HIGH-VELOCITY CLOUD COMPLEX C: GALACTIC FUEL OR GALACTIC WASTE?

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ABSTRACT

We present HST Goddard High Resolution Spectrograph and Space Telescope Imaging Spectrograph observations of five quasi stellar objects that probe the prominent high-velocity cloud (HVC) Complex C, covering $\sim 10\%$ of the northern sky. Based upon a single sight-line measurement (Mrk 290), a metallicity $[S/H] = -1.05 \pm 0.12$ has been associated with Complex C by Wakker et al. When coupled with its inferred distance (5 $\leq d \leq$ 30 kpc) and line-of-sight velocity ($v \sim -100$ to -200 km s⁻¹), Complex C appeared to represent the first direct evidence for infalling low-metallicity gas onto the Milky Way, which could provide the bulk of the fuel for star formation in the Galaxy. We have extended the abundance analysis of Complex C to encompass five sight lines. We detect S II absorption in three targets (Mrk 290, 817, and 279); the resulting [S II/H I] values range from -0.36 (Mrk 279) to -0.48 (Mrk 817) to -1.10 (Mrk 290). Our preliminary O I FUSE analysis of the Mrk 817 sight line also supports the conclusion that metallicities as high as 0.3 times solar are encountered within Complex C. These results complicate an interpretation of Complex C as infalling low-metallicity Galactic fuel. Ionization corrections for H II and S III cannot easily reconcile the higher apparent metallicities along the Mrk 817 and Mrk 279 sight lines with that seen toward Mrk 290, since H α emission measures preclude the existence of sufficient H II. If gas along the other lines of sight has a similar pressure and temperature to that sampled toward Mrk 290, the predicted H α emission measures would be ~900 mR. It may be necessary to reclassify Complex C as mildly enriched Galactic waste from the Milky Way or processed gas torn from a disrupted neighboring dwarf, as opposed to low-metallicity Galactic fuel.

Key words: Galaxy: evolution — Galaxy: halo — ISM: abundances — ISM: clouds

1. INTRODUCTION

The infall of low-metallicity gas onto the Milky Way is a crucial component of virtually all Galactic formation and evolution scenarios. The simple closed-box model of chemical evolution assumes no infall, inflow, or outflow within the given region being modeled, and it is successful at explaining many of the observational characteristics of the Galactic disk. However, it fails to reproduce the metallicity distribution of nearby G and K dwarfs, the so-called G-dwarf problem (Pagel 1994; Flynn & Morell 1997), related to the well-known paucity of metal-poor G and K dwarfs in the solar neighborhood.

Closed-box models, in which star formation proceeds as some functional form dependent upon local gas density, tend to overproduce low-metallicity stars before selfenrichment affects subsequent generations of stars. Conversely, infall models are attractive because Galactic disk formation proceeds by gradual accretion of pristine or partially processed material. The initial reservoir of Z = 0 gas in a given volume of the disk is presumed to be negligible, and the number of first generation stars is likewise negligible. The processed ejecta of this first generation mixes with infalling low-metallicity gas, and a second, more substantial, generation of star formation begins, now with Z > 0. This process continues, presumably unabated, to the present day, regulated in a manner that recovers the local G-dwarf metallicity distribution and avoids the overproduction of metal-poor disk stars (e.g., Pagel 1994, Fig. 23).

It should be stressed that infalling fuel does not necessarily need to be pristine in order to satisfy the G-dwarf problem. Under the scenario explored by Tosi (1988), for example, infalling gas metallicities⁵ $[O/H] \leq -1.0$ yield results essentially indistinguishable from primordialmetallicity gas. Infalling gas metallicities $[O/H] \geq -0.5$ can be ruled out, owing to their inability to recover the present-day radial distribution of H II region oxygen abundances in the Galactic disk; intermediate metallicities $-1.0 \leq [O/H] \leq -0.5$ are marginally consistent with this same H II region constraint. More sophisticated models, based upon the dual infall scenario of Chiappini et al. (1999), are currently being examined and are discussed elsewhere (Gibson et al. 2001a, 2001b).

While tenable theoretically, observational proof of the existence of this infalling low-metallicity Galactic fuel had been difficult to obtain prior to the work of Wakker et al. (1999a, 1999b). Larson (1972) suggested that the population of Galactic high-velocity clouds (HVCs) was the most likely culprit, a scenario that has been explored in detail by Tosi (1988). HVCs are defined as neutral hydrogen clouds traveling at velocities incompatible with those allowed by differential Galactic rotation (e.g., Wakker, van Woerden, & Gibson 1999c and references therein). Despite the ubiquity of HVCs, with a sky covering factor as great as 37% (Murphy, Lockman, & Savage 1995), our ignorance con-

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 $^{^{5}}$ Under the assumption of scaled-solar abundance ratios, [O/H] can be replaced by [S/H] for the arguments that follow.

cerning their distance and metallicity makes an unambiguous identification of the Galactic HVCs as infalling Galactic fuel very difficult.

Wakker et al. (1999a, 1999b) derive a metallicity of [S/H] = -1.05 ± 0.12 for one portion of HVC Complex C, using the background Seyfert Mrk 290 as a probe of the intervening gas. This metallicity is 3-5 times lower, for example, than that encountered in the Magellanic Stream ([S II/H I] = -0.5; Gibson et al. 2000). This metallicity is also consistent with Tosi's infalling Galactic fuel model. Wakker et al. conclude that Complex C is a prototypical example of infalling low-metallicity gas responsible for fueling Galactic star formation. As they discuss, the source of this infalling gas could be primordial gas left over from the formation of the Galaxy or from mildly processed gas stripped from local group dwarfs, and it remains undetermined. More metal-rich HVCs must have another association, such as tidal disruption of the Magellanic Clouds (Lu et al. 1998; Gibson et al. 2000) or Galactic fountains (Richter et al. 1999) (Galactic waste) and are unlikely candidates for Galactic fuel. Because of the implications for Galactic formation and evolution, we have undertaken further analysis of Complex C to confirm the inferred low metallicity through studies of four additional sight lines.

In § 2, we present the data and analysis for five *HST* Goddard High Resolution Spectrograph (GHRS) and Space Telescope Imaging Spectrograph (STIS) targets, Mrk 290, 817, 279, 501, and 876. Each target probes the intervening gas associated with HVC Complex C. Because sulfur is little affected by depletion onto dust (Savage & Sembach 1996, Fig. 6), the column densities provided by the S II $\lambda\lambda$ 1250, 1253, 1259 lines yield a robust measure of the metallicity of Complex C and form the basis for much of our analysis. The HVC gas probed by Mrk 290 appears to be of low metallicity (~0.1 × solar), confirming the work of Wakker et al. (1999a, 1999b). The Mrk 817 and Mrk 279 sight lines, however, probe Complex C gas that appears to

be more metal-rich (~ $0.2-0.4 \times$ solar). Conversely, the neutral nitrogen abundance along the Mrk 876 sight line is less than 0.1 times solar. We attempt to reconcile these new observations with the Mrk 290 data by invoking variable ionization conditions within Complex C. To first order, such a reconciliation is difficult. We summarize our results in § 3 and briefly discuss the implications of known published and preliminary metallicity measurements of Complex C made with FUSE. We then suggest future observational tests with *HST*, FUSE, and 21 cm telescopes that may unequivocally discriminate between the low-metallicity galactic fuel and associations appropriate for higher metallicity gas.

2. ANALYSIS

The analysis of Wakker et al. (1999a, 1999b) was restricted to a single probe of Complex C, provided by the background Seyfert Mrk 290. A by-product of the Stocke-Shull *HST* GHRS and STIS program on the origin and physical conditions in the low-redshift $Ly\alpha$ forest (*HST* PID No. 6593+7345) has been the serendipitous detection of several major high- and intermediate-velocity cloud Complexes (Penton, Stocke, & Shull 2000). Our analysis of Magellanic Stream absorption features is described elsewhere (Gibson et al. 2000).

Five of the 31 targets in our full GHRS+STIS sample, including Mrk 290, intersect the foreground HVC Complex C. Figure 1 shows a 2100 deg² region of Complex C, constructed from the Leiden-Dwingeloo H I Survey (Hartmann & Burton 1997). To avoid confusion with Galactic low- and intermediate-velocity gas, we show only the velocity range $-250 < v_{LSR} < -110$ km s⁻¹ in Figure 1. The five targets discussed in the present Complex C abundance analysis (Mrk 290, 817, 279, 501, and 876) are labeled appropriately.

The Complex C H I column densities N(H I) along each sight line span an order of magnitude, ranging from $1.6 \times 10^{19} \text{ cm}^{-2}$ (Mrk 876 sight line) to $11.5 \times 10^{19} \text{ cm}^{-2}$



FIG. 1.—Contours of HVC neutral hydrogen column density N(H I) centered on Complex C over the velocity range $-250 < v_{\text{LSR}} < -110 \text{ km s}^{-1}$. Contour levels are $2 \times 10^{19} \text{ cm}^{-2}$, with the outermost level $N_{\text{HI}} = 1 \times 10^{19} \text{ cm}^{-2}$. The H I data were taken from the Leiden-Dwingeloo Survey (Hartmann & Burton 1997). The five background probes discussed here (Mrk 290, 817, 279, 501, and 876) are labeled. A more detailed map of the area is shown in Wakker (2001).

TABLE 1
HST OBSERVATIONS

PID/PI ^a	Data Set ^b	Date	Target	t_{exp} (s)	Instrument	Grating	$\overset{\lambda_i}{({ m \AA})}$	$\overset{\lambda_f}{(A)}$
6590/Wakker	z3kh0104t	1997 Jan 10	Mrk 290	1622.0	GHRS	G160M	1231.8	1269.0
6590/Wakker	z3kh0105t	1997 Jan 10	Mrk 290	2433.0	GHRS	G160M	1231.8	1269.0
6590/Wakker	z3kh0107t	1997 Jan 10	Mrk 290	2230.3	GHRS	G160M	1231.8	1269.0
6593/Stocke	z3e70104t	1997 Jan 12	Mrk 817	8870.4	GHRS	G160M	1222.6	1258.7
6593/Stocke	z3e70106t	1997 Jan 12	Mrk 817	8236.8	GHRS	G160M	1222.6	1258.7
6593/Stocke	z3e70108t	1997 Jan 12	Mrk 817	7907.3	GHRS	G160M	1222.6	1258.8
6593/Stocke	z3e70304t	1997 Jan 17	Mrk 279	5702.4	GHRS	G160M	1222.5	1258.7
6593/Stocke	z3e70306t	1997 Jan 17	Mrk 279	5702.4	GHRS	G160M	1222.6	1258.7
6593/Stocke	z3e70308t	1997 Jan 17	Mrk 279	5702.4	GHRS	G160M	1222.6	1258.7
6593/Stocke	z3e7030at	1997 Jan 17	Mrk 279	1419.3	GHRS	G160M	1222.6	1258.8
3584/Stocke	z1a65204m	1993 Feb 28	Mrk 501	29196.3	GHRS	G160M	1221.4	1257.6
7295/Coté	o4n30801o	1998 Sep 19	Mrk 876	2298.0	STIS	G140M	1194.8	1249.2

^a HST proposal ID and principal investigator.

^b HST Archive data set filename.

(Mrk 290). We use the Effelsberg H I data of Wakker et al. (2001) in the analysis that follows; the relevant column densities are listed in column (6) of Table 4. It is important to bear in mind that these H I column densities are derived using the 10' Effelsberg beam, while the absorption measurements discussed below sample gas at far higher subarcsecond-scale resolution. It remains an open question as to how accurately H I emission radio measurements represent the gas that is sampled in the pencil beam represented by absorption measurements. Variations as large as a factor of five in N(H I) may be encountered at the arcminute level (Wakker & Schwarz 1991). However, for seven targets for which both less than 1' and 10'-12' H I data exist (Table 1 of Wakker et al. 2001), the ratio of $N(\text{H I})_{1/2}$ $N(\text{H I})_{10}$ is only 0.90 ± 0.13 (with extrema of 0.75 and 1.24). This might lead one to conclude that such spatial resolution limitations are not as critical as first imagined, although this conclusion is based upon only seven data points.

Comparisons have also been made of N(H I) derived from 21 cm mapping with measurements of N(H I) derived from Ly α absorption along the lines of sight to early type stars in the Galactic halo (Lockman, Hobbs, & Shull 1986) and toward extragalactic sources (Savage et al. 2000). The ratio $N(\text{H I})_{\text{Ly}\alpha}/N(\text{H I})_{21\,\text{cm}}$ is somewhat less than unity, with a variation of less than $\pm 50\%$, in agreement with the $N(\text{H I})_{1/}/N(\text{H I})_{10}$, comparison noted above.

In summary, we adopt a conservative first-order estimate of the uncertainty of the adopted N(H I) for each sight line due to this mismatch in resolution of $\pm 0.2 \text{ dex} (\pm 50\%)$. It remains possible that we may have been unfortunate enough to encounter a line of sight with a 10' inferred N(H I)that differs from the "pencil beam" N(H I) by a factor of 5 or more. Higher resolution radio mapping will better address this possibility.

Table 1 lists the 12 *HST* spectra, distributed over the five targets employed in the present study; all but one (Mrk 876) are GHRS G160M data. Of the GHRS data, only one spectrum (Mrk 501) was a pre-COSTAR observation. The data for Mrk 290 (PI: B. Wakker, PID No. 6590) and Mrk 876 (PI: S. Coté, PID No. 7295) were extracted from the *HST* Archive, to supplement the three targets from our GO programs. Details concerning spectrum preparation are described by Penton et al. (2000).

In deriving the metallicity of Complex C, we have employed two different techniques, one based upon the assumption of optically thin absorption features and the other based upon the apparent optical depth method of Sembach & Savage (1992). In the weak-line (optically thin) limit, the column density $N_{\tau=0}$ (per square centimeter) and equivalent width of a line W_{λ} (in milliangstroms) are related through

$$N_{\tau=0} = 1.13 \times 10^{17} \, \frac{W_{\lambda}}{f \lambda_0^2} \,, \tag{1}$$

where λ_0 (in angstroms) is the rest wavelength of the line and f is its oscillator strength (e.g., Savage & Sembach 1996; eq. [3]). For the lines considered in this paper, the relevant values of λ_0 and f are provided in columns (2) and (3) of Table 2.

Under the apparent optical depth method of Sembach & Savage (1992), the apparent column density N_{τ_v} , in the limit of a finite number of data points, is given by

$$N_{\tau_v} = \frac{3.767 \times 10^{14}}{f \lambda_0} \sum_{i=1}^n \ln \left[\frac{I_c(v_i)}{I(v_i)} \right] dv_i , \qquad (2)$$

where $I(v_i)$ and $I_c(v_i)$ are the observed and estimated continuum intensities at velocity v_i (eqs. [A21] and [A29] of Sembach & Savage). The statistical noise uncertainty associated with the apparent column density of equation (2)

TABLE 2ATOMIC DATA^a

ID	λ (Å)	f	$A_{X_{\odot}}{}^{\mathtt{b}}$
N I λ1199 S II λ1250 S II λ1253 S II λ1259 Si III λ1206 Si III λ1206	1199.5496 1250.578 1253.805 1259.518 1206.500 1260.4221	0.1328 0.00545 0.0109 0.0162 1.669 1.007	$(1.122 \pm 0.104) \times 10^{-4}$ $(1.862 \pm 0.215) \times 10^{-5}$ " (3.548 \pm 0.164) × 10^{-5}

^a Rest wavelengths and oscillator strengths from Morton (1991).

^b Solar (meteoritic) abundance from Table 2 of Anders & Grevesse (1989) for the element X (where X corresponds to N, S, and Si here).

is

$$\sigma_{N_{\tau_v}} = N_{\tau_v} \left\{ \sqrt{\sum_{i=1}^n \sigma^2(v_i) / I(v_i)^2 (dv_i)^2} / \sum_{i=1}^n \ln\left[\frac{I_c(v_i)}{I(v_i)}\right] dv_i \right\},$$
(3)

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 signal-to-noise ratio (S/N) GHRS data, the uncertainty associated with the continuum placement is only an additional $\sim 5\%$ beyond that of equation (3) (Penton et al. 2000) and is neglected here.

Generally, our Complex C metallicity determinations are made via the singly ionized S II $\lambda\lambda$ 1250, 1253, 1259 lines. S II is a good species for these measurements because: (1) sulfur is only mildly depleted onto dust, and (2) S II is the dominant ionization stage in the cold and warm photoionized portions of the interstellar medium (Savage & Sembach 1996). It remains true that we do not directly measure [S/H], the sulfur abundance with respect to that of the Sun, but rather S II/H I. Our assumed solar abundances for relevant elements may be found in Table 2.

In §§ 2.1–2.5, we present our GHRS+STIS spectra for each of the five background probes of HVC Complex C. We provide detections and upper limits for N(S II), for Mrk 290, 817, and 279, which, in combination with the H I column densities of Table 4, these yield the ratio S II/H I. Uncertainties in the conversion of this ratio to the *true* metallicity [S/H] will be discussed for the individual sight lines.

2.1. Mrk 290

Wakker et al. (1999a, 1999b) were the first to derive a metallicity for HVC Complex C. Using the S II λ 1253 and S II λ 1259 lines, they found $[S/H] \equiv [(S II + S III)/(H I + H II)] = -1.05 \pm 0.12$, under the assumption that, within the portion of the cloud where hydrogen is fully ionized, sulfur is two-thirds S II and one-third S III, and N(H II) = 0.2N(H I). The latter was derived empirically from their WHAM H α emission measure analysis of the Mrk 290 sight line, for which $I(H\alpha) = 187 \pm 10$ mR. The former assumption is more uncertain, as only upper limits on S II λ 6716 emission were available for this field. However, with such a small inferred H II fraction, their conclusions were insensitive to the assumed S III/S II ratio in the H II region.

Figure 2 shows a 10 Å region of the co-added GHRS G160M spectrum used in our analysis. This spectrum has been smoothed by the post-COSTAR line-spread function (Gilliland 1994) to improve the S/N, although we measure absorption feature equivalent widths from the raw spectra. The Galactic (G) and Complex C (C) S II λ 1253 and S II λ 1259 lines are clearly seen, as is the saturated blend of (G+C) Si II λ 1260. The latter, because of this saturation, provides only a loose lower limit on the silicon abundance along this sight line. The S II λ 1253 line resides on the redward wing of the broad, intrinsic Mrk 290 Ly α emission line, complicating continuum placement.

Normalizing by the local continua, we obtain the S II λ 1259, S II λ 1253, and Si II λ 1260 profiles shown in Figure 3. The abscissa has been transformed from the GHRS heliocentric wavelength scale to velocity with respect to the local



FIG. 2.—HST GHRS spectrum of Mrk 290 taken with the G160M grating. The co-added spectrum has been smoothed by the post-COSTAR, GHRS, large science aperture, line-spread function (Gilliland 1994). The Galaxy (G) and Complex C (C) are seen in S II λ 1253, S II λ 1259, and Si II λ 1260, and labeled accordingly. The expected S II λ 1250 feature is obscured by intrinsic Ly α absorption.

standard of rest (LSR). An a posteriori shift of $+20 \text{ km s}^{-1}$ was applied, in order to reconcile a residual systematic offset between the Galactic and HVC S II absorption features (*middle two panels*) and H I emission features (*top*). The GHRS line profiles shown in Figure 3 are the raw data, unsmoothed by the post-COSTAR GHRS line-spread function. The Effelsberg H I spectrum for this sight line is shown in the top panel of Figure 3, and was kindly provided by Peter Kalberla and Bart Wakker prior to publication (Wakker et al. 2001).

Two individual Complex C components are clearly seen⁶ in both H I and S II λ 1259 but only marginally so in S II λ 1253. The S II and H I centroids for both components agree to within 4 km s⁻¹. We have not deconvolved the line profiles in order to treat components 1 and 2 separately; instead, we have simply integrated over the full line profile in both the Effelsberg and *HST* data sets, just as we did in our earlier analysis of the Magellanic Stream (Gibson et al. 2000).

In Table 3, the first three entries list the relevant information for the S II and Si II detections of Complex C in the Mrk 290 sight line. The line centroid (col. [3]) and velocity range over which the line profile was integrated (col. [4]) yield the quoted equivalent width (col. [5]). These are supplemented by the previously mentioned two determinations of the inferred column density, $N_{\tau=0}$ (optically thin assumption, col. [6]) and N_{τ_v} (apparent optical depth method of Sembach & Savage 1992, col. [7]). Our S II $\lambda\lambda 1253$, 1259 equivalent widths are indistinguishable from those of Wakker et al. (1999a, 1999b) and consistent with the expected theoretical ratio (1.5), suggesting that optical depth effects are minimal.

Using equations (2) and (3), the apparent column densities of the Complex C S II and Si II features seen

⁶ Wakker et al. (1999a, 1999b) state that the $v_{\rm LSR} \approx -105$ km s⁻¹ component of S II λ1259 is missing in the GHRS spectrum. We believe we have detected it, based upon the middle panel of Fig. 3.



FIG. 3.—Velocity stack showing H I (top), S II (middle panels), and Si II (bottom) absorption features along the Mrk 290 sight line. The Effelsberg H I data are from Wakker et al. (2001). The raw (i.e., not smoothed by the post-COSTAR line-spread function) GHRS data are shown in the bottom three panels. Centroid, equivalent widths, and column densities for the Complex C absorption features are listed in Table 3.

in the Mrk 290 GHRS spectrum are $(N)_{\tau_v}(S \Pi \lambda 1259) = (1.81 \pm 0.24) \times 10^{14}$ cm⁻², $N_{\tau_v}(S \Pi \lambda 1253) = (1.65 \pm 0.17) \times 10^{14}$ cm⁻², and $N_{\tau_v}(S \Pi) > 1.0 \times 10^{14}$ cm⁻². The S Π -weighted average is $N_{\tau_v}(S \Pi) \equiv N(S \Pi) = (1.70 \pm 0.14) \times 10^{14}$ cm⁻². With a solar abundance $A_{S_{\odot}} = (1.862 \pm 0.215) \times 10^{-5}$ (col. [4] of Table 2) and $N(H \Pi) = (11.5 \pm 0.5) \times 10^{19}$ cm⁻² (Table 4), we can now write the S Π and Si Π abundances for Complex C (sampled by Mrk 290), as

 $[S \text{ II/H I}] = -1.10 \pm 0.06$ $[Si \text{ II/H I}] > -1.61 \pm 0.03$

The above quoted uncertainty only represents the random statistical component; a conservative systematic uncertainty of ± 0.10 dex is assumed for both N(H I) (Wakker 2001) and the GHRS continuum placement (Penton et al. 2000), for a total systematic uncertainty of ± 0.14 dex.

Of potentially greater concern are the ionization corrections required to derive [S/H] from our [S II/H I] determination. Based on their WHAM data, Wakker et al. (1999a, 1999b) find $N(H II) = (0.20 \pm 0.07)N(H I)$, and under the assumption that within the portion of the cloud where hydrogen is fully ionized, 0%-100% of the sulfur is in the form of S III, $N(S III) = (0.0-0.2 \pm 0.07)N(S II)$. This implies a correction that may reach 0.08 ± 0.03 dex, if N(S III) = 0, in the sense of [S/H] = [S II/H I] - 0.08. However, one must bear in mind that the WHAM field of view is 1°, and the same resolution uncertainties that plague H I column density determinations also affect the H II measurements. In addition, for systems with larger fractions of H II, uncertainties in the fraction of S III present in these ionized regions become increasingly important. Because we have as yet no emission measure information for any of our remaining sight lines,⁷ we generally restrict our discussion to [S II/H I], but we draw attention to important implications for future emission measure work where appropriate.

As an additional way to explore the uncertainties associated with converting [S II/H I] to [S/H], we have constructed a grid of photoionization models using the code CLOUDY (Ferland 1996). We make the very simplified assumption that the absorbers are plane-parallel slabs of gas illuminated on one side by incident ionizing radiation dominated by Galactic OB associations. We approximate this integrated spectrum with a power-law v^{-2} spectrum between 1 and 4 ryd, with a factor of 100 drop beyond 4 ryd, which includes the harder extragalactic component. We assume a level of ionizing radiation compatible with Complex C being at a distance of order 10-20 kpc and exposed to approximately 5% of the ionizing radiation produced in the Galaxy, that is, a one-sided, normally incident photon flux (photons per square centimeter per second) of $\log \phi \approx 5.5$. While this power law is a reasonable approximation of the integrated spectrum of OB associations (Sutherland & Shull 2001), we also consider a softer spectrum, that based upon a T = 35000 K Kurucz model atmosphere. Such a soft ionizing spectrum has been suggested to account for emission-line ratios in the warm interstellar medium (Sembach et al. 2000).

Figure 4 summarizes the results of our calculations. The top panel, which assumes the absorber has $N(\text{H I}) = 10^{20}$

 7 Murphy et al. (2000) recently reported the nondetection of H α in the WHAM data for the Mrk 876 sight line; we return to this in § 2.5.

			COMPLEX C ABSO	rption Featu	RES	
Probe	Line ID	λ_c^{a} (Å)	$\Delta v_{\rm LSR}^{\ \ b}$ (km s ⁻¹)	W _λ (mÅ)	$\frac{N_{\tau = 0}^{c}}{(cm^{-2})}$	$N_{ au_v}{}^{\mathbf{d}}_{\mathbf{c}_v}$ (cm ⁻²)
Mrk 290 Mrk 290 Mrk 290 Mrk 817 Mrk 817 Mrk 279 Mrk 876 Mrk 876	S π λ1253 S π λ1259 Si π λ1260° S π λ1250 S π λ1253 S π λ1250 N τ λ1199.5 Si m λ1206	1253.2 1258.9 1259.9 1249.9 1253.3 1249.8 1198.9 1205.8	$-170 \leftrightarrow -85$ $-170 \leftrightarrow -85$ $-180 \leftrightarrow -60$ $-140 \leftrightarrow -80$ $-140 \leftrightarrow -80$ $-180 \leftrightarrow -90$ $-210 \leftrightarrow -95$ $-250 \leftrightarrow -95$	$\begin{array}{c} 23 \pm 3 \\ 37 \pm 5 \\ 399 \pm 5 \\ 13 \pm 3 \\ 27 \pm 3 \\ 18 \pm 3 \\ 134 \pm 15 \\ 363 \pm 12 \end{array}$	$\begin{array}{c} (1.61\pm 0.21)\times 10^{14}\\ (1.70\pm 0.23)\times 10^{14}\\ (2.82\pm 0.04)\times 10^{13}\\ (1.81\pm 0.42)\times 10^{14}\\ (1.89\pm 0.21)\times 10^{14}\\ (2.50\pm 0.70)\times 10^{14}\\ (0.65\pm 0.07)\times 10^{14}\\ (1.68\pm 0.06)\times 10^{13} \end{array}$	$\begin{array}{c} (1.65\pm0.17)\times10^{14}\\ (1.81\pm0.24)\times10^{14}\\ >1.0\times10^{14}\\ (1.83\pm0.29)\times10^{14}\\ (1.90\pm0.14)\times10^{14}\\ (2.48\pm0.68)\times10^{14}\\ (1.01\pm0.13)\times10^{14}\\ >4.1\times10^{13} \end{array}$

^a Line centroid.

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

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

^d Inferred column density, employing the τ_v technique of Sembach & Savage (1992), neglecting continuum placement uncertainties.

^e Blended with Complex C Fe II λ 1260 absorption.



FIG. 4.—Ionization correction to S II/H I vs. density $n_{\rm H}$. All curves are based upon photoionization models which assume a one-sided, normally incident photon flux $\phi = 10^{5.5}$ photons cm⁻² s⁻¹. The top panel assumes plane-parallel slab with $N({\rm H~I}) = 10^{20}$ cm⁻². Solid and dotted curves assume spectral shape for ionizing radiation as labeled. Upper curves assume $Z/Z_{\odot} = 0.1$. Lower curves assume solar metallicity. Bottom panel is the same as top, except $N({\rm H~I}) = 10^{19}$ cm⁻².

cm⁻², indicates that little ionization corrections are required for high column density lines of sight such as those toward Fairall 9 (Gibson et al. 2000). Even for the case when the density $n_{\rm H} = 0.01$ cm⁻³ and metallicities are 0.1 of solar, [S II/H I] provides only a 50% overestimate of [S/H]. For higher densities, the correction is negligible. For much lower column densities $N({\rm H~I}) = 10^{19}$ cm⁻², the bottom panel shows that the ionization correction remains small for $n_{\rm H} \gtrsim 0.1$ cm⁻³.

2.2. Mrk 817

Figure 5 shows a 16 Å region of our GHRS G160M co-added spectrum of Mrk 817, centered on the intervening Galactic S II λ 1250 feature. The spectrum was smoothed with the post-COSTAR line-spread function (Gilliland 1994). As was the case for Mrk 290, Galactic (G) and Complex C (C) S II features, here at 1250 and 1253 Å, are clearly seen in absorption. Because the S II λ 1253 features coincide with the peak of the intrinsic Ly α emission line associated with Mrk 817, identification of the local continuum is more challenging than it was for Mrk 290, although we retain confidence in the third-order polynomial employed.

The normalized velocity stack of relevant S II absorption features is shown in Figure 6. We employed a shift of +20 km s⁻¹ to bring the centroids of the Galactic S II features into alignment with those of the Galactic H I (*top*, Fig. 6). The Complex C H I column density along this sight line is $N(\text{H I}) = (3.0 \pm 0.1) \times 10^{19} \text{ cm}^{-2}$ (Wakker et al. 2001).

The equivalent widths for the two Complex C S II absorption features, $W_{\lambda}(1253 \text{ \AA}) = 27 \pm 3 \text{ m\AA}$ and $W_{\lambda}(1250 \text{ \AA}) = 13 \pm 3 \text{ m\AA}$ (see relevant entries in Table 3), are consistent



FIG. 5.—HST GHRS spectrum of Mrk 817 taken with the G160M grating. The co-added spectrum has been smoothed by the post-COSTAR, GHRS, large science aperture, line-spread function (Gilliland 1994). The Galaxy (G) and Complex C (C) are seen in S II λ 1250 and S II λ 1253 and labeled accordingly.

with the expected theoretical ratio (2.0), again suggesting that saturation effects are minimal, as they were for the Mrk 290 sight line. Using equations (2) and (3), we find the S II column density to be $N(S II) = (1.89 \pm 0.13) \times 10^{14} \text{ cm}^{-2}$.

Coupling the S II and H I column densities, we infer the Complex C sulfur abundance along this Mrk 817 sight line to be

$$[S II/H I] = -0.48 \pm 0.06$$

a factor of 4 times greater than the inferred [S II/H I] along the line of sight to Mrk 290 (§ 2.1). Again, the quoted error budget reflects internal statistical uncertainties alone.

It is tempting to now explore whether our Mrk 817 result, [S II/H I] = -0.48 ± 0.06, could be reconciled with the



FIG. 6.—Velocity stack showing H I (top), S II $\lambda 1253$ (middle), and S II $\lambda 1250$ (bottom) absorption features along the Mrk 817 sight line. The Effelsberg H I data are from Wakker et al. (2001). The raw (i.e., not smoothed by the post-COSTAR line-spread function) GHRS data are shown in the bottom two panels. Centroid, equivalent widths, and column densities for the Complex C absorption features are listed in Table 3.

Wakker et al. (1999a, 1999b) result for Mrk 290, $[S/H] = -1.05 \pm 0.12$, via ionization corrections. We assume a simple model where the gas is either completely neutral in H or completely ionized in H. In the H I region, S is entirely S II, being photoionized by diffuse ultraviolet radiation. In the H II region, S is divided between S II and S III, with a ratio r = S III/S II. In this case, it may be shown that the additional ionized hydrogen column density N(H II), which must be invoked to reconcile [S II/H I] with [S/H] is

$$\frac{N(\text{H II})}{N(\text{H I})} = (1 + r)(10^{[\text{SII/HI}] - [\text{S}/\text{H}]} - 1) .$$
 (4)

Under the assumption that the Mrk 290 metallicity determination ([S/H] = -1.05) is correct, and r = 0.5, equation (4) implies that a column density N(H II) = 4.1N(H I) must be present to be consistent with [S II/H I].⁸

This estimate represents an unreasonably large amount of additional ionized hydrogen, for reasons that we now explain. Combined with the Effelsberg H I data, $N(\text{H I})_{\text{Eff}} =$ $3.05 \times 10^{19} \text{ cm}^{-2}$, this implies $N(\text{H II}) = 1.24 \times 10^{20} \text{ cm}^{-2}$. If we assume that the temperature and pressure of the Complex C gas probed by Mrk 817 and 279 are similar to that inferred for the Mrk 290 sight line, and adopt the Wakker et al. (1999a) standard model of constant density, neutral core, and ionized shell, we can scale the observational results provided by WHAM (see § 2.1), to yield a first-order prediction for the H α emission measure $I(\text{H}\alpha)_{\text{pred}}$ along the Mrk 817 sight line,

$$I(\mathrm{H}\alpha)_{\mathrm{pred}} = \frac{N(\mathrm{H}\ \mathrm{II})_{\mathrm{Mrk}817}}{N(\mathrm{H}\ \mathrm{II})_{\mathrm{Mrk}290}} I(\mathrm{H}\alpha)_{\mathrm{Mrk}290} , \qquad (5)$$

where $N(\text{H II})_{\text{Mrk 290}} = (1.93 \pm 0.52) \times 10^{19} \text{ cm}^{-2}$ and $I(\text{H}\alpha)_{\text{Mrk 290}} = 187 \pm 10 \text{ mR}$. For $N(\text{H II})_{\text{Mrk 817}} = 1.24 \times 10^{20} \text{ cm}^{-2}$, equation (5) predicts an H α emission measure of $I(\text{H}\alpha)_{\text{pred}} \approx 1200 \text{ mR}$. Arbitrarily setting N(S III) = 0 (i.e., not allowing S III to track H II, contrary to expectations) for Mrk 817, the inferred N(H II) would be reduced to 2.7N(H I). The predicted H α emission measure, under this scenario, is $I(\text{H}\alpha)_{\text{pred}} \approx 800 \text{ mR}$, still a surprisingly high result. We emphasize, however, that this is a highly tentative suggestion for the magnitude of $I(\text{H}\alpha)_{\text{pred}}$. If we assume a range in r = 0.2–0.8 and propagate our formal uncertainties as well as the uncertainties in the Wakker et al. (1999a, 1999b) results through equations (4) and (5), this would introduce a range in $I(\text{H}\alpha)_{\text{pred}} \approx 600$ –4000 mR. Inclusion of the systematic uncertainties in our measurements would broaden this range still further.

We estimate that the true H I column density along the Mrk 817 sight line would have to be $N(\text{H I})_{\text{true}} \approx 2.5N$ (H I)_{Eff}, in order to reconcile the apparent metallicity ([S II/ H I] = -0.48) with that seen toward Mrk 290 ([S/ H] = -1.05). As we have discussed, one cannot exclude the suggestion that $N(\text{H I})_{\text{Eff}}$ underestimates the true H I column density by a factor of 2.5. However, despite the fact that N(H I) toward the Mrk 290 sight line was measured with additional 2' Westerbork data, one similarly cannot dismiss the suggestion that its column may be overestimated by the same factor of 2.5, since the 2' Westerbork beam is still 2 orders of magnitude greater than the solid angle probed by GHRS. Indeed, the intermediate velocity

gas in the foreground of globular clusters such as M13, M15, and M92 show factors of 10 and more variations in N(Na I). One also sees variations approaching a factor of 10 in N(Ca II), and possibly N(H I), on 10" angular scales. At distance d = 100 pc, this corresponds to order-of-magnitude variations on 0.005 pc spatial scales (Shaw et al. 1996; Meyer & Lauroesch 1999; Andrews, Meyer, & Lauroesch 2001; see references therein for similar studies using binary or single stars). The latter scale is three orders of magnitude smaller than the Complex C spatial scale probed by the 2' Westerbork beam for d = 10 kpc. While these metal ions are generally not the dominant ion and so may not trace H I faithfully, they do suggest that significant H I column variations at subarcminute scales may complicate both Mrk 290 and Mrk 817 analyses. Further evidence of significant subarcsecond H I column density variations in the interstellar medium are provided by Davis, Diamond, & Goss (1996).

2.3. Mrk 279

Our co-added GHRS G160M spectrum of Mrk 279 is the final sight line for which we claim a detection of S II. Figure 7 shows a 14 Å region of the spectrum employed, again centered upon the Galactic S II λ 1250 absorption feature. Complex C is seen in S II λ 1250 absorption, as identified. The detection is admittedly significant only at the 4 σ level (Penton et al. 2000), but was identified in a survey unbiased by any knowledge of corresponding H I. It is apparent in each of the four individual subexposures, and we currently see no compelling reason to dismiss the line assignment, despite its lower significance.

The H I profile along this sight line is significantly more Complex than that encountered in any of the others included in the present study. Wakker et al. (2001) decompose the full profile (*top*, Fig. 8) into eight components at low, intermediate, and high velocity. Two Complex C components can be identified (centered at -102 km s^{-1} and -137 km s^{-1}), with combined H I column density $N(\text{H I}) = (3.1 \pm 0.4) \times 10^{19} \text{ cm}^{-2}$. We have made no



FIG. 7.—HST GHRS spectrum of Mrk 279 taken with the G160M grating. The co-added spectrum has been smoothed by the post-COSTAR, GHRS, large science aperture, line-spread function (Gilliland 1994). The Galaxy (G) and Complex C (C) are seen in S II λ 1250 and labeled accordingly.

⁸ For r = 0 (1), N(H II) = 2.7 (5.4)N(H I).



FIG. 8.—Velocity stack showing H I (top), S II λ 1253 middle), and S II λ 1250 (bottom) absorption features along the Mrk 279 sight line. The Effelsberg H I data are from Wakker et al. (2001). The raw (i.e., not smoothed by the post-COSTAR line-spread function) GHRS data are shown in the bottom two panels. Intrinsic Mrk 279 Ly α absorption obscures the expected Complex C S II λ 1253 absorption feature in the middle panel. Centroid, equivalent widths, and column densities for the Complex C S II λ 1250 absorption feature are listed in Table 3.

attempt to deconvolve the S II $\lambda 1250$ absorption feature and simply integrate both the S II and H I profiles over the full velocity range spanned by the two components. The result of the S II integration is a measured equivalent width of 18 ± 3 mÅ, where the uncertainty is a reflection of the formal statistical error.

The middle and bottom panels of Figure 8 show the normalized GHRS spectrum in the vicinity of S II λ 1253 and S II λ 1250, respectively. A velocity shift of +20 km s⁻¹ was applied, in order to align the centroids of the Galactic S II $\lambda\lambda$ 1250, 1253 lines with the Galactic H I. It should be stressed that the appropriate correction to the velocity scale was difficult to ascertain. Strong $Ly\alpha$ absorption intrinsic to Mrk 279 is seen "redward" of the Galactic S II $\lambda 1250$ absorption, spanning $+50 \leq v_{LSR} \leq +350$ km s⁻¹) and complicating the velocity scale determination. While +20km s^{-1} was the applied shift, we estimate that this is uncertain at the ± 20 km s⁻¹ level. This additional uncertainty compounds the systematic uncertainty arising from the assumption that the lower angular resolution H I map is a faithful guide to the S II velocity profile. We have explored the extent of this uncertainty by stepping our integration from -200 to -110 km s⁻¹ to -160 to -70 km s⁻¹. This can introduce high excursions in the measured equivalent width as the integration begins to include Galactic absorption. The lowest excursion in measured equivalent width is 16.1 ± 3 mÅ. While this is an external value, to be conservative we have added this 1.9 mÅ excursion to the formal uncertainty.

Complex C S II absorption along this sight line is only apparent in the S II $\lambda 1250$ line, at $-180 \leq v_{LSR} \leq -90$ km s⁻¹ (bottom, Fig. 8). The characteristics of the feature (i.e., centroid, equivalent width, etc.) are listed in Table 3. The centroid of the Complex C S II $\lambda 1250$ absorption is offset by ~ 20 km s⁻¹ from the H I, but the aforementioned uncertainty in the velocity scale makes the significance of this offset unclear. Unfortunately, the predicted location of the expected Complex C S II $\lambda 1253$ absorption coincides with strong Ly α absorption intrinsic to Mrk 279 at $v_{LSR} \approx -150$ km s⁻¹ (*middle*, Fig. 8). Our conclusions here are necessarily based upon the single S II λ 1250 line.

With $N(\text{H I}) = (3.1 \pm 0.4) \times 10^{19} \text{ cm}^{-2}$ and an apparent S II column density $N(\text{S II } \lambda 1250) = (2.48 \pm 0.68) \times 10^{14} \text{ cm}^{-2}$, equations (2) and (3) yield

$$[S \Pi/H \Pi] = -0.36 \pm 0.18$$
.

Recall that for the Mrk 290 and 817 sight lines we found $[S II/H I] = -1.10 \pm 0.06$ and $[S II/H I] = -0.48 \pm 0.06$, respectively. The inferred metallicity along this Mrk 279 sight line seems surprisingly high.

As was found to be the case for Mrk 817, it seems untenable to appeal to ionization corrections to reconcile our derived $[S II/H I] = -0.36 \pm 0.18$ with the [S/H] = -1.05 ± 0.12 found for Mrk 290 by Wakker et al. (1999a, 1999b), Using equation (4) for Mrk 279, we find N(H II) = 1.79×10^{20} cm⁻², assuming S III/S II = 0.5. Via equation (5), the predicted H α emission measure in this case would be $I(\text{H}\alpha)_{\text{pred}} \approx 1700 \text{ mR}, \sim 40\%$ greater than that predicted for the Mrk 817 sight line (§ 2.2), and a factor of ~ 9 times greater than that seen toward Mrk 290.9 The marginal detection of S III $\lambda 1012$ in our high S/N FUSE spectrum implies $N(S \text{ III}) \approx (0.3-0.4) \times 10^{14} \text{ cm}^{-2}$, which is only 14% that of the S II column density. This would imply N(H)II) $\approx 1.4 \times 10^{20}$ cm⁻² and $I(\text{H}\alpha) \approx 1300$ mR. Even in the limit of N(S III) = 0 in the ionized regions of the cloud, an H II column density of $N(H II) \gtrsim 10^{20} \text{ cm}^{-2}$ is needed to bring the Mrk 279 metallicity into formal 1 σ agreement with that inferred from Mrk 290. In this case, N(H II) is still a factor of 5 greater than that seen along the Mrk 290 sight line.

Since the S II $\lambda 1250$ absorption is real and visible in each of the four subexposures, we are left with two options. Either our line assignment is valid and the inferred metallicity is a factor of ~5 times higher than that along the Mrk 290 line of sight, or the 1250 Å feature is an intrinsic Ly α feature, and (perhaps) there is no metallicity discrepancy. The detection of Fe II $\lambda\lambda 1122$, 1144 and Si II $\lambda 1020$ with FUSE lends indirect support to our line assignment. Regardless, without S II $\lambda\lambda 1253$, 1259 we are unable to unequivocally rule out a line misidentification for our claimed S II $\lambda 1250$ HVC feature.

2.4. Mrk 501

For completeness, we include here our GHRS pre-COSTAR G160M spectrum of Mrk 501. This background Seyfert probes a small clump of Complex C approximately 30° from Mrk 290 (see Fig. 1). Figure 9 shows a 16 Å region of the spectrum, smoothed with the pre-COSTAR linespread function. The identification of line-free continuum regions in Figure 9 is clearly difficult, complicated by the significant undulations seen throughout the spectrum. The latter can masquerade as broad, shallow, absorption features.

The normalized spectra in the vicinity of S II $\lambda 1253$ and S II $\lambda 1250$ are shown in the middle and bottom panels, respectively, of Figure 10; the top panel shows the Effelsberg H I profile along this line of sight. The two-component structure of Complex C is apparent, as it was for Mrk 279 (Fig. 8). The total H I column density, integrating over both components, is $N(\text{H I}) = (1.6 \pm 0.1) \times 10^{19} \text{ cm}^{-2}$.

 $^{^9}$ And a factor of $\gtrsim\!\!85$ times greater than that seen toward Mrk 876 (Murphy et al. 2000).



FIG. 9.—HST GHRS spectrum of Mrk 279 taken with the G160M grating. The spectrum has been smoothed by the pre-COSTAR, GHRS, large science aperture, line-spread function (Gilliland 1994). The Galaxy (G) is seen in S II λ 1250 and S II λ 1253, and labeled accordingly. The continuum in the vicinity of both Galactic features is poorly determined, complicating the identification of any potential Complex C absorption features.

The continuum near S II $\lambda 1250$ is particularly poorly constrained, as witnessed by the middle panel of Figure 10, so we will restrict the following discussion to the *marginally* better determined continuum near S II $\lambda 1253$. With a local continuum defined over the $-1400 \le v_{\text{LSR}} \le +800 \text{ km s}^{-1}$ region surrounding S II $\lambda 1253$, the nondetection of Complex C S II $\lambda 1253$ absorption sets an upper limit¹⁰ to N(S II

 10 The local continuum employed here is to be preferred over the global one used by Penton et al. (2000), at least for the analysis of Complex C absorption.



FIG. 10.—Velocity stack showing H I (top), S II λ 1253 (middle), and S II λ 1250 (bottom) absorption features along the Mrk 501 sight line. The Effelsberg H i data are from Wakker et al. (2001). The raw (i.e., not smoothed by the pre-COSTAR line-spread function) GHRS data are shown in the bottom two panels. Absorption due to Complex C is not seen unambiguously in either S II line, yielding only a loose constraint on the upper limit on the metallicity along this sight line of [S II/H I] ≤ -0.1 .

 $\lambda 1253$) of 2.0 × 10¹⁴ cm⁻². This conservative upper limit sets a fairly unrestrictive upper limit to the sulfur abundance of

$$[S II/H I] < -0.16 \pm 0.06$$
.

Because of the uncertain local continuum identification, we do not wish to belabor further the Mrk 501 constraint. Complicating the analysis still further is the fact that there appears to be an IVC along this sight line whose properties may have contaminated our analysis (see Wakker 2001 for details).

2.5. Mrk 876

Mrk 876 was observed by Coté et al. (PID No. 7295), as part of their STIS G140M program designed to probe the outer disk/halo of nearby spirals. As Figure 11 shows, Coté et al. have been successful in detecting Ly α absorption associated with the halo of NGC 6140. A second, serendipitous, detection of Ly α associated with a small group of galaxies at $v \approx 3500$ km s⁻¹ is also seen. Because the Coté et al. program was centered on relatively low-redshift Ly α , their STIS G140M wavelength range did not encompass the S II lines. Instead, we will restrict ourselves to the constraints imposed by the detection of Complex C in N I λ 1199.5 and Si III λ 1206. The S/N in this single STIS spectrum is only ~8, with a 3 σ detection limit of ~58 mÅ near both of these features. Despite the low S/N, our analysis does provide a useful complement to the FUSE Early Release Observations described by Murphy et al. (2000).

Murphy et al. (2000) found [Fe II/H I] = -0.32 ± 0.19 and [N I + N II/H I] > -0.83 ± 0.10 for Complex C along the Mrk 876 line of sight. This apparent high iron abundance is at odds with the sulfur abundance derived toward Mrk 290, but in agreement with the higher sulfur values derived from our Mrk 817 and Mrk 279 data. Wakker



FIG. 11.—HST STIS spectrum of Mrk 876 taken with the G140M grating. Complex C absorption is seen in the blueward wings of the saturated Galactic N I and Si III lines. Galactic Ly α dominates the spectrum. Two intervening galactic halos are detected in Ly α : (1) the extended halo of NGC 6140, at $v \approx +930$ km s⁻¹ (impact parameter of ~180 h_{70}^{-1} kpc); and (2) the extended halo of UGC 10294, at $v \approx 3490$ km s⁻¹ (impact parameter of ~270 h_{70}^{-1} kpc) and will not be discussed further.

(2001) favors a photoionization interpretation to the FUSE Mrk 876 iron results, such that $N(H II) \approx 3N(H I)$ and $N(Fe) \approx N(Fe II)$, and therefore [Fe/H] ≈ -1.0 . Such ionization ratios are unusual in the ISM. The nondetection of H α (Murphy et al. 2000) is also somewhat surprising (see the related discussions of predicted emission measures in §§ 2.2 and 2.3).

While the overall shape of the continuum near N I λ 1199.5 and Si III λ 1206 is well defined, the low S/N makes setting its "zero point" somewhat uncertain. Regardless, normalizing by the best-fit third-order polynomial leads to the N I λ 1199.5 and Si III λ 1206 profiles shown in the middle and bottom panels, respectively, of Figure 12. The top panel shows the same H I two-component structure seen in previous sight lines; the total H I column density is $N(\text{H I}) = (2.3 \pm 0.2) \times 10^{19} \text{ cm}^{-2}$.

The first thing to note from Figure 12 is that both Galactic and Complex C Si III λ 1206 absorption features are clearly saturated and blended. We can do little more than set an unrestrictive lower limit on [Si III/H I]. Integrating the line profile over the range $-250 \le v_{LSR} \le -95$ km s⁻¹ yields the equivalent width (col. [5]) and apparent column densities (col. [7]) listed in the final entry of Table 3. These data imply

$$[Si III/H I] > -1.30 \pm 0.04$$
.

Unlike sulfur, silicon is easily depleted onto dust, so an upward correction of 0.3-1.0 dex would not be unexpected (Savage & Sembach 1996). Both ionization and line saturation effects act in the direction of increasing [Si III/H I], although it should be noted that Si III is not expected to coincide spatially with the H I.

The middle panel of Figure 12 is perhaps more intriguing. While the data are noisy, there is clear evidence for an extended "blue" wing to the saturated Galactic N I λ 1199.5 absorption feature, coinciding with the position of the Complex C H I emission (*top*). The inferred apparent column density (Table 3), coupled with the Effelsberg



FIG. 12.—Velocity stack showing H I (top), N I λ 1199.5 (middle), and Si III λ 1206 (bottom) absorption features along the Mrk 876 sight line. The Effelsberg H I data are from Wakker et al. (2001). N(N I λ 1199.5) inferred from the blueward absorption "wing" of the Galactic N I λ 1199.5 feature is consistent with N(N I λ 1134.1), derived by Murphy et al. (2000). Centroids, equivalent widths, and column densities for the Complex C N I λ 1199.5 and Si III 1206 absorption features are listed in Table 3.

N(H I), yields a measure of the nitrogen abundance for Complex C of

$$[N I/H I] = -1.41 \pm 0.08$$

In the absence of any ionization correction, this inferred metallicity is surprisingly low in comparison with the previous sight lines discussed here (§§ 2.1–2.4). A grid of CLOUDY models (see § 2.1) was constructed to explore the magnitude of any potential ionization correction. For $N(\text{H I}) > 10^{19} \text{ cm}^{-2}$ and density $n_{\text{H}} > 0.01 \text{ cm}^{-3}$, we find [N I/H I] = (0.6-1.0)[N/H]. For $n_{\text{H}} > 0.1 \text{ cm}^{-3}$, [N I/H I] is equivalent to [N/H] to within 10%. Thus, for a wide range of ionization and density conditions, the ratio of neutral nitrogen to hydrogen is a very good representation of the true nitrogen metallicity. This result is also insensitive to variations in the shape of the spectrum of the incident radiation field. Since nitrogen is not depleted onto dust (Savage & Sembach 1996) and the N I λ 1199.5 is not severely saturated, the current constraint upon [N I/H I] appears robust.¹¹

Since we expect that [N I/H I] should trace [N/H], we are left with three possibilities for the low [N I/H I] metallicity inferred along this sight line: either (1) there are significant and unexpected ionization corrections for higher ion species of nitrogen, without a consequent correction for ionized hydrogen; (2) the nucleosynthetic history of Complex C nitrogen is significantly different from that of its sulfur enrichment; or (3) our inferred N I column density is underestimated by approximately a factor of 2. In the absence of proof to the contrary concerning point 3, we believe that option 2 is most likely, since nitrogen and sulfur have different nucleosynthetic origins. Sulfur is produced in equal measure by Type Ia and Type II supernovae (Gibson, Loewenstein, & Mushotzky 1997), while nitrogen is primarily produced by hot-bottom burning in thermally pulsating asymptotic giant branch (AGB) stars (Gibson & Mould 1997). Primary nitrogen might be a by-product of primordial-metallicity, high-mass stars, but it is not the dominant nitrogen production mechanism. If the Mrk 876 sight line probes a region of Complex C that, for whatever reason, is free of AGB stellar "pollution," a significantly lower [N/S] or [N/Fe] might be expected. The Murphy et al. (2000) analysis of the FUSE Early Release Observations found [N I/Fe II] = -0.74, in agreement with our (current) favored interpretation of this low-S/N STIS data.

3. DISCUSSION

We have undertaken a self-consistent GHRS and STIS analysis of five different probes of HVC Complex C. It has been suggested that Complex C represents the best example of the predicted infalling low-metallicity gas responsible for fueling the bulk of star formation in the Galaxy. Such infalling gas is a necessary component of Galactic chemical evolution models in order to reconcile the paucity of observed low-metallicity stars in the solar neighborhood with those predicted upon theoretical grounds.

Based solely upon the Mrk 290 sight line, we confirm the earlier analysis of Wakker et al. (1999a, 1999b), who found

¹¹ This value is consistent with the N I λ 1134.1 FUSE analysis of Murphy et al. (2000), who found $N(N I \lambda 1134.1) = (1.6 \pm 0.6) \times 10^{14} \text{ cm}^{-2}$, in comparison with our value $N(N I \lambda 1199.5) = (1.0 \pm 0.1) \times 10^{14} \text{ cm}^{-2}$.

 $[S/H] = -1.05 \pm 0.12$ and support their low-metallicity claim. However, both the Mrk 817 and Mrk 279 sight lines appear to probe significantly more metal-rich gas, at odds with the Mrk 290 result. For Mrk 817, we found $[S II/H I] = -0.48 \pm 0.06$, a factor of 4 higher metallicity than that found toward Mrk 290, in keeping with metallicities observed in several other HVCs (Lu et al. 1998; Richter et al. 1999; Gibson et al. 2000). For Mrk 279. $[S II/H I] = -0.36 \pm 0.18$, a factor of 5 higher than that toward Mrk 290. Despite the detection of Fe II $\lambda\lambda$ 1122, 1144 and Si II $\lambda 1020$ along this line of sight, we cannot rule out the possibility that our S II λ 1250 feature is actually Ly α intrinsic to Mrk 279. The poorly constrained continuum near the expected Mrk 501 S II features allowed us to place only approximate upper limits to [S II/H I]. Finally, for Mrk 876, we were able to place limits on the nitrogen abundance along this Complex C sight line. Our result, [N I/ H I] = -1.41 ± 0.08 , suggests that scaled-solar abundance ratios are not encountered in Complex C, a suggestion supported by Murphy et al.'s (2000) conclusion that [N I/Fe II] < 0. Based on [N I/H I] from Mrk 876 and [S II/H I] from Mrk 290 and Mrk 817, it would appear that $[N_{I}/S_{II}] = -0.6 \pm 0.4$, suggestive of mild α -element enrichment from supernovae, with only marginal nitrogen pollution from hot-bottom burning in intermediate-mass stars.

Table 4 summarizes the extant GHRS and STIS data pertaining to HVC Complex C. We reference all of our results to the H I column densities provided by the Effelsberg spectra of Wakker et al. (2001). While it is tempting to attach a ± 0.2 dex systematic uncertainty to the abundances because of the resolution mismatch, counterexamples do exist in the literature, which show that significantly larger variations in column might be encountered at the arcsecond level. We emphasize that our results are limited by the 9' beam-size H I data used here. We will revisit our conclusions once higher spatial resolution 21 cm data become available.

We attempted to reconcile the higher inferred sulfur abundances along the Mrk 817 and 279 sight lines with that seen toward Mrk 290 by invoking an ionization model similar to that of Wakker et al. (1999a). The predicted H α emission measures are unrealistically high, 1200 and 1700 mR, respectively. We could also construct unrealistic ionization models in which sulfur remains in the S II state, even in regions of the cloud in which all of the hydrogen is ionized. This would bring both the Mrk 817 and Mrk 279 sight lines into $\sim 1 \sigma$ agreement with the lower metallicity Mrk 290 data. The predicted Ha emission measures, $I(H\alpha) \approx 900$ mR, are substantially lower, although still fairly high. It is also quite possible that the other sight lines have different density distributions, which introduces still more uncertainties into an estimate of the expected $I(H\alpha)$. The remaining (large) uncertainties in the H I column density determination at arcsecond levels suggest that detailed discussion of ionization conditions is not fruitful at this stage.

The Mrk 290 sight line through HVC Complex C does support the suggestion that this cloud may be lowmetallicity Galactic fuel. However, our analysis of the nearby Mrk 817 and Mrk 279 sight lines does not, nor does the iron abundance found in the FUSE analysis of Mrk 876 (Murphy et al. 2000). On the other hand, the analysis of Richter et al. (2001) of the sight line toward PG 1259 + 593 indicates an $[O I/H I] = -1.03 \pm 0.34$, an abundance determination that is robust to ionization or depletion corrections. Our preliminary analysis of three O I absorption profiles toward Mrk 817 in the FUSE band yields [O I/H I] = -0.88 to -0.65, assuming the same Grevesse & Noels (1993) solar oxygen abundance O/H = 7.4×10^{-4} as Richter et al. (2001); adopting the revised Holweger (2001) solar oxygen abundance results in a Complex C oxygen abundance of [O I/H I] = -0.73 to -0.51. In other words, the oxygen abundance along the Mrk 817 sight line is $\sim 0.2-0.3$ times solar. If Complex C has a single characteristic metallicity, a compelling case does not exist to reconcile all observations with either the low-metallicity Galactic fuel scenario ([S/H] ≈ -1.0) or the higher metallicity Galactic waste/disrupted processed gas scenario (with [S/H] $\gtrsim -0.5$).

In the absence of a compelling argument for retaining the above assumption of monometallicity, it is worth considering the hypothesis that the observed differences may simply reflect internal abundance variations within the HVC. A useful example of such variations is provided by the SMC. First, the mean metallicity of the SMC is ~ 0.2 times solar (Gibson et al. 2000, Table 6), which is comparable to that of Complex C. Second, its linear extent is also comparable to that of Complex C, assuming the latter is at a distance of ~10 kpc (Wakker et al. 1999a, 1999b).¹² Our analysis of the Mrk 290, 817, and 279 sight lines, in conjunction with that of Mrk 876 by Murphy et al. (2000), implies the presence of Complex C abundance differences on the order of factors of 3-4 over scales of 1-2 kpc, the typical impact parameter between these four probes. For comparison, both F-type supergiants (Russell & Bessell 1989) and B stars (Rolleston et al. 1999) in the SMC show abundance variations on the order of a factor of ~ 3 . In other words, a nearby system of both comparable size and metallicity to Complex C shows abundance variations at the level of ~ 0.5 dex, similar to the magnitude of abundance variations implied by Table 4 and Murphy et al. (2000). This argument does not prove that abundance variations in Complex C exist, but is simply provided to show that they cannot be excluded at this point and, indeed, may not be unexpected.

Between latitudes $+15 \le b \le +30$, it has long been recognized (e.g., Davies 1972; Verschuur 1975, and references therein) that Complex C connects smoothly (in terms of kinematics) to what is now dubbed the outer arm Complex (adopting the Wakker & van Woerden 1991 nomenclature) of the Milky Way (in the Galaxy's first quadrant). The models of Davies and Verschuur place Complex C (and indeed, many of the northern HVCs) in the outer Galaxy, either as a high-scale height extension of the outer arm (where the maximum in the disk's warp occurs) or a separate spiral arm. In contrast, Haud (1988) suggests the Milky Way is a polar ring galaxy, with the Magellanic Stream and Complex C part of a lengthy, near-continuous feature, surrounding the Galaxy. Metallicity differences between the two HVCs (compare Gibson et al. 2000 with the results presented here) likely make the Haud scenario untenable (as does the fact that the Stream and Complex C have significantly different position angles on the sky); on the other hand, the metallicity of Complex C does match

 $^{^{12}}$ The H I mass of the SMC is of course much greater than that of Complex C, by approximately 2 orders of magnitude (Wakker & van Woerden 1991).

			4							
Probe	$N({ m S~II})$ (10 ¹⁴ cm ⁻²)	N(N I) (10 ¹⁴ cm ⁻²)	N(Si II) (10 ¹⁴ cm ⁻²)	N(Si III) (10 ¹⁴ cm ⁻²)	$N({\rm H~I})^{\rm b}$ (10 ¹⁹ cm ⁻²)	[S II/H I]	[1 H/I N]	[Si n/H 1]	[Si m/H 1]	I(Hα)° (mR)
Mrk 290	1.70 ± 0.14^{d}	:	>1.0	:	11.5 ± 0.5	-1.10 ± 0.06	:	$> -1.61 \pm 0.03$:	187 ± 10
Mrk 817	$1.89\pm0.13^{ m e}$:	:	:	3.0 ± 0.1	-0.48 ± 0.06	:	:	:	:
Mrk 279	$2.48\pm0.68^{ m f}$	÷	:	÷	3.1 ± 0.4	-0.36 ± 0.18	:	:	:	:
Mrk 501	<2.0 ^g	:	:	:	1.6 ± 0.1	$< -0.16 \pm 0.06$:	:	:	:
Mrk 876	÷	$1.01\pm0.13^{ m h}$:	> 0.4	2.3 ± 0.2	:	-1.41 ± 0.08	÷	$>$ -1.30 ± 0.04	<20

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TABLE 4

^a Quoted column densities reflect those derived using the τ_o technique of Sembach & Savage (1992). Quoted uncertainties correspond to the total statistical noise (their eq. [A27]); continuum placement uncertainties are not included here.
^b Based on Effelsberg H 1 from Wakker et al. (2001).
^b Based on Effelsberg H 1 from Wakker et al. (2001).
^c Based on observations made with the Wisconsin Hα Mapper: Mrk 290 (Wakker et al. 1999a, 1999b); Mrk 876 (Murphy et al. 2000).
^e Based on the weighted mean of N(S II λ1253) and N(S II λ1259).
^e Based on the weighted mean of N(S II λ1250) and N(S II λ1259).
^e Based on the weighted mean of N(S II λ1250) and N(S II λ1253).
^f Based on the weighted mean of N(S II λ1250) and N(S II λ1253).
^f Based on uncertain N(S II λ1250).
^g Based on N(S II λ1253). Highly uncertain upper limit, due to poorly constrained local continuum.
^b Based on N(N II λ1199). Consistent with N(N I λ11134.1) = (1.6 ± 0.6) × 10¹⁴ cm ⁻² (Murphy et al. 2000).

that of the outer disk (e.g., Gibson et al. 2001a; Fig. 2), as one might expect if the connection to the outer arm was true. It should be stressed though that this metallicity match may simply be coincidental. Regardless, a revisit to the classic Davies and Verschuur models appears timely. We are currently pursuing three-dimensional hydrodynamical simulations of the outer arm Complex and Complex C, in an attempt to unravel the kinematics in this region of the Galaxy.

At this point, we urge that caution be exercised in identifying the HVC Complex C as the long-sought lowmetallicity infalling gas. Future observations with FUSE and HST/STIS (e.g., Mrk 205 by Bowen et al.) of Complex

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C should clarify many of the unanswered questions raised here.

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