THE METALLICITY AND DUST CONTENT OF HVC 287.5+22.5+240: EVIDENCE FOR A MAGELLANIC CLOUDS ORIGIN

Limin Lu, Blair D. Savage, Kenneth R. Sembach, Bart P. Wakker, Wallace L. W. Sargent, and Tom A. Oosterloo

Received 1997 August 18; revised 1997 September 29

ABSTRACT

We estimate the abundances of S and Fe in the high-velocity cloud HVC 287.5+22.5+240, which has a velocity of 240 km s⁻¹ with respect to the local standard of rest and Galactic direction l ~ 287° and b ~ 23°. The measurements are based on UV absorption lines of these elements in the Hubble Space Telescope spectrum of NGC 3783, a background Seyfert galaxy, as well as new H i 21 cm interferometric data taken with the Australia Telescope Compact Array. We find S/H = 0.25 ± 0.07 times solar, Fe/H = 0.033 ± 0.006 times solar, and S/Fe = 7.6 ± 2.2 times solar. The S/H value provides an accurate measure of the chemical enrichment level in the HVC, while the supersolar S/Fe ratio clearly indicates the presence of dust, which depletes the gas-phase abundance of Fe. The metallicity and depletion information obtained here, coupled with the velocity and position of the HVC, strongly suggest that it originated from the Magellanic Clouds. It is likely, though not necessary, that the same processes that generated the Magellanic Stream are responsible for HVC 287.5+22.5+240.

Key words: galaxies: individual (NGC 3783) — galaxies: Seyfert — Galaxy: halo — ISM: abundances

1. INTRODUCTION

High-velocity clouds (HVCs) are H i clouds moving at velocities inconsistent with simple models of Galactic rotation, and are generally defined as having |v₀,LSR| exceeding 90 km s⁻¹ (see, e.g., Wakker & van Woerden 1997). HVCs cover a significant fraction of the sky: about 37% at an H i column density limit of 7 × 10¹⁷ cm⁻² (Murphy, Lockman, & Savage 1995). Though HVCs were traditionally found only by their H i emission, there are now several cases of high-velocity gas seen in absorption in C iv and Si iv (Sembach et al. 1995, 1997; Savage, Sembach, & Lu 1995) or in Ca ii/Mg ii (D’Odorico, Pettini, & Ponz 1985; Meyer & Roth 1991; Bowen et al. 1994; Ho & Filippenko 1995), without counterparts in H i emission.

HVCs represent an important Galactic or Local Group constituent that is poorly understood. Their cause remains largely unknown decades after their initial discovery. The only exception is the Magellanic Stream, which is generally accepted as comprising gas pulled out of the Magellanic Clouds (either via tidal interactions with the Milky Way or through drag forces caused by an extended tenuous corona in the Galactic halo). Many models have been proposed for the origin of HVCs, ranging from disk gas accelerated to high velocities by energetic events to infalling primordial gas from extragalactic space (see Wakker & van Woerden 1997). Understanding the HVC phenomenon may provide valuable information about the interactions between the Galactic disk and halo, and about the evolution of the Galaxy.

The two most important parameters for investigating the origin of HVCs are their distance and chemical composition. Recent efforts using stellar and extragalactic probes to detect the optical and UV absorption lines from HVCs have provided useful constraints on the distances of several HVCs (see Wakker & van Woerden 1997 for a summary and references), indicating that several major HVC complexes are at least 4 kpc distant, and at least 2.5 kpc above the Galactic plane. Absorption-line studies at the ultraviolet (UV) and optical wavelengths also indicate that most, and perhaps all, HVCs contain some heavy elements (cf. Wakker & van Woerden 1997). However, deriving accurate elemental abundances for HVCs has proved difficult for several reasons: (1) one needs relatively high-resolution (FWHM < 20 km s⁻¹) data in order to separate the HVC absorption from the absorption at lower velocities arising from Milky Way disk gas, as well as to derive accurate column densities (such data are difficult to obtain in the UV); (2) optical Ca ii and Na i absorption lines, which are much easier to observe, do not provide accurate abundance estimates, since these ions are not the dominant ionization species in H i gas; (3) most measurements can be affected by elemental gas-phase depletion due to dust and, in principle, yield only lower limits to the actual abundance of the elements; and (4) the reference H i column densities must be obtained from high-resolution radio observations because of the presence of small angular scale structures in HVCs.

In an earlier Hubble Space Telescope (HST) program (Lu, Savage, & Sembach 1994), we obtained a UV spectrum of the bright Seyfert galaxy NGC 3783, which is projected onto a high-velocity cloud (denoted HVC 287.5+22.5+240) at Galactic longitude l ~ 287° and latitude b ~ 23° (Mathewson, Cleary, & Murray 1974; Hulsbosch 1975; Morras & Baja 1983). We clearly detected the S ii λλ1250, 1253 absorption lines from the HVC at v₀,LSR = 240 km s⁻¹, which allowed us to derive a sulfur abundance for the HVC. This was the first HVC abundance measurement free of complications by dust,
because S is not readily affected by dust in the Galactic interstellar medium (ISM) (Jenkins 1987). In this paper, we present HST observations of Fe II absorption from the HVC and use the relative abundances of S and Fe to probe the dust content of the HVC. We also present a more reliable measure of H I column density in the HVC in the direction of NGC 3783 based on new interferometric radio observations, which is crucial for an accurate determination of elemental abundances. The observations and data handling are presented in § 2. The abundance measurements are described in § 3. Evidence for dust in the HVC and implications of our results for the origin of the HVC are discussed in § 4. Section 5 briefly summarizes the main conclusions.

2. OBSERVATIONS AND DATA REDUCTION

We obtained a spectrum of NGC 3783 for HST program GO-6500 using the Goddard High Resolution Spectrograph (GHRS) on 1996 July 7. The G270M grating and the large science aperture (2" × 2") were used. The spectrum was obtained with step pattern 4, which provides two samples per diode. Standard FP-SPLIT and comb-addition procedures were used to reduce fixed pattern noise resulting from irregularities in the detector window and in the photocathode response. The total integration time was 9216 s, with 11% of the time spent measuring the background. The spectrum covers the wavelength region 2334–2380 Å, which contains the Fe II λ2344 and λ2374 transitions. The resulting spectrum has a resolution of FWHM = 13 km s⁻¹, which is approximately one diode width. The signal-to-noise ratio in the continuum is ~14 per diode. The data are preserved in the HST archive under identification Z38P0101T.

Data reduction was carried out using the IDL-based GHRS reduction software (Robinson et al. 1992) current as of 1996 June. A continuum was established by fitting a cubic spline function to spectral regions free of absorption lines. Figure 1 shows the continuum-normalized profiles of the Fe II λ2344 and λ2374 lines recorded in the spectrum, as well as that of S II λ1253 obtained by Lu et al. (1994). The conversion between heliocentric velocity and LSR velocity is $v_{\text{LSR}} = v_{\text{helio}} - 7.3 \text{ km s}^{-1}$. Note that the S II absorption was obtained before the installation of COSTAR,7 and the line-spread function had a narrow core with broad wings (see Lu et al. 1994). We also show (Fig. 1) the 21 cm emission profile toward NGC 3783 obtained by Murphy et al. (1996) with the NRAO 140 foot (43 m) single-dish radio telescope, with a beamwidth of 21' at a velocity resolution of 1 km s⁻¹. The NRAO data indicate a total H I column density of $N(\text{H} I) = 1.2 \times 10^{20} \text{ cm}^{-2}$ for the HVC. However, it is known that HVCs can have complex structures down to 1' scales (see Wakker & van Woerden 1997). Consequently, this $N(\text{H} I)$ estimate could differ considerably from the true line-of-sight $N(\text{H} I)$ toward NGC 3783.

To determine a more accurate H I column density for the HVC along the sight line toward NGC 3783, we obtained high angular resolution (1') H I data with the Australia Telescope Compact Array (ATCA) interferometer at 1 km s⁻¹ velocity resolution. The interferometer data will be discussed in detail in a forthcoming paper (Wakker et al. 1998). We note that the properties of the fine-structure map of

---

7 The Corrective Optics Space Telescope Axial Replacement system, installed in HST during the 1993 December Space Shuttle service mission.
used in order to obtain the maximum possible resolution, yielding a synthesized beam of $60'' \times 38''$. The interferometer is sensitive to structure on scales less than 30'. Individual velocity channels were 1 km s$^{-1}$ wide. Since the aperture-plane coverage is fairly uniform, the major artifact in the maps is a "bowl" resulting from the nonobserved zero and short spacings. To correct for this, each channel map was deconvolved with the synthesized beam using the Multi-Resolution CLEAN method (Wakker & Schwarz 1988). The channel maps were then corrected for the primary beam of ATCA, which has an FWHM of 34'. To compare the results with the NRAO 140 foot telescope spectrum, a simulated spectrum was generated by "observing" the final interferometer map with the NRAO single-dish telescope (assuming a Gaussian beam of FWHM = 21') and converting the spatially integrated flux to brightness temperature, using a conversion factor of 0.38 K Jy$^{-1}$. The simulated spectrum represents the flux recovered by the interferometer within the 21' beam of the NRAO single-dish telescope.

Figure 2 shows the spectrum of the HVC from the NRAO single-dish telescope (21' beam) and the simulated spectrum recovered by the ATCA interferometer at 1' resolution. The difference between the two represents the flux filtered out by the interferometer. The single-dish spectrum can be adequately modeled as the superposition of two Gaussian components with a total $N$(H I) of $1.2 \times 10^{20}$ cm$^{-2}$. The spectrum recovered by the interferometer shows three components with a total $N$(H I) of $3.4 \times 10^{19}$ cm$^{-2}$. Thus, emission with an average column density of $8.1 \times 10^{19}$ cm$^{-2}$ was filtered out by the interferometer. Since in the exact direction of NGC 3783 there is essentially no emission in the interferometer map, the above average column density also represents approximately the $N$(H I) toward NGC 3783. The exact $N$(H I) toward NGC 3783 may differ from this average column density, as a consequence of variation on scales greater than 30'. However, experiments show that such variations should be less than $1.0 \times 10^{19}$ cm$^{-2}$. We therefore adopt $N$(H I) = $(8 \pm 1) \times 10^{19}$ cm$^{-2}$, or $log N$(H I) = $19.90 \pm 0.05$, in the analysis.

3. ABUNDANCE MEASUREMENTS

To estimate the column density of Fe II in the HVC, we show in Figure 3 the apparent column density profiles, $N_\lambda$(v), of the Fe II $\lambda 2344$, 2374 lines from the HST spectrum, which give the column density per unit velocity smeared by the line-spread function [see Savage & Sembach 1991 for a detailed discussion of $N_\lambda(v)$]. We adopt the Fe II oscillator strengths from Morton (1991) for the $\lambda 2344$ line ($\beta = 0.11$), and from Cardelli & Savage (1995) and Bergeson, Mullman, & Lawler for the $\lambda 2374$ line ($\beta = 0.0329$). The $N_\lambda(v)$ profiles of the two Fe II lines (Fig. 3), which differ in strength ($\beta$) by a factor of 3.3, agree well to within the measurement uncertainties, which suggests that neither line contains hidden saturated components that are not resolved. It is thus straightforward to integrate the $N_\lambda(v)$ profiles to obtain total column densities. Over the velocity interval 180–300 km s$^{-1}$, we find log $N$(Fe II) = $13.95 \pm 0.13$ and $13.93 \pm 0.05$ from the $\lambda 2374$ and $\lambda 2344$ lines, respectively. Using different velocity intervals does not appreciably change the total column densities. For example, over 200–280 km s$^{-1}$ we find log $N$(Fe II) = $13.88 \pm 0.11$ and $13.89 \pm 0.04$, while over 160–320 km s$^{-1}$ we find log $N$(Fe II) = $14.01 \pm 0.16$ and $13.95 \pm 0.05$. We will therefore adopt log $N$(Fe II) = $13.93 \pm 0.05$, or $N$(Fe II) = $(8.5 \pm 1.0) \times 10^{13}$ cm$^{-2}$ for the HVC.

The $N$(H I) of the HVC implies that the gas is very optically thick at the Lyman limit (f$_{LL}$ $\sim$ 500). Since Fe II is the dominant ionization stage of Fe in H I gas, the ratio $N$(Fe II)/$N$(H I) should provide a reasonable estimate of the Fe abundance. We thus find Fe/H = $0.033 \pm 0.006$ times solar or [Fe/H] = $-1.48 \pm 0.07$ for the HVC, where [Fe/H] is the logarithmic abundance of Fe relative to the solar abundance given by [Fe/H] = log (Fe/H)$_{HVC}$ − log (Fe/H)$_{SOL}$. The abundance of S in the HVC is estimated to be S/H = $0.25 \pm 0.07$ times solar, or [S/H] = $-0.60 \pm 0.11$. The S abundance given here is 1.7 times higher than that of Lu.

![Fig. 2.—Profiles of 21 cm emission from HVC 287.5 + 22.5 + 240 toward NGC 3783. Circles are observations from the NRAO 140 foot telescope at 21' beamwidth, while the triangles represent the flux recovered by the ATCA interferometer at 1' resolution after convolution with the 21' beam of the NRAO 140 foot telescope. The solid curve shows the difference between the NRAO observation and the convolved interferometry measurement. Since no H I emission is seen directly toward NGC 3783 in the high-resolution ATCA map, the solid curve represents the appropriate H I emission to compare to the UV absorption-line observations.](image1)

![Fig. 3.—Apparent column density profiles of Fe II $\lambda\lambda 2374, 2344$ near the HVC absorption at $v_{LSR} = 240$ km s$^{-1}$.](image2)
et al. (1994), for two reasons: (1) Lu et al. estimated $N(S\,\text{II}) = 3.4 \times 10^{14} \text{ cm}^{-2}$ for the HVC, assuming the $S\,\text{II}$ absorption is on the linear part of the curve of growth. Direct integrations of the $N_{\lambda}(\nu)$ profiles of the $S\,\text{II}$ lines from 180 to 300 km s$^{-1}$ yield log $N(S\,\text{II}) = 14.57 \pm 0.19$ and $14.57 \pm 0.15$ from the $\lambda 1250$ and $\lambda 1253$ absorption lines, respectively. We have adopted the more accurate value from the $N_{\lambda}(\nu)$ integrations in this paper: log $N(S\,\text{II}) = 14.57 \pm 0.14$, or $N(S\,\text{II}) = (3.7 \pm 1.0) \times 10^{14} \text{ cm}^{-2}$; (2) the $N(H\,\text{I})$ of the HVC adopted here is 1.5 times lower than the one used by Lu et al. (1.21 $\times 10^{20} \text{ cm}^{-2}$), which was based on lower resolution 21 cm data. In the above calculations, we have adopted the solar abundances log $N(S/H) = 4.49$ and log $N(Fe/H) = -4.49$ from Anders & Grevesse (1989).

In the above analyses, we have assumed that ionization corrections are sufficiently small that the ratios $N(S\,\text{II})/N(H\,\text{I})$ and $N(Fe\,\text{II})/N(H\,\text{I})$ yield reasonable estimates of the $S$ and $Fe$ abundances in the HVC. In reality, the HVC may contain some (or even a substantial amount of) ionized gas; failure to account for this gas can result in large errors in the abundance estimates. Savage & Sembach (1996) have discussed various ionization processes that can have significant effects on interstellar abundance determinations. However, because HVC 287.5 $+22.5+240$ is likely to be at a large distance from the Galactic plane and is not known to contain stars, the processes that normally dominate the ionization of the gas in the Galactic disk and low halo may be less important in the HVC. Rather, the dominant ionization process in the HVC is likely to be photoionization by UV photons from the extragalactic background. For these reasons, we have run simple photoionization calculations using the code CLOUDY (version 90.02; Ferland 1996), assuming a uniform gas density and a plane-parallel geometry for the cloud with photons incident from one side. We assume solar relative abundances (Anders & Grevesse 1989) for the elements and an absolute metallicity of $[Z/H] = -0.6$ based on the $S$ abundance. The UV ionizing background is assumed to have an energy distribution similar to that adopted by Madau (1992) without taking into account absorption by intergalactic clouds. We adopt a value of $J_\nu = 5 \times 10^{-22} \text{ ergs cm}^{-2} \text{ Hz}^{-1} \text{ sr}^{-1}$ for the intensity of the UV background at the Lyman limit, although the exact value is not critical, since it is the ionization parameter, $\Gamma$ (the logarithmic ratio of the ionizing photon density to the gas particle density), that determines the ionization structure of the cloud. Limited constraints on the ionization state of the HVC gas are provided by the following column densities: log $N(S\,\text{II}) \approx 14.57$, log $N(Fe\,\text{II}) \approx 13.93$, log $N(C\ IV) \leq 13.24$, and log $N(N\,\text{V}) \leq 13.27$, with the latter two from the $2 \mu$ upper limits obtained by Lu et al. (1994). The CLOUDY results indicate that all constraints are met if $\Gamma < -3.5$, at which $S/H \approx N(S\,\text{II})/N(H\,\text{I})$ and $Fe/H \approx N(Fe\,\text{II})/N(H\,\text{I})$ to within 0.1 dex. Hence, within the context of this naive photoionization calculation, it appears that our $S$ and $Fe$ abundances obtained above are not subjected to significant ionization corrections. Even assuming $S/C$ $\approx 2$--$3$ times solar (as is observed in Galactic halo stars; see Wheeler, Sneden, & Truran 1989) in the HVC will not change the above conclusion. However, other ionization processes may also be at work, and may even play a dominant role. For example, the HVC may be photoionized by UV photons leaking out of the Galactic disk, or the HVC may be collisionally ionized as a result of interactions with hot diffuse halo gas. Future observations of adjacent ionization stages of some elements (e.g., $C\ IV$, $Si\ II$--$IV$, $Si\ II$--$III$) will help to better constrain the ionization properties of the HVC.

4. DISCUSSION

4.1. Evidence for Dust in the HVC

The abundance ratio of $S$ and $Fe$ in the HVC, $[S/Fe] = 0.88 \pm 0.15$, is a factor of $7.6 \pm 2.2$ higher than the solar value. Supersolar $S/Fe$ ratios are often observed in Galactic ISM clouds, because $S$ is essentially unaffected by dust, while $Fe$ gets incorporated into dust grains easily (see Jenkins 1987). For example, in the cool diffuse disk cloud toward $\zeta$ Ophiuchi, $[S/H] \approx 0$ and $[Fe/H] \approx -2.3$, with an $S/Fe$ ratio 200 times the solar value (see Table 5 of Savage & Sembach 1996 and references therein), implying that 99.5% of the $Fe$ atoms in the cloud are missing from the gas phase and are (presumably) incorporated into dust grains. In the warm diffuse disk clouds, which are more common, Savage & Sembach (1996) report a mean $S/Fe$ $\sim 16$. Even in diffuse halo clouds, a population of interstellar clouds with the lowest known level of depletion, $Fe$ is depleted by a factor of 4 (i.e., $S/Fe = 4$ times the solar value; Sembach & Savage 1996). The high $S/Fe$ ratio in HVC 287.5 $+22.5+240$ is likely caused by the same dust depletion effect. The inferred depletion level of $Fe$ in the HVC will depend on assumptions about the intrinsic $S/Fe$ ratio in the HVC. If the HVC has an intrinsically solar $S/Fe$ ratio, then $Fe$ is depleted by a factor of $\sim 8$ (i.e., seven out of every eight $Fe$ atoms are locked up in grains). On the other hand, if the HVC has an intrinsic $S/Fe$ ratio that is similar to metal-poor Galactic halo stars, where $S/Fe \approx 2.5$ the solar value (see Wheeler, Sneden, & Truran 1989), then the implied $Fe$ depletion is only a factor of $\sim 3$. In either case, however, some depletion of $Fe$ is required to explain the high observed $S/Fe$ ratio.

Attempts to search for dust in HVCs through their thermal emission in the infrared have all produced negative results (see review by Wakker & van Woerden 1997). Such searches are severely hampered by the strong contamination from dust emission associated with foreground gas in the disk and low halo. Probing the dust content of HVCs through the effects of dust on elemental abundances appears to be more fruitful, as evidenced by this study. However, this type of study is limited to HVCs with suitable background probes and requires assumptions about the reference abundances. As discussed below, HVC 287.5 $+22.5+240$ probably has its origin in the Magellanic Clouds. The low dust-to-gas ratios in the SMC, $N_{HII}/E_{B-V} = 10^{23}$ atoms cm$^{-2}$ mag$^{-1}$, and in the LMC, $N_{HII}/E_{B-V} = 2 \times 10^{22}$ atoms cm$^{-2}$ mag$^{-1}$ (Koornneef 1984), imply a reddening of $E_{B-V} \approx 0.0008$--$0.004$ for HVC 287.5 $+22.5+240$. Consequently, it will be extremely difficult to detect the dust in the HVC via its extinction.

4.2. Implications for the Origin of the HVC

Information on the abundances and dust content in HVCs can provide valuable clues to their origin. HVC 287.5 $+22.5+240$ is at the tip of an HVC complex that, projected onto the sky, appears to originate from the Magellanic Clouds, but is on the opposite side of the Magellanic Stream with respect to the Magellanic Clouds (see Figs. 2 and 3 of Mathewson et al. 1974). Based on this positional coincidence, Mathewson et al. suggested that HVC 287.5 $+22.5+240$ may be part of the Magellanic
Stream produced by tidal interactions between the Magellanic Clouds and the Milky Way. West et al. (1985) reported a detection of Ca II absorption associated with HVC 287.5 + 22.5 + 240 and deduced a low metallicity ([Ca II]/N[H I] ~ 1/500 the solar Ca/H value) for the HVC. West et al. argued that the low metallicity and the high Galactic-centric velocity of HVC 287.5 + 22.5 + 240 make it unlikely that the gas originated within the Galactic plane. Rather, they suggested that the HVC is probably an independent extragalactic object, possibly associated with the Magellanic Stream. The low metallicity of the HVC was confirmed by the S abundance determination of Lu et al. (1994). The S abundance determination is significant because S is not readily affected by dust in the ISM & Sembach (1996 and references therein), while more than 90% of the Ca atoms are generally found in dust grains (Phillips, Pettini, & Gondhalekar 1984).

The new S and Fe abundance measurements obtained here can shed new light on the origin of HVC 287.5 + 22.5 + 240. The new measurements have the added significance that they are referenced to a more reliable H I column density obtained from the high-resolution interferometric data. The low [S/H] = −0.6 found for the HVC is broadly consistent with the S abundance found in the Magellanic Clouds: [S/H] ~ −0.57 for the LMC and [S/H] ~ −0.68 for the SMC (Russell & Dopita 1992). The S/Fe ratio in the HVC is also similar to that found in the interstellar gas of the Magellanic Clouds. For example, Welty et al. (1997; see also Roth & Blades 1997) presented the most extensive and accurate observations to date of interstellar gas-phases abundances in an H I region in the SMC, finding [Zn/H] ~ −0.7 and [Zn/Fe] ~ 0.6 (note that Zn, like S, suffers little dust depletion in diffuse Galactic ISM clouds). Since the intrinsic abundance pattern in the Magellanic Clouds obtained from stellar abundance studies appears similar to the solar abundance pattern to within 0.2 dex or so (Russell & Dopita 1992), one expects [S/H] ~ −0.7 and [S/Fe] ~ 0.6 dex for the interstellar gas in the SMC. The similarities in the absolute S abundance and in the S/Fe ratio (i.e., the level of Fe depletion) between HVC 287.5 + 22.5 + 240 and the Magellanic Clouds’ gas provide additional support for the theory that the HVC may have been part of the LMC/SMC system previously.

One of the main criticisms of the tidal model for the Magellanic Stream (summarized by Moore & Davis 1994) has always been that tidal interactions would naturally lead to both a trailing tail and a leading arm. While a trailing tail is identified with the Magellanic Stream, no evidence for a leading arm is evident. However, recent model calculations by Gardiner & Noguchi (1996) predict that the leading arm falls in the range l = 270°−310°, b = −30° to 60°, v = 100−200 km s⁻¹, with most of the arm at b = 40°−60°. The observed HVC distribution in this part of the sky does not fit this arm precisely, but there are many HVCs in the region l = 270°−310°, b = 0°−30°, and v = 100−250 km s⁻¹, including the clouds identified by Wakker & van Woerden (1991) as population EP (containing HVC 287.5 + 22.5 + 240) and complex WD. Gardiner & Noguchi note that the precise position and velocities of the leading arm depend on the potential of the LMC, which they assumed to be spherical and constant in time. In light of our abundance and depletion information, it may be worthwhile to revisit some of the tidal models to see if detailed agreement can be made between the leading arm and the observed HVC distributions in the general region of HVC 287.5 + 22.5 + 240.

Very recently, Blitz et al. (1996) proposed that HVCs are most plausibly explained as members of the Local Group of galaxies, essentially gas left over from the formation of the Local Group. Evidence cited includes the following: (1) the velocity centroid of the HVCs (after excluding the Magellanic Stream) is similar to that of the Local Group; (2) if the clouds are stable entities and are gravitationally bound to the Local Group, theoretical considerations place them at distances consistent with members of the Local Group; (3) the clouds exhibit a relation between their angular sizes and their velocities relative to the Local Group standard of rest, with clouds inferred to be closer to the Milky Way having larger angular sizes. It was concluded that no other models can explain all these observed properties. However, the S abundance obtained for HVC 287.5 + 22.5 + 240 appears too high to be consistent with the (almost) primordial material required in the model of Blitz et al. (1996). Clearly, it will be extremely important to obtain reliable metallicity determinations for a sample of representative HVCs in order to test this model rigorously.

Some of the HVCs have a two-phase H I structure consisting of cold cores and warm envelopes (see Wakker & van Woerden 1997). Wolfire et al. (1995) have explored the thermal instabilities occurring in halo gas in order to try to understand such multiphase structures. They demonstrated that the two-phase nature of HVCs can set constraints on the properties and origins of the clouds. The implications of the Wolfire et al. theory for the HVC along the sight line to NGC 3783 will be considered in our forthcoming paper presenting the full results of the H I interferometry data (Wakker et al. 1998).

5. SUMMARY

We present an HST GHRS spectrum of the Seyfert galaxy NGC 3783 in the spectral region 2334−2380 Å in order to determine the abundance of Fe in the high-velocity cloud HVC 287.5 + 22.5 + 240, which is projected onto the background Seyfert galaxy. The HVC has a velocity of 240 km s⁻¹ with respect to the local standard of rest and is in the Galactic direction l ~ 287° and b ~ 23°. To obtain an accurate H I reference for the HVC, we also obtained a high-resolution (1") 21 cm map of the HVC, using the Australia Telescope Compact Array interferometer. Coupling the Fe abundance obtained here with our earlier determination of S abundance in the HVC, we discuss evidence for the presence of dust in the HVC and implications for the origin of the HVC. Our main conclusions are as follows:

1. Our high-resolution interferometer data indicate that the actual H I column density in the HVC along the NGC 3783 sight line is (8 ± 1) x 10¹⁹ cm⁻², which is a factor of 1.5 lower than that obtained previously from lower resolution (21′ beam) data. This result highlights one of the difficulties in abundance studies of HVCs: because HVCs usually contain very complex fine structures down to 1′ scales, it is difficult to obtain accurate measures of line-of-sight N(H I) toward background probes unless one obtains high angular resolution radio observations.

2. We find the following metal abundances for the HVC using our more accurate N(H I) determination: S/H = 0.25 ± 0.07 and Fe/H = 0.033 ± 0.006 times solar. The S/H value provides an accurate measure of the metal-
licity level in the HVC, since S is not readily affected by dust depletion. The supersolar S/Fe ratio \((7.6 \pm 2.2 \text{ times solar})\) indicates that Fe is depleted by dust in this HVC. This result provides strong evidence that at least some HVCs contain dust grains. The results also demonstrate that elemental abundance studies provide an effective way of probing the dust content of HVCs.

3. The metallicity level and the amount of Fe depletion found in the HVC are very similar to those found in the interstellar gas of the Magellanic Clouds. These similarities, coupled with the velocity and the position of the HVC in the sky, strongly suggest that the HVC originated from the Magellanic Clouds. The same processes that produced the Magellanic Stream may also be responsible for HVC \(287.5 + 22.5 + 240\) and the HVC complex in that general region of the sky (e.g., population EP and complex WD of Wakker & van Woerden 1991). In particular, HVC \(287.5 + 22.5 + 240\) may represent gas in the “leading arm” that was predicted in tidal models for the Magellanic Stream (see, e.g., Gardiner & Noguchi 1996). The metallicity of the HVC appears too high to be consistent with the model of Blitz et al. (1996), who suggested that HVCs are gas left over from the formation of the Local Group. However, reliable metal abundance determinations for a sample of representative HVCs are needed in order to test the Blitz et al. model rigorously.

The authors thank Ed Murphy for providing an electronic version of the NRAO 140 foot spectrum, and an anonymous referee for helpful comments. This project was supported by NASA through grant GO-06500.01-95A from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555. L. L. also acknowledges a Hubble Fellowship through grant HF 1062.01-94A. B. D. S. and B. P. W. are appreciative of support from NASA through grant NAG 5-1852. K. R. S. acknowledges support from NASA grant GO-06412.01-95A. The Australia Telescope is funded by the Commonwealth of Australia for operation as a National Facility managed by CSIRO.

REFERENCES

Anders, E., & Grevesse, N. 1989, Geochim. Cosmochim. Acta, 53, 197
Bergeson, S. D., Mullman, K. L., & Lawler, J. E. 1996, ApJ, 464, 1050
Blitz, L., Spergel, D., Teuben, P., Hartmann, D., & Burton, W. B. 1996, BAAS, 28, 1349
Boven, D. V., Roth, K. C., Blades, J. C., & Meyer, D. M. 1994, ApJ, 420, L71
Cardelli, J. A., & Savage, B. D. 1995, ApJ, 452, 275
D’Odorico, S., Pettini, M., & Ponz, D. 1985, ApJ, 299, 852
Ferland, G. J. 1996, HAZY, a Brief Introduction to Cloudy (Univ. Kentucky Phys. Astron. Dept. Internal Rep.)
Gardiner, L. T., & Noguchi, M. 1996, MNRAS, 278, 191
Ho, L. C., & Filippenko, A. V. 1995, ApJ, 444, 165 (erratum 463, 818 [1996])
Hulsbosch, A. N. M. 1975, A&A, 40, 1
Jenkins, E. B. 1987, in Interstellar Processes, ed. D. J. Hollenbach & H. A. Thronson, Jr. (Dordrecht: Reidel), 533
Koornneef, J. 1984, in IAU Symp. 108, Structure and Evolution of the Magellanic Clouds, ed. S. van den Berg & K. S. de Boer (Dordrecht: Kluwer), 133
Lu, L., Savage, B. D., & Sembach, K. R. 1994, ApJ, 426, 563
Madau, P. 1992, ApJ, 389, L1
Mathewson, D. S., Cleary, M. N., & Murray, J. D. 1974, ApJ, 190, 291
Meyer, D. M., & Roth, K. C. 1991, ApJ, 383, L41
Moore, B., & Davis, M. 1994, MNRAS, 270, 209
Morras, R., & Bajaja, E. 1983, A&AS, 51, 131
Morton, D. C. 1991, ApJS, 77, 119
Murphy, E. M., Lockman, F. J., Laor, A., & Elvis, M. 1996, ApJS, 105, 369
Murphy, E. M., Lockman, F. J., & Savage, B. D. 1995, ApJ, 447, 642
Phillips, A. P., Pettini, M., & Gondhalekar, P. 1984, MNRAS, 206, 337
Robinson, R. D., Blackwell, J., Feggans, K., Lindler, D., Norman, D., & Shore, S. N. 1992, A User’s Guide to the GHRS Software (version 2.0; Greenbelt, MD: GSFC)
Roth, K. C., & Blades, J. C. 1997, ApJ, 474, 95
Russell, S. C., & Dopita, M. A. 1992, ApJ, 384, 508
Savage, B. D., & Sembach, K. R. 1991, ApJ, 379, 245
———. 1996, ARA&A, 34, 279
Savage, B. D., Sembach, K. R., & Lu, L. 1995, ApJ, 449, 145
Sembach, K. R., & Savage, B. D. 1996, ApJ, 457, 211
Sembach, K. R., Savage, B. D., Lu, L., & Murphy, E. M. 1995, ApJ, 451, 616
———. 1997, in preparation
Wakker, B. P., & Schwarz, U. J. 1988, A&A, 200, 312
Wakker, B. P., & van Woerden, H. 1991, A&A, 250, 509
———. 1997, ARA&A, 35, 217
Wakker, B. P., et al. 1998, in preparation
Welty, D. E., Lauroesch, J. T., Blades, J. C., Hobbs, L. M., & York, D. G. 1997, ApJ, 489, 672
West, K. A., Pettini, M., Penston, M. V., Blades, J. C., & Morton, D. C. 1985, MNRAS, 215, 481
Wheeler, J. C., Sneden, C., & Truran, J. W. 1989, ARA&A, 27, 279
Willfire, M. G., McKee, C. F., Hollenbach, D., & Tielens, A. G. G. M. 1995, ApJ, 453, 673