 \). If we had chosen to use \( N_{\tau=0} \), as opposed to \( N_{\tau_v} \), the derived value of \( [S\,\text{II}/\text{HI}] \) would have been reduced by only 0.04\,dex. If 25% of the total hydrogen column is in the form of ionized hydrogen, as appears to be the case for the
Mrk 290 sightline through Complex C (Wakker et al. 1999), the derived $[\text{SII}/\text{H} \text{I}]$ could be 0.12 dex greater than $[\text{SII}/\text{H}]$. This is (perhaps) a conservative overestimate since, in the ionized gas, additional sulfur may be in the form of S III.

A further source of systematic error in our estimate of $N(\text{H})$ is far more challenging to quantify. Our $\text{H I}$ column was derived using the 14' beam provided by the Parkes dish, while the HST absorption measurements toward Fairall 9 sample the gas at sub-arcsecond resolution. Comparisons have been made of $N(\text{H I})$ derived from 21cm mapping with measurements of $N(\text{H I})$ derived from Ly$\alpha$ absorption along the lines of sight to early type stars in the Galactic halo (Lockman, Hobbs & Shull 1986; Savage et al. 2000; Wakker & Savage 2000). The ratio $N(\text{H I})_{\text{Ly} \alpha} / N(\text{H I})_{21\text{cm}}$ is somewhat less than unity, with a dispersion less than $\pm$50%. This low dispersion is in apparent contrast with the results of 21cm surveys of different angular resolution, which show variations in $N(\text{H I})$ as large as a factor of five over arcminute spatial scales (Wakker & Schwarz 1991).

A simple, yet elegant, argument put forth by Bart Wakker suggests that the two observations may not be in contradiction with one another. Radio surveys with higher angular resolution (1') reveal that the number of fields with a given $N(\text{H I})$ is a steep inverse power law function of $N(\text{H I})$. This implies that higher resolution probes of a large beam will be more likely to intersect low $N(\text{H I})$ sightlines. In principle, this same argument could be extended to much smaller scales, as the gulf between high resolution 1' 21cm maps and the scales probed by absorption lines remains large.

To be conservative, we have incorporated a factor $\pm 0.17$ dex ($\pm 50\%$) in our systematic error budget, to reflect the systematic uncertainty in our estimate of $N(\text{H I})$. It remains possible that we have been unfortunate enough to encounter a line of sight with $N(\text{H I})$ that differs from the “pencil beam” $N(\text{H I})$ by a factor of five or more. Higher resolution radio mapping will better address the likelihood of this possibility. It is reassuring to note that, within the measurement errors, the S II and H I velocity profiles are similar (Figure 4). This lends some credence to the suggestion that the H I revealed by our Parkes data is representative of the “pencil beam” H I along the Fairall 9 sightline.

Adding this second factor in quadrature with the systematic uncertainty in converting H I to H, we write our final derived value for the sulfur abundance of the Stream in the Fairall 9 sightline as

$$[\text{SII}/\text{H}] = -0.55 \pm 0.06 (r) \pm 0.17(s),$$

where 'r' and 's' correspond to the associated random and systematic uncertainties, respectively. This result can now be compared with that derived in the earlier Lu et al. (1994) study. Their best S II constraint was set by their 3σ upper limit on the S II $\lambda 1253$ absorption, $W_{\lambda} \leq 87 \text{ mÅ}$ (consistent with our result of $W_{\lambda} = 62 \pm 5 \text{ mÅ}$). Using our H I column density for this sightline, as opposed to the Morras (1983) value used by Lu et al., results in an upper limit to the sulfur abundance $[\text{SII}/\text{H I}] \leq -0.46$, consistent with our result of $[\text{SII}/\text{H I}] = -0.55 \pm 0.06$.

For comparison, the gas-phase sulfur abundances of the Magellanic Clouds are $[\text{S/H}]_{\text{LMC}} = -0.57 \pm 0.10$ and $[\text{S/H}]_{\text{SMC}} = -0.68 \pm 0.16$ (Russell & Dopita 1992). Because of the magnitude of the residual uncertainties (particularly those of a systematic nature), associating the MSI gas with only one of the

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9Of the seven sightlines for which both <1' and 10'−12' H I data exists (Table A1 of Wakker 2000), in only 4/7 of these cases is $N(\text{H I})_{1'} < N(\text{H I})_{10'}$. The ratio of $N(\text{H I})_{1'} / N(\text{H I})_{10'}$ for all seven is 0.90±0.13, with extrema of 0.75 and 1.24. This might lead one to conclude that the importance of the predicted “resolution effect” has been overestimated, but it should be stressed that it is based upon only seven data points. To be conservative we have retained the assumed ±50% uncertainty in $N(\text{H I})$. 
Clouds remains difficult. Equation 6 has a somewhat ad hoc provision for ionization corrections, and no provision for potential dust depletion effects. Fortunately, there is some confidence that S II is effectively free of both of these complicating effects (Wakker et al. 1999).

In analogy to the derivation of equation 6, we can use the Si II $\lambda 1260$ column density (Table 2) to derive a lower limit on the MS I silicon metallicity of

$$\frac{[\text{SiII}/\text{H}]}{1.55 \pm 0.03(r) \pm 0.17(s)}.$$  \hspace{1cm} (7)$$

Because we are limited to the saturated Si II $\lambda 1260$ line, we could derive only the above lower limit with the current data. Lu et al. (1994) find $W_{\lambda} = 449 \pm 53$ mÅ for the Si II $\lambda 1526$ Stream absorption. For the total line of sight HI column density $N(\text{HI}) = 9.35 \times 10^{19}$ cm$^{-2}$, this corresponds to a lower limit on the silicon abundance of $\frac{[\text{SiII}/\text{HI}]}{1.1}$. This particular limit is set by the much lower S/N Si II $\lambda 1526$ line, which is not included in our G160M GHRS spectra. Therefore, we retain the more conservative limit set by Si II $\lambda 1260$ (i.e., equation 7).

### 3.2. III Zw 2

Figure 5 shows the velocity profiles of the detected Galactic (G) and Magellanic Stream (MS) lines of Mg II $\lambda \lambda 2796,2803$ in our G270M GHRS spectrum of III Zw 2. The centroids, equivalent widths, and inferred column densities (both optically thin and following the apparent optical depth methodology described in § 3.1) are listed in Table 4. While our GHRS spectrum is clearly of low signal-to-noise (S/N=8 at $\lambda = 2800$ Å), both Stream Mg II lines appear unsaturated, supported by the fact that the ratio of their equivalent widths, $W_{\lambda}(\text{Mg II} \lambda 2796)/W_{\lambda}(\text{Mg II} \lambda 2803) = 2.11 \pm 0.94$, is consistent with the expected theoretical ratio of 2.0. $N_{\tau=0}$ and $N_{\tau_*}$ agree to within the uncertainties, further evidence that only a mild degree of saturation is present.

Employing the apparent optical depth technique, we derive Mg II column densities of $N(\text{Mg II} \lambda 2796) = (1.08 \pm 0.10) \times 10^{13}$ cm$^{-2}$ and $N(\text{Mg II} \lambda 2803) = (0.91 \pm 0.14) \times 10^{13}$ cm$^{-2}$. We adopt the weighted average in the analysis which follows, $N(\text{Mg II}) = (1.02 \pm 0.08) \times 10^{13}$ cm$^{-2}$. Analogous to the derivation of equation 5, we can use $N(\text{Mg II})$ along the line of sight to III Zw 2 to write

$$\frac{[\text{Mg II}/\text{HI}]}{17.429 \pm 0.039} - \log N(\text{HI}).$$  \hspace{1cm} (8)$$

Unlike the case for Fairall 9, we have little in the way of useful observational constraints on the log N(HI) term of equation 8. The upper panel of Figure 5 shows the Hanning-smoothed H I spectrum from Hartmann & Burton (1997); the non-detection of H I and the position and velocity of our Mg II detection sets an upper limit to the H I column density of $\sim 5 \times 10^{18}$ cm$^{-2}$.\(^{10}\)

The MS V concentration of the Stream is centered on $(\ell, b) \approx (92^\circ, -51^\circ)$, with $v_{\text{LSR}} \approx -350$ km s$^{-1}$ (Mathewson 1985). The upper panel of Figure 6 shows an $\sim 2000$ deg$^2$ region encompassing all of MSV, including the III Zw 2 sightline shown in the lower panel and the neighboring NGC 7469 sightline discussed in § 3.3. The lower panel of shows contours of neutral hydrogen, derived from the Leiden-Dwingeloo Survey (Hartmann & Burton 1997), in a $14^\circ \times 7^\circ$ region centered on the III Zw 2 sightline. The H I contour

\(^{10}\)The 5$\sigma$ detection limit for the Leiden-Dwingeloo Survey (Hartmann & Burton 1997) is $T_B = 0.35$ K (unsmoothed). For an HVC with a linewidth of 8 km s$^{-1}$, the 5$\sigma$ H I column density detection limit corresponds to $5 \times 10^{18}$ cm$^{-2}$; for a 20 km s$^{-1}$ linewidth, $N(\text{HI}) = 5 \times 10^{18}$ cm$^{-2}$ corresponds to a 2$\sigma$ detection limit.
levels are $3 \times 10^{18} \text{ cm}^{-2}$, with the outermost level being $N(\text{H I})=1 \times 10^{18} \text{ cm}^{-2}$. Only the velocity range $-400 < v_{\text{LSR}} < -250 \text{ km s}^{-1}$ was included in this figure. The “edge” of the Stream proper coincides with the increased number of H I clouds between $\ell \approx 98^\circ$ and $\ell \approx 104^\circ$.

In the lower panel of Figure 6, we have highlighted three nearby ($\lesssim 4^\circ$ away from the line of sight) HVCs to the III Zw 2 sightline. While these HVCs are at the threshold of the Leiden-Dwingeloo Survey detection limit, each has been detected previously (Hulsbosch & Wakker 1988; Wakker & van Woerden 1991): HVC 104.0-51.0-337 was detected by Hulsbosch & Wakker (1988), but is subsumed into HVC#493 by Wakker & van Woerden (1991); HVC 110.0-50.0-290 corresponds to HVC#520 in Wakker & van Woerden; HVC 108.0-53.0-325 corresponds to HVC#523. Much of the H I detected with $N(\text{H I}) \lesssim 10^{18} \text{ cm}^{-2}$ is probably noise (and therefore the lower panel of Figure 6 should be used cautiously), but at least these three nearby HVCs have been independently detected by Hulsbosch & Wakker (1988). More importantly, these neighboring HVCs demonstrate that gas presumably associated with the Stream exists $> 15^\circ$ away from the peak of the H I emission. Because the “width” of the MSV concentration seen in the upper panel of Figure 6 is $\sim 10^\circ$, the existence of MS “froth” beyond the outermost contour is not surprising.

Equipped only with our measurement of the Mg II column density and the upper limit on the neutral hydrogen column density, it is difficult to constrain the metallicity of the absorbing gas. As an exploration of the possible range in inferred metallicity, we have constructed a grid of photoionization models using the photoionization code CLOUDY (Version 90.04 - Ferland 1996). We hope to constrain this range of physical parameters more tightly with future observations.\footnote{Being radio-loud, III Zw 2 may lend itself to potential future 21cm absorption analyses.}

We model the absorbing gas as a plane-parallel slab illuminated on one side with a normally incident ionizing photon flux, $\log \phi = 5.5 \text{ photons cm}^{-2} \text{ s}^{-1}$. This is consistent with the estimates of Bland-Hawthorn & Maloney (1999a,b) for this region of the Magellanic Stream, based on measurements of the H\alpha emission near our line of sight. As Bland-Hawthorn & Maloney discuss, this level of radiation is much higher than that due to the general metagalactic background, $\log \phi = 4$ (Shull et al. 1999), and is likely due to escaping stellar radiation from the Milky Way. As a result, we model the spectrum as a power law with spectral index $\alpha_s = 2$, assuming $F_\nu \propto \nu^{-2}$ between 1 and 4 ryd, with a dropoff above 4 ryd of a factor of 100. This represents a rough approximation to the integrated radiation from Galactic OB associations, as well as a harder extragalactic component. However, adopting a $T_{\text{eff}} = 35000 \text{ K}$ stellar atmosphere for the incident spectrum yields a grid of models which are indistinguishable from the following results.

For a given density $n(\text{H})$ and total hydrogen column density $N(\text{H})$, the assumed metallicity of our cloud model was allowed to vary until $N(\text{Mg II})=(1.0 \pm 0.05) \times 10^{13} \text{ cm}^{-2}$ was achieved. The results of the grid of models are shown in Figure 7. Also shown is the area that can be currently excluded by the requirement that $N(\text{H I}) < 5 \times 10^{18} \text{ cm}^{-2}$ (shaded region). Our Mg II column density determination, coupled with the upper limit to $N(\text{H I})$, allows us to set a lower limit $[\text{Mg II}/\text{H I}] > 1.3$. Even this has only limited use as a constraint on the metallicity $[\text{Mg}/\text{H}]$, however, as for $N(\text{H I}) < 5 \times 10^{18} \text{ cm}^{-2}$ and $\log \phi = 5.5$, the ionization correction for H I is substantially more sensitive to changes in density than that for Mg II.
3.3. NGC 7469

As already noted in § 2.3, the Stream was detected in Mg $\Pi$ $\lambda$2796 in the FOS G270H spectrum of NGC 7469 (bottom panel of Figure 8). The Mg $\Pi$ $\lambda$2803 line lies below the 3σ detection threshold and is not discussed further. The Mg $\Pi$ column density inferred from the apparent optical depth method (Table 5) is $N$(Mg $\Pi$)$>$(0.47 ± 0.11) $\times$ 10$^{13}$ cm$^{-2}$. While the line does not appear saturated, the inferior spectral resolution of FOS ($\sim$230 km s$^{-1}$), in comparison with GHRS ($\sim$19 km s$^{-1}$), does not allow us to unequivocally rule out the presence of saturation effects. To be conservative, we assume the measured Mg $\Pi$ column is a lower limit and will revisit this sightline with our FUSE Science Team Cycle 1 observations of NGC 7469, the O VI properties for which have already been discussed by Sembach et al. (2000).

An NRAO 140' H I spectrum (upper panel of Figure 8), kindly provided by Ken Sembach (to be published in Murphy et al. 2000), shows that the H I column density along this MS V sightline is $N$(H I)$=(0.40 \pm 0.04) \times 10^{19}$ cm$^{-2}$. These constraints lead to

$$[\text{Mg II}/\text{H I}] > -1.51 \pm 0.11 (r).$$  

(9)

Errors in converting this measurement to an abundance [Mg/II] are potentially large, since as discussed, for $N$(H I)$ \approx 10^{18}$ cm$^{-2}$, the ionization correction for H I is substantially more sensitive to density than the correction for Mg $\Pi$. For an assumed density n(H)$=0.1$ cm$^{-3}$, [Mg II/H I] may overestimate [Mg/II] by an order of magnitude or more. In addition, the large uncertainty in $N$(H I) about this $\sim 10^{18}$ cm$^{-2}$ range has the secondary effect of enhancing the density sensitivity of the ionization correction to H I. In general, however, ionization corrections imply that [Mg II/H I] is an overestimate of [Mg/II], ranging from a factor of 2 to 10 for n(H) ranging from (1−0.1) cm$^{-3}$.

4. Discussion

4.1. Fairall 9

Based on its proximity to the SMC and the disrupted appearance of the SMC, it is likely that the MS I (and the Stream as a whole) originated in the SMC. If the Stream was drawn out of the SMC $\sim$1.5 Gyrs ago, as the best tidal models predict (Gardiner 1999), one would expect the metallicity to reflect that of the SMC at that epoch. According to the best chemical evolution models (Pagel & Tautvaisiene 1998; Figure 5), that should actually be $\sim$0.2 dex smaller than the present-day value of [S/H]$=-0.68$ (Russell & Dopita 1992). Note that this argument also holds for an LMC origin as well; the LMC metallicity 1.5 Gyrs ago, in the mean, is also predicted to be $\sim$0.2 dex lower than the present-day LMC value of [S/H]$=-0.57$ (Pagel & Tautvaisiene; Figure 4). In either scenario, the predicted [S/H] would appear to be mildly inconsistent with our observations, [S II/H I]$=-0.55\pm0.06 (r) \pm ^{+0.17}_{-0.21} (s)$. On the other hand, the stochastic nature of star formation and the magnitude of the observational scatter (see Figures 4 and 5 of Pagel & Tautvaisiene), severely limits the predictive power of even the best Magellanic Cloud chemical evolution models, applied to the most recent 1−2 Gyrs. Thus, this apparent discrepancy should not be overinterpreted.

An inherent assumption in the above picture is that the MS I gas can be linked directly to disk gas-phase abundances. The present-day population of disk H II regions, in both the LMC and SMC, shows no evidence for any substantial abundance gradients (Dufour 1975), nor are the gaseous disks of the Clouds (currently) substantially larger than their optical disks. In other words, based on the present state of the Magellanic Clouds, there is no reason to suspect that the Stream abundances should not reflect the disk
gas-phase abundances. A caveat to this statement is that the present-day conditions may not necessarily reflect those when the Stream was purported to form ∼1.5 Gyrs ago. Even if an abundance gradient or extended gaseous disk existed when the Stream formed, unless the gradient was inverted (highly unusual), one would then expect the Stream abundances to be even lower than the disk gas-phase abundances. This would worsen the comparison of equation 6 with either the present-day Russell & Dopita (1992) LMC/SMC abundances, or those corrected downward by 0.2 dex based upon conservative chemical evolution model predictions. Higher spatial resolution H I data will be required to reduce the remaining substantial systematic uncertainties discussed in § 3.1, and to better ascertain whether a legitimate discrepancy exists between the MS I metallicity and that expected for an SMC disk origin. Impending synthesis data from our Australia Telescope Compact Array program (Putman & Gibson 2000) should aid in this regard.

Complicating the above interpretation is the recent work of Rolleston et al. (1999), who found that, for three B-stars in the Magellanic Bridge, [Mg/H]=−0.94 ± 0.14 and [Si/H]=−1.23 ± 0.25. These Bridge stars appear to be ∼0.5 dex deficient in metals compared to a similar B-star (AV 304) in the SMC itself. These stars do not appear to have formed from gas of the present-day SMC or LMC composition. Some unenriched component most likely mixed with the SMC gas to yield abundances low enough to produce the Rolleston et al. results. Evidence is presented therein for the SMC not being as well-mixed as Dufour (1975) had claimed earlier, potentially providing a source for metal-poor contaminating gas. Invoking this metal-poor contamination is counter to that implied by our Fairall 9 MS I sightline, which appears to be enriched (by 0.1−0.2 dex), in comparison with the present-day mean gas-phase abundance of the SMC.

Equations 6 and 7 imply [Si/S] ≳ −1. While this lower limit marginally excludes dust depletion of the magnitude seen in cool diffuse Galactic disk clouds (Savage & Sembach 1996; Figure 6), it is not sufficiently restrictive to discriminate between depletion of the magnitude seen in warm Galactic halo clouds (as might be expected for an SMC origin for the Stream gas – Welty et al. 1997) and warm Galactic disk clouds (as might be expected for an LMC origin – Welty et al. 1999), which typically show silicon depletion of order [Si/S] ≈ −0.4 ± 0.1 (Savage & Sembach 1996; Figure 6). Further, it is known that the gas-phase in both the LMC and SMC is relatively overabundant in silicon, showing [Si/S] ≈ +0.08 ± 0.04 (Welty et al. 1997, 1999). In other words, our limit limit of [Si/S] ≳ −1 for the Magellanic Stream cannot be used as a constraint to differentiate between an LMC versus SMC origin. Impending FUSE Cycle 1 Science Team observations of Fairall 9 (scheduled for July 2000), when coupled with our GHRS data, should shed further light on the dust depletion pattern of the Magellanic Stream.

4.2. III Zw 2

Assuming that the gas near MS V, ∼80° down-Stream from Fairall 9, originates from within the Magellanic Clouds, it is tempting to assign it a magnesium abundance that reflects that of either the LMC or SMC. Unfortunately, the gas-phase magnesium abundance for both Clouds is highly uncertain. Only for the LMC is there a direct measure of the interstellar medium (ISM) gas-phase magnesium, through the IUE absorption line analysis of R136 (de Boer et al. 1985; Welty et al. 1999), the result for which was [Mg/H]=−1.1 ± 0.3. In contrast, spectral synthesis of B-star and F-type supergiant atmospheres implies the much higher abundance [Mg/H]≈ −0.5 −−− 0.1 (Welty et al. 1999; Table 11). For the SMC, no direct ISM absorption line abundances have been published yet, but B-star and supergiant spectral synthesis studies lead to [Mg/H]≈ −0.7 −−− 0.4 (Welty et al. 1997; Rolleston et al. 1999).

As the model curves of Figure 7 show, neither an LMC nor an SMC origin can be excluded based upon
our knowledge of $N({\text{Mg II}})$ and $N({\text{H I}})$, as even the most extreme allowable values for the LMC and SMC magnesium abundances (see above) reside in the parameter space not yet excluded by the upper limit to $N({\text{H I}})$ – i.e., the shaded region. In either case, the total hydrogen column along this sightline would be dominated by $N({\text{H II}})$ and not $N({\text{H I}})$, and the total magnesium column would be dominated by $N({\text{Mg III}})$. This latter result should not be surprising, since the ionization potentials of $\text{H I}$ and $\text{Mg II}$ lie within 10% of each other. Where hydrogen is predominantly ionized, magnesium follows suit, although as discussed above, more magnesium remains in the singly ionized state.

From the Leiden-Dwingeloo Survey (Hartmann & Burton 1997), we can derive the $\text{H I}$ volume density for both the marginally resolved HVC 100.0-48.5-390 (Figure 6) and the clearly resolved MS V concentration at $(\ell, b) \approx (92^\circ, -51^\circ)$. In both cases, $\text{H I}$ column densities $\sim 2 \times 10^{19} \text{ cm}^{-2}$ are found. If the radial extent of the clouds is assumed to be similar to their lateral extent, the angular width times the distance to the clouds must be of order $N(\text{H I})/n(\text{H I})$. At the assumed distance of the LMC ($\sim 50$ kpc), this corresponds to an $\text{H I}$ volume density of $n(\text{H I}) \approx 10^{-1.7} \text{ cm}^{-3}$. If one were to make the assumption that this $\text{H I}$ volume density truly reflected the total hydrogen volume density in those higher column density clouds, and that this represented the typical total hydrogen density of this part of the Magellanic Stream, this would imply that the total hydrogen column density for the absorber toward III Zw 2 was $N(\text{H})=(1-4) \times 10^{18} \text{ cm}^{-2}$ with $N(\text{H II}) \gg N(\text{H I})$.

Because we have no definitive evidence of the nature (if any) of the dust depletion pattern in the Magellanic Stream, the above CLOUDY analysis necessarily adopted the simplifying assumption of zero dust – i.e., pure photoionization effects were employed, in an attempt to reconcile the observed $\text{Mg II}$ and $\text{H I}$ Stream constraints with the observed $[\text{Mg/H}]$ of the LMC and SMC. Such an analysis is a useful exercise, but is no doubt an over-simplification, due to the potential complicating effects of dust depletion. If we subscribe to the conclusion of § 4.1, that the Stream dust depletion may range anywhere from nonexistent, to that seen in warm diffuse Galactic clouds, then our measured gas-phase $\text{Mg II}$ abundance may underestimate the true magnesium abundance by up to a factor of ten. More sensitive $\text{H I}$ observations, coupled with additional absorption measurements for other ions, are necessary.

The LMC and SMC possess magnesium abundances of $[\text{Mg/H}] \approx -1.1 \rightarrow -0.1$ and $[\text{Mg/H}] \approx -0.7 \rightarrow -0.4$, respectively. Regardless of the origin of the high-velocity Stream, it is likely that some degree of dust depletion will be present, since both the LMC and SMC exhibit distinct depletion patterns; the former displays a pattern similar to that seen in warm Galactic disk clouds (Welty et al. 1999), while the pattern seen in the latter resembles that of warm Galactic halo clouds (Welty et al. 1997). Our silicon analysis of the Fairall 9 sightline (§ 3.1) showed that we could not exclude dust depletion patterns similar to those of warm diffuse Galactic gas clouds. This implies a potential correction of $\sim 0 \rightarrow +1$ dex to the measured magnesium abundance (Savage & Sembach 1996; Figure 6). This would retain the consistency of the inferred $[\text{Mg II}/\text{H I}]$ limits of both III Zw 2 ($[\text{Mg II}/\text{H I}] \gtrsim -1.3$) and NGC 7469 ($[\text{Mg II}/\text{H I}] \gtrsim -1.5$) with the present-day SMC stellar abundance value of $[\text{Mg/H}] \approx -0.7 \rightarrow -0.4$.

5. Summary

We summarize in Table 6 the results of our column density measurements and limits for three sightlines through the Magellanic Stream. We have also included our inferences about the abundances of the gas seen along these sightlines, many of which remain uncertain. For the line of sight toward Fairall 9, where ionization corrections are expected to be small, measurements of $[\text{S II}/\text{H I}]$ are consistent with the
present-day abundances of both the LMC and SMC. If this gas was tidally-stripped from the SMC 1.5 Gyrs ago, its abundance is approximately a factor of two greater than that expected. Stochastic star formation effects and remaining systematic uncertainties (particularly in the HI column density) could weaken this statement. New HST/STIS and FUSE observations of Fairall 9 at S III will test the inherent assumption that S III ionization corrections are negligible. Similarly, both III Zw 2 and NGC 7469 need to be revisited with HST/STIS, in order to derive S II and S III column densities. NGC 7469 has been observed by FUSE and its O VI properties discussed by Sembach et al. (2000); further analysis of this FUSE dataset is currently underway. Fairall 9 will likewise be observed by the FUSE Science Team in July 2000.

A fourth potential probe of the Magellanic Stream, in a high HI column density region of MS III, is NGC 7714. It was observed with GHRS by González-Delgado et al. (1999), but with the low-resolution G140L grating. The resulting resolution (>100 km s\(^{-1}\)) was insufficient to accurately separate MS III absorption features from the saturated Galactic lines, as the expected separation (based upon the LDS HI spectrum for this sightline) is only \(\sim 50 \text{ km s}^{-1}\). Scheduled FUSE observations of NGC 7714 should resolve any far-UV MS III lines.

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Fig. 1. – HST GHRS spectrum of Fairall 9 taken with the G160M grating. Fairall 9 samples Magellanic Stream gas associated with the MS I concentration (see Figure 1 of Mathewson 1985). The raw spectrum has been smoothed by the inverse of the post-COSTAR, GHRS, large science aperture, line spread function (LSF – Gilliland 1994), in order to improve the S/N (at the admitted expense of some resolution) and eliminate any LSF-induced asymmetries in the line profiles (Penton, Stocke & Shull 2000). Absorption lines from both Galactic (G) and Magellanic Stream (MS) S II (at 1250 and 1253 Å) and Si II (at 1260 Å) are seen and labeled accordingly. Galactic S II λ 1259 is also seen, but since the corresponding Stream line is blended with Galactic Si II λ 1260, we exclude it from our analysis. Similarly, we will not discuss further the \( z = 0.032 \) Ly α line seen at \( \lambda = 1254.15 \) Å.

Fig. 2. – HST GHRS spectrum of III Zw 2 taken with the G270M grating. III Zw 2 lies \( \sim 15^\circ \) from the peak of the H I emission associated with the MS V concentration of the Magellanic Stream (see Figure 1 of Mathewson 1985). The raw spectrum has been smoothed by the inverse of the post-COSTAR LSF (Gilliland 1994), as noted in the caption to Figure 1. Both Galactic (G) and Magellanic Stream (MS) Mg II λλ 2796,2803 Å is seen in absorption. The centroid of the Galactic lines are blueshifted 0.24 Å with respect to their rest wavelengths (Pickering, Thorne & Webb 1998), reflecting the blended two-component structure of the Galactic gas along this sightline.

Fig. 3. – HST FOS spectrum of NGC 7469 taken with the G270H grating. Galactic (G) and Magellanic Stream (MS) Mg II λλ 2796,2803 Å is seen in absorption, although the Stream is clearly detected in Mg II λ 2796 only.

Fig. 4. – Velocity stack showing H I (upper panel), S II (middle panels) and Si II (lower panel) Galactic (G) and Magellanic Stream (MS) features along the Fairall 9 sightline. The Hanning-smoothed H I spectrum was collected with the Parkes Multibeam Narrowband System (Haynes et al. 1999) and was transformed from the heliocentric to the local standard of rest frame via \( v_{\text{LSR}} = v_{\odot} - 11.6 \text{ km s}^{-1} \). A mild fourth-order polynomial baseline was subtracted from the raw spectrum, and the native Jy/beam converted to T\(_B\) via a multiplicative scale factor of 0.82 (Staveley-Smith 1999). The corresponding H I column densities for both the Galactic and Magellanic Stream components are labeled.

Fig. 5. – Velocity stack showing H I (upper panel) and Mg II (middle and lower panels) Galactic (G) and Magellanic Stream (MS) features along the III Zw 2 sightline. The Hanning-smoothed H I spectrum was taken from the Leiden-Dwingeloo Survey (Hartmann & Burton 1997).

Fig. 6. – Upper Panel: Contours of neutral hydrogen column density \( N(\text{H I}) \) in the vicinity of the MS V component of the Magellanic Stream. Contour levels are \( 5 \times 10^{18} \) cm\(^{-2}\), with the outermost level \( N(\text{H I})=5 \times 10^{18} \) cm\(^{-2}\) over the velocity range \( -400 < v_{\text{LSR}} < -250 \) km s\(^{-1}\). The H I data were taken from the Leiden-Dwingeloo Survey (Hartmann & Burton 1997); the spatial resolution is restricted by the 1/2-degree sampling grid (with a 1/2-degree beam) employed. Both the III Zw 2 and NGC 7469 sightlines are noted. The peak of the H I emission associated with MS V lies near \((l,b)\approx(92^\circ,-51^\circ)\).

Lower Panel: Neutral hydrogen in the immediate vicinity (i.e., the area covered by the marked box in the upper panel) of our III Zw 2 sightline. Contour levels are now \( 3 \times 10^{18} \) cm\(^{-2}\), with the outermost level \( N(\text{H I})= 1 \times 10^{18} \) cm\(^{-2}\), over the velocity range \( -400 < v_{\text{LSR}} < -250 \) km s\(^{-1}\). The local standard of rest velocities of three independently-confirmed (Hulsbosch & Wakker 1988) High-Velocity Clouds within 4° of our III Zw 2 sightline are labeled. The lack of detectable H I at the position and velocity of our Mg II detection in the spectrum of III Zw 2 sets an upper limit of \( N(\text{H I})=5 \times 10^{18} \) cm\(^{-2}\).

Fig. 7. – Grid of CLOUDY (Version 90.04 - Ferland 1996) models showing contours of total magnesium to total hydrogen \(([\text{Mg/H}])\) as a function of total hydrogen column \( N(\text{H}) \) and volume \( n(\text{H}) \) densities. The
models satisfy the observational constraints that $N(\text{Mg II}) = 1 \times 10^{13} \text{cm}^{-2}$ and $N(\text{H I}) < 5 \times 10^{18} \text{cm}^{-2}$, representative constraints imposed by our III Zw 2 analysis. A normally-incident ionizing photon flux of $\phi = 3 \times 10^{53} \text{photons cm}^{-2} \text{s}^{-1}$ was assumed, consistent with that expected at MS V, according to the models of Bland-Hawthorn & Maloney (1999a,b). The shaded region corresponds to the (unfortunately) small part of parameter space excluded by the H I column density constraint.

Fig. 8. – Velocity stack showing H I (upper panel) and Mg II $\lambda2796$ (middle and lower panels) Galactic (G) and Magellanic Stream (MS) features along the III Zw 2 sightline. The Hanning-smoothed H I spectrum was collected at the NRAO 140′ and kindly provided by Ken Sembach prior to publication (Murphy, Sembach & Lockman 2000).
Table 1. HST Observations

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<th>Instrument</th>
<th>Grating</th>
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aHST Proposal ID and Principal Investigator.
bHST Archive dataset filename.

The signal-to-noise ratio per resolution element for the merged Fairall 9 spectrum employed in our analysis is $S/N=30$ (at $\lambda = 1250$ Å). For the single III Zw 2 spectrum, $S/N=8$ (at $\lambda = 2800$ Å); for the single NGC 7469 spectrum, $S/N=29$ (at $\lambda = 2800$ Å). The $3\sigma$ minimum equivalent width detectable for the merged Fairall 9 spectrum is 6 mÅ (at $\lambda = 1250$ Å). For the III Zw 2 spectrum, 27 mÅ (at $\lambda = 2800$ Å), and for the NGC 7469 spectrum, 160 mÅ (at $\lambda = 2800$ Å).
Table 2. Galactic and Magellanic Stream Absorption Features in Fairall 9 Spectrum

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<th>λc [Å]</th>
<th>Δv_{LSR} [km s(^{-1})]</th>
<th>Wλ [mÅ]</th>
<th>N_{v=0} (e) [cm(^{-2})]</th>
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<td>-55→+45</td>
<td>75±4</td>
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<td>(1.25±0.06)(\times)10^{15}</td>
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<td>1251.4</td>
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<td>36±4</td>
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<td>114±3</td>
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<td>(1.03±0.03)(\times)10^{15}</td>
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<td>&gt;9.29(\times)10^{13}</td>
<td>Si II λ1260: Stream</td>
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</table>

\(a\)Line centroid.  
\(b\)Velocity range over which the spectral line integration was applied.  
\(c\)Inferred column density, under the assumption that the line in question is optically thin.  
\(d\)Inferred column density, employing the \(\tau_v\) technique of Sembach & Savage (1992), neglecting continuum placement uncertainties.  
\(e\)Galactic Fe II λ1260 and C I λ1260 appear at +26 km s\(^{-1}\) and +75 km s\(^{-1}\), respectively, in this reference frame. This will impact the lower limit on the column density for the Galactic Si II λ1260 line, and to a lesser extent, the Stream Si II λ1260 line.
Table 3. Atomic Data

<table>
<thead>
<tr>
<th>ID</th>
<th>$\lambda_0$[Å]</th>
<th>$f^b$</th>
<th>$A_{X_\odot}^c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>S II λ1250</td>
<td>1250.578</td>
<td>0.00520</td>
<td>$(1.862 \pm 0.215) \times 10^{-5}$</td>
</tr>
<tr>
<td>S II λ1253</td>
<td>1253.805</td>
<td>0.0103</td>
<td>$(1.862 \pm 0.215) \times 10^{-5}$</td>
</tr>
<tr>
<td>Si II λ1260</td>
<td>1260.4221</td>
<td>1.18</td>
<td>$(3.548 \pm 0.164) \times 10^{-5}$</td>
</tr>
<tr>
<td>Mg II λ2796</td>
<td>2796.354</td>
<td>0.629</td>
<td>$(3.802 \pm 0.175) \times 10^{-5}$</td>
</tr>
<tr>
<td>Mg II λ2803</td>
<td>2803.531</td>
<td>0.314</td>
<td>$(3.802 \pm 0.175) \times 10^{-5}$</td>
</tr>
</tbody>
</table>

$^a$Rest wavelengths from Verner, Barthel & Tytler (1994), except Mg II, which are from Pickering et al. (1998).

$^b$Oscillator strength from Verner et al. (1994).

$^c$Solar (meteoritic) abundance from Table 2 of Anders & Grevesse (1989), for the element X (where X corresponds to S, Si, and Mg, here).
### Table 4. Galactic and Magellanic Stream Absorption Features in III Zw 2 Spectrum

<table>
<thead>
<tr>
<th>$\lambda_c^a$</th>
<th>$\Delta v_{LSR}^b$</th>
<th>$W_\lambda$</th>
<th>$N_{\tau=0}^c$</th>
<th>$N_{\tau_s}^d$</th>
<th>ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Å]</td>
<td>[km s$^{-1}$]</td>
<td>[mÅ]</td>
<td>[cm$^{-2}$]</td>
<td>[cm$^{-2}$]</td>
<td></td>
</tr>
<tr>
<td>2793.1</td>
<td>−400→−320</td>
<td>315±45</td>
<td>(0.72±0.10)$\times10^{13}$</td>
<td>(1.08±0.10)$\times10^{13}$</td>
<td>Mg II $\lambda$2796: Stream</td>
</tr>
<tr>
<td>2796.2</td>
<td>−100→+50</td>
<td>765±47</td>
<td>(1.76±0.11)$\times10^{13}$</td>
<td>$&gt;3.39\times10^{13}$</td>
<td>Mg II $\lambda$2796: Galaxy</td>
</tr>
<tr>
<td>2800.3</td>
<td>−400→−320</td>
<td>149±63</td>
<td>(0.68±0.29)$\times10^{13}$</td>
<td>(0.91±0.14)$\times10^{13}$</td>
<td>Mg II $\lambda$2803: Stream</td>
</tr>
<tr>
<td>2803.3</td>
<td>−100→+50</td>
<td>816±78</td>
<td>(3.74±0.36)$\times10^{13}$</td>
<td>$&gt;7.54\times10^{13}$</td>
<td>Mg II $\lambda$2803: Galaxy</td>
</tr>
</tbody>
</table>

$a$Line centroid.

$b$Velocity range over which the spectral line integration was applied.

$c$Inferred column density, under the assumption that the line in question is optically thin.

$d$Inferred column density, employing the $\tau_v$ technique of Sembach & Savage (1992), neglecting continuum placement uncertainties.
Table 5. Galactic and Magellanic Stream Absorption Features in NGC 7469 Spectrum

<table>
<thead>
<tr>
<th>$\lambda$</th>
<th>$\Delta v_{\text{LSR}}$</th>
<th>$W_{\lambda}$</th>
<th>$N_{\tau=0}$</th>
<th>$N_{\tau_v}$</th>
<th>ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Å]</td>
<td>[km s$^{-1}$]</td>
<td>[mA]</td>
<td>[cm$^{-2}$]</td>
<td>[cm$^{-2}$]</td>
<td></td>
</tr>
<tr>
<td>2793.4</td>
<td>−500→−200</td>
<td>191±42</td>
<td>(0.44±0.10)×10$^{13}$</td>
<td>&gt;0.47±0.11×10$^{13}$</td>
<td>Mg II λ 2796: Stream</td>
</tr>
<tr>
<td>2796.9</td>
<td>−200→+300</td>
<td>652±57</td>
<td>(1.50±0.13)×10$^{13}$</td>
<td>(1.67±0.16)×10$^{13}$</td>
<td>Mg II λ 2796: Galaxy</td>
</tr>
<tr>
<td>2803.7</td>
<td>−150→+250</td>
<td>520±51</td>
<td>(2.38±0.23)×10$^{13}$</td>
<td>(2.65±0.27)×10$^{13}$</td>
<td>Mg II λ 2803: Galaxy</td>
</tr>
</tbody>
</table>

*a* Line centroid.  
*b* Velocity range over which the spectral line integration was applied.  
*c* Inferred column density, under the assumption that the line in question is optically thin.  
*d* Inferred column density, employing the $\tau_v$ technique of Sembach & Savage (1992), neglecting continuum placement uncertainties.
Table 6. Summary of Magellanic Stream Abundance Determinations

<table>
<thead>
<tr>
<th>Probe</th>
<th>N(S II)$^b$ [10$^{14}$ cm$^{-2}$]</th>
<th>N(Si II)$^c$ [10$^{13}$ cm$^{-2}$]</th>
<th>N(Mg II)$^d$ [10$^{13}$ cm$^{-2}$]</th>
<th>N(H I) [10$^{19}$ cm$^{-2}$]</th>
<th>[S II/H I]</th>
<th>[Si II/H I]</th>
<th>[Mg II/H I]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fairall 9</td>
<td>4.95 ± 0.34</td>
<td>&gt;9.29</td>
<td>9.35 ± 0.47</td>
<td>−0.55 ± 0.06</td>
<td>&gt;−1.55±0.03</td>
<td></td>
<td></td>
</tr>
<tr>
<td>III Zw 2</td>
<td>1.02 ± 0.08</td>
<td>&lt; 0.5</td>
<td>0.40 ± 0.04</td>
<td>−0.57 ± 0.10</td>
<td>&gt;−1.27±0.04</td>
<td>&gt;−1.51±0.11</td>
<td></td>
</tr>
<tr>
<td>NGC 7469</td>
<td>&gt;0.47±0.11</td>
<td></td>
<td></td>
<td>−0.57±0.16</td>
<td></td>
<td>I.1→−0.1</td>
<td></td>
</tr>
<tr>
<td>LMC$^e$</td>
<td></td>
<td></td>
<td></td>
<td>−0.68±0.16</td>
<td></td>
<td></td>
<td>−0.7→−0.4</td>
</tr>
<tr>
<td>SMC$^e$</td>
<td></td>
<td></td>
<td></td>
<td>−0.57±0.17</td>
<td></td>
<td></td>
<td>−0.7→−0.4</td>
</tr>
</tbody>
</table>

$^a$Column densities N(S II), N(Si II), and N(Mg II) reflect those derived using the $\tau_v$ technique (Sembach & Savage 1992). Quoted uncertainties correspond to the total statistical noise (equation A27 of Sembach & Savage 1992); continuum placement uncertainties are not included here.

$^b$Based on the weighted mean of N(S II $\lambda$1250) and N(S II $\lambda$1253).

$^c$Based on the saturated line of Si II $\lambda$1260.

$^d$Based on the weighted mean of N(Mg II $\lambda$2796) and N(Mg II $\lambda$2803). In the case of NGC 7469, only N(Mg II $\lambda$2796) was considered.

$^e$Gas-phase abundances – S II from Russell & Dopita (1992); Si II for the LMC from Welty et al. (1999); Si II for the SMC from Welty et al. (1997). The gas-phase magnesium abundances for both the LMC and SMC are highly uncertain. For the LMC, IUE interstellar medium (ISM) absorption line analyses along the line of sight to R136 imply [Mg/H]=−1.1±0.3 (Welty et al. 1999; de Boer et al. 1985); analyses of supernova remnants, B-stars, and supergiants all yield [Mg/H]≈−0.5→−0.1 (Welty et al. 1999; Table 11). For the SMC, no ISM absorption line analyses have been undertaken; spectral synthesis of B-star and supergiant atmospheres yield [Mg/H]≈−0.7→−0.4 (Rolleston et al. 1999; Welty et al. 1997; Table 9).