DUST IN THE IONIZED MEDIUM OF THE GALAXY: GHIRS MEASUREMENTS OF AL III AND S III

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ABSTRACT
We present interstellar absorption line measurements of the ions S III and Al III towards the stars β1 Sco, μ Col, ξ Per, ζ Oph, ρ Leo, and HD 18100 using archival data from the Goddard High Resolution Spectrograph on board the Hubble Space Telescope. The ions Al III and S III trace heavily depleted and non-depleted elements, respectively, in ionized gas along the sightlines to these late-O/early-B stars. We use the photoionization equilibrium code CLOUDY to derive the ionization correction relating the ratio $N(\text{Al III})/N(\text{S III})$ to the gas-phase abundance $[\text{Al}/\text{S}]_i (\approx \log\{N(\text{Al})/N(\text{S})\}_i - \log\{N(\text{Al})/N(\text{S})\}_0)$ in the ionized gas. For spectral types considered here, the corrections range from 0.1 to 0.3 dex and are independent of the assumed ionization parameter, i.e., the ratio of ionizing photon density to mean electron density.

Using the results of these photoionization models, we find $[\text{Al}/\text{S}]_i \sim -1.0$ in the ionized gas towards β1 Sco, ξ Per, and ζ Oph; along the low-density path towards μ Col we find $[\text{Al}/\text{S}]_i \approx -0.8$. Since S is not depleted onto grains these values of $[\text{Al}/\text{S}]_i (\approx [\text{Al}/\text{H}]_i)$ imply that Al-bearing grains are present in the ionized nebulae around these stars. If the WIM of the Galaxy is photoionized by OB stars, the observations of ρ Leo and HD 18100 imply $[\text{Al}/\text{S}]_i = -0.4$ to −0.5 in the WIM and thus the presence of dust grains containing Al in this important phase of the ISM. While photoionization appears to be the most likely origin of the ionization for Al III and S III, we cannot rule out confusion from the presence of hot, collisionally ionized gas along the sightlines to β1 Sco and HD 18100. We find that $[\text{Al}/\text{S}]_i$ in the ionized gas along the six sightlines is anti-correlated with the electron density and average sightline density. The degree of grain destruction in the ionized medium of the Galaxy is not much higher than in the warm neutral medium. The existence of grains in the ionized regions studied here has important implications for the thermal balance of these regions.

Subject headings: ISM: abundances—dust, extinction—H III regions—Galaxy: halo—ultraviolet: ISM

1. INTRODUCTION
Warm ($10^4$ K) ionized hydrogen is an important component of our Galaxy’s interstellar medium (ISM). The diffuse warm ionized medium (WIM) of the Galaxy has a mass surface density one third that of neutral hydrogen (HI), with an extended vertical scale height ($h_z \approx 900$ pc), and a power requirement equivalent to the total kinetic energy injected into the ISM by supernovae (Kulkarni & Heiles 1987; Reynolds 1991b). The WIM has principally measures of radio emission from distant pulsars (Taylor & Cordes 1993; Reynolds 1991a). The goal of this work is to determine if there is evidence for dust grains in the ionized medium of the Galaxy, including low-density H II regions and the diffuse WIM. The distinction between H II regions and the WIM in this work is mainly one of distance from the source of ionization and possibly fractional ionization. The existence of dust in the WIM of the Galaxy has important ramifications for the heating (and cooling) of the gas and possibly also for the power requirements of the ionization. Photoelectric emission of electrons from the surfaces of dust grains is an important source of heating in the warm neutral medium (WNM) of the Galaxy (Wolfire et al. 1995a). Reynolds & Cox (1992) have shown that, if grains are present in the WIM, photoelectric emission may be the dominant source of heating in the WIM and may also be responsible for the enhanced forbidden line strengths that are characteristic of the WIM (e.g., Dettmar & Shulz 1992; Rand 1997, 1998).

To provide evidence for the existence of dust in this important phase of the ISM, we will measure the gas-phase abundance of Al relative to S in ionized gas. In the warm neutral medium relative gas-phase abundances, derived from absorption line spectroscopy, have been used to infer the elemental composition of dust grains (see Savage & Sembach 1996b and references therein). We apply this method to the ionized medium of the Galaxy.

Absorption line spectroscopy of interstellar material yields column densities of species independent of the prevailing physical conditions (e.g., $T_e, n_e$). In Table 1 we list the properties of several possibly important probes of weakly ionized gas in the vacuum ultraviolet. Along with the wavelengths and f-values (from Morton 1991) for the transitions given, we also give relevant ionization potentials, logarithmic solar-system abundances of the elemental species relative to H (Anders & Grevesse 1989; Grevesse & Noels 1993), and representative values of the gas-phase abundances of each of the elemental species in warm neutral halo gas (see Savage & Sembach 1996b). The lines and ion species listed in Table 1 are those likely to

1Based on observations made with the NASA/ESA Hubble Space Telescope, obtained from the data archive at the Space Telescope Science Institute. STScI is operated by the Association of Universities for Research in Astronomy, Inc. under the NASA contract NAS 5-26555.
provide measurable column densities in the spectral range accessible to the UV spectrographs previously or currently on HST (~1120−3200 Å) and lines accessible to the Far Ultraviolet Spectroscopic Explorer, which will cover the wavelength range ~905−1195 Å after its launch in early-1999. The last two columns of Table give the expected column density of each ionic tracer for a completely ionized region with halo-like abundances having log N(H II) = 19.0 (where N(H II) is expressed in cm^{-2}) and total hydrogen density n_H = 1.0 cm^{-3}, as well as the expected peak optical depth of each line in the case of pure thermal broadening with T = 10^4 K. These optical depths will be less if non-thermal broadening plays a significant role (a likely situation).

Those ions from Table accessible to HST include S III, Al III, P III, Si III, and N III. Given the great strength or weakness of many of the lines from Table one is typically able to measure a tracer of a non-depleted element (see Spitzer & Fitzpatrick 1993: Fitzpatrick & Spitzer 1994, 1997) in the ionized gas (S III) and a tracer of a refractory element in ionized gas (Al III) in the HST bandpass. Relatively little is known about the Galactic distribution of these ionized gas tracers. Savage, Edgar, & Diplas (1990) used the International Ultraviolet Explorer to study the distribution of Al III in the Galaxy. They find an exponential scale-height of h_{AlIII} = 1.02_{-0.21}^{+0.36} kpc for the distribution of Al III, thereby showing the distribution of Al III is slightly more extended than the neutral gas (h_{HII} = 0.67_{-0.16}^{+0.21} kpc towards these same objects) and similar to that of free electrons. From the ratios of the estimated vertical column densities of Al III and free electrons (which are assumed to trace the protons of the WIM) they infer a gas-phase abundance of [Al/H]_i > −1.7 in the ionized gas (using the solar system abundance Al/H given in Table). Sembach & Savage (1992) have also studied the properties of Al III absorption towards a number of halo stars. They find that the absorption due to Al III is significantly different than that of the more highly-ionized species Si IV, C IV, and N V.

In this work we present observations of interstellar absorption due to the ions S III and Al III along the sightlines to six late-O/early-B stars: ξ Persei (HD 24912), ζ Ophiuchi (HD 149757), β1 Scorpii (HD 144217), μ Columbae (HD 38666), ρ Leonis (HD 91316), and HD 18100. These spectra are taken from the Goddard High Resolution Spectrograph (GHRS) data archive. The stellar and sightline properties relevant to this study are given in Table. The first four targets are relatively nearby disk stars (z < 200 pc). For these sightlines, the column density of ionized gas is likely dominated by H II region material, i.e., by fully-ionized gas immediately surrounding these stars. For the latter two stars, which are more distant and at high latitude, the paths through the ionized ISM are dominated by the WIM, by which we mean diffuse gas at large distances from any ionizing star. The species Al III and S III require more energy for creation than the H+ typically used to probe the WIM; however, these ions likely represent significant fractions of the S and Al associated with the WIM. In all cases we depend upon the use of an ionization correction factor to determine the relative abundances presented here. However, we will show that these small corrections are relatively insensitive to model assumptions.

In §2 we discuss the GHRS archival data and our reductions and analysis of these data. This includes in §2.2 a description of the component-fitting analysis required for two of our six sightlines, and measurements of Fe III from the literature in §2.3. We discuss the physical conditions and velocity structure of the ionized gas in §3 and we include in this a description of the complex kinematics along the sightline to ζ Oph in §3.1.1. We use the photoionization code CLOUDY (Ferland 1996; Ferland et al. 1998) to model ionized regions about hot stars in §3 and use the results of these models to derive the gas-phase Al/S abundance in the ionized gas of the Galaxy. The abundances imply the existence of dust in the ionized gas towards these six stars. We also discuss in §3.4 the confusing effects of collisionally ionized gas along our six sightlines. In §4 we discuss the implications of our derived abundances and dust in the ionized phase of the Galaxy. A summary of our work and major conclusions is given in §5.

2. GHRS ARCHIVAL DATA

In this section we discuss our reduction of the GHRS archival data and measurements of interstellar absorption features in these data. A more complete discussion can be found in Howk, Savage, & Fabian (1998). Included in this section (§2.2) is a description of our approach to model component fitting. Component fitting is required to disentangle the S III λ1190.208 Å absorption line from the strong Si II line at λ1190.416 Å in intermediate resolution data. Also, we discuss the literature values of Fe III λ1122.526 Å absorption used in this paper (§2.3).

2.1. Reductions and Measurements

We have retrieved the GHRS archival data containing the S III and Al III transitions for the stars listed in Table. The STScI archive identification codes are relevant information including exposure times, grating mode, and aperture are given for each spectrum in Table. The spectra have been calibrated using the standard CALHRS routine which includes conversion of raw counts to count rates and corrections for particle radiation contamination, dark counts, known diode non-uniformities, paired pulse events and scattered light. The final data reduction was performed using software developed and tested at the University of Wisconsin-Madison. This includes the merging of individual spectra and allowing for additional refinements to the scattered light correction for the echelle-mode data (Cardelli, Ebbets, & Savage 1993).

The spectra used for this study include data taken both before and after the installation of the Corrective Optics Space Telescope Axial Replacement (COSTAR). For information regarding the pre-COSTAR performance of the GHRS, see Heap et al. (1995); the post-COSTAR performance of the GHRS is discussed by Robinson et al. (1998). The pre-COSTAR data used here were taken through the Small Science Aperture (SSA), thereby avoiding the complication of the very broad wings found in the pre-COSTAR Large Science Aperture (LSA) line-spread function (LSF). The GHRS echelle-mode spectra (Ech-A and Ech-B) used here have a resolution of ~3.5 km s^{-1}.

2In many sightlines the S III λ1190.208 Å line is blended with intermediate-velocity absorption from the strong S II line at λ1190.416 Å (v ≈ +52 km s^{-1} relative to S III); this is particularly true for observations made at intermediate resolution (FWHM ≳ 15 km s^{-1}).
(FWHM). The observations of the S III λ1190 Å region using the G160M grating have a velocity resolution of ~20 km s\(^{-1}\), while in the Al III λ1855, 1862 Å region the resolution is ~11 km s\(^{-1}\) (FWHM). For the G160M data we have used the SPYBAL observations taken before the science integrations to refine the absolute velocity scales (see Soderblom, Sherbert, & Hulbert 1993, 1994). The SPYBAL observations contain emission lines observed in the wavelength range ~1500–1540 Å range. We have calculated the average offset between the observed and expected wavelengths of these lines, and applied these wavelength offsets to the appropriate science observations (Soderblom et al. 1994). Using the SPYBAL observations, we find offsets of −0.003 Å and −0.033 Å, respectively, are appropriate for the S III and Al III observations towards HD 18100. Towards β\(^3\) Sco the G160M observations of S III require an offset of −0.014 Å. These wavelength adjustments should make the absolute velocities for the G160M observations good to ~3 km s\(^{-1}\). The velocity scale of the echelle data presented here is likely good to ±1 resolution element (i.e., 3.5 km s\(^{-1}\)).

Most of the data presented here employed the FP-SPLIT=4 procedure, which takes four exposures at different grating carousel positions. These scans are identified in Table 3. The FP-SPLIT exposures can be used to solve for the fixed-pattern noise spectrum of the GHRS (Cardelli & Ebbets 1994) and remove it from the observations. In general we have solved for the fixed-pattern noise, but only applied the solution in the cases where the noise spectrum showed significant structure within a few hundred km s\(^{-1}\) of the line of interest. In this way we avoid adding noise to those spectra with few or no fixed-pattern features. Only for the ζ Oph scans and the echelle observations of Al III towards β\(^3\) Sco was there structure deemed to be possibly significant to the current work; these are the only observations for which we have applied the fixed-pattern noise solutions.

We have normalized the spectra using low-order (<4) Legendre polynomial fits to the local stellar continuum in regions free from interstellar absorption. Figures 4 and 6 present the normalized absorption line profiles of S III and Al III for the stars considered here. Also shown in Figure 4 are the profiles of Zn II λ2026.14 Å or λ2062.66 Å. The Zn II profiles trace the column density of neutral material along these sightlines. Absorption from the Si II λ1190 Å line can be seen in all of the plots showing the S III absorption. The expected shift of the Si II line relative to S III is +52.4 km s\(^{-1}\). If intermediate negative velocity Si II is present, it can be blended with the S III line. The S III+Si II profile towards the star ρ Leo is a good example of this behavior; narrow intermediate velocity Si II features are present at \(v_\odot \approx +12\) and +25 km s\(^{-1}\) relative to the restframe S III along this sightline. These two features make it impossible to determine the S III absorption for \(v_\odot > 5\) km s\(^{-1}\). Therefore our study of the ρ Leo sightline is limited to \(v_\odot < 5\) km s\(^{-1}\). The behavior of Si II can be determined from the Si II λ1193.29 Å transition.

Table 3 contains the measured equivalent widths and column densities of interstellar S III and Al III towards our six targets, along with the 1σ uncertainties in these quantities. These uncertainties include contributions from photon statistics, continuum placement uncertainties, and zero-level uncertainties. We have adopted a 2% zero-level uncertainty throughout. This may overestimate the errors in regions near heavily saturated lines, i.e., in the wavelength region of S III. See Sembach & Savage (1992; their Appendix) and Howk et al. (1998) for a more thorough discussion of these sources of uncertainty.

For the echelle data the values of the column densities presented in Table 3 were derived by a straightforward integration of the apparent column density profiles (Savage & Sembach 1991). In the absence of unresolved saturated structure, \(N_a(X^i) = N(X^i)\), where \(N_a(X^i)\) and \(N(X^i)\) are the apparent and true column densities of the ion \(X^i\), respectively. The S III lines observed towards ξ Per and ζ Oph are the only profiles for which we might expect the presence of unresolved saturated structure. Though the profiles seem resolved by the echelle-mode resolution, the value \(N(S\ III)\) for the ξ Per and ζ Oph sightlines may underestimate the total column density. For gas at \(T = 10^4\) K, the thermal Doppler spread parameters for S III and Al III are \(b(S\ III) \approx 2.3\) km s\(^{-1}\) and \(b(Al\ III) \approx 2.5\) km s\(^{-1}\) (FWHM ~ 3.8 and 4.2 km s\(^{-1}\), respectively). Thus the profiles of photoionized gas traced by these species should be marginally resolved, even without the likely addition of non-thermal broadening.

As mentioned above, intermediate velocity Si II absorption is seen towards ρ Leo at velocities near the restframe of S III. In both the Al III and Zn II profiles, an absorbing component is present near \(v_\odot \approx +20\) km s\(^{-1}\). The corresponding S III absorption is blended with the intermediate velocity Si II absorption. Therefore we report the column densities of Al III and S III for this sightline integrated over the velocity range \(v_\odot = -19\) to +2 km s\(^{-1}\). This only includes the lower-velocity Al III absorbing component. We do not expect any Si II absorption in this velocity range given the profile of the Si II λ1193.29 Å line present in the same GHRS observation.

### 2.2. Component Fitting Measurements

The S III λ1190.208 Å lines observed towards β\(^3\) Sco and HD 18100 with the G160M grating are blended with the nearby Si II λ1190.416 Å line (\(v = +52.4\) km s\(^{-1}\) relative to S III). To assess the extent of the blending, we have performed a component fitting analysis of these profiles using software kindly provided to us by E. Fitzpatrick and described in Spitzer & Fitzpatrick (1993; hereafter SF93). A model of the interstellar absorption was convolved with the instrumental LSF given for the pre-COSTAR SSA, and the value of \(\chi^2\) minimized between this model and the data. The LSF adopted here for the SSA follows Spitzer & Fitzpatrick (1995) in using instrumental LSF given for the G160M grating in the GHRS Instrument Handbook (v3.0; Duncan 1992, Table 4-8). The LSF is well characterized by a Gaussian with a FWHM ~ 1.08 diodes at the detector array. From these models, we derive the best-fit column density, \(N_k\), Doppler parameter, \(b_k\), and central velocity, \(v(k)\), for the \(k\) absorbing components of Si II and S III along these lines of sight.

For the β\(^3\) Sco observations, we have used the high-resolution GHRS Ech-B observations of the Si II λ1808.013 Å line along this sightline to provide more information about the component structure of the Si II λ1190 Å line. We have fit the λ1808 Å line with a four-component model and subsequently fixed the values of \(N_k\) and \(b_k\) from this
fit, though allowing common shifts in the velocities, to describe the Si II λ1190 A absorption. The S III column density presented for $\beta^1$ Sco in Table 3 is derived from the best-fit one component model. Figure 2 displays the G160M data for this sightline as points, while the model derived from our fitting is displayed as a solid line. The central velocity for the S III profile is $\langle v_0 \rangle = -10.0 \pm 0.4$ km s$^{-1}$ (fitting error only). The $b$-value is not well constrained but is likely signficantly less than the resolution of the G160M observations.

For the sightline towards HD 18100, no high-resolution observations of Si II were available. However, we have fit the Si II λ1193.290 Å line present in the G160M observation to assess the contribution of intermediate-velocity Si II absorption to the S III profile. The model fit to the Si II λ1193 Å profile is over-plotted as the dotted line on the S III profile for HD 18100 in Figure 2. This model has been scaled by the appropriate factor to account for the differing oscillator strengths of the 1190 and 1193 transitions of Si II and shifted to the velocity scale of S III. It is clear from this presentation that there is a component of Si II overlapping the S III absorption in velocity. We have held the column density of this Si II component fixed when fitting the S III+Si II blend at 1190 Å. We find the Si II component is relatively weak, of order 12% of the S III column density at these velocities. Table 2 gives the total column density derived for S III along this sightline. The total column density of S III we obtain agrees with the value $\log N$(S III) = 14.26 ± 0.06 derived by Savage & Sembach (1996a, hereafter SS96).

We have similarly fit the Al III profile for HD 18100 with a component model. We find evidence for at least two components in the S III and Al III absorption along this sightline. While the $b$-values are ill-constrained and likely much less than the G160M instrumental resolution, the column densities and central velocities for the individual absorbing components of S III are as follows:

$\langle v_0 \rangle_1 = -20 \pm 6$ km s$^{-1}$; $\log N$(S III)$_1 = 13.51 \pm 0.25$;
$\langle v_0 \rangle_2 = +5.8 \pm 0.9$ km s$^{-1}$; $\log N$(S III)$_2 = 14.21 \pm 0.03$.

For Al III we find:

$\langle v_0 \rangle_1 = -19 \pm 13$ km s$^{-1}$; $\log N$(Al III)$_1 = 12.1 \pm 0.4$;
$\langle v_0 \rangle_2 = +4.8 \pm 1.6$ km s$^{-1}$; $\log N$(Al III)$_2 = 12.58 \pm 0.11$.

We do not believe unresolved saturation is a significant problem for either species for this sightline. Column densities derived for the two Al III transitions through a straight integration of the are the $N_0(v)$ profiles are the same within the errors, and their $N_0(v)$ profiles show no evidence for saturation effects (see Savage & Sembach 1994; their Figure 4). For the S III profile we find that the equivalent width is within the range covered by the two Al III transitions, and the peak optical depth is very similar to that found in the Al III λ1855 Å profile (though it includes a small contribution from the overlapping Si II λ1190 Å line). The data for Al III and S III along the sightline to HD 18100 are shown in Figure 4 as points, while the component models for each species are plotted as solid lines. Considering the difficulty in deriving precise values for the $\langle v_0 \rangle_1 \sim -20$ km s$^{-1}$ component, we will use the integrated sight-line column densities in our analysis. We also note that the component structure buried in the intermediate resolution G160M data may be significantly more complex than our component-fitting analysis suggests (see SS96; Ryans, Sembach, & Keenan 1996).

2.3. Literature Measurements of Fe III

For the stars $\mu$ Col, $\beta^1$ Sco, and $\zeta$ Oph measurements of the Fe III λ1122.526 Å line are available. Howk et al. (1998) report on the profile and column density of Fe III towards $\mu$ Col as measured with the G140M grating. Savage & Bohlin (1979) and Morton (1975) report on the gas-phase column density of Fe III towards $\beta^1$ Sco and $\zeta$ Oph, respectively, based upon Copernicus measurements. The column densities derived by these authors for Fe III are given in Table 3. The data derived from the earlier Copernicus papers have been modified to reflect more recent determinations of the $f$-values of this transition (Morton 1991). We adopt $f = 0.0788$, which amounts to a modification of $-0.15$ dex to the column densities adopted in the works of Savage & Bohlin (1979) and Morton (1975).

The Fe III absorption towards $\beta^1$ Sco and $\zeta$ Oph could be substantially blended with C I absorption at λ1122.438 Å and λ1122.518 Å. Howk et al. (1998) have put restrictive limits on the degree of contamination to the Fe III absorption towards $\mu$ Col. They find the level of contamination is not significant compared with the errors. For the Copernicus results, we have estimated the errors quoted in Table 3, though these column densities should be considered upper limits due to the possible contamination from C I absorption.

3. Physical Conditions and Velocity Structure of the Ionized Gas

The sightlines to the stars in our sample cover a wide range of physical conditions and environments. The absorption lines due to ionized gas along the sightlines towards $\beta^1$ Sco, $\zeta$ Oph, and $\xi$ Per are likely dominated by photoionized gas in the H II regions of these disk stars. The sightlines towards the higher-latitude stars sample the WIM of the Galaxy. Towards $\mu$ Col, the gas being sampled may well be a mixture of both H II region and WIM gas, though to our knowledge no H II region has previously been identified about this star. Given the range of conditions and velocity structure, we mention some of the more important aspects of these ionized gas properties here.

3.1. H II Region Sightlines

The H II regions of some of our disk stars have been studied in detail. Reynolds & Ogden (1982) and Reynolds (1988b) have studied the H II region S27 surrounding $\zeta$ Oph. Their analysis of faint Hα and [S II] emission from the nebula suggests $n_e f^{1/2} \approx 4$ cm$^{-3}$ with $T_\epsilon \approx 6700$ K, where $n_e$ is the local electron density and $f$ is the volume filling factor. Reynolds (1988b) has similarly studied Sivan 4, the H II region surrounding $\xi$ Per. The Hα and [S II] emission suggest $n_e f^{1/2} \approx 1.4$ cm$^{-3}$ for this nebula with $T_\epsilon \approx 8000$ K. Howk et al. (1998) and Shull & York (1977) have derived $n_e \approx 0.2$ cm$^{-3}$ for the ionized gas along the line of sight towards $\mu$ Col, which is similar to that in the Galactic WIM. This average density has been derived from analyses of the excited states
of Si II and N II, respectively, and is a lower limit to the true electron density.

The Hα emission towards ζ Per is centered at $v_\odot = +7$ km s$^{-1}$ (Reynolds 1988b). Emission from the nebula S220 1° to the north, which is also thought to be powered by ζ Per, is centered at $v_\odot = +12$ km s$^{-1}$. These velocities are well within the limits of Al III and S III absorption towards this star. Towards ζ Oph the Hα emission is centered at $v_\odot = -13$ km s$^{-1}$ (Reynolds 1988b), which is roughly consistent with the Al III absorption and the positive-velocity edge of the S III absorption.

Recent observations with the Wisconsin Hα Mapper (WHAM) Fabry-Perot instrument (M. Haffner, private communication) have similarly shown that Hα-emitting gas towards μ Col lies at velocities quite similar to the center of S III and Al III absorption along this sightline. The sightline towards this star may be associated with an H II region, the WIM along this sightline, or a combination of both. At the distance and latitude of μ Col, we expect only ~ 20% of the WIM in the direction of μ Col to be in front of the star (Reynolds 1991b). Given that the Hα emission in this direction is at velocities consistent with the S III profile presented here, even though the WIM along this direction should mostly come from beyond the star, we will assume the emission and absorption along the sightline towards μ Col are mostly probing H II region gas.

When comparing the velocities of the tracers of ionized gas being studied here and tracers of neutral gas, such as Zn II, we see three distinct arrangements in the nearby disk stars. The ionized gas along the sightline to β Zn II is aligned quite well with the positive velocity edge. The velocity edge of the S III absorption towards this star may be in front of the star (Reynolds 1991b). Given that the Hα emission in this direction should mostly come from beyond the star, we will assume the emission and absorption along the sightline towards μ Col are mostly probing H II region gas.

3.1.1. The Complicated Case of ζ Oph

The velocity structure observed in tracers of ionized gas along the path to ζ Oph is quite complex and warrants a more complete description. The profiles of Al III, S III, and Zn II towards ζ Oph shown in Figure 6 have distinctly different velocity structure. The S III absorption is broader than either the Zn II or Al III profiles. The Zn II absorption lines are broadened by the negative velocity edge of the S III profile, while the Al III absorption is aligned quite well with the positive velocity edge.

Sembach, Savage, & Jenkins (1994) studied the Al III, Si IV, and C IV absorption along this sightline in some detail. These authors attributed the Al III and Si IV absorption to the photoionized nebula about ζ Oph and suggested the velocity offsets seen between these two species indicated the H II region was expanding. In Figure 7 we plot the apparent column density profiles (see Savage & Sembach 1991) of the ions Al III, Si IV, and S III. The Si IV and Al III profiles have been scaled upwards by factors of 40 and 100, respectively. The lower panel of Figure 8 shows the log of the apparent column density ratios of Al III and Si IV to S III as a function of velocity. The value of log[N(Al III)/N(S III)] varies by about one dex between the peak of the Al III profile at $v_\odot \approx -8$ km s$^{-1}$ and the peak Si IV absorption near $v_\odot \approx -15$ km s$^{-1}$.

The component at $v_\odot \approx -15$ km s$^{-1}$ coincides in velocity with the dense neutral/molecular cloud seen in the Zn II profile (see also Savage, Cardelli, & Sofia 1992).

Figure 6 shows the complexities that arise when looking in detail at a given interstellar sightline. The other sightlines in our sample may be similarly complex, with complications hidden in the absorption profiles. The modeling we present in § 3.2 is highly idealized and does not account for the physics of stellar wind bow-shocks, for example. For the ζ Oph sightline we will give results derived from the integrated sightline values of log N(Al III) and N(S III); we will, however, note the results for the case of log N(Al III)/N(S III) ≈ -2.0 along this sightline, which is appropriate for gas associated with the strongest component of Al III along this sightline.

3.2. The High-Latitude Sightlines to HD 18100 and ρ Leo

The average electron densities towards the higher-latitude stars can be estimated using the $^4P_{3/2}$ fine structure level of C II (denoted C II$^*$). Savage & Sembach (SS96) have studied the excitation of C II$^*$ towards HD 18100. They find, assuming the excitation is caused by electron collisions, $\langle n_e \rangle = 0.071$ cm$^{-3}$. This treatment assumes that all of the C II$^*$ and S II along the line of sight arise in the same gas and is a lower limit to the true electron density in the ionized gas. The value $\langle n_e \rangle$ for ρ Leo given in Table 1 is our own determination assuming electron collisions are populating the upper fine-structure level of C II. We have measured log N(C II$^*$) = 14.13 ± 0.02 and log N(S II) = 15.51 ± 0.02 from archival GHRs data for this sightline.

The column of C II$^*$ was derived from observations using the G160M grating and should be considered a lower limit given the possible presence of unresolved saturated structure. The average electron density is then determined using Eqn. (7) of SF93, though we adopt [C/S] ≈ [C/H] = −0.4 from Cardelli et al. (1996). We find $\langle n_e \rangle \geq 0.074 (T / 6000 K)^{0.5}$ cm$^{-3}$. Thus, $\langle n_e \rangle$ towards ρ Leo is similar to that towards the halo stars HD 18100 and HD 93521 as well as the direction towards 3C 273, which also probes halo gas. Reynolds (1991a) finds the high-latitude WIM is clumped in regions having electron densities $\langle n_e \rangle \approx 0.08$ cm$^{-3}$, a value quite close to the average densities derived for the high-latitude sightlines discussed here.

For the two distant high-latitude stars HD 18100 and ρ Leo we find a very good velocity correspondence between low-ionization gas (traced for example by Zn II) and ionized gas traced by Al III and S III. Savage & Sembach (1994, 1996) present GHRs observations of the high and low stages of ionization, respectively, towards HD 18100.

3The cooling rate per neutral H-atom for the ρ Leo sightline in the C II 158 µm line is therefore also similar to these other halo sightlines, with $L_e \sim (1.4 \pm 0.3) \times 10^{-26}$ ergs s$^{-1}$ H-atom$^{-1}$. The cooling in the 158 µm line along the ζ Oph and ζ Per sightlines may be as low as a factor of five below this value (Gry, Lequeux, & Boulanger 1992), further illustrating the differences in the ionized gas along the low- and high-latitude sightlines.
The low-ionization lines along this sightline are found at the same velocities as Al III and S III, as well as the high-ionization species such as Si IV and C IV; Savage & Sembach (1994) find the observed profile widths increase with the ionization potential of the species.

Toward ρ Leo we also see that the Al III and Zn II profiles are quite similar, showing two principal absorbing components (blends) centered at velocities $v_0 \approx -7$ and $+20$ km s$^{-1}$. To show this correspondence more clearly we plot the apparent column density profiles (Savage & Sembach 1991) of Zn II, S III, and Al III for the sightline towards ρ Leo in Figure 3. Also shown is the profile of the $^{2}P_{3,2}$ C II fine structure level as observed by the GHRG G160M grating with a resolution of $\sim 17$ km s$^{-1}$ (FWHM). The absolute velocity scale of the C II$^+$ observations was determined through the use of a SPYBAL observations as discussed in §3. The nominal wavelengths were shifted by $-0.039$ Å (or $-8.7$ km s$^{-1}$ at 1335.77 Å) based upon the analysis of the SPYBAL observations.

The apparent column density profiles of Al III and S III have shapes very similar to the Zn II profile, and the alignment of the Al III and Zn II component structure is excellent. The S III profile is systematically shifted by $\sim -2.2$ km s$^{-1}$ with respect to Zn II. This may be due to uncertainties in the absolute velocity scale; however, Fitzpatrick & Spitzer (1994) have found a similar offset ($-2.4$ km s$^{-1}$) in their S III observations towards γ Vel and suggested a possible error in the rest wavelength of the transition. Given the similarities of the two profiles, we have applied a $+2.2$ km s$^{-1}$ shift to the observed S III velocities in producing the profile in Figure 3. The profile for C II$^+$, which is likely tracing thermal electrons that are responsible for exciting C II to the fine structure level (see SF93), also seems to trace the Zn II component structure very well, though the difference in resolution between the two data sets make a direct comparison somewhat uncertain.

The detailed velocity correspondence between tracers of ionized and primarily neutral gas seen towards the two high-$z$ stars in our sample suggests the ionized gas is associated physically with the neutral material. There is no kinematic evidence that the ionized and neutral phases are spatially separated towards ρ Leo. The good velocity correspondence between neutral and ionized gas tracers could arise if S III and Al III absorption were tracing ionized edges of neutral clouds (e.g., McKee & Ostriker 1977) or if the clouds seen towards these high-altitude stars were partially ionized with neutral and ionized tracers mixed (e.g., SF93). The kinematic profiles in our data do not allow us to distinguish between these two scenarios, or other more complex arrangements of the two phases. The ionized and neutral media along the HD 18100 sightline seem to show a similarly close relationship, though we will not make as strong a claim in this case given the lower resolution of the data. The ionization produced by decaying neutrinos as proposed by Sciama (1995, 1997) would result in partially ionized gas. However, the decay photons from neutrinos with $E_\gamma = 13.7 \pm 0.1$ eV (Sciama 1995) are incapable of ionizing Al$^+$ and S$^+$. Therefore other sources of ionization (e.g., star light, X-ray background photons, or collisional ionization) are required to produce the Al$^{+2}$ and S$^{+2}$ we observe.

The close association of neutral and ionized tracers was also observed along the sightline to HD 93521 by SF93, a high-altitude star at $z \approx 1500$ pc from the Galactic plane. The component structure along the sightline towards HD 93521 is more complex than that towards ρ Leo, but the correspondence between C II$^+$ and tracers of neutral gas (e.g., S II) is very good. Spitzer & Fitzpatrick interpreted the data for the HD 93521 sightline to imply the free electrons and neutral gas were copatial and well-mixed. Thus, they argue for the existence of a partially ionized phase of the ISM at high-$z$.

Recent WHAM observations of the Perseus Arm have shown the intensity ratio of [O I] λ6300 to H$\alpha$ is in the range 0.01 to 0.04 (Reynolds et al. 1998a). The weakness of [O I] emission implies the fractional ionization in the WIM of the Galaxy is very high since the ionization of O and H are strongly coupled through charge-exchange reactions. Reynolds et al. comment that the observed ratio implies that most of the observed emission from the Galactic WIM cannot arise from partially-ionized gas along these sightlines, which probe gas at distances from the plane $|z| \lesssim 300$ pc. Similar results have been obtained for the WIM in the edge-on galaxy NGC 891 (Dettmar & Schulz 1992; Rand 1998). The assumption by SF93 of a partially-ionized phase of the ISM would seem to be contradicted by these [O I] measurements, although the WHAM observations were taken along a different path through the ISM and probe distances $z \lesssim 300$ pc.

Further high-resolution observations of neutral and ionized gas tracers will help to disentangle the connections between these phases of the ISM. Given the presence of C IV and N V absorption at similar velocities towards HD 18100, it is also possible that these high-latitude sightlines are not tracing gas photoionized by stellar radiation, but rather photoionization by cooling hot gas or more complicated interactions between various phases of the ISM, such as conductive interfaces or turbulent mixing layers (see SS96 and references therein). The contribution to the column densities of S III and Al III by hot, collisionally ionized gas could compromise our results and is discussed in §4.4.

Although the source of ionization of the WIM is not well understood, in §4.3 we will derive the gas-phase abundances in the ionized gas towards the high-altitude stars ρ Leo and HD 18100 by assuming the clouds to be photoionized by radiation from OB stars.

4. GAS-PHASE ABUNDANCES IN IONIZED GAS

Deriving the gas-phase abundance of Al relative to S from the column densities of Al III and S III requires the application of an ionization correction factor (ICF) to account for the unobserved ionization stages of Al and S (primarily Al$^+$ and S$^+$). The logarithmic gas phase abundance normalized to solar, $[\text{Al/S}]_i$, where the subscript $i$ denotes this value in the ionized gas, is related to the measured column densities of S III and Al III by

$$[\text{Al/S}]_i \equiv \log\{N(\text{Al}^{+2})/N(S^{+2})\} - \log\{\text{Al/S}\}_0$$

$$- \log\{x(\text{Al}^{+2})/x(S^{+2})\},$$

(1)

where $x(\text{Al}^{+2}) \equiv N(\text{Al}^{+2})/N(\text{Al})$ and $x(S^{+2}) \equiv N(S^{+2})/N(S)$ are the ionization fractions of Al$^{+2}$ and S$^{+2}$ in the ionized gas. The ratio $\{x(\text{Al}^{+2})/x(S^{+2})\}^{-1}$ is the
ICF, which we will write ICF(Al$^{+2}$). More generally in
this work, ICF($X^+$) $\equiv \{x(X^+)/x(S^{+2})\}^{-1}$.

In this section we derive $x(Al^{+2})/x(S^{+2})$ for moderate
to low-density ionized gas near late-O/early-B stars. We
then apply the ICFs to our measurements to derive gas-
phase abundances [Al/S].

4.1. CLOUDY Photoionization Equilibrium Models

We use the photoionization equilibrium code CLOUDY
(v90.04; Ferland 1996 and Ferland et al. 1998) to model
the ionization and temperature structure of diffuse, low-
excitation H II regions. Our models assume spherically
symmetric nebulae excited by a single star. We use a
volume filling factor $f$, which is the fraction of the vol-
ume filled with constant hydrogen particle density $n_H$ (in
cm$^{-3}$); the rest of the space is assumed to be filled with
very tenuous material and in these models is treated as a
vacuum. From the radially-averaged ionization structure
of the nebula, we can derive the ICF appropriate for di-
rect measures of the column densities toward the central
ionizing stars.

We use ATLAS line-blanketed, LTE stellar atmosphere
models (Kurucz 1991) as input spectra to the CLOUDY
models. Our models follow the temperature and ioniza-
tion structure of the model H II region from 0.3 pc dis-
tance from the exciting star to the point where the
electron density falls to $\lesssim 5\%$ the ambient density $n_H$ (i.e.,
$x(H^+)=0.95$). While the models we present here assume
 solar abundances with no dust opacity, we have found
the inclusion of sub-solar abundances of the refractory
elements and the addition of dust grain opacity does not
significantly alter our conclusions. This is because highly
refractory elements, i.e., Fe, Ni, Al, Cr, etc., are not dom-
inant nebular coolants. Further, grain opacity tends to
mimic the absorbing characteristics of H; including this
opacity therefore removes the same ionizing photons as H
(see Mathis 1986b). While the inclusion of photoelectric
heating by dust and the absence of minor nebular coolants
may have a more pronounced effect on the predicted emis-
sion line strengths, these thermal differences cause little or
no change in the predicted ionization fractions, and hence
column densities, of the species we are considering.
Detailed descriptions of our use of CLOUDY models to gain
information regarding the high-ionization species towards
$\mu$ Col and the contribution of H II region material to the
neutral tracers towards this star can be found in Brandt
et al. (1998) and Howk et al. (1998), respectively.

We have computed a grid of model H II regions with
varying input spectra and ambient densities. Table 1
shows the radially-averaged ionization fractions for sev-
eral UV tracers of photoionized gas in model H II re-

regions. These models used ATLAS model atmospheres with
$T_{eff} = 33,000$ K, $\log L_* / L_\odot = 4.4$ and solar system abun-
dances. This stellar effective temperature and luminosity
are appropriate for $\mu$ Col or $\zeta$ Oph. We have adopted
$f = 1.0$ in these models while varying the ambient density
of the gas. Many authors define an ionization parameter, 
which is related to the ratio of hydrogen-ionizing photon
density, $n_\gamma$, to particle density, $n_H$, in the ionized region.
A traditional definition of the ionization parameter (e.g.,
Mathis 1986b; Shields & Kenney 1995) is

$$U \equiv \frac{L}{4\pi R_S^2 n_H c},$$

where $L$ is the hydrogen ionizing photon luminosity in
photons s$^{-1}$, and the Strömgren radius is $R_S = [3L/(4\pi n_H^2 f \alpha_B)]^{1/3}$, where $\alpha_B$ is the case B recom-
bination coefficient of H (Osterbrock 1989), and $f$ is again
the volume filling factor. Using this definition $U \propto n_H^{-3}$,
and we find $3U = \langle n_\gamma / n_H \rangle$, where the average is over
volume. In this work we will primarily adopt the equivalent
definition given by Domgørgen & Mathis (1994; hereafter
DM94). We write the alternate ionization parameter $q$ as

$$q \equiv n_H f^2 L_{50},$$

where $L_{50}$ is the stellar ionizing luminosity in units of 10$^{50}$
photons s$^{-1}$. This definition is related to the traditional $U$
by $q = 10^{-50}(36 \pi c^3 / \alpha_B^2) f^2 U^3$, though it removes the de-
pendence on temperature that is hidden in $\alpha_B$ (Osterbrock
1989). Bright high-density H II regions are typically de-
scribed by models with $\log(q) \gtrsim -1.0$, while Domgørgen &
Mathis use $-4.0 \lesssim \log(q) \lesssim -3.0$ in modelling the Galac-
tic DIG. We give the value of $\log(q)$ for each model in
Table 1 for comparison with the models of DM94, Mathis
(1986a) and others. We also give the equivalent values of
$\log(U)$. The values $U$ quoted assume $\alpha_B = 2.59 \times 10^{-13}$
cm$^3$ s$^{-1}$ appropriate for $T_e = 10^4$ K (Osterbrock
1989).

In general the ionization and thermal structure of low-
density models is determined by the ionization parameter,
the adopted gas-phase abundances, and the shape of the
ionizing continuum. Table 1 shows the ionization fraction
of $S^{+2}$ is a function of the ionization parameter $q$; how-
ever the ratios of the ionization fractions $x(Al^{+2})/x(S^{+2})$,
$x(Si^{+2})/x(S^{+2})$, and $x(Pi^{+2})/x(S^{+2})$ are quite insensitive
to changes in $q$ for a given stellar effective temperature.
Further, these ratios, which give us the ICF for determin-
ing the relative gas-phase abundances of Al, Si, and P to
S, are not large. The greatest correction, for Al, is only of
order $\sim 0.2$ dex. The ICF relating $N(Fe II)/N(S III)$ to
$[Fe/S]$ is also relatively well-behaved with respect to
the ionization parameter, but we shall see that it shows
substantial variation with the input stellar effective tem-
perature.

Table 1 gives the ratios of ionization fractions for
$\log(q) = -4.0$ as a function of stellar effective temperature
in the range 27,000 $\leq T_{eff} \leq 39,000$. One can see that
the relative ionization fractions $x(He)/x(S^{+2})$ are more
sensitive to changes in the shape of the underlying contin-
uum than to changes in the ionization parameter $q$. Even
so, the spread of values $x(Al^{+2})/x(S^{+2})$, $x(Si^{+2})/x(S^{+2})$,
and $x(Pi^{+2})/x(S^{+2})$ are still relatively small. Table 1 also
gives the average ionization corrections appropriate for
relating the ratio of the various ionized species to their
gas-phase abundances in the ionized gas. Two values are
given: one representing the radially-averaged physical
properties of the nebula (ICF$_{rad}$) and one the volume-

$\mu$ Col or $\zeta$ Oph. We have adopted
f = 1.0 in these models while varying the ambient density
of the gas. Many authors define an ionization parameter, 
which is related to the ratio of hydrogen-ionizing photon
density, $n_\gamma$, to particle density, $n_H$, in the ionized region.
A traditional definition of the ionization parameter (e.g.,
The volume-averaged ICFs tend to weight the outer portions of the model nebulae more strongly, and therefore the volume-averaged values tend to favor lower stages of ionization. This can be seen in the difference between \( \log(\text{ICF(Si}^{+3})_{\text{vol}}) \) and \( \log(\text{ICF(Si}^{+3})_{\text{rad}}) \) in Table 3; the radially-averaged ICF suggests a greater fraction of Si is in Si\(^{+3}\) than in the volume-averaged case. The ICFs given at the bottom of Table 3 are averages over the seven stellar effective temperatures considered in our models with \( \log(q) = -4.0 \) and \( -2.0 \). Also given are the standard deviations about the means. The standard deviations give us a measure of how sensitive our derived ICFs are to uncertainties in the effective temperature of the ionizing radiation source, and we will use these values as estimates of the errors in our derived ICFs.

In Figure 3 we show \( \log(x(X^i)/x(S^{+2})) \) as a function of \( T_{eff} \) for the ionized species \( X^i = \text{Al}^{+2}, \text{Fe}^{+2}, \text{Si}^{+2}, \text{P}^{+2}, \text{C}^{+2}, \text{and} \text{N}^{+2} \). Also shown in the bottom panel of this figure are the logarithms of \( x(S^{+2}), x(A1^{+2}), \) and \( x(Fe^{+2}) \). It is clear that the ICFs relating these ions to the gas-phase abundances of these elements (relative to S) in the ionized gas are functions of the assumed stellar effective temperatures. However, for Al III, Si III, and P III, the dependence on \( T_{eff} \) is relatively small, having a total spread of \( \lesssim 0.25 \) dex over the range 29,000 \( \lesssim T_{eff} \lesssim 39,000 \) K. The bottom panel shows that even when \( \text{S}^{+2} \) and \( \text{Al}^{+2} \) are not the dominant ionization stages of Al and S, the fractional abundances of the two ions follow each other very well. The \( 1\sigma \) uncertainties quoted for the ratios of ion column densities using absorption line spectroscopy are often \( \sim 0.1 \) dex (e.g., Savage, Cardelli, & Sofia 1992; SF93; Howk et al. 1998), which is similar to or greater than the standard deviations found for the predicted ICFs given in Table 3 for Al III, Si III, and P III relative to S III.

The ICF for Fe III (also C III and N III) shows a greater dependence on the effective temperature of the underlying stellar atmosphere than those for Al III, Si III, and P III. However, even uncertainties on the order 0.2 to 0.3 dex for the value of ICF(Fe\(^{+2}\)) can distinguish between depleted and non-depleted abundance ratios for an element that is typically found to be as heavily incorporated into grains as Fe.

A concern when interpreting these results is the accuracy of the atomic data used in deriving these models. In particular the atomic data for Fe are a concern (e.g., Pradhan & Bautista 1998). The atomic data adopted by CLOUDY are discussed in Ferland (1996) and Ferland et al. (1998). In general the photoionization cross-sections [using fits to the Opacity Project results by Werner et al. (1996)] and radiative recombination rates (see references in Ferland et al. 1998) are relatively secure. The dielectronic recombination coefficients \( \alpha_{di} \) for recombinations into the first two ions of Al are also relatively secure (Nussbaumer & Storey 1986). Though \( \alpha_{di}(\text{Al}^{+2}) \) and \( \alpha_{di}(\text{Al}^{+3}) \) are estimated, Ferland (1996) predicts the ionization balance of Al\(^{0} - \text{Al}^{+2} \) is relatively reliable. The low-temperature dielectronic recombination coefficients for the various ionic stages of S, Si, and Fe are not well constrained (Ferland 1996; Ferland et al. 1998).

CLOUDY estimates the unknown low-temperature dielectronic recombination coefficients of the first four ionization stages of elements in the third and fourth rows of the periodic table by adopting a mean of the rate coefficients for the first four ionization stages of C, N, and O (Ali et al. 1991). We have disabled CLOUDY’s approximation of \( \alpha_{di} \) for these elements to test its effects on the observed ratios. The ICFs derived for Al\(^{+2}, \text{Si}^{+2}, \text{and} \text{P}^{+2} \) differ in models with and without the assumptions regarding dielectronic recombination by less than the standard deviations given in Table 3. For Fe III the models with \( \alpha_{di}(\text{Fe}^0) = 0.0 \) give values close to that given in Table 3.

However, the density dependence of \( \chi(\text{Fe}^{+2})/\chi(S^{+2}) \) is greatly increased. The values of ICF(Fe\(^{+2}\)) is less certain than the ICFs for the other species considered here given their strong dependence on the shape of the ionizing spectrum. The same can be said for ICF(Si\(^{+3}\)). The adopted error of \( \sigma = 0.2 \) to 0.3 dex for ICF(Fe\(^{+2}\)) likely encompasses enough of parameter space to make our error estimates not unreasonable. We will make estimates for [Fe/\text{Si}] where the data for Fe III are available, but it is important to recognize the strong dependence of the ionization correction on \( T_{eff} \) and the possibly inappropriate atomic parameters for Fe.

4.2. [Al/S] \(_i\) and [Fe/S] \(_i\) in H II Regions

In this section we derive [Al/S] \(_i\) and [Fe/S] \(_i\) for the sightlines probing H II regions in the Galactic disk. The results of 4.1] give ICFs that are directly applicable to H II regions about the stars \( \zeta \text{ Oph}, \xi \text{ Per}, \beta\text{^1 Sco}, \) and \( \mu \text{ Col}. \) The distances to these stars are small enough that it may be reasonable to assume their H II regions dominate the column density of ions considered here. For \( \zeta \text{ Oph}\) this comparison is complicated by the velocity structure, which suggests there are a number of processes at work along this sightline. A comparison of the integrated column densities of Al III and S III towards this star will not necessarily provide us a good measure of the gas phase abundance \([\text{Al}/\text{S}]_i\). As discussed in §3.1.1, the sightline towards \( \mu \text{ Col}\) may be probing H II region or WIM gas, or a mixture of both. We will assume here that the ionized gas along this sightline is probing an H II region.

Table 3 presents the observed ratios of the integrated column densities of Al III and Fe III (where available) to S III for our program stars. Also given in this table are the derived logarithmic abundances \([\text{Al}/\text{S}]_i\) and \([\text{Fe}/\text{S}]_i\). The abundances \([\text{Al}/\text{S}]_i\) and \([\text{Fe}/\text{S}]_i\) for the sightlines to \( \mu \text{ Col}, \xi \text{ Per}, \beta\text{^1 Sco}, \) and \( \zeta \text{ Oph}\) were derived using the ICFs appropriate for the stellar effective temperatures of these stars, with the error estimates as discussed in §3.1.1. We are assuming in this approach that the measured material is mostly photoionized H II region gas. Given the velocity structure discussed in 3.1.1, \([\text{Al}/\text{S}]_i\) in the \( \zeta \text{ Oph}\) H II region may be as high as \( -1.0\). The values \([\text{Al}/\text{S}]_i\) and \([\text{Fe}/\text{S}]_i\) presented in Table 3 for these disk sightlines suggest grains are present in the H II regions surrounding all of these stars.

Federman et al. (1993) present a GHRS measurement of P III \( \lambda \text{1334.813} \) A along the sightline to \( \zeta \text{ Oph}. \) They find \( \log(N(\text{P III}) = 12.94 \pm 0.04. \) From the results presented in Table 3, we see \( \log(\text{ICF(P}^{+2})) = +0.01 \pm 0.06. \)
We thus find \([P/S]_{1} = -0.11 \pm 0.07\) for the ionized gas towards \(\zeta\) Oph. This value assumes the integrated sightline column densities of P and S are tracing the same regions, which may be incorrect given the velocity structure towards this star (§3.2.1). The element P is thought to be very lightly depleted. In their study of the neutral gas abundances along the \(\zeta\) Oph sightline, Savage et al. (1992) find \([P/H] = -0.23\) for the warm neutral cloud centered at \(v_{\odot} = -27\) km s\(^{-1}\) (their component A). For the sightline towards \(\mu\) Col, Howk et al. (1998) derive \([P/S] = -0.03 \pm 0.03\) in the low-velocity absorbing complex centered at \(v_{\odot} = +23\) km s\(^{-1}\), which shows abundance patterns similar to component A towards \(\zeta\) Oph. The \([P/S]_{1}\) derived here for the \(\zeta\) Oph sightline is consistent with previous \([P/S]\) measurements for neutral material: P is lightly depleted if at all.

### 4.3. \([Al/S]_{1}\) in the WIM

In this subsection we consider the gas-phase abundances \([Al/S]_{1}\) in the halo WIM. The interpretation of the \(N(Al\,III)/N(S\,III)\) measurements along the sightlines to \(\rho\) Leo and HD 18100 is subject to uncertainties regarding the ionization of the WIM and contamination from collisionally ionized gas (see §4.2). The long path-lengths through the WIM and the likelihood that any \(\text{HII}\) regions around these stars are in very low-density environments imply that a large fraction of the observed \(Al\,III\) and \(S\,III\) along these sightlines arises in the WIM of our Galaxy. Rho Leo should lie above \(\sim 60\%\) of the WIM of the Galaxy, while HD 18100 should lie above almost all of the high-\(z\) layer of ionized material (Reynolds 1989; Savage et al. 1990). Though the ionization source of the diffuse ionized material is not well known, the power requirements ionization by OB stars may be a viable mechanism (Reynolds 1984; DM94). Here we estimate \([Al/S]_{1}\) towards \(\rho\) Leo and HD 18100 for the case where the WIM of the Galaxy is photoionized by OB stars.

We will follow DM94 and model the WIM of the Milky Way using low-density \(\text{HII}\) region photoionization models. The ratio \(x(Al^{+2})/x(S^{+2})\) derived for our \(\text{HII}\) region models is relatively insensitive to the ionization parameter and is not heavily dependent on the shape of the input ionizing spectrum; we therefore believe it is appropriate to apply the results derived in §3.1 to the WIM of the Galaxy. Our observations of ionized gas towards \(\rho\) Leo and HD 18100 probe the WIM and thus are not a simple radial integration through an \(\text{HII}\) region. A volume-averaged set of ICFs are more appropriate for application to the WIM than the radially-averaged values used in the previous subsection (DM94). Volume-averaged ICFs from the models treated in §3.1 are given in the last row of Table 3. We see that there are significant differences in the ICFs derived for most of the ions studied here when adopting volume-versus radially-averaged values.

We do not know well the shape of the ionizing spectrum appropriate for the WIM. We will continue by adopting the mean of the volume-averaged values \(ICF(Al^{+2})\) for our models. These values are given in Table 3 as \(ICF_{\text{Vol}}\). The values \([Al/S]_{1}\) given for HD 18100 and \(\rho\) Leo in Table 3 are therefore derived assuming \(x(Al^{+2})/x(S^{+2}) = -0.37 \pm 0.07\), or \(log\,ICF(Al^{+2}) = +0.37\) in the WIM. For the sightline towards \(\mu\) Col, the value \([Al/S]_{1}\) given in Table 3 was derived assuming \(log\,ICF(Al^{+2}) = +0.25 \pm 0.07\) in an \(\text{HII}\) region about this star; if this sightline instead probes the WIM along this direction, the gas-phase abundance could be \([Al/S]_{1} = -0.66 \pm 0.08\).

We can estimate values for \(log(x(S^{+2})\) among our two high-latitude sightlines. Assuming \(N_{e} = 7 \times 10^{19}/\sin|b|\) cm\(^{-2}\) (Reynolds 1991b), and accounting for the 40% of this value expected to reside beyond \(\rho\) Leo, the predicted electron column densities along the high-latitude sightlines are \(log\,N_{e} = 19.7\) and 19.9 for \(\rho\) Leo and HD 18100, respectively. Assuming \(N_{e} \approx N(H^{+})\) and the solar abundance of S/H (Anders & Grevesse 1989), for \(\rho\) Leo and HD 18100 we find \(log\,x(S^{+2}) \sim -1.3\) and \(-0.9\), respectively. Compared with our volume-averaged results for models having \(log(q) = -4.0\), this implies the characteristic “effective temperature” for the ionizing radiation field of 28,000 \(< T_{\text{eff}} < 33,000\) K is appropriate for these sightlines. This result is consistent with the limits derived from observations of diffuse \(\text{HeI}\) recombination radiation (Reynolds & Tufte 1995).

The \(\text{AlIII}\) and \(\text{SIII}\) data presented here, when compared with our model results, are inconsistent with a solar relative abundance of Al to S in the WIM. We have assumed that the intrinsic or cosmic abundance (gas+dust) of Al to S is given by the solar system values. Even in the presence of mildly sub-solar metallicities, \([X/H] \gtrsim -1.0\), the abundance of Al relative to S is expected to be quite close to the solar abundance. Though Al is an odd-Z element, it is primarily produced in the C-Ne-burning stages of massive stars. Thus, S and Al are both deposited into the ISM by Type II supernovae.

In their study of elemental abundances in solar neighborhood low-mass stars, Edvardsson et al. (1993) derive abundances for Al as well as several \(\alpha\)-elements. The behavior of \([\text{Al}/\text{Fe}]\) versus \([\text{Fe}/\text{H}]\) in their dataset mimics that of the \(\alpha\)-elements. For their sample of 189 stars, all having \([\text{Fe}/\text{H}] \gtrsim -1.0\), the average value of \([\text{Al}/\text{Fe}]\) is \(+0.02 \pm 0.07\), where \(\alpha\) in this context represents an average over the elements Mg, Si, Ca, and Ti. The yield of Al relative to the \(\alpha\)-elements does depend upon the initial stellar abundances, but this effect is negligible for the range of metallicities of the Edvardsson et al. sample (and for our halo clouds). We do not expect the intrinsic ratio of \([\text{Al}/\text{S}]\), as long as the metallicity of the gas is \(\gtrsim 0.1\) solar, to be significantly different than the solar-system value adopted here. Therefore the values of \([\text{Al/S}]_{1} < 0.0\) presented here for the WIM are not due to nucleosynthetic effects and imply the existence of dust in this phase of the ISM.

### 4.4. Collisionally Ionized Gas and its Effects on \([Al/S]_{1}\)

If hot, collisionally ionized gas is present along the sightlines studied here, its imprint on the ionization balance of the gas could cause us to misinterpret the column density

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5It is important to note that we are using the volume-averaged ICFs here, rather than the radially-averaged values given in Table 3. For models having \(log(q) = -4.0\) we find \(log\,x(S^{+2}) = -1.38\), \(-1.16\), \(-0.99\), \(-0.84\), \(-0.77\) and \(-0.53\) for \(T_{\text{eff}} = (27, 29, 31, 33, 35, 37,\) and 39) \(\times 10^{4}\) K, respectively, in the volume-averaged model results.

6The element S is not included in their dataset, though see Wheeler, Sneden & Truran (1989) and references therein.
As a first step for approaching the problem, we have collected column density measurements of Si IV, and the ratio of Si IV and S III column densities, for all of our sightlines in Table 3. Several of the Si IV column densities given in Table 3 are taken from literature measurements using the GHRS (with references given in the table); others were derived from archival GHRS spectra using the techniques described in §2. With an ionization potential of 33.5 eV, the ion Si IV is potentially a tracer of collisionally ionized gas with T in the range $(0.3 - 1) \times 10^5$ K, though Si IV can also be produced in warm gas via photoionization by hot stars.

In the following discussion we consider the observational constraints regarding collisional ionization for each sightline.

**ζ Oph** - The absorption towards ζ Oph, as discussed in §1.1 and shown in Figure 3, shows evidence for changes in the ionization structure as a function of heliocentric velocity. The gas at $v_0 \lesssim -15$ km s$^{-1}$ is characterized by large amounts of Si IV absorption and relatively low amounts of Al III. Higher velocity gas along this sightline, $-13 \lesssim v_0 \lesssim -5$ km s$^{-1}$ shows relatively little Si IV and higher ratios of Al III to S III. The peak of the Si IV profile may trace gas that is collisionally ionized. Our CLOUDY models, e.g., Table 3 cannot explain the large value of the ratio $N(\text{Si IV})/N(\text{S III}) \approx -1.8$ observed near $v_0 \approx -20$ km s$^{-1}$. However, Sembach et al. (1994) note that the Si IV line width implies gas with $T < 5 \times 10^4$ K. This temperature limit and the absence of associated C IV absorption lead Sembach et al. to suggest the Si IV absorption is due to photoionized gas in an expanding H II region. The gas between $v_0 = -8$ and $-13$ km s$^{-1}$ is also likely photoionized gas in the H II region about ζ Oph. This gas shows values of log $N(\text{Si IV})/N(\text{S III}) \lesssim -2.0$, which can be generally explained by photoionization models. The profile width of the Al III absorption measured by Sembach et al. (1994) implies gas with $T < 3 \times 10^4$ K. Morton (1975) also finds absorption from N II, N II*, N II** at $v_0 = -8$ km s$^{-1}$, suggesting the presence of (photo)ionized gas and a significant density of electrons at these velocities. Our earlier suggestion that a value of log $N(\text{Al III})/N(\text{S III}) \sim -2.0$ is most appropriate for the photoionized H II region gas towards ζ Oph is based upon the observed ratio at velocities corresponding to the peak of the Al III (and N II) absorption. Reynolds (1988b) has observed Hα emission centered at $v_0 = -13 \pm 1$ km s$^{-1}$ along this sightline, which is quite near the peak of the S III absorption. The temperature implied by an analysis of the breadth of the S II and Hα emission profiles is $T = 6700 \pm 700$ K (Reynolds 1988b). Thus if we associate the Hα and [S II] emission with the absorption seen in S III, Al III, and N II, the temperatures are too low to produce significant amounts of these ions through collisional ionization.

**ξ Per** - The sightline towards ξ Per shows a complex of Hα-emitting regions at several different velocities. Reynolds (1988b) finds ionized regions excited by this star at velocities $v_0 = +3$, $+7$, $+12$, and $+14$ km s$^{-1}$. Figure 6 shows the $N_h(v)$ profiles of S III, Al III, and Si IV towards ξ Per and the ratios of the latter two ions to S III, as Figure 3 did for ζ Oph. The vertical dashed lines in this figure represent the velocities at which Reynolds (1988b) detects Hα emission, though shifted by $-2.2$ km s$^{-1}$. The peaks in the $N_h(v)$ profile for S III give a good match to the components detected in emission by Reynolds. In his analysis, Reynolds (1988) used the emission from [S II] and Hα to separate the thermal and non-thermal components of the observed velocity widths. He found that the emitting regions excited by ξ Per had temperatures between $T \approx 5,000$ and $11,000$ K, consistent with expectations for photoionized gas. We associate the emitting regions studied by Reynolds with the material seen in S III and Al III absorption in our GHRS spectra. At the implied temperatures, the contribution to the S III and Al III column densities from collisionally ionized gas should be negligible. The ICFs derived using photoionization models should therefore be appropriate for this material.

**β¹ Sco** - The derived log $N$(Si IV)/$N$(S III) towards β¹ Sco is quite similar to the measured values along the ζ Oph and ξ Per sightlines. Unfortunately, we have virtually no information on the velocity structure of the S III absorption profile given the low resolution of the G160M data. The logarithmic ratio of log $N$(Si IV)/$N$(Al III) is in the range $-0.2$ to $0.0$ over the velocity range of Al III absorption. The profile-weighted average velocities (Sembach & Savage 1992) for Al III and Si IV are $(v_0) = -13.9 \pm 0.6$ and $-11.4 \pm 0.5$ km s$^{-1}$, respectively. It is tempting to use the similarities between the ζ Oph and β¹ Sco sightlines to argue that collisionally ionized gas is not confusing our analysis of this sightline. The neutral gas absorption profiles towards these stars are very similar (e.g., the Zn II profiles of Figure 3) and the two stars lie at approximately the same distance from the sun and from the Galactic mid-plane. However, the differences in spectral type would suggest that in the case of purely photoionized gas and equal gas densities, the ratio $N$(Si IV)/$N$(S III) should be smaller for β¹ Sco, i.e., for the star with lower $T_{eff}$. Also, we have seen (§3.1.1) that there are some peculiarities along the ζ Oph sightline, possibly including the presence of collisionally ionized gas at velocities $v_0 \lesssim -15$ km s$^{-1}$. We cannot rule out contributions from collisionally ionized gas to the S III and Al III absorption towards β¹ Sco.

**µ Col** - For the sightline towards µ Col, measurements with the WHAM Fabry-Perot spectrometer (Reynolds et al. 1998) show the Hα emission at velocities consistent with the S III absorption profile. The WHAM measurements, with a 1° beam, are well fit by a gaussian with $(v_0) = 22.9 \pm 0.5$ km s$^{-1}$ and $b = 17.0 \pm 1.5$ km s$^{-1}$ (M. Haffner, private communication). The breadth of the profile suggests that the gas traced by this emission has
$T \lesssim 18,000$ K; in collisional ionization equilibrium models of gas at this temperature S III and Al III represent less than 1% of the total S and Al abundances (Sutherland & Dopita 1993). The profile-weighted average velocity (Sembach & Savage 1992) of the S III is \( \langle v_0 \rangle = 23.2 \pm 0.3 \text{ km s}^{-1} \), with the Al III \( \lambda \lambda 1855 \) and 1862 Å lines having \( \langle v_0 \rangle = 21.4 \pm 1.0 \) and 23.9 \( \pm 0.9 \text{ km s}^{-1} \), respectively. Due to the similarity of the velocities, we associate the Hα-emitting gas to the S III line suggest that the contribution of hot, collisionally ionized gas may be the case of HD 18100, the velocity overlap of the absorption components along this sightline suggest that such contamination may in some way be related to collisionally ionized gas. The Si II gas we are studying. Thus our application of the ICFs for HD 18100 – the archival GHRS spectra of Si IV towards \( \rho \) Leo show no evidence for absorption in the velocity range covered by the S III absorption studied here (i.e., \(-19 \leq v_0 \leq +2 \text{ km s}^{-1} \)). The \( 2\sigma \) upper limit to \( N(\text{Si IV}) \) given in Table 6 implies \( \log [N(\text{Si IV})/N(\text{S III})] \leq -2.1 \) in this velocity range, assuming \( b_{\text{H}1\text{V}} \approx 10 \text{ km s}^{-1} \). Though there is Si IV absorption overlapping the higher-velocity Al III absorption, it appears to be significantly broader than the Al III absorption. We believe that the lack of detectable Si IV absorption at the velocities of the stronger absorbing complex seen in Al III (and S III), with limits that place the ratio \( N(\text{Si IV})/N(\text{S III}) \) at levels well below those detected along our H II region sightlines, suggests collisionally ionized gas is not an important contributor to the column densities of Al III and S III towards \( \rho \) Leo.

**HD 18100** – The sightline towards the star HD 18100 has been studied by Sembach & Savage (1994), and their values of \( N(\text{Si IV}) \) are given in Table 6. As mentioned in §4, the velocities of S III and Al III along this sightline are quite similar to those of the low ions (e.g., Zn II and Mn II), as well as those of the highly-ionized species Si IV and C IV. Indeed, Figure 4 of Sembach & Savage (1994) shows that the profiles of Al III, Si IV, and C IV are quite similar as viewed with the resolution of the GHRS G160M grating. Though the breadth of the profiles increases with ionization potential along this sequence, the increase seems mostly to occur towards negative velocities. It is possible that the highly ionized species discussed by Sembach & Savage have more complex velocity structures that would reveal themselves at higher resolution [the 1.4 \( \text{ km s}^{-1} \) resolution Ca II profile presented by SS96 and Ryans et al. (1996) shows evidence for many closely-spaced absorbing components along this sightline]. However, we have no evidence with which to rule out the possibility that the observed columns of S III and Al III are produced in collisionally ionized gas. The Si IV and C IV absorption profiles, which are at the same velocities as the lower ionization species, suggest that such contamination may indeed be a real problem for this sightline. That the ratio of \( N(\text{Si IV})/N(\text{S III}) \) along this sightline is the highest in our sample also suggests collisionally ionized gas may be playing a role in determining the ionization balance in the gas we are studying. Thus our application of the ICFs derived from photoionization for this sightline may be inappropriate.

In summary it appears, with the exception of the sightline to HD 18100 and possibly \( \beta^1 \) Sco, collisional ionization does not likely explain the origin of the Al III and S III. In the case of HD 18100, the velocity overlap of the absorption due to low, moderate, and highly ionized species, as well as the large column density of Si IV relative to S III, raises the possibility that much of the observed Al III and S III along this sightline could arise in collisionally ionized gas.

### 5. DISCUSSION

The Al III and S III column densities, when combined with the results of our photoionization modelling, suggest that Al-bearing dust is indeed present in the ionized gas along the sightlines considered here. For H II region gas this result is not surprising. The existence of dust in H II regions has been implied by several independent lines of reasoning (see Osterbrock 1989, Chap. 7; Mathis 1986b; Peimbert & Goldsmith 1972), though little can be discerned about the composition of the grains or the degree to which dust grains are processed in the ionized ISM using these methods.

Our measurements of [Al/S], for the nearby sightlines that probe the H II regions surrounding the stars ζ Oph, ζ Per, \( \beta^3 \) Sco, and \( \mu \) Col give us a measure of the incorporation of Al into dust grains in these nebulae. Assuming \( [\text{Al}/\text{S}] = [\text{Al}/\text{H}] \), the dust-phase abundances of Al in the ionized material along these sightlines, in units of atoms per million hydrogen, are \( 10^6(\text{Al}/\text{H})_d \approx 10^6(\text{Al}/\text{H})_i - 10^6(\text{Al}/\text{H})_i = 2.8 \pm 0.6, 2.6 \pm 0.5, 2.7 \pm 0.8, \) and \( 2.5 \pm 0.5 \) for ζ Oph, ζ Per, \( \beta^3 \) Sco, and \( \mu \) Col, respectively. These values are an order of magnitude less than the dust-phase abundance of Fe, Si, or Mg in the warm neutral ISM (Savage & Sembach 1996b; Howk et al. 1998). The dust-phase abundances of Al presented here are similar to the values derived for Ni in the WNM, which has a similar solar system abundance (Savage & Sembach 1996b; Howk et al. 1998).

Unfortunately, little is known about the gas-phase abundance of Al in the WNM of the Galaxy due to the great strength of the only available Al II transition at \( \lambda 1670 \) Å. Barker et al. (1984) have performed a curve-of-growth analysis of interstellar Al II absorption in the WNM using data from the Copernicus observatory. However, for many of their sightlines the absorption due to Al is far up the flat portion of the curve of growth, making the uncertainties in the determination of the Al column densities quite large. In deriving the column density of Al II, Barker et al. employ an empirical curve of growth derived from Si II. However, since Al and Si are expected to have different gas-phase abundances from component to component due to changing depletion effects, it is likely that Si II and Al II have somewhat different curves of growth. Jenkins (1983), with several important caveats summarized at the beginning of his paper, has compared the equivalent widths of Al II \( \lambda 1670 \) Å with the similarly strong Si II transition at \( \lambda 1304 \) Å. While the nature of his comparison tends to heavily weight low-column density intermediate velocity features, Jenkins finds no evidence for changing [Al/Si] with \( z \)-height of the probe star with the implied value \( [\text{Al}/\text{Si}] \approx -0.2 \). This is near the upper range found by Barker et al. (1984), but is roughly consistent with their values. Again, there are many uncertainties with Jenkins’ approach, among them that the Al II and Si II transitions are likely both on the flat part of the curve of growth, which may hide significant changes in the relative abundances.

For comparison with our results, we look to those sight-
lines with the least saturated lines in the Barker et al. survey. For these sightlines Barker et al. consistently find \([\text{Al/H}] \approx -1.1\) to \(-1.0\). This selection is strongly biased towards low-density sightlines. If we take \([\text{Al/S}]_i \approx -1.0\) as representative of the H II region sightlines in our sample, this suggests the refractory grain material is not heavily affected by the conditions in low-density H II regions. However, the validity of this comparison is somewhat suspect given the uncertainties and biases in the Barker et al. results.

Our estimates of \([\text{Fe/S}]_i\) in three of the sightlines considered here (see Table 6) yield values roughly consistent with those for \([\text{Fe/H}]_i\) in the Orion nebula from a variety of authors (Osterbrock et al. 1992; Peimbert et al. 1993; Baldwin et al. 1996; Rodríguez 1996; and Rubin et al. 1997) and suggest Fe is incorporated into grains in these ionized regions. The relative values \([\text{Al/S}]_i\) versus \([\text{Fe/S}]_i\) suggest that the fraction of Al incorporated into grains is consistent with that of Fe or a bit less. For the sightlines towards \(\zeta\) Oph and \(\mu\) Col we can directly compare the gas-phase abundances of Fe derived for the neutral and ionized sightlines. In each case, the velocity of the ionized gas is closest to the components that show the lowest value of \([\text{Fe/H}]_i\), which are \([\text{Fe/H}] = -2.4\) for \(\zeta\) Oph (Savage et al. 1992) and \([\text{Fe/H}] \approx [\text{Fe/S}] = -1.3\) for \(\mu\) Col (Sofia et al. 1993; Howk et al. 1998). Using the values of \([\text{Fe/S}]_i\), given in Table 6, we find that \(\sim 3\%\) and \(\sim 9\%\) of the dust-phase Fe in the neutral gas has been returned to the gas-phase in the ionized gas (with a factor of two uncertainty). Our measurements of significantly sub-solar Al and Fe abundances in H II regions suggest the processing of grains in low-excitation H II regions is not much different than the destruction that occurs in the WNM of the Galaxy.

The implications of dust within H II regions have been discussed by several authors (e.g., Shields & Kennicutt 1995; Henry 1993; McGaugh 1991; Aannestad 1989; Mathis 1986b). The most important effects are caused by the incorporation of possibly important coolants into the solid phase (Shields & Kennicutt 1995), the change in the thermal balance due to photoelectron emission (heating) and far-infrared thermal dust emission (cooling), and the competition of the dust opacity with H and He for ionizing photons (Mathis 1986b). McGaugh (1991) has shown that the existence of dust can significantly alter the Balmer line strengths expected from an H II region. This effect comes about because the dust is able to absorb a significant number of photons that would otherwise go towards ionizing H (Mathis 1986b). As a consequence McGaugh suggests calculations of the star formation rates using only Balmer line intensities may underestimate the number of ionizing stars present. Also, the true volume of a dusty H II region will be smaller than the dust-free Strömgren volume. For low-density H II regions like those studied here, however, Mathis (1986b) has shown that the effects of dust absorption may not provide a significant optical depth to ionizing photons. Mathis also points out that although dust is an additional source of opacity, the opacity due to dust does not affect the ionization balance of most species in H II regions given its similarity to the H opacity. Shields & Kennicutt (1995) discuss the important effects of dust on emission line strengths from metal rich \((Z > Z_\odot)\) H II regions, particularly those found near the centers of galaxies.

Sembach & Savage (1996) have shown that in general, the gas-phase abundances of elements increases as one moves from the disk to the halo of our galaxy. This suggests an increasing degree of (incomplete) grain destruction with increasing height above the plane of the Galaxy. In Figure 6 we show the gas-phase abundances \([\text{Al/S}]_i\) as a function of \(z\)-distance of the observed stars. Since S is generally not depleted \([\text{Al/S}]_i\) should closely follow \([\text{Al/H}]_i\). There is a general trend of increasing gas-phase abundance of Al in the ionized gas with increasing height above the plane of the Galaxy. This is qualitatively consistent with the behavior observed by Sembach & Savage for the WNM.

It is also known that the gas-phase abundances of elements increase with decreasing \(\langle n_H \rangle \equiv N(\text{H I})/d\) in the warm neutral ISM (Jenkins 1987; Savage & Bohlin 1979). Both the ionized and neutral gas densities are thought to decrease exponentially with \(z\)-height (Dickey & Lockman 1990; Reynolds 1989), suggesting that the behavior seen in Figure 6 may be tracing the density-dependence of the gas. In Figure 7 we plot the values \([\text{Al/S}]_i\) versus the electron density (top) and the average line of sight neutral density (bottom), as given in Table 6. Given the many definitions of the electron densities (average versus rms, etc.) we have used different symbols to represent the determinations of rms and average electron densities (see §).

Figure 8 shows a striking relationship between the average densities and the gas-phase abundances of \([\text{Al/S}]_i\) along the sightlines considered here. We find that the gas-phase abundance \([\text{Al/S}]_i\) increases with decreasing electron densities. The observed relationship between \([\text{Al/S}]_i\) and \(n_e\) is similar to the observed dependence of WNM abundances on average sightline neutral hydrogen \((\text{H I} + \text{H}_2)\) density (Edgar & Savage 1989; Jenkins 1987; Savage & Bohlin 1979). The slope of \([\text{Al/S}]_i\) versus log \(n_e\) is \(-0.37\), similar to the value \(-0.38\) derived for \([\text{Fe/H}]_i\) versus log \(n_{\text{HI}}\) by Jenkins (1987).

Though we are measuring the gas-phase abundance \([\text{Al/S}]_i\), i.e., the abundance of Al to S in the ionized gas, the bottom panel of Figure 8 shows a significant correlation between \([\text{Al/S}]_i\) and log \(n_{\text{HI}}\), the average line of sight neutral density. Savage et al. (1990) have also noted a correlation of log \(N(\text{Al III})/N(\text{H I})\) with decreasing log \(n_{\text{HI}}\). These authors point out that this trend may be due to the changing ionization fraction of Al\(^{+2}\) with density, to changing values \([\text{Al/H}]_i\) with density, or perhaps both. Figure 8 shows that at least part of the trend observed by Savage et al. is due to the changes in the gas-phase abundance of Al with average neutral density. The trend observed by these authors, which is nicely matched by our data, and that seen in Figure 8 suggest that \(\langle n_{\text{HI}} \rangle\) is a good indicator of the conditions in the ionized gas. The slope of \([\text{Al/S}]_i\) versus log \(n_{\text{HI}}\) in our data is less steep than the slope of log \(N(\text{Al III})/N(\text{H I})\) versus log \(n_{\text{HI}}\) in the Savage et al. dataset, suggesting that a combination of changing gas-phase abundances and ionization fraction is causing the trend observed by Savage et al. and that perhaps the behavior seen in Figure 8 is more widespread than our six sightlines.

In general Figure 8 implies that the ionized and neutral densities along a sightline follow the same trends, i.e., low \(\langle n_{\text{HI}} \rangle\) also implies low values of \(n_e\). This relationship may simply be a manifestation of the known decrease in both ionized and neutral gas densities as a function of height.
above the Galactic plane. This is also the expected behavior if neutral clouds with ionized edges are providing most of the observed absorption (though see Reynolds et al. 1998a). Spitzer (1985) and Jenkins, Savage, & Spitzer (1986) have interpreted the dependence of elemental gas-phase abundances on the average sightline density \( \langle n_H \rangle \) in the neutral ISM as a dependence on the relative contribution of two neutral media: clouds (cold and warm) and an intercloud medium. In this picture the warm intercloud medium has greater gas-phase abundances than the denser clouds. With an appropriate mix of each medium, the integrated gas-phase abundance for a given line of sight can be reproduced. Perhaps a variation on this scenario is also appropriate for the ionized medium of our Galaxy. The relative mix of clouds may be similar between the neutral and ionized phases depending on the poorly-known relationship between these phases.

As discussed in §4.3, if the WIM of the Galaxy is photoionized by starlight from OB stars (DM94; Reynolds 1984), our measurements of Al III and S III absorption towards HD 18100 and \( \rho \) Leo imply the existence of dust in this important phase of the ISM. The values \([\text{Al}/S]_d\) for \( \rho \) Leo and HD 18100 are significantly higher than those for the other four stars (see Figures 3 and 4), suggesting that the grain population in the high-latitude WIM has undergone a greater degree of processing (e.g., by shocks) than have the grains in the low-\( z \) H II regions. For the halo WIM we find a dust phase abundance of \( 10^6(\text{Al}/H)_d \approx 1.9 \) to 2.1. It would appear that \( \sim 20\% - 30\% \) of the Al has been liberated from the solid phase in the high-\( z \) WIM compared with the results derived above for the disk H II regions.

Very little is known about dust in the WIM of the Milky Way (or other galaxies) from previous studies. Though in principle one might be able to separate the thermal dust emission in the WIM from that of the H I and H\(_2\) gas, this has proven difficult. Boulanger et al. (1996) have studied the correlation of the far infrared (FIR) flux with the column density of neutral hydrogen \( N(\text{H}^\text{I}) \) at high Galactic longitudes. They find that the correlation between the \( \lambda 21-cm \) H I emission and the FIR emission detected by the Cosmic Background Explorer mission is quite good. They are not, however, able to rule out a dust abundance in the WIM similar to that observed in the neutral component.

The existence of dust is important for maintaining the temperature of the WIM (Reynolds & Cox 1992; Dettmar & Schulz 1992). Reynolds & Cox (1992) show that the heating of the WIM may be in large part provided by photoelectron emission from grains. This requires the amount of grain heating per H atom to be similar to that found in the WNM. The presence of grains in the WIM has important ramifications for the diagnostic emission lines used to study this gas. Reynolds & Cox point out that the total heating per H nucleus per second in the low-density WIM may be twice that of a typical, higher-density H II region. This has profound effects on the forbidden lines that provide the cooling for the gas. The increased cooling required over H II region gas increases the ratios of [S II], [N II], and [O III] to H\(_\alpha\) over H II regions. Reynolds & Cox suggest this extra heating may in part be responsible for the enhanced forbidden line strengths observed from the WIM of our Galaxy and others (Reynolds 1985; Rand 1997).

Our data suggest that the destruction of the dust grains in the high-\( z \) WIM has not been extreme. The value \( \sim 20\% - 30\% \) given above for the amount of Al liberated from the solid- to gas-phase when going from disk H II regions to the halo WIM is consistent with differential measurements of warm neutral cloud abundances between the disk and the halo. For a small sample of halo and warm disk clouds, Howk et al. (1998) find roughly \( 20\% - 30\% \) of the dust-phase Fe and Si on average have been returned to the gas-phase between the disk and halo clouds. Therefore, the processing of grains in the halo WIM does not appear to be significantly greater than that experienced by clouds associated with the halo WNM.

This discussion does not suggest that grain destruction mechanisms have not played an important role in the evolution of the gas being considered. The \( \sim 20\% - 30\% \) of dust-phase Al we see returned to the gas-phase in the halo WIM may be material that was initially bound in a refractory coating or mantle surrounding the grains. Savage & Sembach (1996b, see their Table 7) have tabulated the dust-phase abundances of a number of elements. The derived dust-phase abundances for the WNM of the Galactic disk give the composition of the grain cores and mantles, while the observed abundances of the halo material gives information on the composition of the resilient grain cores that have probably been stripped of their mantles (Sembach & Savage 1996). Savage & Sembach (1996b) argue that the Fe returned to the gas-phase in halo material comes predominantly from the mantles thought to surround the resilient cores that survive the trip into the halo. They find the dust-phase abundance of Fe in grain cores to be \( 10^6(\text{Fe}/H)_d = 25 \), while for the mantles they find \( 10^6(\text{Fe}/H)_d = 7 \). Thus \( \sim 22\% \) of the Fe incorporated into grains in the Milky Way disk resides in a mantle that is relatively easily stripped. The liberated Al seen in the WIM at high-\( z \) may also come from the mantles of grains, leaving the resilient grain cores to account for the remaining \( 70\% - 80\% \) of the Al missing from the gas phase.

In considering the multiphase structure of neutral clouds in the Galactic halo, Wolfire et al. (1995b; see also Wolfire et al. 1995a) show that the stability of multiphase neutral clouds is affected by the intrinsic abundances in the gas and by the dust content of the clouds. Thus, the presence of dust in ionized halo clouds will have important implications for the physical structure of the resulting neutral clouds if the ionized gas recombines. Indeed, in the case where the dusty multiphase clouds envisioned by Wolfire et al. (1995b) are situated above the disk of the galaxy, where they are bathed in ionizing radiation from the disk (assuming photons are able to leak out of the disk), they will be surrounded by ionized skins. If no processes beyond photoionization are responsible for producing the ionized edges of such clouds, the differences in the dust content of the neutral and ionized phases should be minimal. This may explain why the gas-phase abundances in the ionized gas towards \( \rho \) Leo and HD 18100, where the neutral and ionized phases of the ISM seem to coexist (at least in velocity space), are so similar to the derived refractory element gas-phase abundances in warm neutral halo clouds (Sembach & Savage 1996).

6. SUMMARY
This work represents one of the first absorption line studies of the WIM of the Galaxy. The observations imply the existence of Al- and Fe-bearing dust grains in the ionized gas of the Galactic disk and halo.

A summary of the work presented here and our major conclusions is as follows:

1) We present archival G HRS intermediate- and high-resolution absorption line observations of the moderately-ionized species Al III and S III in the ionized ISM towards six stars. The sightlines towards ζ Oph, ζ Per, β1 Sco, and μ Col probe primarily H II region gas in the Galactic disk. The extended high-latitude sightlines towards HD 18100 and ρ Leo probe the WIM of the Galaxy at high z. Results for Fe III from the literature are presented for μ Col, β1 Sco, and ζ Oph.

2) We show, with the possible exceptions of the sightlines to β1 Sco and HD 18100, that collisional ionization does not likely explain the origin of the observed amounts of Al III and S III.

3) We have computed a grid of photoionization equilibrium models for low-density regions excited by late-O/early-B stars using the CLOUDY code (Ferland et al. 1998). We show using our photoionization models that the ionization corrections for determining [Al/S]i, [P/S]i, and [Si/S]i, using the species Al III, P III, Si III, and S III are relatively insensitive to the ionization parameter and the effective temperature of the ionizing spectrum. Deriving [Fe/S]i from the ratio N(Fe III)/N(S III) requires a greater knowledge of the stellar effective temperature.

4) We derive the logarithmic gas-phase abundances [Al/S]i ≈ [Al/H]i in the ionized material towards the six stars in our sample using the results of our photoionization modelling. All of these stars have [Al/S]i ranging from −1.2 to −0.4. Since S is normally not incorporated into dust, these abundance results indicate the incorporation of Al into dust grains in the ionized material along these six sightlines, though for the most distant stars, we cannot rule out the confusing effects of collisional ionization. For three stars we find [Fe/S]i ranges from −1.6 to −0.9.

5) The gas-phase abundances [Al/S]i and [Fe/S]i derived here for the disk sightlines probing H II region material show that a significant degree of Al incorporation into grains is still present in the vicinity of stars, i.e., neither the UV radiation fields from the stars nor any shocks associated with the stellar winds from these stars are sufficient to completely disrupt the refractory grains. The abundances we derive here are similar to the gas-phase Fe abundances [Fe/H]i derived for the Orion nebula using emission lines (e.g., Osterbrock et al. 1992; Baldwin et al. 1996).

6) If the WIM of the Galaxy is ionized by the light from OB stars (Reynolds 1984), the observed Al III and S III column densities towards HD 18100 and ρ Leo imply the existence of Al-bearing dust in the WIM. To our knowledge this is the first evidence for dust in the Galactic diffuse ionized gas, though the effects of collisional ionization cannot be ruled out, particularly for the sightline towards HD 18100.

7) The gas-phase abundances [Al/S]i in the ionized material increases with height z above the Galactic plane. Further, the values [Al/S]i increase with decreasing average or rms electron densities and with decreasing average sightline neutral hydrogen density. This behavior is similar to that of the gas-phase refractory abundances in the warm neutral medium of the galaxy (Jenkins 1987; Bohlin & Savage 1979). This general trend implies a greater return of elements to the gas phase in more diffuse environments.

8) The observed values of [Al/S]i are similar to the abundances of other refractory elements seen in the WNM of the disk and halo. Further, the variation of [Al/S]i with density (electron or neutral) is also similar to the values observed for refractory elements in the WNM (esp., Fe or Mn). Our analysis implies that the processing of dust grains in the ionized gas may not be much different than that in the low-density warm neutral medium.

9) We discuss the velocity structure of the WIM along the two high-latitude sightlines in our sample. These directions show a very close relationship between the tracers of neutral material and ionized gas, similar to the correspondence observed by Spitzer & Fitzpatrick (1993). The data show no kinematic evidence for a separation of the ionized and neutral material. This is consistent with a partially-ionized medium in which the neutrals and ions are well mixed (e.g., SF93), the neutral clouds are surrounded by ionized envelopes (e.g., McKee & Ostriker 1977), or other more complex scenarios.

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## Table 1

### UV Probes of Weakly Ionized Gas

| Ion  | $\lambda^a$ [Å] | $f^b$ | IP $(x^{-1}\rightarrow x^1)$ [eV] | IP $(x^{-1}\rightarrow x^{+1})$ [eV] | $\log\{X/H\}_\odot^c$ | $[X/H]_{\text{halo}}^d$ | $\log N(X)_{H\text{II}}^e$ | $\tau_o^f$ |
|------|-----------------|-------|-----------------------------------|-----------------------------------|---------------------------|--------------------------|---------------------------|--------|
| C III | 977.020         | 0.762 | 24.4                              | 47.9                              | 8.55                      | −0.4^g                    | 14.46                     | 86.4   |
| N II  | 1083.990        | 0.103 | 14.5                              | 29.6                              | 7.97                      | 0.0                      | 14.88                     | 36.9   |
| N III | 989.799         | 0.107 | 29.6                              | 47.4                              | 7.97                      | 0.0                      | 14.11                     | 5.95   |
| Si III| 1206.500        | 1.67  | 16.3                              | 33.5                              | 7.55                      | −0.25                    | 13.96                     | 111.7  |
| Fe III| 1122.526        | 0.0788| 16.2                              | 30.7                              | 7.51                      | −0.6                     | 13.78                     | 4.6    |
| S III | 1190.208        | 0.0222| 23.3                              | 34.8                              | 7.27                      | 0.0                      | 14.02                     | 1.81   |
| Ti III| 1012.502        | 0.0355| 23.3                              | 34.8                              | 7.27                      | 0.0                      | 14.02                     | 2.46   |
| Ar II | 919.781         | 0.00887| 15.8                             | 27.6                              | 6.56                      | 0.0^h                     | 13.37                     | 0.14   |
| Al III| 1862.789        | 0.279 | 18.8                              | 28.4                              | 6.48                      | −0.6^i                    | 12.42                     | 0.82   |
| Cr III| 1854.716        | 0.560 | 18.8                              | 28.4                              | 6.48                      | −0.6^j                    | 12.42                     | 1.65   |
| P III | 1040.050        | 0.122 | 16.5                              | 31.0                              | 5.68                      | −0.35                    | 12.21                     | 0.17   |
| Ti III| 1033.331        | 0.0640| 16.5                              | 31.0                              | 5.68                      | −0.35                    | 12.21                     | 0.09   |
| P III | 1030.100        | 0.0625| 16.5                              | 31.0                              | 5.68                      | −0.35                    | 12.21                     | 0.09   |
| P III | 1334.813        | 0.0253| 19.7                              | 30.2                              | 5.57                      | 0.0                      | 12.30                     | 0.04   |
| Ti III| 998.000         | 0.112 | 19.7                              | 30.2                              | 5.57                      | 0.0                      | 12.30                     | 0.14   |
| P III | 1298.697        | 0.0951| 13.6                              | 27.5                              | 4.93                      | −0.65                    | 11.28                     | 0.02   |
| Ti III| 1295.884        | 0.0668| 13.6                              | 27.5                              | 4.93                      | −0.65                    | 11.28                     | 0.01   |

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^a Vacuum wavelengths from Morton (1991).

^b Oscillator strengths from Morton (1991).

^c The logarithmic “solar” abundances of the elements, $\log\{X/H\}_\odot$. We have adopted the solar system meteoritic abundances from Anders & Grevesse (1989) except for C which is the photospheric value from Grevesse & Noels (1993).

^d Typical values of the logarithmic normalized gas-phase abundance seen in warm neutral halo clouds, defined such that $[X/H] = \log\{N(X)/N(H)\} - \log\{X/H\}_\odot$. These values are for the warm cloud at $v_\odot \approx +41$ km s$^{-1}$ seen towards µ Col (Sofia, Cardelli, & Savage 1993; Shull & York 1977), which is typical of “halo”-type neutral clouds (Howk et al. 1998).

^e Expected column density of each species for a fully-ionized cloud with $\log N(H\text{II}) = 19.0$ cm$^{-2}$ as calculated using the CLOUDY photoionization equilibrium code (see §4.1). The assumed gas-phase abundances of each of the elements are dictated by the solar system values modified by the normalized gas-phase abundances typical of halo material. The shape of the ionizing spectrum was taken to be that of an O9.5V star with $T_{\text{eff}} = 33,000$ K.

^f Expected peak optical depth of each line assuming the column densities given in column 8 with $b$-values appropriate for gas at $T = 10,000$ K and no non-thermal broadening.

^g The gas-phase abundance of C has only been measured accurately in cool neutral clouds found in the disk. We tentatively adopt the Cardelli et al. average $[C/H] \approx −0.4$ for our “halo” abundances.

^h The ratio Ar I/H I has recently been measured to be significantly sub-solar along a number of low-$N(H\text{I})$, partially ionized sightlines by Sofia & Jenkins (1998). However, these authors argue that the large ionization cross-section of Ar$^0$ implies that much of the Ar may reside in the form of Ar$^+$, which they did not observe. We therefore adopt $[Ar/H] \approx 0.0$ in warm neutral halo gas.

^i The abundance of Al is poorly known in the warm neutral medium because the Al II $\lambda 1670$ Å line requires very large saturation corrections (Barker et al. 1984). We have assumed $[Al/H] \approx [Fe/H]$. 

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## Table 1

**Stellar and Sightline Properties**

| Star (HD>Name) | l   | b   | $d^a$ | $z^b$ | Spectral Type | $T_{\text{eff}}^c$ | E(B-V)$^d$ | $\langle n(H)\rangle^e$ | $n_e^f$ |
|----------------|-----|-----|-------|-------|---------------|------------------|----------|----------------|---------|
| 24912(ξ Per)  | 160$^\circ$4 | -13$^\circ$1 | 540   | 122   | O7.5 I        | 36,000          | 0.33     | 1.2            | 1.4     |
| 38666(µ Col)  | 237$^\circ$3 | -27$^\circ$1 | 400   | 180   | O9.5 V        | 33,000          | 0.01     | 0.06           | 0.2     |
| 149757(ζ Oph) | 237$^\circ$3 | 23$^\circ$6  | 140   | 56    | O9.5 V        | 31,900          | 0.32     | 3.1            | 4.0     |
| 144217(β$^1$ Sco) | 237$^\circ$3 | 23$^\circ$6  | 160   | 60    | B0.5 V        | 28,000          | 0.20     | 2.9            | ...     |
| 91316(ρ Leo)  | 234$^\circ$9 | +52$^\circ$8 | 870   | 690   | B1 Ib         | 26,800          | 0.05     | 0.10           | 0.07    |
| 18100         | 217$^\circ$9 | -62$^\circ$7 | 3100  | 2800  | B1 V          | 26,400          | 0.02     | 0.01           | 0.07    |

$^a$Distances, with the exception of ρ Leo and HD 18100, are based upon *Hipparcos* measurements of stellar parallax (Perryman et al. 1997). The distance estimates to ρ Leo and HD 18100 are from Keenan, Brown, & Lennon (1986) and Diplas & Savage (1994), respectively.

$^b$Distance from the mid-plane of the galaxy given the derived distances.

$^c$Adopted effective temperatures for each of the stars. These data are from the following: Code et al. (1976; ζ Oph); Holmgren et al. (1997; β$^1$ Sco); Howarth & Prinja (1989; µ Col); Keenan et al. (1986; HD 18100); Keenan & Dufton (1983; ρ Leo); Sokolov (1995; 23 Ori); and Vacca, Garmany, & Shull (1996; ξ Per).

$^d$The dust color excess, E(B-V), is taken from Diplas & Savage (1994).

$^e$Average line of sight neutral hydrogen densities towards these stars, where $\langle n(H) \rangle \equiv \{N(H\ I) + 2N(H_2)\}/d$. We have taken values for N(H I) from Diplas & Savage (1994) and N(H_2) from Bohlin, Savage, & Drake (1978). The value listed for HD 18100 is $\langle n(H\ I) \rangle$.

$^f$Electron densities along these lines of sight, when available. The data presented here are from Howk et al. (1998; µ Col); Reynolds (1988b; ξ Per and ζ Oph); Savage & Sembach (1996; HD 18100); and this work (ρ Leo). The values quoted for ξ Per and ζ Oph are the values $\langle n_e^2 \rangle^{1/2}$ characteristic of the H II regions surrounding these stars. For µ Col the value quoted is $\langle n_e \rangle$ of the H II region. The values quoted for HD 18100 and ρ Leo are the values $\langle n_e \rangle$ of the warm ionized gas in these directions.
### Table 2
Log of GHRS Archival Data

| Star  | Spectral Range [Å] | Rootname<sup>a</sup> | Exp.<sup>b</sup>[sec] | Mode & Order<sup>c</sup> | Aper.<sup>d</sup> | FP-SPLIT/COSTAR?<sup>e</sup> |
|-------|-------------------|----------------------|----------------------|----------------------|------------------|------------------------|
| ξ Per (HD 24912) | 1187.7-1194.2 | Z0GY010LT | 691.2 | Ech-A/47 SSA | 4/F |
| | 1857.1-1867.4 | Z0GY011ST | 172.8 | Ech-B/30 SSA | 4/F |
| μ Col (HD 38666) | 1184.8-1191.1 | Z2AF010PT | 108.8 | Ech-A/47 LSA | 0/T |
| | 1184.8-1191.1 | Z2C0020PP | 108.8 | Ech-A/47 LSA | 0/T |
| | 1846.7-1856.9 | Z2D0118T | 54.4 | Ech-B/30 LSA | 0/T |
| | 1859.8-1869.8 | Z2CX010LT | 27.2 | Ech-B/30 LSA | 0/T |
| | 1855.9-1866.0 | Z2D020KT | 54.4 | Ech-B/30 LSA | 0/T |
| ζ Oph (HD 149757) | 1188.6-1195.0 | Z2VX010CT | 691.2 | Ech-A/47 SSA | 4*/T |
| | 1189.8-1196.2 | Z2VX010ET | 691.2 | Ech-A/47 SSA | 4*/T |
| | 1856.9-1866.9 | Z0LD020TT | 172.8 | Ech-B/30 SSA | 4*/F |
| β<sup>1</sup> Sco (HD 144217) | 1180.1-1216.3 | Z0YU010AT | 172.8 | G160M/01 SSA | 4/F |
| | 1856.7-1866.7 | Z0YU020AT | 172.8 | Ech-B/30 SSA | 4*/F |
| ρ Leo (HD 91316) | 1188.7-1195.3 | Z2ZX010CT | 870.4 | Ech-A/47 SSA | 4/T |
| | 1852.7-1862.9 | Z0ZI0314T | 86.4 | Ech-B/30 SSA | 0/F |
| | 1853.5-1863.6 | Z0ZI0315T | 86.4 | Ech-B/30 SSA | 0/F |
| | 1854.3-1864.4 | Z0ZI0316T | 86.4 | Ech-B/30 SSA | 0/F |
| | 1855.0-1865.1 | Z0ZI0317T | 86.4 | Ech-B/30 SSA | 0/F |
| HD 18100 | 1181.4-1217.6 | Z13Z010AT | 1324.8 | G160M/01 SSA | 4/F |
| | 1842.9-1876.9 | Z13Z010NM | 1209.6 | G160M/01 SSA | 4/F |

<sup>a</sup>STScI archival rootname.

<sup>b</sup>Total exposure time given in seconds.

<sup>c</sup>Grating mode and spectral order used for the observation.

<sup>d</sup>Aperture used for the observation. The LSA subtends 1"74 × 1"74 on the sky for post-COSTAR observations, 2"0 × 2"0 for pre-COSTAR data. The pre-COSTAR SSA subtends 0"25 × 0"25, while the post-COSTAR SSA is 0"22 × 0"22 on the sky.

<sup>e</sup>The number of FP-SPLIT sub-exposures composing each observation. Asterisks mark those observations for which we have explicitly derived the fixed-pattern noise spectrum and removed it. This column also notes with a “T” those observations taken after the installation of COSTAR, and with an “F” for those taken before COSTAR.
### Table 3

**Equivalent Widths and Column Densities of S III, Al III and Fe III**

| Star   | \( W_\lambda \pm \sigma \) [mA] \(^a\) | \( \log N \pm \sigma \) [cm\(^{-2}\)] \(^b\) |
|--------|-----------------------------------------|------------------------------------------|
|        | S III \( \lambda 1190.2 \) Å | Al III \( \lambda 1854.7 \) Å | Al III \( \lambda 1862.8 \) Å | S III | Al III | Fe III \(^c\) |
| \( \xi \) Per | 87 ± 3 | ⋯ | 51.2 ± 1.7 | 14.82 ± 0.02 | 12.85 ± 0.02 | ⋯ |
| \( \mu \) Col | 16.3 ± 0.6 | 15.0 ± 2.0 | 9.9 ± 1.5 | 13.82 ± 0.02 | 12.01 ± 0.05 | 13.37 ± 0.09 \(^{0.11}\) |
| \( \zeta \) Oph | 66.6 ± 1.4 | ⋯ | 19.7 ± 0.8 | 14.76 ± 0.02 | 12.42 ± 0.02 | 13.45 ± 0.10 |
| \( \beta^1 \) Sco | 27 ± 5 \(^d\) | ⋯ | 9.5 ± 0.7 | 13.98 ± 0.08 \(^d\) | 12.06 ± 0.04 | 13.10 ± 0.10 |
| \( \rho \) Leo | 12.7 ± 0.8 | 17.5 ± 1.6 \(^e\) | ⋯ | 13.72 ± 0.03 | 12.06 ± 0.04 \(^e\) | ⋯ |
| HD 18100 | 54 ± 8 \(^d\) | 74 ± 6 | 40 ± 6 | 14.29 ± 0.06 \(^d\) | 12.70 ± 0.04 | ⋯ |

\(^a\)Equivalent widths \( W_\lambda \) in mA for the lines of S III and Al III with 1σ uncertainties.

\(^b\)Column densities of interstellar S III and Al III in units atoms cm\(^{-2}\). Also given are the 1σ error estimates for these measurements.

\(^c\)The Fe III column densities quoted here are taken from the following: Howk et al. (1998; \( \mu \) Col); Morton (1975; \( \zeta \) Oph); and Savage & Bohlin (1979; \( \beta^1 \) Sco). These column densities are all derived from the Fe III \( \lambda 1122.5 \) Å line. The latter two are based upon *Copernicus* observations, while the former comes from GHRS G160M observations. The *Copernicus* observations have been adjusted by \(-0.15\) dex to account for newer oscillator strengths (Morton 1991; \( f = 0.07884 \)) and the errors are estimates by the current authors. In the case of \( \zeta \) Oph and possibly \( \beta^1 \) Sco, C I absorption could be contributing to these column densities. For \( \mu \) Col Howk et al. (1998) have put restrictive limits on the degree of this contamination and find it not to be significant compared with the quoted uncertainties.

\(^d\)These values are based upon GHRS G160M data and have been derived through a component fitting analysis.

\(^e\)These values are for the velocity range \(-19 \leq v_\odot \leq +2\) km s\(^{-1}\), which corresponds to the uncontaminated velocity range for the S III absorption. The total integrated sightline values for Al III are \( W_\lambda = 29 \pm 3 \) mA and \( \log N(\text{Al III}) = 12.27 \pm 0.05 \).
Table 4

CLOUDY H II Region Model for an O9.5 V Star

| \( n_H \) [cm\(^{-3}\)] | \( \log(q) \) | \( \log(U) \) | \( \log(x(S^{+2})) \) | \( \log(x(X^+)/x(S^{+2})) \) |
|-----------------|--------|--------|----------------|----------------|
|                 |        |        | \( \text{Al}^{+2} \) | \( \text{Fe}^{+2} \) | \( \text{Si}^{+2} \) | \( \text{Si}^{+3} \) | \( \text{P}^{+2} \) |
| 0.02            | -4.1   | -4.3   | -0.45          | -0.25          | 0.24           | -0.15          | -2.03          | -0.01          |
| 0.05            | -3.7   | -4.1   | -0.40          | -0.24          | 0.21           | -0.13          | -2.08          | -0.01          |
| 0.1             | -3.4   | -4.0   | -0.36          | -0.23          | 0.19           | -0.12          | -2.14          | -0.02          |
| 0.2             | -3.1   | -3.9   | -0.33          | -0.23          | 0.17           | -0.11          | -2.22          | -0.02          |
| 0.5             | -2.7   | -3.8   | -0.28          | -0.22          | 0.14           | -0.10          | -2.36          | -0.02          |
| 1.0             | -2.4   | -3.7   | -0.25          | -0.21          | 0.12           | -0.09          | -2.46          | -0.02          |
| 1.5             | -2.2   | -3.6   | -0.24          | -0.20          | 0.11           | -0.09          | -2.55          | -0.02          |
| 10.0            | -1.4   | -3.4   | -0.18          | -0.18          | 0.08           | -0.07          | -2.94          | -0.02          |
| 100.0           | -0.4   | -3.0   | -0.15          | -0.20          | 0.10           | -0.06          | -3.77          | -0.03          |

\(^a\)The ionization fractions reported here are the radially-averaged values of nebular models with an input stellar effective temperature \( T_{\text{eff}} = 33,000 \text{ K} \) and total luminosity \( \log L/\log L_\odot = 4.4 \). The ionizing photon luminosity in these models is \( \approx 4 \times 10^{47} \text{ photons s}^{-1} \).

\(^b\)Total hydrogen density (neutral plus ionized) used in the model.

\(^c\)\( q = n_H f^2 L_{50} \), where \( n_H \) is the ambient hydrogen density, \( f \) the filling factor, and \( L_{50} \) the stellar ionizing flux in units of \( 10^{50} \text{ photons s}^{-1} \).

\(^d\)\( U = L/(4\pi R_S^2 n_{\text{He}}) \), where \( n_H \) is the ambient hydrogen density and \( L \) is the hydrogen ionizing photon luminosity in photons s\(^{-1} \). The Strömgren radius is \( R_S = [2L/(4\pi n_{\text{He}}^2 f_{\alpha_B})]^{1/3} \), where \( \alpha_B \) is the case B recombination coefficient of H. We give values assuming \( \alpha_B = 2.59 \times 10^{-13} \text{ cm}^3 \text{ s}^{-1} \) appropriate for \( T_e = 10^4 \text{ K} \) (Osterbrock 1989).

\(^e\)\( \log x(X^+)/x(S^{+2}) \equiv N(S^{+2})/N(S\text{total}) \).

\(^f\)These columns give \( \log x(X^+)/x(S^{+2}) \equiv -\log \text{ICF} \) (see §4).


Table 5
CLOUDY H II REGION MODEL FOR log(q) = −4.0a

| $T_{\text{eff}}$ [K] | log $x$(S$^{+2}$) | Al$^{+2}$ | Fe$^{+2}$ | Si$^{+2}$ | Si$^{+3}$ | P$^{+2}$ |
|----------------------|------------------|----------|----------|----------|----------|----------|
| 27,000               | −0.71            | −0.11    | 0.55     | 0.12     | −4.93    | 0.12     |
| 29,000               | −0.58            | −0.16    | 0.40     | −0.01    | −3.85    | 0.05     |
| 31,000               | −0.49            | −0.21    | 0.30     | −0.10    | −2.78    | 0.01     |
| 33,000               | −0.44            | −0.25    | 0.23     | −0.14    | −2.04    | −0.01    |
| 35,000               | −0.40            | −0.30    | 0.15     | −0.19    | −1.58    | −0.04    |
| 37,000               | −0.37            | −0.33    | 0.10     | −0.22    | −1.43    | −0.06    |
| 39,000               | −0.34            | −0.36    | 0.04     | −0.27    | −1.30    | −0.10    |

\[ \log \langle \text{ICF} \rangle_{\text{Rad}} \equiv +0.24 \pm 0.07 \]
\[ \log \langle \text{ICF} \rangle_{\text{Vol}} \equiv +0.37 \pm 0.07 \]

aThe ionization fractions and ratios reported here are the radially-averaged values of nebular models with log(q) ≡ log($n_{\text{H}} f^2 L_{50}$) = −4.0. The alternate definition of the ionization parameter gives log(U) = log$\{L/(4\pi R^2 n_{\text{H}})\}$ = −4.22 assuming $\alpha_B = 2.59 \times 10^{-13}$ cm$^3$ s$^{-1}$ appropriate for $T_e = 10^4$ K (Osterbrock 1989).

bThe mean value of the radially-averaged ionization corrections and standard deviation about the mean for each species considered. These numbers are the average and dispersion of the ICFs for all stellar effective temperatures considered for models having log(q) = −4.0 and −2.0.

cThe values of ICF(Si$^{+3}$) are highly uncertain given the strong dependence upon the stellar effective temperature and ionization parameter.

dThe mean value of the volume-averaged ionization corrections and standard deviation about the mean for each species considered. These numbers are the average and dispersion of the ICFs for all stellar temperatures considered for models having log(q) = −4.0 and −2.0.

Table 6
COLUMN DENSITY RATIOS AND LOGARITHMIC GAS-PHASE ABUNDANCES

| Star       | log $N$(Al III)/$N$(S III) | log $N$(Fe III)/$N$(S III) | [Al/S]$^a_i$ | [Fe/S]$^a_i$ |
|------------|-----------------------------|-----------------------------|--------------|--------------|
| $\xi$ Per  | −1.97 ± 0.03                | ...                         | −0.87 ± 0.08 | ...          |
| $\mu$ Col  | −1.82 ± 0.05                | −0.40 ± 0.11                | −0.78 ± 0.08 | −0.87 ± 0.21 |
| $\zeta$ Oph | −2.23 ± 0.03                | −1.05 ± 0.10                | −1.19 ± 0.08 | −1.52 ± 0.21 |
| $\beta^1$ Sco | −1.92 ± 0.09            | −0.88 ± 0.12                | −1.00 ± 0.11 | −1.59 ± 0.21 |
| $\rho$ Leo | −1.66 ± 0.06                | ...                         | −0.50 ± 0.10$^b$ | ...          |
| HD 18100   | −1.59 ± 0.07                | ...                         | −0.43 ± 0.10$^b$ | ...          |

aThe values given here for $\zeta$ Oph are the for the integrated sightline.

bThe values given here for [Al/S]$^a_i$ towards $\rho$ Leo and HD 18100 assume the shape of the ionizing spectrum of the diffuse ionized gas is not very different than that of a star with 27,000 $\lesssim T_{\text{eff}} \lesssim$ 39,000 K.
Table 7
Measurements of Si IV Column Densities

| Star     | log $N$(Si IV) | log[$N$(Si IV)/$N$(S III)] | Ref. |
|----------|----------------|----------------------------|------|
| ξ Per    | 12.89 ± 0.03   | −1.93                      | 1    |
| µ Col    | 12.17 ± 0.05   | −1.65                      | 2    |
| ζ Oph    | 12.79 ± 0.02   | −1.97$^a$                  | 3    |
| β¹ Sco   | 12.02 ± 0.03   | −1.96                      | 1    |
| ρ Leo    | < 11.6$^b$     | < −2.1$^b$                 | 1    |
| HD 18100 | 13.10 ± 0.04   | −1.19                      | 4    |

References.—(1) This work; (2) Brandt et al (1998); (3) Sembach et al (1994); (4) Sembach & Savage (1994).

$^a$The value log[$N$(Si IV)/$N$(S III)] given for the ζ Oph sightline is the value integrated over all velocities. Figure B shows that this ratio is a strong function of velocity. Near $v_\odot \approx −15$ km s$^{-1}$, corresponding to the peak of the Si IV absorption, a value of −1.6 to −1.8 is more appropriate; while at the peak of the Al III absorption near $v_\odot \approx −8$ km s$^{-1}$, log[$N$(Si IV)/$N$(S III)] $\approx −2.4$ is more appropriate.

$^b$This 2σ upper limit to log $N$(Si IV) for the ρ Leo sightline only applies to the velocity range $v_\odot = −19$ to +2 km s$^{-1}$ (the range over which the S III measurements are made). There is detectable Si IV absorption at more positive velocities. The integrated sightline column density is log $N$(Si IV) = 12.24$^{+0.07}_{−0.09}$. 
Fig. 1.— Continuum-normalized absorption line profiles of Zn II, Al III, and S III for the disk stars ξ Per, ζ Oph, and β1 Sco are displayed on a heliocentric velocity scale. Echelle-mode data are plotted as histograms. The G160M data for the S III profile towards β1 Sco are plotted as points, while the component model convolved with the instrumental spread function is overlapped as the solid line (see §2.2). Strong Si II λ1190.416 Å absorption is seen in the S III λ1190.208 Å region of the spectrum (v = +52.4 km s⁻¹ relative to S III).
Fig. 2.— As for Figure 1 but for the higher-\( z \) stars \( \mu \) Col, \( \rho \) Leo, and HD 18100. The G160M data for the Al III and S III profiles towards HD 18100 are overplotted with the component model convolved with the instrumental LSF; the dashed line in the S III profile for this star shows the absorption model for Si II \( \lambda 1190 \) \AA derived from the Si II \( \lambda 1193 \) \AA transition (see §2.2).
Fig. 3.— The top panel shows the apparent column density profiles of Al III, S III, and Si IV observed towards ζ Oph at 3.5 km s$^{-1}$ resolution displayed on a heliocentric velocity scale. The profiles of Al III and Si IV have been scaled upwards by factors of 100 and 40, respectively. The bottom panel shows the logarithm of the ratio of Al III and Si IV to S III as a function of velocity.
Fig. 4.— Apparent column density profiles of S III, Al III, C II*, and Zn II towards ρ Leo are plotted against heliocentric velocity. The C II* observations were obtained with the G160M grating, the other measurements were made with the GHRS echelle gratings. The profiles of the first three ions have been scaled to match that of Zn II. The scale factors are noted in the plots. The S III profile has been shifted by +2.2 km s\(^{-1}\) (see text). The S III profile is not plotted for \(v_\odot > 5\) km s\(^{-1}\) because of strong contamination with intermediate negative velocity Si II \(\lambda 1190.416\) Å absorption components.
Fig. 5.— The values of \( \log \left( \frac{x(X)}{x(S^{+2})} \right) = - \log \text{ICF}(X) \) for several tracers of ionized gas as a function of the effective temperature, \( T_{\text{eff}} \), of the ionizing star. The fractional ionization \( x(X) \equiv \frac{N(X)}{N(X)} \) is derived using column densities integrated from the star to the edge of the model H II region. These data are for models characterized by the ionization parameter \( \log(q) = -4.0 \). Also shown in the bottom panel is the behavior of the ionization fractions \( x(S^{+2}) \), \( x(Fe^{+2}) \), and \( x(Al^{+2}) \) as a function of the assumed stellar effective temperature.
Fig. 6.— The behavior of $[\text{Al}/\text{S}]_{i} = \log(\text{Al}/\text{S})_{i} - \log(\text{Al}/\text{S})_{\odot}$, as a function of $z$-height of the probe star. Since S is not depleted onto grains $[\text{Al}/\text{S}]_{i} \approx [\text{Al}/\text{H}]_{i}$ gives a measure of the fraction of Al incorporated into dust grains in the ionized gas.
Fig. 7.— The behavior of $\text{[Al/S]}_i \equiv \log(\text{Al}/\text{S})_i - \log(\text{Al}/\text{S})_\odot$ as a function of average density. Since S is not depleted onto grains $[\text{Al}/\text{S}]_i \approx [\text{Al}/\text{H}]_i$ gives a measure of the fraction of Al incorporated into dust grains in the ionized gas. The bottom panel shows $[\text{Al}/\text{S}]_i$ versus the average sightline neutral density $\langle n_H \rangle \equiv \frac{N(\text{H I}) + 2N(\text{H}_2)}{d}$. The top panel shows $[\text{Al}/\text{S}]_i$ versus the electron density $n_e$. The filled circles in the top panel represent determinations of rms electron densities $\langle n_e^2 \rangle^{1/2}$, while the triangles are for determinations of average electron densities $\langle n_e \rangle$. 
Fig. 8.— The top panel shows the apparent column density profiles of Al III, S III, and Si IV observed towards ξ Per at 3.5 km s\(^{-1}\) resolution displayed on a heliocentric velocity scale. The profiles of Al III and Si IV have been scaled upwards by a factor of 70. The bottom panel shows the logarithm of the ratio of Al III and Si IV to S III as a function of velocity. The vertical dotted lines of the top panel represent the velocities of H\(\alpha\) emission detected by Reynolds (1988b), though shifted by \(-2.2\) km s\(^{-1}\).