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# CARBON AND OXYGEN DEPLETION AND EXTINCTION IN THE TRANSLUCENT CLOUD TOWARD HD 24534 (X PERSEI)

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## ABSTRACT

Recent studies of the gas-phase abundances of carbon and oxygen in diffuse clouds have suggested that the depletions of both elements are invariant and independent of extinction curve properties. We show, however, that in the line of sight toward HD 24534 (X Persei), the depletion of carbon is at least a factor of 3 greater than in the diffuse clouds previously surveyed. For HD 24534, the interstellar gas-phase C/H ratio is lower than the mean of diffuse sight lines by a factor of about 3.5. We conclude that the carbon depletion may be enhanced in translucent molecular clouds and also that carbon begins to show an enhanced level of depletion at lower extinctions than oxygen, which is also discussed. We argue that it is imperative to measure abundances and depletions in translucent and denser clouds in order to understand the interaction between gas and dust as the thicknesses and densities of clouds increase.

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

## 1. INTRODUCTION

The Goddard High-Resolution Spectrograph (GHRS) on the *Hubble Space Telescope* (*HST*) has provided accurate measurements of gas-phase species in the diffuse interstellar medium (ISM), and great strides have been made in quantifying the abundances and depletions of many elements. Among the most significant species, because of their probable roles in dust grains and interstellar extinction, are carbon and oxygen.

Both carbon and oxygen have very weak, spin-forbidden absorption lines in the wavelength region accessible to the *HST*. For carbon, the C II] line at 2325 Å, which has an oscillator strength of $f = 5.8 \times 10^{-8}$ (Fang et al. 1993; Lennon et al. 1985), has provided accurate column densities for a few lines of sight (see Table 1 below), while for oxygen, the O I] line at 1355 Å ($f = 1.25 \times 10^{-6}$; Morton 1991) has yielded accurate column densities for several more lines of sight. Thus, the *HST* provides an opportunity to constrain the composition of the interstellar dust, through observations of gas-phase abundances and depletions.

To date, analyses of the observed carbon and oxygen abundances have led to the conclusion that neither element is highly depleted in the diffuse ISM and that the depletions of both are essentially constant (Cardelli et al. 1996; Sofia et al. 1997; Meyer, Jura, & Cardelli 1998). Because the observed sample of stars includes a wide range in UV extinction properties, this leads to the unexpected suggestion that variations in extinction are unrelated to the depletions of carbon and oxygen. What makes this so surprising is the general expectation that both carbon and oxygen are key constituents of interstellar grains (e.g., Mathis 1990, 1996; Hong & Greenberg 1980; Li & Greenberg 1997; for summaries of the carbon and oxygen requirements of various dust models, see Snow & Witt 1995, 1996). Also, the modeling of the chemistry of carbon-bearing molecules in translucent and dense clouds suggests depletions of carbon of factors of 2–4 compared with diffuse cloud values (e.g., van Dishoeck & Black 1989; Jansen et al. 1996). Information on elemental abundances in denser clouds is essential for chemical modeling of dark interstellar clouds, where the carbon and oxygen abundances are often taken to be depleted by as much as a factor of 5–8 (e.g., Millar et al. 1997). This evidence that in dense clouds the depletions of carbon and oxygen are substantially greater than in diffuse clouds leads us to expect that at some intermediate point between diffuse and dense clouds, enhanced depletions of these elements must set in.

In this Letter, we examine the abundances and depletions of both carbon and oxygen toward the star HD 24534, whose line of sight contains a translucent cloud known to have high molecular abundances (e.g., Lien 1984a, 1984b, 1984c), and for which both H I and $H_2$ column densities have been observed directly (Diplas & Savage 1994; Mason et al. 1976). In the next section, we briefly describe the observations and the results, while in § 3 the extinction is described, and in § 4 we provide a discussion of the implications.

## 2. OBSERVATIONS AND RESULTS

The star HD 24534 (spectral type O9.5pe; $V = 6.10$; nominal $E_{B-V}$ value 0.62) is best known as the Be star X Persei, with an X-ray–emitting companion. But apart from the interest in this object for its stellar evolutionary significance, its interstellar line of sight has proved to be rich in absorption lines due to atoms, ions, and molecules (e.g., Lien 1984a, 1984b, 1984c; Federman & Lambert 1988), and this, combined with its relatively bright magnitude and high ultraviolet flux, makes it an ideal candidate for studies of interstellar physics and chemistry.

Thus, in 1993 we proposed extensive GHRS observations of HD 24534 and were rewarded with a limited amount of

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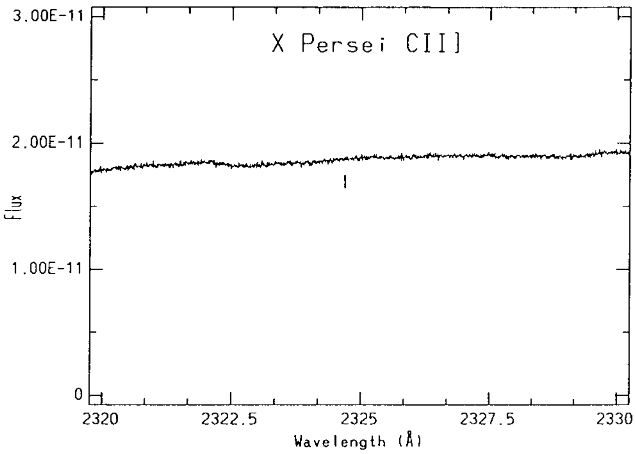


FIG. 1.—The C II] data toward HD 24534. No trace of a line due to ionized carbon is seen in this spectrum, which is the sum of 32 individual exposures totaling about 160 minutes of exposure time with the GHRS. The inferred (2 $\sigma$) upper limit on the equivalent width of the feature is 0.33 mÅ, yielding a column density limit of $N(C^+) \leq 1.2 \times 10^{17}$ cm$^{-2}$.

time, enough to observe several selected lines of atoms, ions, and molecules of interest. The observations took place in early 1995. The FP-SPLIT observing technique was used, in which successive exposures are taken at small offsets in the spectral direction, which helps to reduce the impact of fixed-pattern detector noise. The data were then shifted and co-added to produce the final spectra, after inspection to eliminate any individual exposures containing anomalous noise spikes. Here we report on the results of observations of the C II] line at 2325 Å and the O I] line at 1355 Å; further analysis of abundances and depletions, as well as the molecular observations, will be reported separately.

The C II] line was not detected (Fig. 1). The 2 $\sigma$ upper limit is 0.33 mÅ, yielding a column density limit of $N(C^+) \leq 1.2 \times 10^{17}$ cm$^{-2}$. The O I] line was detected, yielding an equivalent width of 11.0 $\pm$ 0.8 mÅ. Lien (1984c) has shown that a $b$-value of 1.0 km s$^{-1}$ is appropriate for this line of sight (for both neutral species and dominant ions), in which case the O I] line is partially saturated. Assuming $b = 1.0$ km s$^{-1}$ yields an O I column density of log $N$(O I) = 18.09($\pm$0.06), corresponding to a column density in the range (1.07–1.41) $\times$ $10^{18}$ cm$^{-2}$.

The atomic hydrogen column density for HD 24534, $N$(H I) = (5.4 $\pm$ 1.1) $\times$ $10^{20}$ cm$^{-2}$, was taken from Diplas & Savage (1994) and the molecular hydrogen column density, $N(H_2)$ = 1.1 $\times$ $10^{21}$ cm$^{-2}$, from Mason et al. (1976). The latter value is somewhat uncertain, since the star was quite faint for *Copernicus* observations. The $H_2$ column density, however, is in harmony with the well-established correlation between CH and $H_2$ (Mattila 1986), which actually suggests a somewhat higher value $N(H_2) \approx 1.4 \times 10^{21}$ cm$^{-2}$ for clouds with a standard carbon abundance. Taking the Mason et al. value for $H_2$, we find a total hydrogen column density of $N_H = 2.8 \times 10^{21}$ cm$^{-2}$. This yields a molecular fraction for hydrogen of $f(H_2) = [2N(H_2)]/[2N(H_2) + N(H)] = 0.80$, the highest value yet measured. A more accurate determination of this value may come from *Far-Ultraviolet Spectroscopic Explorer* observations of $H_2$ toward HD 24534.

## 3. EXTINCTION

Derivation of the ultraviolet extinction curve for HD 24534 was complicated by the fact that the star is a *B* emission-line object with a variable circumstellar disk that can contribute to the $B - V$ color. From the papers of Roche et al. (1993, 1997), we find that the intrinsic spectral type is closer to B0 V than the more widely quoted O9 V and that the interstellar color excess is closer to $E_{B-V} = 0.45$ than 0.62, the nominal value that is usually cited. When we assumed the spectral type to be B0 V and the color excess to be $E_{B-V} = 0.45$, we found a smoothly continuous curve that conforms to established interstellar curves (whereas adoption of spectral type O9 V and $E_{B-V} = 0.62$ led to discontinuities in the curve).

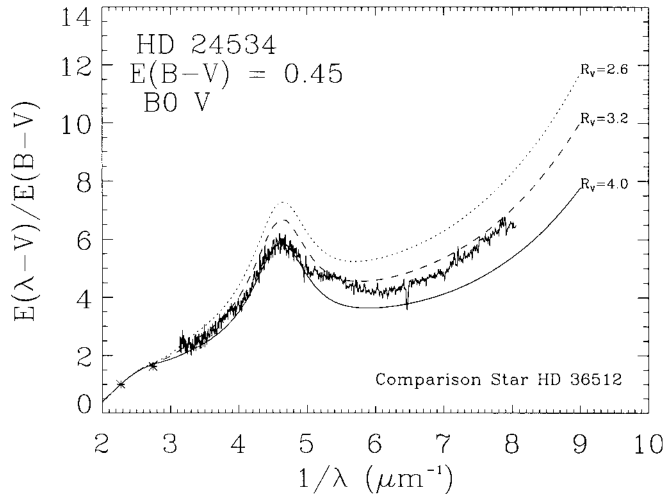


FIG. 2.—The extinction curve toward HD 24534. This shows the curve as derived using HD 36512 (B0 V) as the comparison star, with "standard" curves (from Cardelli et al. 1988) superimposed for different values of $R_V$. It appears that the curve best fits the case for $R_V \approx 3.2$.

The resulting extinction curve is shown in Figure 2, which illustrates the curve derived from a comparison with the star HD 36512; other comparison stars were used as well, with very similar results. We see that the curve has a wide bump (whose width we measured as $\gamma = 1.18$ $\mu$m$^{-1}$ following the notation of Fitzpatrick & Massa 1986, 1988, 1990) and a far-UV rise that best fits the standard curve (from Cardelli, Clayton, & Mathis 1988, 1989) for a ratio of total to selective extinction $R_V = 3.2$. The Fitzpatrick & Massa parameters were derived and found to be normal for diffuse clouds, except for the wide bump and moderately large value for the far-UV rise parameter ($c_4 = 0.552$), placing this curve within the family of "dark cloud" curves, as defined by Cardelli et al. (1988, 1989) and discussed further by Mathis & Cardelli (1992) and Cardelli & Clayton (1991). We note, for example, that the value of $c_4$ for HD 24534 is comparable to those for such well-known molecular translucent clouds as those toward HD 21483, HD 73882, HD 147701, and $\zeta$ Oph (Fitzpatrick & Massa 1988). Such curves are usually associated with relatively dense, isolated clouds with significant molecular column densities (e.g., Snow 1992).

## 4. DISCUSSION: DEPLETIONS AND EXTINCTION

Table 1 summarizes the existing data on $C^+$ abundances derived from *HST* data on the weak line of C II] at 2325 Å. The sources of the carbon data, all from GHRS observations, are indicated in the footnotes to Table 1. The hydrogen column densities are based on *Copernicus* data from Bohlin, Savage, & Drake (1978), except for HD 24534, which is described above, HD 154368, which is taken from Snow et al. (1996),

TABLE 1
DATA ON CARBON ABUNDANCES

| Star | log $N_H$[a] | $E_{B-V}$ | $A_V$ | $f(H)_2$ | $N$(C II)[b] | $10^6$ C/H |
|---|---|---|---|---|---|---|
| $\kappa$ Ori ............ | 20.52 | 0.07 | 0.22: | 0.00 | $\leq 6.4 \times 10^{16}$ | ≤193 |
| $\tau$ CMa .......... | 20.70 | 0.17 | 0.53: | 0.00 | $(7.57 \pm 2.52) \times 10^{16}$ | 151(±50) |
| $\delta$ Sco ............ | 21.16 | 0.16 | 0.50: | 0.02 | $(2.16 \pm 1.08) \times 10^{17}$ | 149(±75) |
| $\lambda$ Ori ............ | 20.80 | 0.12 | 0.37: | 0.04 | $(8.3 \pm 3.2) \times 10^{16}$ | 132(±51) |
| $\beta^1$ Sco .......... | 21.14 | 0.20 | 0.80 | 0.10 | $(1.95 \pm 0.39) \times 10^{17}$ | 141(±28) |
| $\xi$ Per ............ | 21.30 | 0.32 | 1.09 | 0.34 | $(4.92 \pm 1.35) \times 10^{17}$ | 247(±68) |
| $\zeta$ Per ............ | 21.20 | 0.33 | 0.92 | 0.59 | $(1.84 \pm 0.32) \times 10^{17}$ | 116(±20) |
| $\zeta$ Oph ........... | 21.14 | 0.32 | 0.99 | 0.65 | $(1.80 \pm 0.42) \times 10^{17}$ | 130(±30) |
| HD 154368 ...... | 21.62 | 0.82 | 2.54 | 0.76 | $\leq 7.1 \times 10^{17}$ | ≤170 |
| HD 24534 ....... | 21.44 | 0.45 | 1.44 | 0.80 | $\leq 1.2 \times 10^{17}$ | ≤44 |

[a] Total hydrogen column densities are taken from Bohlin et al. 1978 and are based on *Copernicus* data. Note that for two stars ($\xi$ Per and $\zeta$ Oph), the more recent *IUE*-based H I column densities of Diplas & Savage are significantly smaller, thus implying larger C/H ratios than listed here.

[b] The C II] data are from the following sources: for $\kappa$ Ori, $\lambda$ Ori, $\beta^1$ Sco, and $\zeta$ Per: Cardelli et al. 1996; for $\tau$ CMa and $\delta$ Sco: Sofia et al. 1997; for $\xi$ Per and $\zeta$ Oph: Cardelli et al. 1993; and for HD 154368: Snow et al. 1996.

and $\xi$ Per and $\zeta$ Oph, where the more recent *IUE*-based H I column densities are adopted. Figure 3 shows graphically how the ratio of carbon to hydrogen varies with molecular fraction.

In order to verify that we are not overlooking an important reservoir of carbon, we have made preliminary determinations of the column densities of both C I and CO toward X Per. Our data include several multiplets of C I, leading to a preliminary column density of $\approx 2 \times 10^{16}$ cm$^{-2}$. Analysis of the $A$–$X$ (7, 0) and (11, 0) bands of CO yields a CO column density of $N(\mathrm{CO}) \approx 7 \times 10^{15}$ cm$^{-2}$. Thus, the abundance of carbon in forms other than $C^+$ is far below our upper limit from the C II] 2325 Å line, so these forms of carbon will not alter our main conclusion regarding carbon depletion. The abundances

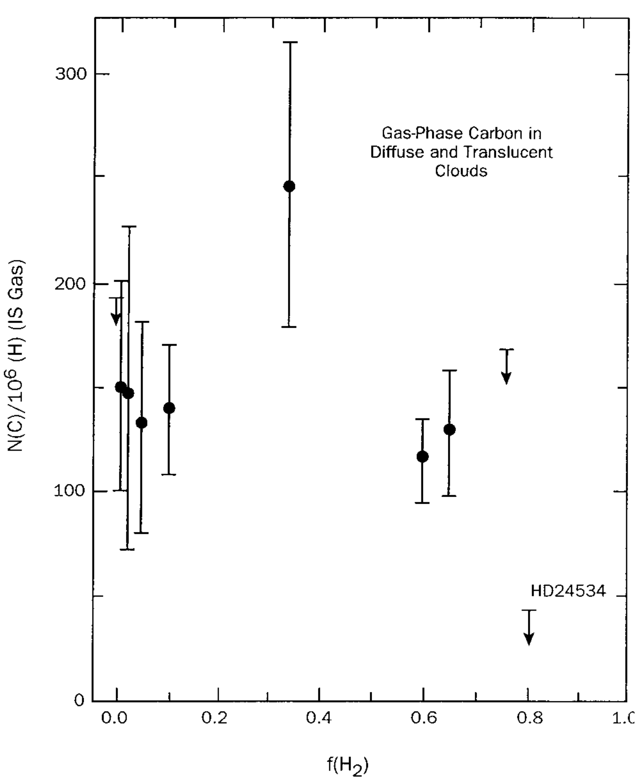


FIG. 3.—Gas-phase abundances of carbon. This figure summarizes all existing data on the observed ratio of carbon to hydrogen in diffuse and translucent clouds.

and excitation of the neutral atomic and molecular species will be discussed in greater detail in a subsequent paper.

The most striking feature of Table 1 and Figure 3 is that for HD 24534, the carbon abundance relative to hydrogen is far below that for other stars. The upper limit on the $C^+$ abundance, expressed in terms of carbon atoms per $10^6$ H nuclei, is a factor of 3.5 lower than the weighted mean of the seven detections listed in Table 1 (weights were assigned as inversely proportional to the fractional 1 $\sigma$ errors). Thus, the line of sight toward HD 24534 has significantly greater depletion of carbon than any previously measured line of sight. We point out that except for HD 154368 (which also resulted in an upper limit for the C II] line), *all* previous measurements of the weak C II] line have applied to stars with total extinctions $A_V \lesssim 1$ mag. Thus, the previously existing sample was too limited to support general conclusions about a supposed invariance of the carbon depletion.

In contrast, the oxygen depletion toward HD 24534 appears to fall within the range observed for more diffuse clouds. The Meyer et al. (1998) study summarizes the current state of knowledge of O I abundances based on the weak line at 1355 Å and argues that the oxygen depletion is quite invariant (a claim that we question, based on the large variations in the *Copernicus* results quoted by Meyer et al.). In any event, we conclude that oxygen does not show evidence of enhanced depletion (relative to diffuse clouds) toward HD 24534, in contrast to the behavior of carbon.

In view of the relatively small total extinction toward HD 24534 (roughly $A_V = 3.2E_{B-V} = 1.44$ mag), it may seem surprising that the cloud shows such strong molecular abundances and displays an extinction curve that is characteristic of molecular clouds. One possible interpretation is that the cloud toward HD 24534 is the remnant of a dense molecular cloud that originally had a high depletion of carbon and that in the subsequent dispersal of this cloud, there has not yet been enough time to sputter the accreted and processed mantles off the grains. In this case, the observed depletions are more representative of molecular cloud depletions than diffuse or translucent cloud conditions. Jansen et al. (1996) concluded that this situation prevails in the small molecular cloud IC 63 seen near $\gamma$ Cas.

Not much is known about elemental depletions in translucent or dark clouds, but what is known appears to be consistent with our results. Observed abundances of the carbon-bearing molecules CH, $C_2$, and CN (e.g., Crutcher 1985; van Dishoeck & Black 1989; Gredel, van Dishoeck, & Black 1993; Federman & Lambert 1988; Federman et al. 1994) suggest a carbon depletion in translucent clouds of a factor of 2–4 (van Dishoeck & Black 1988, 1989). Only a few observational determinations of the carbon abundance in dark clouds have been made. Lacy et al. (1994) measured CO (the dominant form of carbon in dense clouds) and $H_2$ through infrared absorption lines toward NGC 2024 IRS 2. Their inferred CO/$H_2$ ratio of $2.7 \times 10^{-4}$ corresponds to a $10^6$ C/H of 135, very similar to that found toward $\zeta$ Oph, suggesting no enhanced depletion in warm, dense clouds. On the other hand, Jansen et al. (1996) infer a $10^6$ C/H of $52^{+24}_{-20}$ for the dense [$n(H_2) = 5 \times 10^4$ cm$^{-3}$] reflection nebula IC 63 located close to the star $\gamma$ Cas from submillimeter observations of $C^+$, C, and CO, close to the value found here.

With a sample of only one translucent cloud for which we have both UV extinction and carbon depletion data, it is difficult to say much about what the relationship between the two might be. It is noteworthy that for HD 24534, both the gas-phase and extinction measures indicate a high cloud molecular content, so we can say that these separate indicators seem to be consistent with each other. The UV extinction curve shape may be dictated by the grain size distribution, which would be consistent with enhanced depletions of carbon and possibly other species (though not oxygen in this case) if the depletions affect the sizes of the same grains that produce the UV extinction. Clearly it will be useful to obtain similar data for a larger sample of translucent clouds, thereby obtaining information on how grain growth (or mantle retention), as evidenced by the depletions, is related to the nature of the extinction curve.

If we are correct in our conclusion that depletions are enhanced in translucent clouds as compared with the standard depletion pattern seen in diffuse clouds (e.g., Morton 1974; Joseph 1988), then it is *imperative* that further observations be carried out, in order to find out where the thresholds are for the depletion of carbon and other elements onto grains and to find out how these thresholds may be related to the shape of the extinction curve and to the appearance of mantles on the grains. It will be extremely interesting, for example, to probe the $C^+$ and O abundances in additional translucent cloud lines of sight (particularly those classified as “dark cloud” environments) to see whether HD 24534 represents a trend or whether it is an isolated case; and it will be fascinating to compare the depletion thresholds of oxygen and carbon with those for the appearance of water ice (e.g., Whittet et al. 1988) and hydrocarbon (e.g., Pendleton et al. 1994) grain mantle absorption features in the near-infrared. Then we may be able to see where the depleted materials go when they leave the gas phase, and thus develop a comprehensive view of the interaction of gas and dust in regions that represent the transition between diffuse and dense molecular clouds.

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