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This project was aimed at acquiring a better understanding of the physical conditions in the interstellar medium by using the Copernicus satellite to measure C I and CO absorption lines in selected lines of sight. We successfully accumulated all the data, and we are currently analyzing it. Enclosed is a rough draft of a paper to be submitted to the Astrophysical Journal. This paper has not yet been submitted for two reasons. First, the collaboration between Princeton and Los Angeles is more difficult than we had originally expected. Second, we have discovered that the oscillator strengths of the C I lines as currently given in the literature are inconsistent with our data and are almost certainly in error. Therefore, we have spent a considerable amount of time estimating better values for the C I oscillator strengths. Ultimately, we do not expect the final conclusions, as given in the Abstract of the draft paper, to change.

No inventions were produced with this grant.

COPERNICUS OBSERVATIONS OF C I AND CO IN DIFFUSE INTERSTELLAR CLOUDS

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ABSTRACT

We have used Copernicus to observe absorption lines of C I in its ground state and excited fine structure levels and CO toward 29 stars. We use the C I data to infer densities and pressures within the observed clouds, and because our results are of higher precision than previous work, we have much more precise estimates of the physical conditions in clouds. In agreement with previous work, the interstellar thermal pressure appears to be variable, with most clouds having values of p/k between 10^3 cm^{-3} K and 10^4 cm^{-3} K, but there are some clouds with p/k as high as 10^5 cm^{-3} K. Our results are consistent with the view that the interstellar thermal pressure is so variable that the gas undergoes continuous dynamic evolution.

Our observations provide useful constraints on the physical processes on the surfaces of grains. In particular, we find that grains are efficient catalysts of interstellar H_2 in the sense that at least half of the hydrogen atoms that strike grains come off as part of H_2.

Our results place strong constraints on models for the formation and destruction of interstellar CO. In particular, in many clouds, we find an order of magnitude less CO than predicted in some models.

I. INTRODUCTION

Ultraviolet observations are an extremely powerful way to investigate diffuse interstellar clouds (e. g. Spitzer and Jenkins 1975). Here we describe our observations with Copernicus of interstellar C I and CO. We observed C I because the populations in the fine structure levels of this atom can be used to estimate the density, temperature and pressure within a cloud. In particular, we can infer densities much more accurately from studies of C I than from studies of any other species except perhaps H_2. Since there are some uncertainties about the analysis of the populations of H_2 in the different rotational levels, the C I analysis seems to be especially important.

We emphasize that the measurement of cloud densities is critical for understanding the physical processes within interstellar clouds such as heating and cooling, molecule formation and depletion onto grains. The thermal pressure also plays a key role in the dynamics of interstellar clouds. Therefore, although Jenkins and Shaya (1979) have performed an initial survey of C I, we have extended their work with more detailed observations.

In this survey we have also observed CO. Since CO is apparently the most common molecule in diffuse clouds besides H_2, studies of CO are one of the best ways to evaluate critically models for interstellar chemistry. Among other reasons, this is important because interstellar chemistry may play a key role in the evolution of interstellar clouds into stars.

II. OBSERVATIONS

A. Line List

Our basic goal was to detect at least one line that was sufficiently weak to lie on or near the linear portion of the curve of growth so that the determination of column densitite was straightforward. Our line list was taken from de Boer and Morton (1974) and Morton (1975), and in table 1 we list the observed lines and the f values that we adopted as described below. Similarly, for CO we observed lines with a wide range of f values which we took from Morton (1975) and which we also list in table 1. We observed each line with four Copernicus scans, and we used the dipping mirror to block stray light as described by York et al. (1973). Also, to calibrate the amount of stray light, we observed some very saturated lines.

B. Star List

Our observed stars were taken from the H_2 surveys of Spitzer et al. (1974) and Savage et al. (1979). From these lists we excluded stars for which detailed observations of C I were performed by others including ζ Pup (Morton 1978), ζ Oph (Morton 1975), γ Vel (Morton and Bhavsar 1979), ζ Ori Pottasch and Drake (1977) and α Vir (York and Kinahan 1979). Also, we only observed stars that are brighter than $m_V = 5$. In table 2 we list the 29 stars that we observed along with their reddening and projected rotational velocities as given by Savage et al. (1977).

C. Results

We list our results for the observed equivalent widths, the FWHM (in parenthesis) and the 2σ errors in tables 3a-3d. We used the formulation of Jenkins et al. (1973) to derive the errors we give. For this procedure, we assumed a single cloud in the line of sight. In some lines of sight with multiple clouds, our upper limits may be misleadingly small. In table 4 we list the observed radial velocities in kilometers per second.

There were some difficulties in performing these line measurements. Because we aimed at measuring C I* 1276.750 A and C I** 1277.954 A, our Copernicus scans did not cover very well the spectral region near C I 1276.483 A. Consequently, our measurements for this line are quite uncertain because of a lack of a good continuum and not being able sometimes even to see the entire line profile. Our measurements of the C I lines near 1260 A are in some cases blended with Si II 1260.421 A. Since Si III and perhaps Si II can have high velocity wings (Cohn and York 1977), the continuum in this spectral region was not always completely flat. Finally, there were cases where we might expect multiple clouds in the line of sight. For the most part, our results are probably not severely affected by these systematic errors, but it should be recognized that they may be present in the measurements.

III. OSCILLATOR STRENGTHS

Since there is some uncertainty about the C I oscillator strengths we can use our data to refine the accepted values.

Following de Boer and Morton (1979), we adopt 0.038 as the f value for multiplet 9 near 1260 A, and we scale all our inferred f values from this result. To infer the f values of the other multiplets, we use lines that are not very saturated. However, if we use very weak lines the errors of measurement are so large that we are unable to obtain much useful information.

a) Multiplet 4 at 1329 A

In principle, observations of the lines of the excited fine structure levels could be used to infer the f value of this transition. However, since the lines from the excited fine-structure levels of the C I ground state are actually complex blends we cannot use this method with high precision, and we restrict our analysis to the absorption lines. In any case, the measurements of the excited fine-structure levels are consistent with the f values derived from the ground state transition.

Toward ζ Pup where the C I lines apparently lie on the linear portion of the curve of growth, Morton (1978) measured W (1328.833)/W(1260.736) = 2.47 ± 0.33 so that de Boer and Morton (1979) derived an f value for the line at 1329 Å of 0.082. This f value and the assumption that f(1260 Å) = 0.038 are not consistent with the observations of Morton and Bhavsar (1979) and Drake and Pottasch (1977) toward γ Vel and ζ Ori where it was found that W(1329.833)/W(1260.736) ≥ 5.0.

To refine our estimate for f(1328), we avoid lines of sight with significant amounts of saturation, and we only consider lines of sight with W(1328.833)/W(1260.736) $\gtrsim$ 2.0. Unfortunately we have only one such line of sight, the cloud toward δ Ori. In this direction we find that W(1328.833)/W(1260.736) = 2.3 in agreement with the oscillator strength of de Boer and Morton (1979). Since $W/\lambda<10^{-5}$ toward δ Ori, and since for this region of the curve of growth there is the Na I profiles of Hobbs (1969, 1974) which are unsaturated, we adopt f(1328) = 0.082 in agreement with de Boer and Morton (1979). This result is not far from the experimental value of 0.033 measured by Brooks, Rohrlich and Smith (1977). In this analysis, we do not consider the lines of sight toward ι Ori or ρ Leo because there are multiple components in the line of sight (Spitzer, Cochran and Hirshfield 1974) so that our upper limits for W_λ(1260.736 Å) are probably too low.

b) Multiplet 23 at 1138.383 A

From the f value of 0.004 given by de Boer and Morton (1979) we could expect that W(1138.383)/W(1260.736) = 0.09 in the absence of saturation. However as can be seen from the C I curve-of-growth of Morton (1975) from which this result is obtained, there is considerable uncertainty in this result. Here, in our survey, there are only a few clouds for which we have measurements of both W(1138.383) and W(1260.736). The set of upper limits that we have imply that in the absence of saturation W(1260.736/W(1138.383) $\gtrsim$ 10 in agreement with the f values of de Boer and Morton (1979). The line of sight from which we can best estimate the f value of this transition is toward 1 Sco where the lines are detected, yet the amount of saturation in C I 1260.736 is not too great. According to Hobbs (1978) the Na D_1 line with an equivalent width of 135 mA is saturated by about a factor of 4 in the sense that if the line lay on the linear portion of the curve of growth, the column density of Na I would be a factor of 4 smaller than inferred. A D_1 line with an equivalent width of 135 mA would have the same degree of saturation as the line of equivalent width 29 mA at 1260 Å. Since the observed equivalent width of the line at 1260 Å is 24 mA we may presume a "saturation factor" of about 3. Also, we may presume that the 1138 Å line with an equivalent width of 4.2 mA is unsaturated. Therefore, we derive an f value for 1138.383 of 0.003 with an uncertainty of at least 30%. This result is in essential agreement with the result of de Boer and Morton (1979).

c) Other Lines

For the other C I and CO lines we do not have very much data from our survey. We find that our observations are consistent with the oscillator strengths given in de Boer and Morton (1974, 1979) and Morton (1979). Therefore we adopt those values, and in table 3 we summarize our assured parameters.

IV. COLUMN DENSITIES

a) Results

We derive column densities from the measured equivalent widths of the weakest lines for which we have a positive measurement; in this fashion we hope to minimize the corrections for saturation. Specifically, we use the f values derived above and the relationship between equivalent width and column density for optically thin lines to derive the column densities. To perform this analysis, we must also make some correction for saturation. For many stars we can use the high spectral resolution ground-based observations by Hobbs of the sodium D lines or the K I line at 7699Å to estimate the amount of saturation in a given line of sight. That is, we define a "saturation factor" to equal the actual column density divided by the column density computed from the assumption that the equivalent width of the line lies on the linear portion of the curve of growth. Since we typically consider C I lines where W/λ is smaller than for the Na I or K I lines we can perform this extrapolation with some hope of success. We always assume a single cloud in the line of sight with a Gaussian velocity distribution of absorbers. Although this procedure is somewhat uncertain, it should not lead to any very substantial errors since we restrict our analysis to lines of sight with relatively small saturation corrections. In table 5 we list both the C I column densities and in parenthesis the correction factor for saturation that we derive; our saturation correction factors are usually less than a factor of 2.

Since the random errors are also relatively small, many of our column densities are accurate to 0.1 or 0.2 in the logarithm. One disadvantage with using ground-based observations to estimate the curve-of-growth effects is that we cannot reliably determine whether the C I and Na I curves-of-growth are different from each other. However we find agreement with the results of Jenkins and Shaya that N(C I) is not linearly proportional to N(Na I).

For some stars there are no available high resolution ground-based measurements. In these cases, if the equivalent widths are less than 10 mA, we assume that the line lies on the linear portion of the curve of growth. If all the detected lines are stronger than 10 mA, we use the doublet ratio similar to that described by Spitzer (1978).

For the CO column densities, in most of our lines of sight we have only detected the line at 1087.867Å. We almost always assume this line lies on the linear portion of the curve of growth.

b) Errors

There are three sources of error in our column densities: i) the f values; ii) the equivalent widths and iii) the corrections for saturation. The uncertainties in the f values and equivalent widths are discussed above. The corrections for saturation are somewhat more difficult to estimate quantitatively. The assumption that the C I, Na I and K I lines lie on the same curve of growth is plausible but not necessarily correct. According to Jenkins and Shaya (1979), C I may be more strongly concentrated in cloud centers than Na I. Therefore, all we can do is note that our data are reasonable and self-consistent; we cannot demonstrate that they are completely accurate. In any case, the errors in table 5 are formal; they reflect only the statistical uncertainties in the measurements of the equivalent widths.

c) Individual Clouds

κ Cas: From Hobbs (1978) the K I line at 7699 Å is saturated by a factor of 1.1 for $W/\lambda = 1.4 \times 10^{-5}$. To derive column densities, we use the C I line at 1157.186 Å ($W/\lambda = 2.3 \times 10^{-5}$), the C I* line at 1261.122 Å ($W/\lambda = 2.6 \times 10^{-5}$) and the C I** line at 1329.584 Å ($W/\lambda = 3.2 \times 10^{-5}$) with saturation corrections of 1.2, 1.25 and 1.4 respectively. The C I* and C I** columns densities are consistent with the upper limits obtained from the C I* line at 1276.750 Å and the C I** line at 1261.552. The C I column density derived from the 1157 Å line is greater than that derived from C I 1138 Å which, however, is more saturated. The CO equivalent width is taken from the 1087 Å line.

γ Cas: We derive N(C I), N(C I*), N(C I**) and N(CO) from 1260.736 Å and the upper limits to the equivalent widths of 1329.101, 1329.584 and 1087.867 Å respectively. We perform no corrections for saturation since $W/\lambda \leq 4.6\text{x}10^{-6}$ for all these lines while Hobbs (1978) found that the Na I D_1, line with $W/\lambda = 7.6\text{x}10^{-6}$ is saturated by only a factor of 1.1.

δ Per: No lines were detected toward this star. We use the limits for the C I multiplet at 1329 Å and CO at 1087 Å to place upper bounds on the column densities, and the assumption that the lines are optically thin.

40 Per: Hobbs (1978) found that the Na D_1 line with $W/\lambda = 4.0\times10^{-5}$ is saturated, and there are no useful high resolution ground-based observations toward this star. Using a doublet ratio analysis between C I 1328.833 ($W/\lambda = 3.5\times10^{-5}$) and 1260.736 ($W/\lambda = 4.4\times10^{-5}$) is clearly not possible. It only implies that the 1260.736 Å line is saturated by at least a factor of 3 to give N(C I) > 3×10^{14} cm^{-2}. The 2σ upper limit to 1138.383 Å ($W/\lambda = 7.2\times10^{-6}$) implies that in the absence of saturation that N(C I) < 2.4×10^{14} cm^{-2}. We adopt N(C I) = 3×10^{14} cm^{-2} but there is probably a factor oa 2 uncertainty in this result. For N(C I*) we use the doublet ratio-type analysis between 1261.122 Å ($W/\lambda = 2.4\times10^{-5}$) and 1329.101 Å ($W/\lambda = 4.8\times10^{-5}$) to estimate that a saturation correction of a factor of 1.4 is appropriate for the 1261 Å line. For N(C I**) the 1329.584 ($W/\lambda = 1.5\cdot10^{-5}$) line is used with an inferred saturation correction of 1.2. We place an upper limit to N(CO) from the strongest line of this species and the uncertain assumption that the line lies on the linear portion of the curve of growth. Although our upper limit for CO 1087.867 Å is wide, we presume it lies on the linear portion of the curve of growth since we do not detect the CO line at 1150 Å.

ε Per: According to Hobbs (1974) the Na I D_1 line ($W/\lambda = 1.6\times10^{-5}$) indicates a saturation correction of 2.3. However, a direct integration of the D_1 profile displayed in Hobbs (1969) indicates a saturation correction of only 1.7 is necessary. This discrepancy might result because Hobbs may have considered the D_2 profile in his estimate of N(Na I). In any case, a saturation correction factor of between 1.3 and 1.5 is indicated for the C I line at 1260.736 Å ($W/\lambda = 1.1\times10^{-5}$). We adopt a correction of a factor of 1.4. For N(C I*) we may use the line at 1329.101 with $W/\lambda = 4\times10^{-6}$ without any correction for saturation. For N(C I**) and N(CO) we use the upper limits from the strongest lines with the assumption that they lie on the linear portion of the curve of growth.

ζ Per: The lines at 1157.186, 1276.750 and 1261.426 Å of C I, C I* and C I** have W/λ equal to 5.6×10^{-6}, 5.7×10^{-6} and 4.7×10^{-6} respectively. According to Hobbs (1974) the K I line at 7699 Å is saturated by a factor of 1.2 for $W/\lambda = 8.4\times10^{-6}$, and we therefore assume the very weak carbon lines lie on the linear portion of the curve of growth. Although CO 1087.867 Å is wide, we presume it lies on the linear portion of the curve of growth since we do not detect the CO line at 1150 Å.

α Cam: Since there are no useful ground-based observations toward this star, a doublet ratio analysis is used between the C I line at 1138.383 Å ($W/\lambda = 2.4\times10^{-5}$) and that at 1157.186 Å ($W/\lambda = 1.3\times10^{-5}$) to infer a saturation correction of about 1.5 for the 1157 line. For C I*, the line at 1329.101 Å ($W/\lambda = 3.9\times10^{-5}$) with a saturation correction of 1.7 is used to derive the column density. The 1329.584 line ($W/\lambda = 1.0\times10^{-5}$) is used with an inferred saturation correction of 1.1 to find the column density of C I**. Since the line at 1087.867 Å is too saturated to be of use, the line at 1150.48 Å ($W/\lambda = 1.0\times10^{-5}$) is used to obtain the CO column density.

δ Ori: We use the line at 1260.736 Å to infer N(C I). Since $W/\lambda = 3.8\times10^{-6}$ there is no need for a saturation correction (Hobbs 1974). For the other species we used the highest f value lines to set upper limits to the column densities.

λ Ori: According to Hobbs (1974) the K I line at 7699 Å with $W/\lambda = 6\times10^{-6}$ is saturated by a factor of 1.2. From Hobbs' (1978) measurement of the ultraviolet lines of sodium, the Na I D_2 line with $W/\lambda = 6\times10^{-5}$ is saturated by a factor of 4.7. Therefore, it seems that the 1260.736 line of C I ($W/\lambda = 3.0\times10^{-5}$) is saturated by perhaps a factor of 2 to give $N(\text{C I}) = 1.4\times10^{14}$ cm^{-2}. The upper limit to the 1138.383 Å line implies that $N(\text{C I}) < 1.2\times10^{14}$ cm^{-2} in agreement with this result. For C I* and C I** the lines at 1261.122 Å and 1329.584 Å have $W/\lambda = 6\times10^{-6}$ and 7×10^{-6} respectively so we correct for saturation by a factor of 1.2. Our result estimated for C I* is consistent with the observed strength of C I* 1329 Å if this line is not saturated by more than about a factor of 2. We place an upper limit to N(CO) from the absence of the line at 1087 Å.

ι Ori: For those C I* and C I** and CO we adopt upper limits from the lines with the largest f values. For C I we use the unsaturated line at 1328.833 Å.

ε Ori: According to Hobbs (1974) the Na I D_1 line with $W/\lambda = 2.5\times10^{-5}$ is saturated by a factor of 1.5. We presume that the C I line at 1328.833 Å with $W/\lambda = 2.3\times10^{-5}$ is saturated by an equal factor and this is consistent with our equivalent width for the line at 1260.736 Å. We assume the C I* line at 1329.101 Å is saturated by a factor of 1.1 while for C I** and CO we presume no saturation in setting their upper limits.

κ Ori: Hobbs (1974) found that the Na I D_1 line with $W/\lambda = 2.2\text{x}10^{-5}$ is saturated by a factor of 2.2. As a result we presume that the C I line at 1260 Å with $W/\lambda = 9.8\text{x}10^{-6}$ is saturated by a factor of 1.3. Similarly, we presume the C I* line at 1329.101 Å with $W/\lambda = 7.6\text{x}10^{-6}$ is saturated by a factor of 1.2. We set upper limits to C I** and CO from the upper limits to the lines of the highest f values and the assumption of no saturation.

139 Tau: From Hobbs (1978) the Na D_1 line ($W/\lambda = 4.7\cdot 10^{-5}$) is saturated by a factor of 2.9, so the C I line at 1260.736 with $W/\lambda = 3.4\text{x}10^{-5}$ may have a saturation correction of 1.7. The 1329.101 Å line ($W/\lambda = 1.0\text{x}10^{-5}$) is used with a saturation correction of 1.1 to obtain a column density for C I* consistent with the upper limit obtained from the 1261.122 line. The 1329.584 and 1087.867 lines are used to derive the C I** and CO column densities.

HD 74375: Since there are no useful ground-based observations toward this star, a doublet ratio analysis is used between the C I line at 1328 ($W/\lambda = 3.5\text{x}10^{-5}$) and that at 1260 ($W/\lambda = 1.3\text{x}10^{-5}$). Due to the large error in W(1260) we can only infer that the line is saturated by less than 3.5. We use this to obtain an upper limit for N(C I) and derive a lower limit by assuming the 1328 line is unsaturated. The column density of C I* is obtained by considering the line at 1329 and a saturation correction less than 2. Our values for C I** and CO are derived from the upper limits of the 1329 and 1087 lines, respectively.

ρ Leo: From Hobbs (1974) the Na D_1 line is found to be saturated by 1.2 ($W/\lambda = 1.7\times10^{-5}$). It is therefore inferred that the C I line at 1328.833 Å ($W/\lambda = 1.7\times10^{-5}$) is also saturated by this amount. Upper limits for C I**, C I** and CO are obtained from the lines at 1329.101, 1329.584, and 1087.867 respectively.

1 Sco: For the Na I D_2 line with $W/\lambda = 3.8\times10^{-5}$, the saturation correction is a factor of 2.3 (Hobbs 1974). Consequently for the C I line at 1260.736 Å ($W/\lambda = 1.8\times10^{-5}$) we adopt a saturation correction factor of 1.3. For C I* 1329.101 ($W/\lambda = 2.9\times10^{-4}$) we estimate a saturation correction by a factor of 1.7 to give N(C I*) = 5×10^{13} cm^{-2}. However, this disagrees with the 2σ upper limit derived from the C I* lines at 1261.122 Å of 1.8×10^{13} cm^{-2}. We presume that N(C I*) = 4×10^{13} cm^{-2} with an uncertainty of at least 0.2 in the logarithm. For C I** and CO we use the upper limits given by the lines with the highest f values and the assumption that they lie on the linear portion of the curve of growth.

β^1 Sco: The lines of 1138.383, 1261.122 and 1329.584 Å of C I, C I* and C I** have $W/\lambda = 3.7\times10^{-6}$, 5.0×10^{-6}, and 7×10^{-6} respectively. According to Hobbs (1978) the K I line at 7699 Å with $W/\lambda = 3.5\times10^{-6}$

is saturated by a factor of 1.1. Consequently we adopt corrections for saturation of factors 1.1, 1.2, and 1.2 for C I, C I* and C I** respectively. We obtain the column density of CO from the 1087 Å line and the assumption of no saturation.

ω^1 Sco: From Hobbs (1978) we know that the Na D_2 line ($W/\lambda = 4.1\text{x}10^{-5}$) is saturated by about 2.1. Therefore we infer saturation corrections of 1.4 for the C I line at 1260 ($W/\lambda = 2.6\text{x}10^{-5}$) and one of 1.7 for the C I* line at 1329 ($W/\lambda = 3.50\ \text{x}10^{-5}$), and use these lines to derive the column densities for C I and C I*. Upper limits for the column densities of C I** and CO are obtained from the upper limits of the equivalent widths for the lines at 1329 and 1087 respectively.

ν Sco: From Hobbs (1978) the Na I D_2 line and K I 7699 Å line with $W/\lambda = 4.2\text{x}10^{-5}$ and $4.9\text{x}10^{-6}$ are saturated by factors of 7.3 and 1.2 respectively. For C I these results imply a saturation correction for 1260.736 Å ($W/\lambda = 1.7\text{x}10^{-5}$) of about a factor of 2 to give N(C I) = $8.0\text{x}10^{13}$ cm^{-2}. This result is consistent with the 2σ upper limit from the 1138.383 Å line of $2.0\text{x}10^{14}$ cm^{-2}. The C I* line at 1329.101 Å ($W/\lambda = 1.2\text{x}10^{-5}$) might be saturated by a factor of 1.5. We adopt N(C I*) = $1.0\text{x}10^{14}$ cm^{-2} with an uncertainty of at least a factor of 1.5. For N(CO) we use the lines of the largest f value to estimate 2σ upper limits. For C I** we use the line at 1329.584 ($W/\lambda = 1.5\text{x}10^{-5}$) to estimate a correction of 1.8 and derive N(C I**) = $2.7\text{x}10^{13}$ cm^{-2}.

ρ Oph: According to Hobbs (1978), the K I line with $W/\lambda = 1.8\text{x}10^{-5}$ is too saturated to be useful. Unfortunately, the weakest lines that we can detect with confidence toward this star have $W/\lambda = 1.6\text{x}10^{-5}$.

As a result we can only place lower limits on the column densities toward this star. We do not attempt any limits on the C I** and CO column densities.

χ Oph: Crutcher (1975) found from the 3302 Å sodium lines that $W/\lambda = 7.3 \times 10^{-6}$ corresponds to saturation by a factor of 2.1. Therefore, the best candidate for determining N(C I) is the line at 1157.186 Å although the equivalent width is rather uncertain. With $W/\lambda = 9.5 \times 10^{-6}$ we adopt a correction for saturation of a factor of 2.5. For C I* we place an upper limit to the column density from the 2σ upper limit to the line at 1276.750 Å ($W/\lambda < 6.3 \times 10^{-6}$) with a saturation correction of a factor of 2, to give N(C I*) < 7×10^{14} cm^{-2}. A lower limit can be derived from 1260.996 Å ($W/\lambda = 1.8 \times 10^{-5}$) if we assume a saturation correction by a factor of 3 to give N(C I*) > 5×10^{14} cm^{-3}. Therefore, we adopt N(C I*) = 6×10^{14} cm^{-2} with an uncertainty of at least a factor of 1.5. We may take N(C I**) > 1.0×10^{14} cm^{-2} from the measurement of 1329.584 Å ($W/\lambda = 3 \times 10^{-5}$) and a saturation correction by a factor of 3. The 2σ upper limit to N(C I**) from 1261.426 ($W/\lambda < 5.4 \times 10^{-6}$) is 5.0×10^{13} cm^{-2}. We adopt N(C I**) = 10^{14} cm^{-2} with an uncertainty of a factor of 2. For N(CO) we adopt an upper limit from the line at 1087 Å with the assumption of as much as a factor of 3 saturation.

22 Sco: The strengths of the C I 1326.833 Å and 1260.736 Å lines indicate that the saturation is quite substantial even for $W/\lambda = 1.5 \cdot 10^{-5}$. Since our noise is so large that we are unable to detect lines much weaker than this and since there are no high quality

ground-based observations, we do not attempt to infer column densities.

μ Nor: There are no useful ground-based observations toward this star. The weakest C I line of 1157 Å might be saturated; we estimate that N(C I) $\geq 2.5 \cdot 10^{15}$ cm^{-2}. The C I* line at 1275.750 implies a lower bound to N(C I*) of $6.5 \cdot 10^{14}$ cm^{-2}. N(C I**) is obtained by assuming the line at 1261.552 with $W/\lambda = 8.6 \times 10^{-6}$ is unsaturated. The CO 1087 line is also assumed unsaturated since the 1150 line is undetected.

γ Ara: There are no high resolution ground-based observations toward this star. To determine N(C I) we use the doublet ratio method for 1328.833 ($W/\lambda = 2.9 \times 10^{-5}$) compared to 1260.736 ($W/\lambda = 2.1 \times 10^{-5}$) to estimate that C I 1260 is saturated by a factor of 1.7. Similarly we estimate the C I* line at 1329.101 with $W/\lambda = 9 \times 10^{-6}$ to be saturated by a factor of 1.1. We may take the 2σ upper limit of C I** 1329.584 ($W/\lambda \leq 4 \times 10^{-6}$) and the detected line of CO 1087 ($W/\lambda = 5 \times 10^{-6}$) to be unsaturated.

Θ Ara: Again, there are no useful ground-based observations toward this star. For C I, we use a doublet ratio analysis between C I 1138.383 ($W/\lambda = 6.3 \times 10^{-6}$) and C I 1260.736 ($W/\lambda = 2.5 \times 10^{-5}$) to infer a saturation correction of 1.1 for the line at 1138.383. A doublet analysis for C I* is useless because of the large error in the 1261.122 Å line. Nevertheless, we use this line with $W/\lambda = 6.6 \times 10^{-6}$ to obtain the C I* column density with a saturation correction of 1.1. This result is consistent with the strength of the 1260.996 Å line if a moderate amount of saturation is assumed. Upper limits to column densities of C I** and CO are obtained from the lines at 1329.584 and 1087.867 respectively.

κ Aql: Again there are no high resolution ground-based observations toward this star. To derive N(C I) we perform a doublet ratio analysis between 1260.736 ($W/\lambda = 3.2c10^{-5}$) and 1328.833 ($W/\lambda = 3.9\times10^{-5}$) to estimate that the amount of saturation at 1260.736 is about a factor of 2 so that N(C I) = 1.5×10^{14} cm^{-2}. This column density is consistent with the 2σ upper limit of 2.0×10^{14} cm^{-2} derived from the 1138.383 line. For N(C I*) we use the line at 1329.101 ($W/\lambda = 2.0\times10^{-5}$) with a saturation correction factor of 1.5. The other lines of C I* are too weak to be of use. Finally, we assume that the upper limits for CO 1087 and C I** 1329 lie on the linear portion of the curve of growth.

59 Cyg: The absence of the C I 1138 line indicates a 2σ upper limit to N(C I) of 7.6×10^{13} cm^{-2}. According to Hobbs (1974), the Na I D_2 line with $W/\lambda = 3.1\times10^{-5}$ is saturated by a factor of 2.2. Since C I 1260.736 has $W/\lambda = 2.2\times10^{-5}$ we infer that this line is saturated by a factor of 1.6. We find that N(C I) = 8.4×10^{13} cm^{-2} in essential agreement with the value derived from C I 1138 and we adopt this result. For C I* 1329.101 with $W/\lambda = 1.4\times10^{-5}$ we presume a correction for saturation of a factor of 1.2 to give N(C I*) = 1.7×10^{13} cm^{-2}. The 2σ upper limit to C I* 1261.122 gives 1.4×10^{13} cm^{-2} in essential agreement with the result from C I* 1329 which we adopt. We assume that CO 1087 ($W/\lambda = 5.3\times10^{-6}$) lies on the linear portion of the curve of growth as does the 2σ upper limit to C I** 1329.584.

σ Cas: Toward this star Hobbs (1978) found that the Na I D_1 line density is consistent with the 2σ upper limit of 2.0×10^{14} cm^{-2} derived from the 1138.383 line. For N(C I*) we use the line at 1329.101 ($W/\lambda = 2.0\times10^{-5}$) with a saturation correction factor of 1.5. The other lines of C I* are too weak to be of use. Finally, we assume that the upper limits for CO 1087 and C I** 1329 lie on the line portion of the curve of growth.

59 Cyg: The absence of the C I 1138 line indicates a 2σ upper limit to N(C I) of 7.6×10^{13} cm^{-2}. According to Hobbs (1974), the Na I D_2 line with $W/\lambda = 3.1\times10^{-5}$ is saturated by a factor of 2.2. Since C I 1260.736 has $W/\lambda = 2.2\times10^{-5}$ we infer that this line is saturated by a factor of 1.6. We find that N(C I) = 8.3×10^{13} cm^{-2} in essential agreement with the value derived from C I 1138 and we adopt this result. For C I* 1329.101 with $W/\lambda = 1.3\times10^{-5}$ we presume a correction for saturation of a factor of 1.2 to give N(C I*) = 1.6×10^{13} cm^{-2}. The 2σ upper limit to C I* 1261.122 gives 1.4×10^{13} cm^{-2} in essential agreement with the result from C I* 1329 which we adopt. We assume that CO 1087 ($W/\lambda = 5.3\ 10^{-6}$) lies on the linear portion of the curve of growth as does the 2σ upper limit to C I** 1329.584.

σ Cas: Toward his star. Hobbs (1978) found that the Na I D_1 line is saturated with $W/\lambda = 6.4\ 10^{-5}$. Therefore C I 1260 ($W/\lambda = 5.7\times10^{-5}$) is almost certainly saturated by at least a factor of 3 and we find that N(C I) > 4.0×10^{14} cm^{-2}. The 2σ upper limit to C I 1138.383 ($W/\lambda = 6\times10^{-6}$) implies that if this line lies on the linear portion of the curve of growth that N(C I) < 2.5×10^{14} cm^{-2}. We adopt N(C I) = 3×10^{14} cm^{-2} with an uncertainty of at least a factor of 2.

is saturated with $W/\lambda = 6.4\times10^{-5}$. Therefore C I 1260 ($W/\lambda = 5.7\times10^{-5}$) is almost certainly saturated by at least a factor of 3 and we find that $N(\mathrm{C\ I}) > 4.0\times10^{14}$ cm^{-2}. The 2σ upper limit to C I 1138.383 ($W/\lambda = 6\times10^{-6}$) implies that if this line lies on the linear portion of the curve of growth that $N(\mathrm{C\ I}) < 2.5\times10^{14}$ cm^{-2}. We adopt $N(\mathrm{C\ I}) = 3\times10^{14}$ cm^{-2} with an uncertainty of at least a factor of 2. For N(C I*) we use the 2σ upper limit of 1276.750 ($W/\lambda = 6.6\times10^{-6}$) to find that $N(\mathrm{C\ I^*}) < 3.6\times10^{14}$ cm^{-2} and the lower bound from C I* 1261.122 ($W/\lambda = 1.7\times10^{-5}$) of 9.8×10^{13} cm^{-2} to estimate that $N(\mathrm{C\ I^*}) = 5\times10^{14}$ cm^{-2} within a factor of 2. For N(CO) and N(C I**) we assume that 1087 and 1329.584 lie on the linear portion of the curve of growth although this is somewhat uncertain.

V. DENSITIES AND PRESSURES

To derive the densities and pressures within clouds, we essentially follow the procedures described by Jenkins and Shaya (1979) except that we use the cross sections computed by Yau and Dalgarno (1976). We assume the populations of the fine structure levels are generally controlled by collisions and we assume that there is only one major cloud in each line of sight. Unfortunately, cross sections for collisional excitation of the C I find structure levels by H_2 are unavailable and, as a result, our densities and pressures are uncertain, especially for clouds with high ratios of $n(H_2)/n(H)$. Also, in a few clouds near early type stars, optical pumping of the C I levels could conceivably be important, but, in general, as did Jenkins and Shaya (1979), we ignore this complication. The assumption that there is only one cloud in each line of sight is not accurate. Jenkins and Shaya (1979) have discussed the importance of H II region contributions to the population of the excited fine structure levels of C I, and it is clear from the data of Hobbs that the assumption of a single cloud is a gross simplification. However, with the resolution of *Copernicus* and the signal to noise in our survey, we have little choice but to make this assumption.

Our further complication is that often we have no opportunity to estimate independently the temperature of the clouds since we often do not measure N(C I**). In this case, we have only one ratio, N(C I*)/N(C I**), to infer two parameters, the density and the temperature. For these clouds, we assume the temperature derived from the relative column densities of H_2 in $J = 1$ and $J = 0$ (Savage et al. 1977); or, if these data are not available, we take $T = 80$ K as representative of diffuse clouds.

We find no cases where the C I data cannot be fit by a single cloud model. This is in contrast to the work by Jenkins and Shaya perhaps because we have higher quality data. Our results for the inferred densities and pressures are listed in Table 6. In agreement with previous work, specifically that of Jenkins and Shaya, we find that the pressures in most clouds have values of p/k that range between 10^3 cm^{-3} K and 10^4 cm^{-3}K. However, there also are clouds with pressures well in excess of 10^4 cm^{-3} K with values up to 10^5 cm^{-3} K. It seems quite clear that the thermal pressure within the interstellar medium is distinctly nonuniform. The dynamic evolution created by this pressure imballance must play a critical role in the evolution of the interstellar medium.

VI. MOLECULAR HYDROGEN FORMATION RATE

We can use our observations to infer the rate, R, for the formation of H_2 on grains. That is, because the formation is density dependent, we can use our estimates of the cloud densities to estimate R we assume a steady state and we adopt the simple analysis described by Jura (1975b). From equations (3a) and (3b) of that paper and from the Einstein A's of Dalgarno and Wright (1972), we can write for the formation rate of H_2 that

$$R = 2.34 \times 10^{-9}\ N(4)/[N(H)n] = 9.12 \times 10^{-9}\ N(5)/[N(H)n]$$

In the above equations, N(J) denotes of the column density of H_2 in the J'th rotational level, N(H) denotes the column density of atomic hydrogen and n the cloud density. We use the column densities of rotationally excited H_2 and H from Spitzer, Cochran and Hirshfeld (1974) and Bohlin et al. (1978), respectively. We list our results in Table 7 for R derived both the population in J = 4 and in J = 5. Since the results for the two rotational levels usually agree with each other, this adds confidence to our analysis. Also, we see that the inferred values of R are all within a factor of 3 of the value of $3\ 10^{-17}\ cm^3\ s^{-1}$ derived by Jura (1975a). Of course because of observational errors, because of the approximation used to derive R and because the gas may not be in a steady state, the range of derived values of R does not necessarily imply that R is variable in different clouds. However, our results do imply that the efficiency for the formation of H_2 on grains is nearly unity (e.g. Spitzer 1978). More precisely, at least half the atoms that strike grains become part of an H_2 molecule. This result is quite significant because it is an important constraint on the nature of the surface interaction between grains and H atoms (e.g., Smoluchowski 1979).

VII. CO ABUNDANCES

A large amount of theoretical work has gone into calculating the amount of CO in diffuse interstellar clouds (e.g., Glassgold and Langer 1975, Langer 1976, Oppenheimer and Dalgarno 1976, Mitchell, Ginsburg and Kunze 1978, Barsuhn and Walmsley 1977, Viala, Bel and Clavel 1979). Also, there have been a number of observational studies of CO column densities (Whittet, McNally and Dickman 1979, Knapp and Jura 1976, Snow 1975, 1977, Jenkins and Shaya 1979, Jenkins et al. 1973, Dickman 1978, Smith, Krishna-Swammy and Stecher 1978). However, because of the wide range of density, temperature, gas phase abundances, and the intensity of the ultraviolet radiation, there have not been many detailed comparisons between theory and observation. Black and Dalgarno (1977) and Black, Hartquist and Dalgarno (1978) find good agreement between theory and observations for the lines of sight toward ρ Oph and ζ Per, respectively. Barsuhn and Walmsley (1977) find good agreement between theory and observation for their model for the line of sight toward ζ Oph, but they predict too much CO for the lines of sight toward α Cam, ϵ Per, ζ Per and 139 Tau by roughly an order of magnitude.

Here, rather than analyze each line of sight separately, we compare N(CO) with N(C I). Since C I and CO are both primarily removed by the absorption of ultraviolet photons with wavelengths between 1100 Å and 912 Å, the mean intensity of ultraviolet radiation should not enter into this ratio very significantly. Also, a comparison of C I and CO should be relatively insensitive to the gas phase abundance of carbon. Furthermore, we expect that n(C I) scales as the density squared and while the density dependence of N(CO) is more complicated, it should not be too drastically different from a density squared law. Therefore, the comparison of N(C I) to N(CO) should not be sensitive to variations in the local physical conditions. One difficulty with this comparison is that n(CO) is sensitive to the amount of H_2; that is, in the usual models for gas-phase synthesis of CO there must be a significant amount of H_2 present. However, we expect most C I to be found in the center of clouds which implies that N(C I) is dominated by the inner region of the cloud where CO is found. In addition, we restrict our sample to clouds with $N(H_2) > 10^{19}$ cm^{-2} as given by Savage et al. (1978). With these considerations, we expect that N(C I)/N(CO) is a reasonably good probe of interstellar chemistry.

In Figure 1 we show our results for N(C I) vs. N(CO) for the different clouds that we observed and we include the data from other Copernicus observations as well. Very crudely, we can summarize our results that for N(C I) < 10^{15} cm^{-2}, N(CO) ≃ 1/30 N(C I) while for larger values of N(C I), we find that N(CO) ≃ 1/3 N(C I). In all the observed clouds, we find that N(CO) < N(C I). These results are in agreement with the calculations for the high column density clouds where N(CO) ≃ 1/3 N(C I) is often predicted (e.g. Black and Dalgarno 1977. Black et al. 1978, de Jong, Dalgarno and Boland 1979, Langer 1976). However, it appears that further theoretical work should be devoted to the regions with N(C I) < 10^{15} cm^{-2} where we do not find good agreement between theory and observations. One possible explanation of this discrepancy is that the photo-dissociation rate of CO has been underestimated while the penetration of CO dissociating radiation has been overestimated.

DISCUSSION

The results described here can be used to refine significantly our knowledge of the physical conditions and physical processes within diffuse interstellar clouds. Specifically, we find that the pressure is not uniform and that p/k ranges between 10^3 cm^{-3} K and 10^5 cm^{-3} K. This result is consistent with the dynamical models of McKee and Ostriker (1977) and Bania and Lyon (1980) of a multi-phase interstellar medium. That is, as argued by McCray and Snow (1980), it appears that the interstellar medium undergoes continuous, pronounced, dynamic evolution.

Another consequence of our results is that it appears that a significant fraction, not much less than unity, of all the hydrogen atoms in diffuse clouds that strike grains surfaces react to form molecular hydrogen. This result is in general agreement with the prediction of Hollenbach and Salpeter (1970), although the efficiency for molecule formation may be even somewhat higher than they computed. Of course it is not obvious that our results obtain in all sorts of clouds where conditions can be quite different than in the regions we have studied.

The pressures and densities that we estimate also serve as important constraints for models for the thermal balance within diffuse clouds. In particular, as reviewed by Jura (1978), a density of 50 cm^{-3} and a temperature of 80 K require a heating rate of nearly 10^{-25} ergs H $nuclei^{-1}$ s^{-1}. Further work on the thermal properties of clouds should incorporate this argument.

Finally, our results place severe constraints on models for interstellar chemistry. In particular, as discussed above, at least in some cases there is less CO than predicted by some current models.

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TABLE 1 - Observed Lines

	Line	f Value	Source
CI	1328.833	0.082	(1)
CI	1260.736	0.038	(1)
CI	1138.383	0.003	(2)
CI	1157.186	0.0005	(2)
CI*	1329.101	0.082	(1)
CI*	1260.996	0.0095	(1), (3)
CI*	1260.927	0.013	(1), (3)
CI*	1261.122	0.016	(1), (3)
CI*	1276.750	0.0016	(3)
CI**	1329.584	0.082	(1)
CI**	1261.552	0.028	(1), (3)
CI**	1261.426	0.0095	
CI**	1277.954	0.0016	(3)
CO	1087.867	0.163	(3)
CO	1150.48	0.015	(3)
CO	1281.866	0.0005	(3)

(1) de Boer and Morton (1979)

(2) This paper

(3) Morton (1975)

TABLE 2 - Observed Star List

HD Number	Name	Sp. Type	m_V	E(B-V)	v sin i (km/sec)
2905	κ Cas	B1 Ia	4.17	0.35	62
5394	γ Cas	B0.5 IV	2.58	0.08	300
22928	δ Per	B5 III	2.99	0.04	271
22951	40 Per	B1 IV	4.96	0.24	73
24760	ε Per	B0.5 III	2.90	0.10	150
24912	ξ Per	O8 III	4.03	0.32	216
30614	α Cam	O9.5 Ia	4.29	0.32	95
36486	δ Ori A	O9.5 II-III	2.23	0.07	148
36861	λ Ori A	O8	3.55	0.12	75
37043	ι Ori	O9 III	2.77	0.07	122
37128	ε Ori	B0 Ia	1.70	0.08	85
38771	κ Ori	B0.5 Ia	2.09	0.07	81
40111	139 Tau	B1 Ib	4.83	0.15	131
47839	15 Mon	O7	4.65	0.07	106
74375	...	B1.5 III	4.32	0.10	72
91316	ρ Leo	B1 Iab	3.85	0.08	69

TABLE 2 - Continued

HD Number	Name	Sp. Type	m_V	E(B-V)	v sin i
141637	1 Sco	B1.5 Vn	4.63	0.20	311
144217A	β^1 Sco	B0.5V	2.63	0.20	107
144470	ω^1 Sco	B1 V	3.94:	0.22	141
145502	ν Sco	B2 IVp	4.01	0.27	202
147933	ρ Oph A	B2 IV	4.61	0.47	303
148184	χ Oph	B1.5 Ve	4.43	0.53	123
148605	22 Sco	B2 V	4.78	0.10	241
149038	μ Nor	B0 Ia	4.89	0.36	133
157246	γ Ara	B1 Ib	3.33	0.08	353
165024	Θ Ara	B2 Ib	3.66	0.10	139
184915	χ Aql	B0.5 IIIn	4.96	0.26	276
200120	59 Cyg	B1.5 Ve	4.79	0.18	450
224572	σ Cas	BI V	4.89	0.17	189

TABLE 3a - C I EQUIVALENT WIDTHS. ALL VALUES IN mA

STAR	W_λ (1328.833)	W_λ (1260.736)	W_λ (1138.383)	W_λ (1157.186)
κ Cas	127±19(121)	90±12(91)	44±9.0(90)	26±7.6(109)
γ Cas	9.6±1.8(60)	5.9±1.0(57.5)	≤ 7.8	≤ 8.8
δ Per	≤ 5.0	≤ 4.8	≤ 2.8	≤ 2.6
40 Per	47±9(57.5)	55±11(75)	≤ 8.2	≤ 7.6
ε Per	29±3(55)	14±1.3(52.5)	≤ 1.0	≤ 1.0
ξ Per	63±5.4(70)	51±3.6(65)	20.0±4.0(60)	6.5±2.8(55)
α Cam	102±13(139)	95±10(130)	27±5(69)	16±4.6(68)
δ Ori A	11±1.9	4.8±.0.9(70)	≤ 8	≤ 8
λ Ori A	51±5.2(70)	38±5.2(65)	≤ 4.2	≤ 3.8
ι Ori	9.1±2.0(130)	≤ 1.1	≤ 0.76	≤ 0.78
ε Ori	30±3.2(105)	14±1.7(110)	≤ 2.0	≤ 1.5
κ Ori	25±2.6(55)	12±1.1(50)	≤ 1.0	≤ 1.0
139 Tau	65±13(93)	42±10(110)	≤ 3.2	≤ 3.2
HD 74375	46±10.2(85)	17±8.7(55)	≤ 9.10	≤ 7.9
ρ Leo	23±8(92)	≤ 6.0	16±3.0(93)	≤ 1.6
1 Sco	34±8.8(75)	22±4.8(85)	≤ 2.8	2.7±3.0
β^1 Sco	35±3.6(60)	24±2.2(55)	4.2±2.2(45)	≤ 1.8
ω^1 Sco	62±12.3(65)	33±7.1(70)	≤ 7.4	≤ 6.6
ν Sco	48±13(67.5)	22±7.4(55)	≤ 6.8	≤ 6.4
ρ Oph A	42±11(62.5)	24±11(50)	≤ 13	≤ 11
χ Oph	55±9.8(95)	43±8.4(67.5)	19±8.4(55)	11±7.6(50)

TABLE 3a - C I EQUIVALENT WIDTHS. ALL VALUES IN mA (Continued)

STAR	W_λ (1328.833)	W_λ (1260.736)	W_λ (1138.383)	W_λ (1157.186)
22 Sco	15±8.6(57.5)	21±8.4(95)	≤ 9.4	≤ 8.4
μ Nor	102±13(92.5)	66±5.8(75)	25±6.8(90)	15±6.2(80)
Υ Ara	38±3.8(75)	26±2.8(62.5)	≤ 1.7	≤ 1.7
Θ Ara	44±9(58)	31±6.4(55)	7.2±2.2(42)	≤ 1.6
κ Aql	52±9.6(80)	40±8.0(75)	≤ 7.0	≤ 6.2
59 Cyg	42±7.6(100)	28±4.6(108)	≤ 2.6	3.3±2.8(55)
σ Cas	78±13(100)	72±11(110)	≤ 8.6	≤ 7.8

TABLE 3b - C I* EQUIVALENT WIDTHS. ALL VALUES IN A

STAR	W_λ (1329.101)	W_λ (1260.996)	W_λ (1260.927)	W_λ (1261.122)	W_λ (1276.750)
κ Cas	86±19(83)	43±12(133)[1]		33±2(125)	≤ 15
γ Cas	≤ 1.7	≤ 0.92	≤ 2.0	≤ 1.0	≤ 1.2
δ Per	≤ 5.6	≤ 4.4	≤ 4.0	≤ 4.0	≤ 3.4
40 Per	63±12(60)	12±8(45)[1]	23±8.8(62.5)[1]	30±7.8(57.5)	< 7.2
ε Per	5.4±1.7(55)	≤ 1.2	≤ 1.3	≤ 1.2	≤ 1.6
ξ Per	63±5.6(85)	27±3.4(80)[1]	19±3.0[1](60)	25±3.8(60)	7.3±3.6(40)
α Cam	48±12(99)	≤ 10	≤ 10	≤ 11	
δ Ori A	≤ 1.5	≤ 0.94	≤ 0.86	≤ 0.76	≤ 1.0
λ Ori A	56±6.0(80)	6.3±4.2	≤ 4.2	7.6±4.1	
ι Ori	≤ 1.5	≤ 0.96	≤ 1.1	≤ 0.98	≤ 1.2
ε Ori	9.3±2.2(87.5)	≤ 1.4	≤ 1.4	≤ 1.4	≤ 1.7
κ Ori	10±2.2(47.5)	≤ 1.0	≤ 1.1	≤ 1.0	≤ 1.2
139 Tau	13±10(68)	≤ 10	≤ 10	≤ 10	≤ 11
HD 74375	14±6.2	≤ 7.5	≤ 8.2	≤ 7.18	≤ 8.46
ρ Leo	≤ 7.2	≤ 5.6	≤ 5.6	≤ 5.6	≤ 6.4
1 Sco	38±6.6(100)	≤ 4.4	≤ 4.4	≤ 4.0	≤ 4.4
β^1 Sco	34±3.8(70)	5.0±1.8(38)	6.0±1.8(45)	6.3±1.8(50)	≤ 2.0
ω^1 Sco	47±10.3(95)	≤ 5.7	≤ 5.8	≤ 5.7	≤ 6.4
ν Sco	48±13(72.5)	≤ 7.0	≤ 6.8	15.0±6.6(60)	≤ 8.2
ρ Oph A	67±14(65)	21±9.0(50)[1]	27±9.2[1](55)	42±11(80)	44±10(60)
χ Oph	67±14(73)	23±8.4(60)	24±6.4(75)	32±9(63)	58.0

TABLE 3b - C I* EQUIVALENT WIDTHS. ALL VALUES IN mA (Continued)

STAR	W_λ (1329.101)	W_λ (1260.996)	W_λ (1260.927)	W_λ (1261.122)	W_λ (1276.750)
22 Sco	29±19(75)	≤ 7.6	≤ 8.6	≤ 7.4	≤ 7.8
μ Nor	76±11(92.5)	19±6.0(60)	22±4.8(75)	30±6.6(85)	13±6.2(52.5)
γ Ara	12±3.6(80)	≤ 2.2	≤ 1.9	≤ 2.2	≤ 2.2
Θ Ara	39±8.4(58)	13±6.8(105)[1]		8.2±5.6(50)	≤ 6.4
κ Aql	26±9.6(65)	≤ 7.0	10.3±6.8(35)	≤ 6.4	≤ 6.2
59 Cyg	18±6.4(95)	≤ 3.6	≤ 3.6	≤ 3.2	≤ 3.8
σ Cas	56±10(90)	24±7.4(95)[1]	13±8.2[1](45)	22±7.2(70)	≤ 8.4

1 footnote: In most cases the lines at 1260.927 and 1260.996 are unresolved. In these cases either an attempt was made to determine separate equivalent width, or the combined equivalent width is given.

TABLE 3c - C I** EQUIVALENT WIDTHS. ALL VALUES IN mA

STAR	W_λ (1329.584)	W_λ (1261.552)	W_λ (1261.426)	W_λ (1277.954)
κ Cas	42±18(108)	≤ 12	≤ 12	≤ 15
γ Cas	≤ 1.6	≤ 1.0	≤ 1.0	≤ 1.1
δ Per	≤ 4.8	≤ 3.2	≤ 3.2	≤ 3.6
40 Per	20.5±7.8	≤ 6.6	≤ 6.6	≤ 7.0
ε Per	≤ 2.2	≤ 1.4	≤ 1.4	≤ 1.4
ξ Per	37±6.6(65)	14±3.4(55)	5.9±3.4(45)	≤ 3.6
α Cam	14±9.6(71)	≤ 11	≤ 11	≤ 3.6
δ Ori A	≤ 1.5	≤ 0.96	≤ 0.96	≤ 1.1
λ Ori A	9.5±5.4(78)	≤ 4.4	≤ 4.2	≤ 3.8
ι Ori	≤ 1.6	≤ 1.1	≤ 1.1	≤ 1.2
ε Ori	≤ 2.0	≤ 1.7	≤ 1.7	≤ 1.7
κ Ori	≤ 1.4	≤ 1.2	≤ 1.1	≤ 1.2
139 Tau	≤ 10	≤ 10	≤ 10	≤ 10
HD 74375	≤ 7.1	≤ 7.9	≤ 7.1	≤ 7.8
ρ Leo	≤ 7.1	≤ 5.6	≤ 5.6	≤ 6.0
1 Sco	≤ 5.8	≤ 4.2	≤ 4.2	≤ 4.4
β^1 Sco	9.4±2.8(50)	5.1±2.0(45)	≤ 2.0	≤ 2.0
ω^1 Sco	≤ 7.1	≤ 6.6	≤ 5.8	≤ 6.2
ν Sco	19±12(65)	≤ 9.2	≤ 6.6	≤ 7.8
ρ Oph A	≤ 12	≤ 12	≤ 12	≤ 12

TABLE 3c - C I** EQUIVALENT WIDTHS. ALL VALUES IN mA (Continued)

STAR	W_λ (1329.584)	W_λ (1261.552)	W_λ (1261.426)	W_λ (1277.954)
χ Oph	44±12(42.5)	≤ 7.8	≤ 6.8	≤ 7.8
22 Sco	≤ 11	≤ 8.0	≤ 7.8	≤ 7.8
μ Nor	21±7.4(40)	11±6.2(45)	≤ 5.6	≤ 6.6
γ Ara	≤ 3.2	≤ 2.0	≤ 2.0	≤ 2.2
Θ Ara	≤ 7.0	≤ 6.0	≤ 5.6	≤ 6.0
κ Aql	≤ 9.4	≤ 6.8	≤ 6.8	≤ 6.2
59 Cyg	≤ 5.6	≤ 3.4	≤ 3.4	≤ 3.6
σ Cas	≤ 8.2	≤ 7.6	≤ 7.4	≤ 8.2

TABLE 3d - CO EQUIVALENT WIDTHS. ALL VALUES IN mA

STAR	W_λ (1087.867)	W_λ (1150.48)	W_λ (1281.866)
κ Cas	53±14(73.5)	≤ 12	≤ 14
γ Cas	≤ 1.1	≤ 1.5	≤ 2.4
δ Per	≤ 4.4	≤ 5.2	≤ 6.4
40 Per	≤ 18	≤ 14	≤ 14
ε Per	≤ 1.3	≤ 1.8	≤ 2.2
ξ Per	30±4.8	≤ 5.4	≤ 7.2
α Cam	37±6.8(101)	12±8.0(46)	≤ 11
δ Ori A	≤ 1.2	≤ 1.5	≤ 2.2
λ Ori A	≤ 6.4	≤ 4.6	≤ 12
ι Ori	≤ 0.9	≤ 1.2	≤ 2.0
ε Ori	≤ 3.2	≤ 3.2	≤ 3.4
κ Ori A	≤ 1.4	≤ 1.7	≤ 2.4
139 Tau	≤ 7.8	≤ 7.8	≤ 9.0
HD 74375	≤ 10.2	≤ 10.6	≤ 14.5
ρ Leo	≤ 4.8	≤ 3.6	≤ 5.8
1 Sco	≤ 4.8	≤ 6.0	≤ 8.6
β^1 Sco	7.4±3.0(80)	≤ 3.4	≤ 4.0
ω^1 Sco	≤ 11.3	≤ 10.4	≤ 10.0
ν Sco	≤ 12	≤ 12	≤ 16
ρ Oph A	≤ 18	≤ 22	≤ 19

TABLE 3d - CO EQUIVALENT WIDTHS. ALL VALUES IN mA (Continued)

STAR	W_λ (1087.867)	W_λ (1150.48)	W_λ (1281.866)
χ Oph	≤ 18	≤ 22	≤ 19
22 Sco	≤ 15	≤ 18	≤ 15
μ Nor	48±10(120)	≤ 10	≤ 11
γ Ara	5.5±2.2(55)	≤ 2.6	≤ 4.4
Θ Ara	≤ 5.0	≤ 4.0	≤ 5.2
κ Aql	≤ 14	≤ 12	≤ 11
59 Cyg	5.8±3.0(80)	≤ 5.2	≤ 7.6
σ Cas	≤ 16	≤ 15	≤ 13

TABLE 4 - RADIAL VELOCITIES FROM C I MULTIPLETS (KM/SEC)

STAR	V_r(1328.833)	V_r(1260.736)	V_r(1138.383)	V_r(1157.186)
κ Cas	-17.6	-17.6	-20.6	-17.1
γ Cas	- 9.7	-10.2	-	-
40 Per	-24.2	-25.7	-	-
ε Per	2.3	3.6	-	-
ξ Per	-70.7	-70.9	-73.3	-72.8
α Cam	-23.3	-21.7	-23.2	-17.1
δ Ori A	-13.5	- 7.3	-	-
λ Ori A	-17.6	-12.6	-	-
ι Ori	-17.6	-	-	-
ε Ori	-14.7	-15.7	-	-
κ Ori	-12.0	-11.4	-	-
139 Tau	- 5.2	- 7.4	-	-
HD 74375	- 2.3	- 4.3	-	-
ρ Leo	-59.4	-	-45.6	-
1 Sco	- 9.7	-11.4	-	- 8.6
ρ^1 Sco	-16.5	-16.2	-17.1	-
ω^1 Sco	- 3.4	- 1.9	-	-
ν Sco	-11.7	- 9.1	-	-

TABLE 4 - RADIAL VELOCITIES FROM C I MULTIPLETS (KM/SEC) (Continued)

STAR	V_r(1328.833)	V_r(1260.736)	V_r(1138.383)	V_r(1157.186)
ρ Oph A	-5.0	-3.8	-	-
χ Oph	-11.3	-8.80	-7.9	-10.6
22 Sco	-9.7	-10.9	-	-
μ Nor	-18.5	-18.6	-17.9	-24.9
γ Ara	3.4	3.1	-	-
θ Ara	-9.7	-10.2	-13.2	-
κ Aql	-1.8	-1.9	-	-
59 Cyg	-23.3	-24.5	-	-30.7
σ Cas	-13.1	-15.7	-	-

RADIAL VELOCITIES FROM C I* MULTIPLETS (KM/SEC)

STAR	V_r(1329.101)	V_r(1260.996)	V_r(1260.927)	V_r(1261.122)	V_r(1276.750)
κ Cas	-22.8	-24.6[1]	-19.9[1]	-15.2	-
40 Per	-22.8	-24.5[1]	-20.9[1]	-24.0	-
ε Per	- 0.7	-	-	-	-
ξ Per	-71.8	-72.8[1]	-73.0[1]	-71.8	-72.8
α Cam	-21.1	-	-	-	-
λ Ori A	-17.6	-11.4	-	- 9.3	-
ε Ori	-23.7	-	-	-	-
κ Ori	-11.5	-	-	-	-
139 Tau	- 4.74	-	-	-	-
HD 74375	- 2.5	-	-	-	-
1 Sco	- 8.1	-	-	-	-
β^1 Sco	-16.0	-15.7	-14.0	-14.8	-
ω^1 Sco	- 2.9	-	-	-	-
ν Sco	-10.6	-	-	- 6.4	-
ρ Oph A	- 4.7	- 6.2	- 2.85[1]	- 5.2	- 3.5
χ Oph	- 6.8	- 7.85[1]	- 7.6[1]	- 6.2	-
22 Sco	- 5.2	-	-	-	-
μ Nor	-15.8	-18.	-18.6[1]	-16.4	-15.0
γ Ara	4.3	-	-	-	-
θ Ara	-10.6	-10.9[1]	-12.4[1]	-10.0	-
κ Aql	- 0.7	-	- 3.33	-	-
59 Cyg	-25.5	-	-	-	-
σ Cas	-14.9	-14.0[1]	-14.0[1]	-15.9	-

[1] footnote: velocities are approximate only due to poor resolution of lines at 1260.927 and 1260.996.

RADIAL VELOCITIES FROM C I** MULTIPLETS (KM/SEC)

STAR	V_r(1329.584)	V_r(1261.552)	V_r(1261.426)	V_r(1277.954)
κ Cas	-19.0	-	-	-
40 Per	-23.9	-	-	-
ξ Per	-71.3	-73.5	-73.2	-
α Cam	-22.6	-	-	-
λ Ori A	-15.6	-	-	-
β^1 Sco	-15.6	-14.0	-	-
ν Sco	- 9.3	-	-	-
χ Oph	- 9.0	-	-	-
μ Nor	-15.5	-15.2	-	-
θ Ara	-10.4	-	-	-

RADIAL VELOCITIES FROM CO LINES (KM/SEC)

STAR	V_r(1087.867)	V_r(1150.48)	V_r(1281.866)
κ Cas	-16.3	-	-
ξ Per	-76.4	-	-
α Cam	-19.6	-13.8	-
β^1 Sco	-18.5	-	-
μ Nor	-27.3	-	-
γ Ara	- 3.0		
59 Cyg	-29.5	-	-

TABLE 5

LOGARITHMS OF COLUMN DENSITIES WITH SATURATION PARAMETERS (IN PARENTHESES)

STAR	N(C I)	N(C I*)	N(C I**)	N(CO)
κ Cas	15.72±0.4(1.2)	14.26±0.2	13.66±0.3	13.48±0.2
γ Cas	13.04±0.1	≤ 12.12	≤ 12.10	≤ 11.81
δ Per	≤ 12.59	≤ 12.64	≤ 12.57	≤ 12.41
40 Per	14.5±0.3	14.28±0.2(1.4)	13.28±.0.2(1.2)	≤ 13.02
ε Per	13.57±0.1(1.4)	12.62±0.2	≤ 12.23	≤ 11.88
ξ Per	15.04±0.2	14.50±0.2	13.64±0.2	13.24±0.1
α Cam	15.59±0.1(1.5)	13.80±0.2(1.7)	13.06±0.5(1.1)	13.83±0.5
δ Ori A	12.95±0.1	≤ 12.07	≤ 12.07	≤ 11.85
λ Ori A	14.15±0.1(2.0)	13.60±0.2(1.2)	12.95±0.2(1.2)	≤ 12.57
ι Ori	12.85±0.1	≤ 12.07	≤ 12.10	≤ 11.72
ε Ori	13.55±0.1(1.5)	12.90±0.1(1.1)	≤ 12.19	≤ 12.27
κ Ori	13.48±0.1(1.3)	12.98±0.1(1.2)	≤ 12.04	≤ 11.91
139 Tau	14.13±0.2(1.7)	13.05±0.3(1.1)	≤ 12.89	≤ 12.66
HD 74375	13.83±0.3	13.05±0.3	≤ 12.74	≤ 12.78
ρ Leo	13.32±0.2(1.2)	≤ 12.76	≤ 12.76	≤ 12.45
1 Sco	13.73±0.1(1.3)	13.60 ±0.2	≤ 12.66	≤ 12.45
β^1 Sco	14.13±0.2(1.1)	13.53±0.1(1.2)	12.94±0.1(1.2)	12.64±0.2
ω^1 Sco	13.93±0.2(1.4)	13.79±0.2(1.7)	≤ 12.74	≤ 12.82
ν Sco	13.90±0.3(2.0)	13.90±0.3	13.29±0.3	≤ 12.85
ρ Oph A	≥ 13.65	≥ 14.19	. . .	. . .
χ Oph	15.67±0.5(2.5)	14.8±0.2	14.0±0.3	≤ 13.50

TABLE 5 (Continued)

LOGARITHMS OF COLUMN DENSITIES WITH SATURATION PARAMETERS (IN PARENTHESES)

STAR	N(C I)	N(C I*)	N(C I**)	N(CO)
22 Sco	-	-	-	-
μ Nor	≥ 15.40	≥ 14.81	13.45±0.3	13.45±0.2
γ Ara	13.92±0.1(1.7)	13.01±0.2(1.1)	≤ 12.40	12.51±0.4
θ Ara	14.36±0.2(1.1)	14.60±0.5(1.1)	≤ 12.74	≤ 12.44
κ Aql	14.18±0.1(2.0)	13.48±0.3(1.5)	≤ 12.87	≤ 12.91
59 Cyg	13.92±0.1(1.6)	13.23±0.1(1.2)	≤ 12.64	12.53±0.3
o Cas	14.50±0.3	14.70±0.3	≤ 12.81	≤ 12.97

TABLE 6 - PHYSICAL CONDITIONS

STAR	T(^{o}K)	n(cm^{-3})	p/k(^{o}k cm^{-3})
κ Cas	104	10-40	1040-4200
γ Cas	80	$\leq$ 30	$\leq$ 2400
40 Per	63	60-180	3800-12000
ε Per	81	15-35	1200-2800
ξ Per	61	46-120	2400-7300
α Cam	80	5-20	400-1600
δ Ori A	80	$\leq$ 30	1600
λ Ori A	45	60-230	2700-10000
ι Ori	80	$\leq$ 60	$\leq$ 4800
ε Ori	108	30-50	3200-5400
κ Ori	80-110	40	3200-4400
139 au	117	5-65	590-7600
HD 74375	80	10-160	800-14000
ρ Leo	80	$\leq$ 80	$\leq$ 6400
1 Sco	73	80-100	5800-7300
β^1 Sco	88	40-100	3500-8800
ω^1 Sco	60-80	60-100	3600-8000
ν Sco	90	80-500	7200-45000
ρ Oph A	46	$\geq$ 140	$\geq$ 6400

TABLE 6 - PHYSICAL CONDITIONS (Continued)

STAR	T(^{o}K)	n(cm-3)	p/k(^{o}k cm^{-3})
χ Oph	46	10-180	460-8300
μ Nor	54	20-100	1100-5400
γ Ara	79	10-40	790-3200
Θ Ara	80	10-40	800-3200
κ Aql	59	20-80	1200-4700
59 Cyg	87	30-60	2600-5200
σ Cas	82	40-50	3300-4100

TABLE 7 - MOLECULAR HYDROGEN FORMATION RATE AND EFFICIENCY (α)

STAR	R4	R5	α
ϵ Per	$2.1\times10^{-17}-5.0\times10^{-17}$	$\leq 2.3\times10^{-17}$	0.42- 0.99
ξ Per	$5.4\times10^{-17}-1.6\times10^{-16}$	$2.7\times10^{-17}-8.0\times10^{-17}$	1.08- 6.4
α Cam	$1.7\times10^{-16}-6.6\times10^{-16}$	$1.5\times10^{-16}-6.0\times10^{-16}$	3.2 -12.6
λ Ori	$3.7\times10^{-18}-1.4\times10^{-17}$	$5.4\times10^{-18}-2.1\times10^{-17}$	0.14- 0.82
139 Tau	$4.8\times10^{-17}-2.4\times10^{-16}$	$1.6\times10^{-17}-2.0\times10^{-16}$	0.44- 6.7
μ Nor	$8.8\times10^{-17}-4.4\times10^{-16}$	$6.6\times10^{-17}-3.3\times10^{-16}$	1.8 -12.
γ Ara	$1.7\times10^{-17}-6.8\times10^{-17}$	$3.2\times10^{-17}-1.3\times10^{-16}$	0.61- 4.7
59 Cyg	$6.3\times10^{-17}-1.3\times10^{-16}$	$2.7\times10^{-17}-5.3\times10^{-17}$	.18- 0.62