OBSERVATIONS OF THE INTERSTELLAR MEDIUM IN THE MAGELLANIC BRIDGE

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ABSTRACT

We present ultraviolet and optical spectra of DI 1388, a young star in the Magellanic Bridge, a region of gas between the Small and Large Magellanic Clouds. The data have signal-to-noise ratios of 20–45 and a spectral resolution of 6.5 km s\(^{-1}\). Interstellar absorption by the Magellanic Bridge at \(v_{\text{LSR}} \approx 200\) km s\(^{-1}\) is visible in the lines of C\(\text{I}\), C\(\text{II}\), C\(\text{II}\)^*, C\(\text{IV}\), N\(\text{I}\), O\(\text{I}\), Al\(\text{II}\), Si\(\text{II}\), Si\(\text{III}\), Si\(\text{IV}\), S\(\text{II}\), Ca\(\text{II}\), Fe\(\text{II}\), and Ni\(\text{II}\). The relative gas-phase abundances of C\(\text{II}\), N\(\text{I}\), O\(\text{I}\), Al\(\text{II}\), Si\(\text{II}\), Fe\(\text{II}\), and Ni\(\text{II}\) with respect to S\(\text{II}\) are similar to those found in Galactic halo clouds, despite a significantly lower metallicity in the Magellanic Bridge. The higher ionization species in the cloud have a column density ratio \(N(\text{C\text{I}}^+)/N(\text{Si\text{I}^*}) \sim 9\), similar to that inferred for collisionally ionized Galactic cloud interfaces at temperatures \(\sim 10^4\) K. We identify substructure in the stronger interstellar lines, with a broad component (FWHM \(\sim 20\) km s\(^{-1}\)) at \(\sim 179\) km s\(^{-1}\) and a sharp component (FWHM \(\sim 11\) km s\(^{-1}\)) at \(198\) km s\(^{-1}\). The abundance analysis for these clouds indicates that the feature at \(198\) km s\(^{-1}\) consists of a low electron density, mainly neutral gas that may be associated with an interface responsible for the highly ionized gas. The \(179\) km s\(^{-1}\) cloud consists of warmer, lower density gas that is partially ionized.

Subject headings: galaxies: abundances — ISM: abundances — ISM: structure — Magellanic Clouds

1. INTRODUCTION

The Large and Small Magellanic Clouds (LMC and SMC, respectively) are two small irregular galaxies in orbit around the Galaxy, with the LMC being approximately 3–10 times more massive than the SMC (Dopita 1990). Distance estimates for the LMC and SMC are \(\sim 49\) and \(\sim 60\) kpc, respectively (see, e.g., van den Bergh 1999 and references therein). Evidence for interactions between the Milky Way and the Magellanic Clouds is provided by several high-velocity gas complexes connected to the Clouds: the Magellanic Bridge (MB), a \(10^\circ\) region of H\(\text{I}\) linking the body of the SMC to an extended arm of the LMC; the Magellanic Stream, a \(10^\circ \times 10^2\) H\(\text{I}\) filament that trails the Clouds; and the Leading Arm, a diffuse H\(\text{I}\) region that leads the Galaxy and the Clouds (Putman 2000). Using data from the H\(\text{I}\) Parkes All-Sky Survey (HIPASS), Putman (2000) showed that the “boundary” between the SMC and the MB occurs at \(l = 295^\circ\), \(b = -41^\circ.5\), where the H\(\text{I}\) column density is \(\sim 10^{21}\) cm\(^{-2}\). The H\(\text{I}\) column density slowly decreases toward the LMC to \(\sim 10^{20}\) cm\(^{-2}\) at the LMC boundary near \(l = 287^\circ\), \(b = -35^\circ.5\). The LSR velocity of the MB gas observed in 21 cm emission ranges from \(100\) to 350 km s\(^{-1}\) (McGee & Newton 1986).

Various formation mechanisms for the Bridge, Stream, and Leading Arm have been suggested over the years, and it is now generally agreed that the MB formed via a tidal encounter between the two Clouds. Gardiner & Noguchi (1996) have produced models that can reproduce simultaneously both the MB and the Stream observations. They find that the Bridge was most likely pulled from the wing of the SMC 200 Myr ago during a close encounter between the two Clouds, whereas the Stream was created by a SMC-LMC-Galaxy close encounter \(\sim 1.5\) Gyr ago.

Searches for stars in the Stream have produced largely negative results (see Irwin, Demers, & Kunkel 1990 and references therein). However, photographic surveys employing automatic scans of Schmidt plates have now firmly established the existence of blue stellar objects within the MB (Irwin et al. 1990). Subsequent CCD photometry (Demers & Battinelli 1998) and spectroscopy (Rolleston et al. 1999) have shown that the MB contains massive, young (<20 Myr) stars located between the LMC and SMC. These stars have a metal abundance \(\sim 1.1\) dex lower than their Population I Galactic analogs and \(\sim 0.5\) dex lower than the SMC (Hambly et al. 1994; Rolleston et al. 1999). Their evolutionary lifetimes indicate that star formation is still occurring in the MB, but probably via different mechanisms than those in the Galaxy, since the MB has a very low H\(\text{I}\) column density (but note the recent detection of cool H\(\text{I}\) clouds in the MB by Kobulnicky & Dickey 1999, indicating that some regions have relatively high densities).

The combination of high spectral resolution and high sensitivity available with space-based ultraviolet telescopes makes it feasible to investigate the chemical composition and the physical conditions in various interstellar environments in the Galaxy and Magellanic Clouds (see Savage & Sembach 1996 for a review). Here we report the results of a program to investigate the chemical composition and abundance pattern of the MB gas with the Hubble Space Telescope (HST) and the Space Telescope Imaging Spectrograph (STIS). For this investigation, we have chosen a sight line for which Ca\(\text{II}\) absorption was detected previously by Hambly et al. (1994).

2. OBSERVATIONS AND DATA REDUCTIONS

2.1. DI 1388

Previously, we obtained high-resolution optical spectra for a number of B-type stars in the Magellanic Bridge using...
the 3.9 m Anglo-Australian Telescope (AAT), during observing runs in 1992 November and 1995 December. One of the stars observed by Hambly et al. (1994), DI 1388, is situated approximately midway between the SMC and LMC ($l = 291^\circ 2$, $b = -41^\circ 2$). Interstellar Ca II K absorption at a LSR velocity of 200 km s$^{-1}$ has been detected toward DI 1388 (Rolleston et al. 1999). This velocity is consistent with that of the Bridge material seen in H $\alpha$ 21 cm emission (McGee & Newton 1986; Putman 2000). DI 1388 has relatively weak optical stellar absorption lines and a high projected rotational velocity. DI 1388 has the weakest MB ISM Ca II absorption in the Rolleston et al. (1999) sample ($W_\lambda \sim 42$ mÅ).

Recent work (R. S. I. Ryans 2000, private communication) classifies DI 1388 as a main-sequence, very early B-type or late O-type star. In Table 1 we summarize its atmospheric and other observational parameters.

### Table 1

| Parameter | DI 1388 Value |
|-----------|---------------|
| $\alpha$ (J2000) | 02$^h$57$^m$12$^s$94 |
| $\delta$ (J2000) | $-72^\circ$52$^\prime$54$^\prime\prime$6 |
| $V$ | 14.39 |
| $B-V$ | -0.26 |
| $T_{\text{eff}}$ | 32 ± 1 K |
| log $g$ | 4.0 ± 0.2 dex |
| $v_\text{rot}$ | 5 ± 5 km s$^{-1}$ |
| $v_\text{helio}$ | 150 ± 30 km s$^{-1}$ |
| $v \sin i$ | 180 ± 30 km s$^{-1}$ |

Note.—Results are from Hambly et al. 1994 and references therein.

2.2. *HST STIS Spectra*

*HST* STIS spectra of DI 1388 were obtained on 1997 November 21. The data are cataloged in the *HST* archive under the identification O4A801010. A total exposure time of 26,160 s was obtained with the far-UV echelle spectrograph (FUV, 1150–1730 Å) using the FUV-MAMA detector in the ACCUM mode. The E140M grating was employed centered at 1425 Å in order to arise in the Magellanic Bridge (see Fig. 1). In the *HST* STIS DI 1388 spectra, a high-velocity cloud (HVC) absorption is present at LSR velocities lower than 100 km s$^{-1}$ and velocities between 100 and 350 km s$^{-1}$. Thus, we assumed that absorption at LSR velocities lower than 100 km s$^{-1}$ is from the Milky Way disk and halo, while that at $v_{\text{LSR}} = 200$ km s$^{-1}$ was assumed to be detected in the Magellanic Bridge (see Fig. 1). In the *HST* STIS DI 1388 spectra, a high-velocity cloud (HVC) absorption is present at $v_{\text{LSR}} = 79.7 \pm 3.4$ km s$^{-1}$ (see Lehner, Keenan, & Sembach 2001). In Figure 1, we note the detection of very weak features in the spectra of C II $\lambda 1334$ and Si II $\lambda 1193$ and 1260 at LSR velocities of 113 and 130 km s$^{-1}$. The velocities of these two weak HVCs suggest that they are associated with the MB (Lehner et al. 2001).

To check the consistency between absorption-line velocities in the optical and ultraviolet absorption spectra, we compared the low-velocity portions of the Ni II $\lambda 1370$ and Ca II K lines. These two lines have roughly the same strength and component structure. The difference in the LSR velocities of the two lines is less than 3 km s$^{-1}$, which is less than the instrumental resolution of either data set. The absorption profile velocities also agree well with those of H $\alpha$ emission observations obtained with the ATCA (Lehner et al. 1999a) and Parkes (M. E. Putman 2000, private communication) telescopes. As a final check, we...
compared the stellar radial velocities in both the optical and ultraviolet spectra of DI 1388 and found them to be consistent within their uncertainties.

Table 2 presents the equivalent-width results for the MB absorption. The S/N are sufficient to detect two components in many of the stronger lines arising in the MB; this structure manifests itself as the combination of a broad component at 179 km s$^{-1}$ and a narrow component at 198 km s$^{-1}$ (see Figs. 1 and 2 and discussion in § 3.3). Because of the large stellar projected rotational velocity, contamination by stellar absorption is generally unimportant for the MB absorption, except for the higher ion lines of C IV, Si III, and Si IV, as illustrated in Figure 1.

Errors on the equivalent widths in Table 2 are 1 σ estimates, including statistical noise fluctuations in the lines and systematic errors arising from continuum placement uncertainties. The latter were obtained by changing the continuum by an amount equal to ~0.2–0.4 times the rms noise value, where the scale factor 0.2 corresponds to a flat continuum and 0.4 to a continuum with large curvature (Sembach & Savage 1992). The 3 σ upper limits for the equivalent widths are defined as $W_{\text{min}} = 3 \sigma \delta \lambda$, where $\sigma$ is the inverse of continuum S/N, $\delta \lambda$ is the spectral resolution in mA, and 2$\delta \lambda$ reflects approximately the FWHM of the absorption lines (see Table 3). Other errors, such as background and scattered light uncertainties, are not included.
3.2. Apparent Column Density Profiles

We used the apparent optical depth method to derive column densities and to check for unresolved saturated structures within the observed profiles (Savage & Sembach 1991). We converted the normalized absorption profiles into apparent optical depths per unit velocity, \( \tau_a(v) = \ln[1/I_{\text{obs}}(v)] \), where \( I_{\text{obs}} \) is the normalized observed intensity. These values of \( \tau_a(v) \) are related to the apparent column densities per unit velocity, \( N_a(v) \) [cm\(^{-2}\) (km s\(^{-1}\))\(^{-1}\)] through the relation \( N_a(v) = 3.768 \times 10^{14} \tau_a(v)/[f_J(A)] \). A direct integration of the apparent column density profiles over the velocity range yields the total column densities of the lines, provided that there are no unresolved saturated structures present (Savage & Sembach 1991). We adopted wavelengths and oscillator strengths from the Morton
The last column of Table 2 gives the resulting column densities\(^5\) for the different ions in the MB gas observed toward DI 1388. Errors on the column densities are 1 \(\sigma\) estimates (see the equivalent-width uncertainties in § 3.1). Upper limits (3 \(\sigma\)) are obtained from the corresponding equivalent-width limit and the assumption of a linear curve of growth. Lower limits indicate that the line contains some unresolved, saturated absorption that cannot be reliably estimated with the existing data. In the absence of unresolved saturated structure, two or more lines of a given species with different values of \(f\lambda\) will have the same distribution of \(N_a(v)\). Differences in \(N_a(v)\) suggest that some saturation is present for the stronger line(s). Figure 3 clearly demonstrates this for the MB Si II lines; no unresolved saturated absorption is observed for Si II \(\lambda 1304\) and 1526, while \(\lambda 1190\) is slightly saturated and \(\lambda 1193\) is strongly saturated. The other singly ionized species follow a similar curve of growth (similar \(b\)-values; see § 3.3), and therefore the weaker singly ionized lines are not saturated. C II \(\lambda 1334\) and Si III \(\lambda 1206\) are stronger lines that may contain some unre-

\(^5\) In this table, N I \(\lambda 1199\) and Fe II \(\lambda 1260\) column densities were obtained by component fitting to deblend the lines from lower velocity components and other species.
Figure 2.—Histograms show the observed spectra. Solid lines show the fits with two Voigt components (except for N i λ1200, for which one component is sufficient). Dotted lines show the component centroids at 179 and 198 km s^{-1}. The fit for O i is relatively poor in comparison with the others, indicating that the sharp component has some unresolved saturated structures or perhaps additional weak components.

solved saturated structures at the MB velocity. The N i lines have lower effective b-values that place them on the flat part of the curve of growth. This is confirmed in Figure 3, where comparison of the apparent column density profiles for the different lines shows that some unresolved saturated structure is present (as expected for narrower features). O i λ1302, which probably follows a curve of growth similar to that of the singly ionized species, is strong and probably contains some unresolved saturated structure.

3.3. Component-Fitting Measurements

For the relatively strong lines of C ii, N i, O i, Al ii, Si ii, S ii, Fe ii, and the Ca ii line, we also used a Voigt profile fitting method (Welty, Hobbs, & York 1991) to measure the

| TABLE 3 |
| --- |
| **COMPONENT FITTING MEASUREMENTS AT ~179 AND ~198 km s^{-1}** |

| Ion    | \( \lambda_{\text{lab}} \) (Å) | \( b \) (km s^{-1}) | \( \log N \) (cm^{-2}) |
|--------|-------------------------------|---------------------|------------------------|
|        | \( 179 \text{ km s}^{-1} \)    | \( 198 \text{ km s}^{-1} \) | \( 179 \text{ km s}^{-1} \) | \( 198 \text{ km s}^{-1} \) |
| C ii... | 1334.532                      | 12.0:               | 8.0:                   | >14.54                  | >14.60                  |
| N i.... | 1200.223                      | ...                 | 4.5 ± 0.6              | ...                    | 14.00 ± 0.12            |
|        | 1200.710                      | 11:                 | 5.1 ± 0.5              | 13.05 ± 0.19           | >14.07                  |
| O i.... | 1302.168                      | 10.7 ± 0.3          | 6.7 ± 0.3              | >14.44                  | >14.51                  |
| Al ii...| 1670.787                      | 11.7:               | 8.7:                   | >12.5:                  | >12.6:                  |
| Si ii...| 1304.370                      | 10.9 ± 0.4          | 7.6 ± 0.4              | 13.68 ± 0.06           | 14.06 ± 0.03            |
|        | 1526.706                      | 10.6 ± 0.4          | 6.6 ± 0.4              | 13.73 ± 0.07           | 14.00 ± 0.05            |
| S ii... | 1250.584                      | 7.1 ± 1.2           | 5.1 ± 1.2              | 13.67 ± 0.15           | 14.11 ± 0.08            |
| Ca ii...| 3933.663                      | 12.7 ± 0.7          | 7.8 ± 0.6              | 10.93 ± 0.17           | 11.73 ± 0.05            |
| Fe ii...| 1608.451                      | 10.0 ± 0.5          | 6.0 ± 0.5              | 13.38 ± 0.05           | 13.77 ± 0.04            |
column densities and the \( b \)-values. We modeled these features first with the optimized Gaussian fitting routines (elfinp) in the STARLINK package DIPSO (Howarth et al. 1996) to obtain radial velocities, equivalent widths, and the full widths at half-maximum intensity [FWHM = \( 2(\ln 2)^{1/2}b \), where \( b^2 = 2kT/(Am) + v_{\text{turb}}^2 \), and \( A \) and \( m \) are the ion mass in atomic mass units and the hydrogen mass, respectively]. We then used two of the three parameters from the fit (\( v_{\text{LSR}} \) and \( b \)) as initial estimates in the Voigt profile fitting program. The results of this process are summarized in Table 3, and some spectra with their respective fits are presented in Figure 2. The errors in this table are 1\( \sigma \) estimates, including statistical noise fluctuations in the lines and systematic errors due to uncertainties in the continuum placement (see § 3.2). We note that the component fit results are consistent with the apparent optical depth column densities.

The \( \text{C \ II} \), \( \text{O \ I} \), \( \text{Al \ II} \), \( \text{Si \ II} \), \( \text{S \ II} \), and \( \text{Fe \ II} \) features have a two-component structure, with a broad feature centered at \( \sim 179 \text{ km s}^{-1} \) and sharp component at \( \sim 198 \text{ km s}^{-1} \). The fit for the strong \( \text{C \ II} \) line is uncertain because of the strength of the line. The fit for the \( \text{Al \ II} \) line is also uncertain, since the line falls near the edge of an echelle order and is not completely covered in these data. The \( b \)-values for \( \text{S \ II} \) appear to be smaller than for the other absorption lines. However, for \( b \)-values between 7 and 10 km s\(^{-1}\) (typical values for the other lines), the derived \( \text{S \ II} \) column densities do not change by more than the 1\( \sigma \) error indicated in Table 3. The residuals in the fit for \( \text{O \ I} \) indicate that the sharp component contains either some unresolved saturated structures or additional weak components. The column density of the broader \( \text{O \ I} \) component is also somewhat uncertain, since it lies on the flat part of the curve of growth. The \( \text{N \ I} \) lines exhibit a well-defined sharp component at \( \sim 198 \text{ km s}^{-1} \), but the broad component is not detected in the \( \lambda 1200 \) line and is very weak in the \( \lambda 1201 \) line. The \( \text{N \ I} \) \( \lambda 1200 \) non-detection could be due to the continuum uncertainties on the blue side of this line (see Fig. 1). For the weak \( \text{C \ II} \) and \( \text{Ni \ II} \) lines, the S/N of the data allow identification of only the sharp component. Finer structure seen in higher resolution spectra of Galactic HVCs (Ryans, Keenan, & Sembach 1996; Lehner et al. 1999b) suggests that the true component structure in the MB gas toward DI 1388 may be more complex than is revealed by our data.

4. OVERVIEW OF SPECIES OBSERVED IN THE MAGELLANIC BRIDGE

The wide range of ionization states observed for the MB shows that the ionization structure of these clouds is complex, since the clouds exhibit species ranging from neutral gas tracers (e.g., \( \text{O \ I} \) and \( \text{N \ I} \)) to triply ionized gas tracers (e.g., \( \text{Si \ IV} \) and \( \text{C \ IV} \)). Before interpreting the derived column densities, we present a short description of the observed species and the roles that they might play within the neutral and ionized environments.

\( \text{C \ I} \), \( \text{C \ II} \), \( \text{C \ II}* \), and \( \text{C \ IV} \).—The MB component contains a strong, saturated \( \text{C \ II} \) \( \lambda 1334 \) absorption feature and a moderately strong \( \text{C \ II} \) \( \lambda 1335 \) line. Individual \( \text{C \ I} \) lines are not detected at significant levels. We weighted the \( \text{C \ I} \) lines by their \( gf \)-values and S/N levels and coadded the lines to produce an average \( \text{C \ I} \) line. This resulted in a tentative
Si is saturated local absorption in the N 1200, and 1201 but the 1199 line is blended with the column density of NH.ions with hydrogen ensure that they are primarily found in since their ionization potentials and charge-exchange reactions of the MB. Si II and WIM (Sembach et al. 2000). For Si II is primarily produced by collisional ionization at T_e ~ 10^5 K (Sutherland & Dopita 1993). The combination of C T primarily produced by collisional ionization at 150 km s^−1 at MB velocities is partially blended with a broad stellar Si II lines agree well. Strong Si II absorption present at MB velocities is partially blended with a broad stellar feature. Removing the deepest possible stellar line centered at 150 km s^−1, we find a column density of >13.45 dex for the MB Si III absorption (see Table 2). The Si III line shape differs substantially from that of the singly ionized species in that the 198 km s^−1 component is much broader (b ~ 16 km s^−1). The presence of Si III suggests that the gas could be partially ionized. Si IV is also present in the MB, indicating that some hotter (T ~ 10^4 K) gas may also exist. We estimated the Si IV line strengths by deblending the stellar absorption using the same strategy employed for C IV. The detection of Si III, Si IV, and C IV at velocities similar to the neutral and low-ionization species indicates that the hot component is not circumstellar.

S II and S III.—Sulfur is found mainly in the gas phase (Savage & Sembach 1996) and can be used as a reference to study the depletions of other elements in the gas. The S II λ1250 and 1253 lines are weak but definitely detected, while the feature at 1259 Å is blended with the strong saturated local Si II λ1260 absorption. S III is not detected. Al II, Ca II, Fe II, and Ni II.—These species are grouped together because they have the general property of being readily depleted on to dust grains (Savage & Sembach 1996). With the exception of Ca II, these species are dominant in the neutral and ionized gas (although Fe III can be dominant in some ionized gas; see, e.g., Sembach et al. 2000). Only part of the Al II λ1670 MB feature is present in the HST STIS spectrum, so it is difficult to measure the line strength accurately. Fe II λ1670 and 1608 are detected, while λ1611 is not detected. For Fe II λ1608 and 1611, we have adopted the oscillator strengths of Mullman, Sakai, & Lawler (1997) and Cardelli & Savage (1995), respectively. Only the measured column density of λ1608 is reliable, since Fe II λ1620 is strongly blended with the saturated MB component of Si II λ1260. The Ni II absorption lines are very weak. For Ni II, recent studies (Fedchak & Lawler 1999; Zsargó & Federman 1998) suggest that the oscillator strengths are lower by a factor of 0.53 compared to the previous values; we have therefore adopted this scaling factor. To improve the reliability of the Ni II column density, the three spectra were coadded using a method similar to that employed for C I. The result is shown in Figure 4, where the centroid of the line (198.4 km s^−1) is in good agreement with the centroids of the stronger lines. The b-value is about 5.7 km s^−1, a bit smaller than for the other singly ionized lines. The derived Ni II column density is 12.52 ± 0.20 dex.

5. PHYSICAL CONDITIONS WITHIN THE MAGELLANIC BRIDGE GAS

5.1. Depletions

To determine the depletion pattern of the MB, we compared relative heavy-element column densities. Since S II is only modestly depleted in the Galactic ISM, we used it as the reference ion. The logarithmic normalized gas-phase abundance is defined using the following notation:

\[
[X/S] = \log \left( \frac{X^i}{S^+} \right) - \log \left( \frac{X}{S} \right)_c ,
\]

where X^i is the ion under consideration, (X/S)_c is the ratio for cosmic abundances, and X/S is used for N(X)/N(S). Equation (1) assumes that the ion X^i is the dominant form of element X. When it is not, we will consider explanations other than depletion onto dust grains (such as ionization) for the derived deficiencies. The normalized gas-phase abundances observed in the MB, derived from equation (1), are given in Table 4 and plotted in Figure 5 for the total
column density derived from the apparent optical depth method. Table 5 and Figure 6 show the relative abundance patterns for the two components at 179 and 198 km s\(^{-1}\).

Previous ISM studies using high spectral resolution and high-S/N UV data have shown a general progression of increasingly severe depletion from warm halo clouds to warm disk clouds to colder disk clouds. Therefore, we compare the depletion in the MB to the depletion patterns observed in those three representative Galactic environments. The Galactic results from previous UV studies (Jenkins 1987; Savage & Sembach 1996; Fitzpatrick 1996; Welty et al. 1999b) are summarized in Table 4. Note that the halo values for C, N, O, and Al from Welty et al. (1999b) are estimated values, since no actual measurements yet exist. Figure 5 shows the comparison between the different Galactic environments and the results for the MB. However, in order to compare the depletion pattern of the MB with those in the Galaxy, it may be necessary to correct

### Table 4

| Ions \(X\) | \(\log (X/S)\)\(^a\) | \(\log (N(X'))\)\(^b\) | MB \(D(X)\) | Galactic Depletions | \([X/S]\)\(^c\) |
|---|---|---|---|---|---|
| C II | 0.28 | > 14.87 | > -0.65 | Cold | -0.4 | -0.4 | (-0.4) | -0.14 | +0.06 |
| N I | 0.70 | > 14.00 | > -0.94 | Warm | -0.4 | -0.1 | (-0.1) | -0.66 | -0.26 |
| O I | 0.60 | > 14.83 | > -1.01 | Halo | -0.4 | -0.4 | (-0.4) | -0.16 | +0.05 |
| Mg II | 0.31 | > 15.00 | > -0.45 | SM C | -0.6 | -0.6 | -0.3 | +0.08 | +0.44 |
| Al II | -0.79 | > 12.82 | > -0.63 | L M C | -1.2 | -1.1 | (-0.6) | +0.20 | +0.19 |
| Si II | 0.28 | 14.19 \(\pm\) 0.14 | > -0.33 \(\pm\) 0.16 | | -1.3 | -0.4 | -0.3 | +0.16 | +0.02 |
| P II | -1.70 | < 13.05 | < -0.51 | | -0.5 | -0.2 | (-0.1) | ... | ... |
| Mn II | -1.74 | < 12.78 | < -0.28 | | -1.5 | -1.0 | -0.7 | +0.18 | +0.25 |
| Fe II | 0.24 | 13.91 \(\pm\) 0.05 | < -0.57 \(\pm\) 0.19 | | -2.2 | -1.4 | -0.6 | +0.01 | +0.29 |
| Ni II | -1.02 | 12.52 \(\pm\) 0.20 | < -0.70 \(\pm\) 0.25 | | -2.2 | -1.4 | -0.6 | +0.28 | +0.36 |

\(a\) Solar system meteoritic abundances from Anders & Grevesse 1989, except for C, N, and O, which are photospheric values from Grevese & Noels 1993; \(\log (S/H) = -4.73\).

\(b\) Adopted S II column density, \(\log (N(S^+)) = 14.24 \pm 0.19\) dex.

\(c\) Updated from Jenkins 1987; see Lauroesch et al. 1996 and Welty et al. 1997, 1999b.

\(d\) From Savage & Sembach 1996, Fitzpatrick 1996, and references therein. Values in parentheses are estimated; see Welty et al. 1997, 1999b. For Ni II, the depletions were corrected to take into account the new oscillator strength scaling.

\(\left[ X/S \right] = \log (X/S)_{\text{MC-LMC}} - \log (X/S)_{I} \) (Russell & Dopita 1992) but adjusted for C, N, and O photospheric values, and Al abundances are from Welty et al. 1997, 1999a, while LMC Si abundance is from Korn & Wolf 1999, but see also discussion in Garnett 1999.
the former for any differences in the underlying (undepleted) total elemental abundance for the MB and Galaxy. For the LMC and SMC abundances, we have adopted the results of Russell & Dopita (1992, and references therein; but see also Garnett 1999; Korn & Wolf 1999), except for Al (see discussion in Welty et al. 1997, 1999a, and references therein), and the LMC Si abundance, which is from Korn & Wolf (1999). The last two columns in Table 4 summarize these abundances, where the errors on \([X/S]_{\text{SMC/LMC}}\) are typically ±0.2 dex.

In Figures 5 and 6, we indicate the corrections of the MB depletions assuming \((X/S)_{\text{MB}} = (X/S)_{\text{SMC/LMC}}\), since most of the MB gas may arise from the SMC (Gardiner & Noguchi 1996; Rolleston et al. 1999; but see discussion in § 6). The MB depletions of Si, Fe, and Ni in the MB are very similar to the Galactic halo pattern, with or without these corrections (see Fig. 5). The component analysis in Figure 6 leads to the same conclusion for Si and Fe for the individual components. The lower limits of C II, N I, and O I also are consistent with the Galactic depletion pattern. However, when the cloudlet substructure is considered, the non-saturated broader component of N I appears to be underabundant by ~1.3 dex (or ~0.7 dex when the SMC corrections are applied). The Al II lower limit is consistent with the (estimated) Galactic halo depletion value.

### 5.2. Temperature and Density of the Gas

In principle, the component b-values can be used to determine the kinetic temperature of the gas. For the sharper component of N I, O I, Si II, and Fe II, the inferred temperature has an uncertainty as large as the value itself. However, for the narrower component of N I, we can place an upper limit on the temperature, \(T < 1.7 \times 10^4\) K. The detections of O I and N I suggest \(T < 10^4\) K, since at higher temperatures most of the O and N would be ionized as a result of collisions (Sembach 1995).

If collisions with electrons are the principal source of excitation of C II* in the MB, then the familiar equation between C II and C II* (Spitzer & Fitzpatrick 1993) can be written as

\[
n_e = \frac{1}{5.46} \frac{T^{0.5}}{n} \frac{n(C^+)}{n(C^+)} \text{ cm}^{-3}. \tag{2}
\]

This relation provides an estimate of the electron density when the space densities are replaced by column densities, and therefore we make the standard supposition that the two excited states are spatially coincident along the sight line. C II is strongly saturated, so we use S II as a proxy for C II after scaling by the appropriate relative cosmic abundance and relative depletion of ~0.3 dex (Spitzer & Fitzpatrick 1993), so that \(N(C^+) \sim (5-10)N(S^+)^{(\text{the factor of } 10 \text{ is appropriate for the Galaxy; e.g., Spitzer & Fitzpatrick 1993})}\), while the factor of 5 accounts for the metallicity of the SMC; Russell & Dopita 1992). These ions are also the dominant ionization stages in both the neutral and ionized gas, and assuming that they are spatially coincident along the sight line, the electron density is \(n_e \sim 5-10 \times 10^2 T^{0.5}\) cm\(^{-3}\). For \(T < 1.7 \times 10^4\) K, \(n_e < 0.05-0.10\) cm\(^{-3}\). This density is derived from the total column densities of the ions, which are dominated by the strong, sharp component at 198 km s\(^{-1}\). The cloud at 179 km s\(^{-1}\) is expected to be a low-density gas, since it is partially ionized (see § 6.1).

If ionization equilibrium applies \([\Gamma N(X^0) = \alpha n_e N(X^+)]\), the ratio of photoionization rates to recombination rates, \(\Gamma/\alpha\), can be estimated using the tentative measurement of C I, the estimate of C II, and the upper limit on \(n_e\); \(\Gamma/\alpha < 24-48\). For comparison, in the Galaxy \(\Gamma/\alpha \approx 25 \text{ (T = 100 K)}\), \(\Gamma/\alpha \approx 48 \text{ (T = 300 K)}\), and \(\Gamma/\alpha \approx 100 \text{ (T = 1000 K)}\;\text{Péquignot & Aldrovandi 1986, for the WJ1 radiation field)}\, which indicates that either the MB radiation field is lower than the typical Galactic field or the temperature of the gas is low.

#### 5.3. Highly Ionized Species

The detection of Si IV and C IV lines in the MB places constraints on the temperature of the highly ionized species. In the Galactic halo, the high ionization absorption average ratios are \(N(C^{+3})/N(Si^{+3}) = 4.6 \pm 2.4\) and \(N(Si^{+3})/N(N^{+4}) = 1.2 \pm 0.6\) (Savage, Sembach, & Lu 1997). There is also hot gas in the SMC and LMC detected via Si IV and C IV absorption lines (Fitzpatrick & Savage 1985; de Boer & Savage 1980). The recent study of LMC coronal gas by Wakker et al. (1998) seems to suggest that the processes for producing C IV may be similar in both galaxies.

The widths of the MB Si IV and C IV lines imply a temperature of less than \(1.7 \times 10^5\) K. As discussed previously, the process of deblending the Si IV and C IV lines introduces some relatively large uncertainties in their derived column densities. Therefore, instead of considering the total column density results, we plot the ratio \(N_d(C^{+3})/N_d(Si^{+3})\) versus the LSR velocity in Figure 7. The observed scatter and differences between the two Si IV λλ1393, 1402 lines in this figure reflect primarily the uncertainties introduced by

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**Table 5**

| Ion \(X^i\) | \(\log (X/S)_p\) | \(D_{199}(X)\) | \(D_{198}(X)\) | \(\text{Cold}^a\) | \(\text{Warm}^b\) | \(\text{Halo}^c\) |
|-------------|----------------|----------------|----------------|----------------|----------------|----------------|
| C II \(\ldots\) | +1.28 | >−0.41 | >−0.79 | −0.4 | −0.4 | (−0.4) |
| N I \(\ldots\) | +0.70 | −1.32 ± 0.23 | >−0.79 | −0.1 | −0.1 | (−0.1) |
| O I \(\ldots\) | +1.60 | >−0.83 | >−1.20 | −0.4 | −0.4 | (−0.4) |
| Al II \(\ldots\) | −0.79 | >−0.43 | >−0.74 | −2.4 | −1.1 | (−0.6) |
| Si II \(\ldots\) | +0.28 | −0.25 ± 0.16 | −0.36 ± 0.09 | −1.3 | −0.4 | −0.3 |
| Fe II \(\ldots\) | +0.24 | −0.53 ± 0.16 | −0.58 ± 0.09 | −2.2 | −1.4 | −0.6 |

* Values in parentheses are estimated.

| Updated from Jenkins 1987; see Lauroesch et al. 1996 and Welty et al. 1997, 1999b.

| From Savage & Sembach 1996, Fitzpatrick 1996, and references therein. |
deblending for the stellar lines. However, we find the average ratio \( N_\text{c}(\text{C}^+ 3)/N_\text{s}(\text{Si}^+ 3) \approx 1.9 \pm 0.9 \) to be consistent with values observed along Galactic and extragalactic sight lines. \( N \) \( \text{v} \) is not detected in the DI 1388 spectra (only the stellar lines are detected at 1238.82 and 1242.80 Å), but the measured 3 \( \sigma \) upper limit of \( \log N(\text{N}^+) < 12.8 \) dex (assuming a similar width to Si IV and C IV and that the lines are on the linear part of the curve of growth) implies \( N(\text{Si}^+)/N(\text{Si}^{+4}) > 1.2 \). This value is compatible with values observed in the lower part of the Galactic halo and indicates that the production of the highly ionized species (Sembach & Savage 1992; Sembach, Savage, & Tripp 1997; Savage et al. 1997) may be similar in both the Galactic halo and the MB.

6. DISCUSSION

6.1. Interpretation of the Depletion Patterns

In the Galactic ISM, the underabundances of elements along various sight line are usually attributed to the depletion of these elements into dust. The nucleosynthetic history of the gas can also play a role, especially in a low-metallicity medium such as the MB. Russell & Dopita (1992; see also Welty et al. 1997, 1999a, and references therein) showed that the relative abundances of the \( z \) elements (Ne, Mg, Si, S, Ar, Ca) and Fe-peak elements (Cr, Fe, Ni, Zn) for the SMC and LMC H II regions and young stars are similar to those found in analogous Galactic objects. Welty et al. (1997, 1999a) presented detailed studies of two Magellanic Clouds sight lines (Sk 108 in the SMC, SN 1987A in the LMC) for which the gas-phase abundance patterns resemble those found either for warm Galactic disk clouds or for clouds in the Galactic halo. They concluded that the similar gas-phase abundance patterns in the three galaxies imply similar depletion patterns, despite global differences in their metal and dust content.

A detailed comparison of the relative stellar abundances in the MB with those in these three galaxies is not yet possible, since the derived absolute stellar abundances are poorly determined and are available only for C, N, O, Mg, and Si (Rolleston et al. 1999). However, differential abundance analyses of the young B-type stars in the MB show that, for those elements, the MB is deficient by \(-1.1 \pm 0.2 \) dex relative to the Galaxy. The scatter around this value is fairly small. This result has been confirmed recently in a study of a supergiant star (W. R. J. Rolleston 2000, private communication), and in particular shows that the nitrogen abundance exhibits a similar deficiency (see § 6.3). Our results show that the abundance pattern in the MB gas toward DI 1388 resembles that found in Galactic halo clouds and in the SMC gas toward Sk 108. Therefore, it seems that the dominant factor describing the MB gas-phase abundance pattern is depletion of the elements into dust rather than nucleosynthetic history. Clearly, additional studies of other MB sight lines would help to test this hypothesis.

The properties of the two MB ISM clouds toward DI 1388 can therefore be summarized as follows:

The 198 km \( s^{-1} \) cloud.—The gas-phase abundance pattern shown in Figure 6 follows the Galactic halo pattern. The presence of strong O I and N I suggests that much of the gas is neutral. There is no detectable S III, but Si III is detected, suggesting that some ionized gas is also present. This ionized gas may be associated with the more highly ionized gas associated with Si IV and C IV. This cloud consists of a low electron density, mainly neutral gas that might have a hotter, ionized boundary.

The 179 km \( s^{-1} \) cloud.—The gas-phase abundances of Si II and Fe II shown in Figure 6 indicate that this cloud also follows a Galactic halo depletion pattern. However, N I is remarkably deficient with respect to S II, which probably indicates that the gas is partially ionized. This would also be consistent with the smaller deficiency of Si II and Fe II compared to N I. Similarly, O I is only mildly saturated, which again may indicate that the gas is partially ionized. Si III is present and saturated, but again indicating that a certain amount of gas is partially ionized. S III is not detected, but this is not surprising, since this feature is expected to be weak and below the detection limit of our spectra.

6.2. Absolute Metallicity of the Bridge Gas

Using the HIPASS 21 cm data with a spectral resolution of 1 km \( s^{-1} \) and a spatial resolution of 15.5, M. E. Putman (2000, private communication) found an H I emission column density \( \log N(\text{H}) \approx 20.3 \) dex in the direction of DI 1388. For comparison, the hydrogen column density obtained using S II and scaling by the cosmic reference \( [S/ H] = -4.73 \) dex is \( \log N(\text{H}) \approx 20.07 \) dex after accounting for the metallicity of \(-1.1 \) dex. This is in rough agreement with the column density derived from the 21 cm data. Differences could be due to the large beam of the H I emission data and to the position (in depth along the sight line) of DI 1388 in the MB. However, our data generally support a metallicity of \(-1.1 \) dex compared to the Galaxy metallicity, confirming the results from the B-type star study by Rolleston et al. (1999). This implies that the metallicity in the MB does not reflect the SMC metallicity, which is at odds with the tidal model origin of the MB (Gardiner & Noguchi 1996). Rolleston et al. (1999) proposed that the MB gas was formed from a mixture of SMC gas and an unenriched component.
6.3. The Nitrogen “Problem”

The absolute nitrogen abundance in the SMC is still very uncertain, since H II regions and stellar analyses yield substantially different results (about 0.5 dex, e.g., Garnett 1999; but see Dufton, Fitzsimmons, & Howarth 1990 for a counterexample). The reasons for this behavior are still not well understood, mainly because the production mechanisms for N are still poorly constrained (see, e.g., discussion in Russell & Dopita 1992, and references therein). However, in principle it should be possible to supplement these analyses with interstellar data for the SMC and the MB, since nitrogen is not readily incorporated into dust grains (Meyer, Cardelli, & Sofia 1997).

Our data tentatively suggest that nitrogen is deficient in the MB gas relative to other elements. For the component at 179 km s\(^{-1}\), \([\text{N}^\circ/\text{S}^\circ] = -1.32\) dex. This deficiency is unlikely to be due to depletion of N into grains. N II is also largely deficient (\(< -0.5\) dex) compared to O I, which could be due in part to N I being preferentially ionized relative to O and H because of its larger photoionization cross section. However, Sofia & Jenkins (1998) indicate that N I is generally a good substitute for H I because of the very fast charge transfer of N II with H I, which effectively keeps the ionization fractions of N and H essentially coupled. For the component at 198 km s\(^{-1}\), the saturated oxygen and nitrogen lines do not clarify the situation. The amount of N that has been ionized could be checked with Far-Ultraviolet Spectroscopic Explorer (FUSE) measurements of N II and N III absorptions. A far-UV study would also help to constrain the neutral nitrogen abundance, since there are numerous N I lines in the FUSE bandpass that are weaker than the strong 1200 Å lines observed in our STIS spectrum of DI 1388.

7. SUMMARY AND CONCLUDING REMARKS

We have presented HST STIS E140M UV and AAT optical spectra of the young star DI 1388 located in the Magellanic Bridge. The échelle spectra show interstellar absorption from C I, C II, C II*, C IV, N I, O I, Al II, Si II, Si III, Si IV, S II, Ca II, Fe II, and Ni II. The relative gas-phase abundance of the MB ISM gas toward DI 1388 resembles that of gas in the Galactic halo. Since there is independent information on the total abundances from stars and/or nebulae of the Galaxy, SMC, LMC, and MB, the observed abundance pattern in the MB ISM is attributed to varying degrees of depletion onto dust similar to that in halo clouds and the SMC toward Sk 108.

Fits to the absorption profiles reveal two MB interstellar components at 179 and 198 km s\(^{-1}\). These two clouds along the line of sight have different properties: (1) The cloud at 198 km s\(^{-1}\) has a temperature \(T < 10^4\) K, low electron density \((n_e < 0.05–0.1\) cm\(^{-3}\)), and is mainly neutral, with a possible collisionally ionized boundary detected in Si III, Si IV, and C IV. (2) The cloud at 179 km s\(^{-1}\) is low-density gas, warmer, and partially ionized.

Higher resolution data might allow a more detailed picture of the interstellar structure, which bears on the possibility that these clouds trigger star formation via cloud-cloud collisions (Dyson & Hartquist 1983). As discussed above, star formation is continuing in the MB, since there are young hot stars with evolutionary lifetimes \(\leq 20\) Myr much younger than the age of the MB (~200 Myr). In all known environments, star formation occurs within molecular clouds or cloud complexes, but there is at present no direct evidence of star-forming gas clouds in the MB. Kobulnicky & Dickey (1999) have detected cold H I clouds in the MB, which suggests the presence of atomic or molecular condensations that could harbor star formation. However, no CO emission has yet been detected (Smoker et al. 2000), and therefore cloud-cloud collisions could be the dominant star formation trigger.

Finally, we note that this work is relevant to the study of QSO absorption-line systems (QSOALS). Welty et al. (1997, 1999a) propose that the known depletions patterns in the SMC, LMC, and Galaxy can be used to deduce the total elemental abundances in the QSOALS from the observed gas-phase abundances. Indeed, the MB interstellar gas is characterized by modest depletion and metallicity. Moreover, the results of this study and those of Welty et al. (1997, 1999a) suggest that the observed depletion patterns are independent of the metallicity. These patterns could therefore be applied to the QSOALS. Detailed studies of the interstellar medium along other sight lines in the MB, SMC, and LMC should help us to know whether these results can be generalized to a wider range of environments.

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792 LEHNER ET AL. Vol. 551
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