INTERSTELLAR DETECTION OF THE INTERSYSTEM LINE Si ii λ2335 TOWARD ζ OPHIUCHI

JASON A. CARDELLI,2 ULYSSES J. SORIA,2 BLAIR D. SAVAGE,2 FRANCIS P. KEENAN,3 AND PHILIP L. DUFTON3

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ABSTRACT

We report on the detection of the weak interstellar transition of Si ii λ2335 Å in the sight line toward ζ Oph using the Ech-B mode (3.5 km s⁻¹ resolution) of the Goddard High Resolution Spectrograph. The high-quality spectrum is characterized by an empirically measured signal-to-noise of 450, in excellent agreement with that expected from photon-statistics. The measured equivalent width of the Si ii line is \( W_r = 0.48 \pm 0.12 \) mA. Using the new experimental f-value of Calamai, Smith, and Bergeson, we find a Si ii column density of \( 2.34 \times 10^{15} \) atoms cm⁻² and \( \text{Si/H}_\odot \) = 1.78 \((\pm 0.44) \times 10^{-6}\) for the principal absorbing component(s) at \( v_\odot = -15 \) km s⁻¹. Analysis of the Si ii λ1808 absorption over the same velocity range using the new experimental f-value of Bergeson & Lawler yields a column density (corrected for saturation) that is consistent within the weak line errors and confirms the relative accuracies of these new f-values. Furthermore, these results indicate that accurate abundances can now be derived for Si ii, particularly from the weak Si ii λ2335 Å since it is free of saturation effects. For the ζ Oph \( v_\odot \approx -15 \) km s⁻¹ component(s), we find that greater than 95% of the available cosmic abundance (i.e., the 1989 meteoritic abundances of Anders & Grevesse) of Mg, Fe, and Si is “missing” from the gas phase and is presumably locked up in the dust. These elements are present in the dust grains in ratios of Fe/Si \( \approx 0.9 \) and Mg/Si \( \approx 1.1 \), consistent with the ratio of their cosmic abundances. These ratios are in sharp contrast to more diffuse clouds like those seen toward the high-latitude halo star HD 93521 where in the dust Fe/Si \( \approx 1.8 \) and Mg/Si \( \approx 2.1 \).

Subject headings: ISM: abundances — ISM: stars: individual (ζ Ophiuchi) — techniques: spectroscopic — ultraviolet: interstellar

I. INTRODUCTION

Among the atomic elements present in the interstellar medium, abundant species like carbon, silicon, iron, and magnesium are particularly important because they are believed to comprise most of the mass of interstellar dust. Consequently, accurate measures of their gas-phase abundances are an important key to understanding the nature and processing of interstellar dust and ultimately the evolution of interstellar clouds.

Despite their importance, reliable measures of the abundances of C ii and Si ii, the dominant ionization state in interstellar clouds, have been difficult to obtain. One major reason is that the readily detectable lines tend to be so strong that large saturation corrections are necessary which lead to uncertain column densities. On the other hand, while both C ii and Si ii have interstellar transitions that are weak enough to allow accurate and direct column measures, these transitions have suffered from uncertainties associated with their f-values and have been extremely difficult to detect with past UV spectrographs like Copernicus and the International Ultraviolet Explorer. (Prior to 1991, only one interstellar absorption measure of the interstellar C ii line had been obtained [δ Sco; Hobbs, York, & Oegerle 1982].)

Since the launch of the Hubble Space Telescope (HST), this situation has changed dramatically. Through a combination of high-resolution (3.5 km s⁻¹) and high signal-to-noise (>100) capabilities, the Goddard High Resolution Spectrograph (GHRS) aboard the HST has produced unprecedented UV data on weak absorption lines (e.g., \( W_r < 1-2 \) mA) for a number of species (Cardelli, Savage, & Ebbets 1991a; Cardelli et al. 1993b; Federman et al. 1993; Hobbs et al. 1993) including accurate detections of the interstellar line of C ii toward ζ Per (Cardelli et al. 1991b) and ζ Oph (Cardelli et al. 1993c). In addition, new experimental f-values have been obtained for C ii λ2325 Å (Fang et al. 1993) and Si ii λ2335 Å (Calamai, Smith, & Bergeson 1993).

In this paper we present the first interstellar detection of Si ii λ2335 Å. We compare the derived column density with that obtained from the much stronger line of Si ii λ1808 Å. This comparison is particularly relevant since a new experimental f-value is now available for Si ii λ1808 Å as well (Bergeson & Lawler 1993).

2. OBSERVATIONS AND REDUCTIONS

The ζ Oph data discussed here were obtained with the GHRS in 1993 July using the high-dispersion echelle-B mode with the star placed in the 0′.25 × 0′.25 small science aperture (SSA). The data analyzed consist of two individual observations with the grating carousel positioned to correspond to central wavelengths of \( \lambda_c = 2332.8 \) and 2337.0 Å. Each of the two observations were obtained with an substep sampling strategy corresponding to two samples per science diode width (3.5 km s⁻¹ resolution), a four position comb-addition for the purpose of reducing diode-to-diode variations, and with the procedure FP-SPLIT = 4. With this procedure, an observation is split into four subexposures, each obtained at a slightly different grating position, for the purpose of assessing and...
removing the effects of fixed pattern noise and photocathode granularity.

The specifics of the general reduction of GHRS echelle data applicable to the observations presented here are discussed in Cardelli et al. (1991b), Savage, Cardelli, & Sofia (1992, hereafter SCS), and Lambert et al. (1994). Wavelengths were assigned from the standard HST calibration tables. The final step in the initial reduction for each individual observation involves (1) correcting for fixed pattern noise/granularity (see below), (2) merging the individual FP-SPLIT subexposures, and (3) subtraction of the scattered light background. This background, which consists of the measured background in the interorder above and below the spectral order converted to count rates, is fitted with a low-order polynomial and subtracted from the spectrum. An additional second-order background correction corresponding to 3% of the average net flux (i.e., \( d = 0.03 \)) based on the scattered light analysis of Cardelli, Ebbets, & Savage (1990a, 1993a) was also applied.

For each of the two observations, the individual FP-SPLITs were first corrected for fixed pattern noise/granularity (see Cardelli et al. 1993c and Lambert et al. 1994 for additional details). Since each of the four FP-SPLITs is obtained at a slightly different grating position, spectral features appear at a slightly different position in diode space. The derivation of the noise template involves an iterative procedure in which an estimate of the spectral template (determined by aligning and merging in wavelength space) is divided into the individual FP-SPLITs which are subsequently merged in diode (photocathode) space to determine a fixed pattern noise/granularity “spectrum.” The result is equivalent to determining a flat-field template since the noise information is “fixed” in diode space. This final noise spectrum, normalized to unity “continuum,” is then divided into each FP-SPLIT subexposure.

Due to a lack of statistically significant spectral features from which to align the individual noise-corrected FP-SPLITs for each observation, the subexposures were combined by using the nominally assigned wavelengths as a reference. While such an approach can occasionally result in a slight degradation of the profile resolution due to uncertainties in the assigned wavelengths, extensive analysis of numerous GRS Science Verification (SV) data sets has shown that it does not affect the integrated line characteristics. For the two noise-corrected observations, the Si II \( \lambda 2335 \) Å line was present at a depth of about 2–3 \( \sigma \) in each. A final summed spectrum was produced by aligning the individual spectra using (1) the measured centroid of the Si II line and (2) the nominally assigned wavelengths. Both approaches produced essentially identical results.

The final merged spectrum plotted against the heliocentric velocity is shown in Figure 1. Also shown is the profile for Si II \( \lambda 1808 \) Å obtained with echelle-B as part of the GRS SV program. The data reduction for this line, including corrections for fixed pattern noise, is the same as discussed above. The \(-27 \text{ km s}^{-1}\) (component A) and \(-15 \text{ km s}^{-1}\) (component B) absorption features discussed by SCS can be seen in the Si II \( \lambda 1808 \) Å line. The Si II \( \lambda 2335 \) Å line is only seen in absorption in component B. Also listed in the plot is the empirically derived continuum signal-to-noise. Detailed analyses of the continuum noise distribution for both spectra show it to be Gaussian in nature with the S/N predicted from (total counts)\(^{1/2}\) being within a few percent of the empirically derived continuum value (i.e., the ratio of the continuum to the continuum rms).

![Figure 1](image-url)

**Figure 1.** Spectrum of the Si II \( \lambda 2335 \) Å line observed with the Ech-B mode of the GRS toward ζ Oph in comparison to the GRS Ech-B data of the Si II \( \lambda 1808 \) Å line plotted against heliocentric velocity. Also shown is the empirically derived continuum signal-to-noise values for the two spectra.

3. DISCUSSION

3.1. Column Densities and f-Value Assessment

The equivalent width, \( W_A \), logarithm of the column density, \( \log N \), and ± \( \sigma \) measurement uncertainty for the ground state \( ^2P_{3/2} \) Si II \( \lambda 2335 \) Å transition detected toward ζ Oph are given in Table 1. The measurement uncertainty was derived from the line integration using a combination of the computed point-to-point statistics, uncertainty in the continuum fit (see Cardelli et al. 1990b, 1991b; Sembach, Savage, & Massa 1991), and uncertainty associated with the second-order scattered light correction (see Cardelli et al. 1993a). The line is weak enough that the column density can be computed directly from the weak line limit, \( N = 1.13 \times 10^{20} W_A \lambda^2 \text{ cm}^{-2} \), which assumes no line saturation. The contribution from the excited state \( ^2P_{3/2}; 287 \text{ cm}^{-1} \) to the total column density of Si II is observed to be negligible. The column density was computed using the new experimental f-value of Calamai et al. (1993) which carries a quoted 19% uncertainty. This f-value is nearly midway between the existing theoretical f-values of Dufon et al. (1991) and Nussbaumer (1977). Specifically, use of the Dufon et al. value yields \( \log N(\lambda 2335) = 15.29 \) while the Nussbaumer value yields \( \log N(\lambda 2335) = 15.42 \). If we include the Calamai et al. f-value uncertainty, the uncertainty in the derived column density increases from 0.11 to 0.13 dex.

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Also listed in Table 1 is the equivalent width, logarithm of the column density, and $\pm 1\sigma$ measurement uncertainty for the ground state transition of Si II $\lambda 1808$ Å. These values were derived by integrating the profile shown in Figure 1 over the velocity range where absorption from Si II is seen which corresponds to the velocity range of component B accounted for by SCS. The column density listed corresponds to the integrated apparent column density plus a correction to account for the presence of unresolved saturated structure (see SCS and references therein for details on both the apparent optical depth method and corrections for saturation). This correction was arrived at in the following manner. In SCS, corrections for unresolved saturated structure in component B were derived for a number of species for which the maximum apparent optical depth in the principal component at $-15$ km s$^{-1}$, $\tau_{e}(-15)_{max}$, was less than 1, including three lines of Mn II near 2000 Å. From data of the stronger line of Mn II $\lambda 2060$ Å for which $\tau_{e}(-15)_{max} \approx 2.5$, we compared the integrated apparent column density for component B to the corrected Mn II component B column density derived from the weaker lines. From this, we find a saturation correction for Mn II $\lambda 2060$ Å of about 0.18 dex. For Si II $\lambda 1808$ Å, we find $\tau_{e}(-15)_{max} \approx 2.1$. Given the similarity in $\tau_{e}(-15)_{max}$ values for these two lines, we assumed that the same correction also applies to the Si II $\lambda 1808$ Å line. From an examination of the SCS data, including a comparison between additional weak and strong lines, we believe the correction is no smaller than 0.18 dex. While it is possible that we have underestimated the correction, we feel it is by no more than about 0.06 dex. For example, the correction to the component B integrated apparent column density for Fe II $\lambda 2374$ Å [$\tau_{e}(-15)_{max} \approx 3.7$], derived from the corrected component B column density from the weaker line Fe II $\lambda 2249$ Å [$\tau_{e}(-15)_{max} \approx 0.5$], is only 0.28 dex.

The excellent agreement of the Si II column densities derived from Si II $\lambda 2335$ Å and Si II $\lambda 1808$ Å lines represents a confirmation of the relative accuracy of the $f$-values adopted here. We note that within the errors of the weak line measurement, use of the theoretical $f$-values of Dufort et al. 1991 or Nussbaumer 1977 produces consistent results as well. Also, since these theoretical values are at or within the uncertainty range of the Calama et al. 1993 experimental value, they cannot be arbitrarily dismissed. Given the total uncertainties (measurement plus $f$-value), the above conclusion is unchanged even if our correction to the column density of Si II $\lambda 1808$ Å is too small by as much as 0.06 dex.

### 3.2. Abundance Implications

It is now possible with the GHRSS to produce high-quality abundance measures for Si for a wide range of interstellar sight lines. For example, in sight lines with total hydrogen column densities equal to or exceeding that of ζ Oph, one can use Si II $\lambda 2335$ Å in place of the saturated Si II $\lambda 1808$ Å line. Likewise, for sight lines where the total hydrogen column density is significantly less than that of ζ Oph and where Si II $\lambda 2335$ Å may be too weak to be observed, Si II $\lambda 1808$ Å will be useful since it will likely not be strongly saturated. This is particularly true in sight lines probing warm intercloud gas such as in the case of the halo star HD 93521 (Spitzer & Fitzpatrick 1993) and the low halo star HD 167756 (Cardelli, Sembach, & Savage 1993d). Accurate abundance measures for elements like Si as well as Fe and Mg are important since next to C, these elements represent the bulk of the material comprising interstellar dust. For ζ Oph component B, greater than 95% of the available cosmic abundance of Si, Fe, and Mg (e.g., meteoritic abundances of Anders & Grevesse 1989) is “missing” from the gas phase and is presumably locked up in the dust (the data for Mg utilize newly revised $f$-values for the Mg II $\lambda 2240$ Å doublet [Cardelli et al. 1991b; Sofia, Cardelli, & Savage 1993]) in the forms of the “dust-phase” abundance, we find (Si + Fe + Mg)/H = 1.04 x 10$^{-4}$ and Fe/Si = 0.9, Mg/Si = 1.1, and Mg/Fe = 1.2, values that are essentially the same as those derived from their cosmic abundances. However, these values are in sharp contrast to those found in more diffuse clouds like the v = $-10$ km s$^{-1}$ absorption component toward the high-latitude halo star HD 93521 (Spitzer & Fitzpatrick 1993) where (Si + Fe + Mg)/H = 0.7 x 10$^{-4}$ and Fe/Si = 1.8, Mg/Si = 2.1, and Mg/Fe = 1.1. In deriving these numbers, we adjusted the Spitzer & Fitzpatrick column densities for Si and Mg II to reflect the new $f$-values we have adopted. By far, the largest contribution to the difference in (Si + Fe + Mg)/H is due to Si: relative to the HD 93521 v = $-10$ km s$^{-1}$ cloud,
the dust in ζ Oph component B contains only about 20% more Fe/H and Mg/H while containing 120% more Si/H.

It is possible that the grains in the HD 93521 v = −10 km s⁻¹ cloud represent "refractory" (mineral?) cores with the relative abundances of Si, Fe, and Mg being characteristic of the mineralogy applicable to their formation. Spitzer & Fitzpatrick (1993) suggested that a value of Fe/Si ≈ 2 could indicate that the dust in the HD 93521 v = −10 km s⁻¹ cloud is formed from a mineral such as Fe₂SiO₄. However, this cannot be the dominant contribution since minerals like Mg₂SiO₄ as well as (Fe, Mg)SiO₃ may also participate, and we find Mg/Si ≈ 2 as well. As suggested by Mg/Fe ≈ 1, it is possible that Fe₂SiO₄ and Mg₂SiO₄ participate equally, but again, these cannot be the only compounds involved since they would lead to observed ratios of Fe/Si ≈ Mg/Si ≈ 1. A possible scenario is that in the formation of the grain cores there is a balanced contribution from (Fe, Mg)SiO₃ and oxides like (Fe, Mg)O such that the observed values are obtained. The nearly complete incorporation of Si, Fe, and Mg in the dust in the ζ Oph component B cloud relative to the HD 93521 v = −10 km s⁻¹ cloud may suggest the formation of amorphous coatings of Si, Fe, Mg, and other elements on these grain cores in denser cloud environments. We reach this conclusion because it seems unlikely that minerals are formed in the gas phase under typical interstellar cloud conditions and because of the empirical result that between the HD 93521 and ζ Oph clouds, a significantly larger fraction of Si relative to Fe and Mg appears to enter the dust. A more generalized discussion of this topic is presented by Sofia et al. (1993).

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