A REANALYSIS OF THE CARBON ABUNDANCE IN THE TRANSLUCENT CLOUD TOWARD HD 24534

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ABSTRACT

We have reanalyzed the Goddard High Resolution Spectrograph data set presented by Snow et al., which contains the interstellar intersystem C II λ2325 line through the translucent cloud toward HD 24534 (X Persei). In contrast to the results of Snow et al., we clearly detect the C II feature at the 3 σ confidence level and measure a C+ column density of $2.7 \pm 0.8 \times 10^{17}$ cm$^{-2}$. Accounting for the C I column density along the line of sight, we find $10^6$ C/H = 106 ± 38 in the interstellar gas toward this star. This gas-phase carbon-to-hydrogen ratio suggests that slightly more carbon depletion may be occurring in translucent as compared to diffuse clouds. The average diffuse-cloud C/H, however, is within the 1 σ uncertainty of the measurement toward HD 24534. We therefore cannot rule out the possibility that the two cloud types have comparable gas-phase C/H and therefore comparable depletions of carbon.

Subject headings: dust, extinction — ISM: abundances — ultraviolet: ISM

1. INTRODUCTION

Interstellar carbon is an important contributor to interstellar molecular chemistry and cloud cooling and is thought to be a major component of interstellar dust (Duley & Williams 1981; Draine 1989; Joblin, Léger, & Martin 1992). Unfortunately, reliable measurements of the gas-phase interstellar carbon abundance have been elusive because the available absorption features from the dominant ionization stage, C+, are either so strong as to be hopelessly saturated (λ1334) or so weak as to be undetectable (λ2325). In recent years, however, this situation has changed and high precision measurements of the C II λ2325 line with the Goddard High Resolution Spectrograph (GHSR) aboard the Hubble Space Telescope (HST) have yielded six reliable (>2 σ) measurements of the gas-phase interstellar carbon abundance in diffuse clouds (Cardelli et al. 1993; Cardelli et al. 1996; Sofia et al. 1997), one upper limit in diffuse clouds (Cardelli et al. 1996), and two upper limits in translucent clouds (Snow et al. 1996, 1998).

Absorption line measurements suggest that in diffuse interstellar clouds, there is little exchange of carbon between the gas and dust phases (Cardelli et al. 1996; Sofia et al. 1997), i.e., a relatively constant C depletion level is observed. One might expect, however, that a denser cloud region, such as a translucent cloud, may provide a more protective environment than diffuse clouds and therefore show different depletion characteristics. A recently reported upper limit for gas-phase carbon in a translucent cloud (toward HD 24534) suggested that this was indeed the case and that C was substantially more depleted in this region as compared to the more diffuse clouds (Snow et al. 1998).

Since carbon plays such an important role in the interstellar medium (ISM) and its abundance is such a difficult quantity to measure, we decided to reexamine the spectrum through the translucent cloud toward HD 24534. In § 2 we will discuss our data calibration and reductions and in § 3 our results will be discussed.

2. OBSERVATIONS AND REDUCTIONS

The observations of the C II λ2325 line toward HD 24534 are described in Snow et al. (1998). In summary, the data consist of 40 individual, high resolution GHSR spectra taken with the observing strategy FP-SPLIT = 4. This means that 10 spectra were taken at each of four slightly different positions on the photocathode in order to reduce the effects of fixed pattern noise (FPN) on the final spectrum. We obtained these data from the Hubble Space Telescope Data Archive, and they were processed independently by two of us (U. J. S. and E. L. F.). In both cases the GHSR team software package, CALHRS, was used to calibrate the spectra (Space Telescope pipeline calibrations do not differ significantly from CALHRS). In addition, sophisticated flat-fielding algorithms were employed to further reduce the effects of FPN, beyond the reduction afforded by the FP-SPLIT observing strategy. These algorithms are described in Spitzer & Fitzpatrick (1993), Cardelli & Ebbets (1994), and Cardelli (1995). Once the FPN was removed, the data were co-added using the nominal wavelengths determined from the GHSR carousel grating position to align the individual spectra. We examined the 40 individual spectra and found no reason to exclude any from the final co-added spectrum.

The two independently processed final spectra are essentially identical and have S/N-values of approximately 170 near 2325 Å. Figure 1 shows one of the final spectra; count rate versus heliocentric wavelength are plotted for a 3 Å segment centered near the expected location of C II λ2325.4. The upper and lower spectra show the results with and without, respectively, the application of the additional FPN correction algorithms. The magnitude of the FPN features is small in the region of the detector sampled by these data and the improvement with the additional correction is only marginal. It is important to note, however, the FPN removal algorithm has not added any spurious features to the data.

1 Based on observations obtained with the NASA/ESA Hubble Space Telescope through the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NASA-26555.
3. RESULTS AND DISCUSSION

Figure 1 shows clear evidence for the presence of an absorption feature in the wavelength region expected for C ii] λ2325.4. Figure 2 provides an expanded view of this region (for the FPN corrected data) with normalized flux plotted versus heliocentric velocity (top spectrum). The normalization was accomplished with a second order polynomial fit to the continuum. For comparison, we also show the O i] λ1355 feature seen toward HD 24534 (lower spectrum). These data have been velocity-shifted by +1.0 km s\(^{-1}\), which is well within the velocity uncertainty of ∼3.5 km s\(^{-1}\) expected for G H R S calibrated data (Savage, Cardelli, & Sofia 1992). This comparison demonstrates that the absorption feature seen in the top spectrum is closely aligned in velocity with the O i line; we thus firmly identify this feature as a result of C ii] λ2325.4, in strong contrast to the results of Snow et al. (1998).

We measure the C\(^+\) column density implied by the C ii] feature in two ways, from the equivalent width and from component fitting. The equivalent width of the feature is found to be \(W_W = 0.78 \pm 0.22\) mA (note that this result is more than twice as large as the 0.33 mA upper limit quoted by Snow et al. 1998). We adopt the oscillator strength \(f = 5.80 \times 10^{-8}\) for the C ii] λ2325 transition from Cardelli et al. (1996), who combined the values of Fang et al. (1993) and Lennon et al. (1985). Cardelli et al. estimate an uncertainty of ∼8% in this value. Assuming the weak-line limit, \(W_W\) implies \(N(C^+) = 2.8 \pm 0.8 \times 10^{17}\) cm\(^{-2}\). The 1σ uncertainty includes the effects of statistical error, continuum placement, and scattered light uncertainties added in quadrature, but it does not include the oscillator strength uncertainty. The component-fitting technique (see, e.g., Spitzer & Fitzpatrick 1993) yields a similar result of \(N(C^+) = 2.6 \pm 0.8 \times 10^{17}\) cm\(^{-2}\). Again, the quoted uncertainty does not include the error in the oscillator strength.

Following Snow et al. (1998) we use the Dipsal \& Savage (1994) neutral H column density \([N(H)] = 5.4 \pm 0.8 \times 10^{15}\) cm\(^{-2}\) and the Mason et al. (1976) H\(_2\) column density \([N(H_2)] = 1.10 \pm 0.30 \times 10^{21}\) cm\(^{-2}\) to get the total column density of neutral hydrogen particles toward HD 24534 \(N(H) = 2.74 \pm 0.61 \times 10^{21}\) cm\(^{-2}\). Taking the \(N(C) = 2 \times 10^{17}\) cm\(^{-2}\) from Snow et al. (1998), and the average C ii] abundance from our measurements \([N(C\ ii)] = 2.7 \pm 0.8 \times 10^{17}\) cm\(^{-2}\), we find the gas-phase carbon-to-hydrogen ratio is \(10^6\ C/H = 106 \pm 38\), where the 1σ value takes into account the uncertainties in both the H and C ii] (but not C i) column densities.

The gas-phase interstellar carbon-to-hydrogen ratio in the translucent cloud toward HD 24534 is slightly lower than, although within the 1σ error of, the average ratio seen in the diffuse clouds previously measured \(10^6\ C/H = 142 \pm 13\); Sofia et al. 1997). If we add the HD 24534 sight line to the Sofia et al. sample, the average ratio becomes \(10^6\ C/H = 139 \pm 12\). Figure 3 shows the interstellar gas-phase C/H versus the fraction of molecular hydrogen, \(f(H_2) = 2N(H_2)/[2N(H_2) + N(H)]\), for all of the measured diffuse cloud sight lines, as well as the translucent cloud toward HD 24534. This figure is an update to the Snow et al. (1998) Figure.
3, except that we have only included the sight lines with C II detections. The data points and error bars in Figure 3 do not agree precisely with Snow et al.’s Figure 3 for three reasons: (1) We used a weighted average of the Bohlin, Savage, & Drake (1978) and Diplas & Savage (1994) N(H i) measurements whenever possible, (2) we have used the updated carbon abundance toward ξ Per (Cardelli et al. 1996), and (3) we have included the uncertainties associated with the H abundances in our error bars.

Figure 3 shows a line plotted at the weighted average of the measured gas-phase C/H values (10^6 C/H = 139). This is a statistically acceptable fit to the data. We also plot a weighted linear fit to the C/H data in Figure 3 (dotted line). Although the higher order term is not statistically justified, we show the linear fit in order to illustrate a possible trend in the data. Given the uncertainties in the measurements, it is not possible to conclude with certainty whether or not carbon is more depleted in the translucent cloud as compared to diffuse clouds. If carbon is more depleted in the HD 24534 cloud, it is not by the substantial amount suggested by the Snow et al. (1998) non-detection of C II (which implied 10^6 C/H ≤ 44). It is interesting to note that C is not the only volatile element that does not appear to be significantly more depleted in translucent clouds versus diffuse clouds. Snow et al. (1998) find the gas-phase O/H in the translucent cloud toward HD 24534 agrees well with the measured gas-phase O/H in diffuse cloud sight lines (Meyer, Jura, & Cardelli 1998).

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