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INTERSTELLAR ABUNDANCES OF OXYGEN AND NITROGEN

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ABSTRACT

Neutral nitrogen and oxygen column densities or limits are derived for 53 path lengths through the diffuse interstellar medium and compared with column densities of neutral hydrogen. For neither N nor O is a systematic increase of depletion found as reddening increases. The value found for [O/N] is 8, and the abundances of N and O are both between 40% and 70% of the solar values. Implications of these results for models of interstellar grains are briefly discussed.

Subject headings: interstellar: abundances — interstellar: matter

I. INTRODUCTION

The *Copernicus* satellite has been used for studies of depletion along a number of path lengths for the elements nitrogen (Lugger *et al.* 1978; Ferlet 1981), iron (Savage and Bohlin 1979; Lugger *et al.* 1982), chlorine, phosphorus (Jura and York 1978), and zinc (York and Jura 1982). The depletion of iron compared with these other elements suggests that iron and other missing gas-phase elements are bound to interstellar grains (Spitzer and Jenkins 1976; Savage and Mathis 1979). The detailed depletion pattern of many elements in a few stars (Morton 1974; York 1975; York and Kinahan 1979; Morton 1978) can be used to infer the composition and origin of the grains (Field 1974; Snow 1975; Duley and Millar 1978).

Purcell (1969) and Spitzer (1978) showed that the total mass in grains must be larger than can be provided by the well-known highly depleted species (Fe, Mn, Mg, Si, Ca, Al, etc.). Only carbon or oxygen has a high enough cosmic abundance to provide the mass required (Spitzer 1978; Hobbs, York, and Oegerle 1982). For these reasons, we started in 1976 an extensive observational program with the *Copernicus* satellite to determine accurate abundances for C, N, and O using UV resonance lines. Here we discuss results for N and O.

II. DATA

All data were obtained with the *Copernicus* satellite, which has a nominal resolution of 15 km s^{-1}. Most of the equivalent widths, their errors, and the necessary f-values for lines of O I and N I were obtained from Bohlin *et al.* (1983). The photon-noise–limited data often produce 1 σ errors of less than 1 mÅ in the equivalent widths. Since the detected regions may have $T \sim 80$–100 K, Doppler widths of $b \gtrsim 0.3$ km s^{-1} are to be expected. To minimize line saturation effects, several lines of N I, with a range in f-values of 3×10^{-6} to 2×10^{-3} were scanned for each star. For stars of different UV brightness and reddening, different sets of N I lines were chosen to obtain the high signal-to-noise ratio for lines near the linear portion of the curve of growth.

Only one appropriately weak O I line, λ1356, is known in the *Copernicus* spectral region, so our analysis relies on the assumption that N I and O I lie on the same curve of growth. For the case of thermal or turbulent broadening in a single cloud, this is reasonable (since the masses of N and O are nearly identical). For the usual case where several narrow, unresolvable components exist within the 15 km s^{-1} resolution element of *Copernicus*, the assumption would break down only if [O/N] (defined here as relative abundance of oxygen and nitrogen) were different in different components, giving a difference of effective b-values between N and O. To check the assumption that $b(\text{N I}) \sim b(\text{O I})$, we plot in Figure 1 the equivalent widths of N and O, for cases where the spin-forbidden λ1159 N I line is on or near the linear portion of the curve of growth. Note that $W_\lambda(\text{N I-1160}) \sim W_\lambda(\text{O I-1356})$ if N and O generally fall on the same line-of-sight curve of growth and if $Nf\lambda$ is about the same for the two lines compared, corresponding to $N(\text{O I})/N(\text{N I}) = 10$ for these two lines. Evidently the points do not lie far from the relation for [N/O] = 0.1. If the lines are relatively unsaturated, the data are consistent with [O/N] = 8. If saturation is important, Figure 1 indicates that the difference of effective b-values is not large, supporting our assumption of identical b-values for N and O.

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1983ApJ...266L..55Y

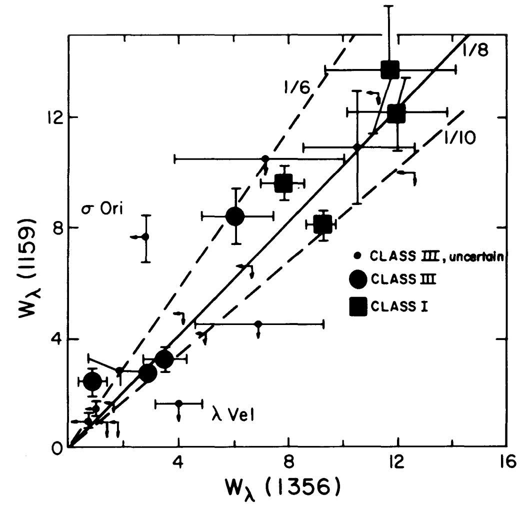

FIG. 1.—Equivalent widths of N I λ1160 vs. O I λ1356 are shown. Since $Nf\lambda$ is equal for the two transitions, if N/O = 1/10, a comparison of equivalent widths can tell whether the two species follow the same curve of growth. The solid line shows the expected relationship if [N/O] = 1/8 and the lines are relatively unsaturated; the two dashed lines apply for relatively unsaturated lines if N/O = 1/10 or 1/6; the solar value is 1/6. Error bars are 1 σ. Upper limits are 2 σ. Data are plotted for 24 stars for which λ1159 was scanned and for which that line is apparently unsaturated. In particular, data are included for all stars listed as class 3 (Table 1) and for all stars listed class 1 (reddened stars) for which W_λ (λ1159)/W_λ (λ1160) > 3.

To derive column densities, the derived values of log W_λ/λ were plotted versus log $f\lambda$ and compared with theoretical single-component curves of growth for $0.3 < b < 6$ km s^{-1} (Spitzer 1978). According to the references cited by Bohlin *et al.* (1983), the errors in the f-values used here may be as large as 30%. For one line, N I λ951.295, we derived a new f-value. For κ Ori, W_λ (951.079) = 22.9 ± 1.9 mÅ, W_λ (951.295) = 5.1 ± 1.4 mÅ, and W_λ (1159.817) = 2.8 ± 0.3 mÅ. Since W_λ (951.079)/W_λ(1159.817) = 8.1, while $f\lambda$ (951.079)/$f\lambda$ (1159.817) = 12.1, the 951.079 Å line is only mildly saturated, and the intermediate value, f (951.295), can be easily inferred from the theoretical curve of growth. Based on N I data for κ Ori, δ Ori, and ε Ori, f (951.295) = 4.7×10^{-5}.

Table 1 lists the derived values of log N(N I), log N(O I), and b(N I) from this work, and of log $N(\mathrm{H_{tot}})$, defined as log[N(H I) + 2$N(\mathrm{H_2})$], from Bohlin, Savage, and Drake (1978) or Bohlin *et al.* (1982). The star class indication given in Table 1 may be used by the reader, in conjunction with Bohlin *et al.* (1982), to determine which N I lines were scanned for each star. Sources of data used for a few stars not observed by Bohlin *et al.* (1982) are given in the footnotes to Table 1.

The ranges in N and b quoted represent the range consistent with the 1 σ errors on all observed points. When the stronger line indicated a relatively high value of b, a weaker line, if present, was generally used to determine the maximum value of N, with the assumed thermal minimum value of 0.3 km s^{-1} taken for b; this procedure allows for the contribution of several unsaturated components to a strong line, in contrast to a more saturated, dominant single component that can often account for the weakest lines observed. Errors in f-values used are not considered in Table 1 or in Figures 2 and 3; this effect is systematic and will affect all the values in a similar manner.

III. RESULTS

The major results of this study are shown in Figure 2 (N I) and Figure 3 (O I). The solid diagonal line shows the predicted relation if log N(N I)/$N(\mathrm{H_{tot}}) = -3.94$ and log N(O I)/$N(\mathrm{H_{tot}}) = -3.16$, the solar values (Withbroe 1971). A dashed diagonal line shows the relation if N or O is depleted by a factor of 2.

The general conclusion from these plots is that neither N nor O is more depleted in reddened stars [large $N(\mathrm{H_{tot}})$] than in unreddened stars [small $N(\mathrm{H_{tot}})$] in striking contrast to the results for Fe II (Savage and Bohlin 1979). Furthermore, [N/H] and [O/H] are less than the solar values, $[\mathrm{N/H}] \equiv \Sigma_{i=1}^{n}[N_i(\mathrm{N\ I})/N_i(\mathrm{H\ I})] \sim 0.5\,[\mathrm{N/H}]_\odot$ and $[\mathrm{O/H}] \sim 0.6\,[\mathrm{O/H}]_\odot$, averaged over the n stars in each case for which the range in log N(N I) or log N(O I) is less than 0.3. There is some evidence that oxygen is more depleted in unreddened stars, since $[\mathrm{O/H}] = 0.4\,[\mathrm{O/H}]_\odot$ for log $N(\mathrm{H_{tot}}) < 20.5$, but $[\mathrm{O/H}] = 0.7\,[\mathrm{O/H}]_\odot$ for log $N(\mathrm{H_{tot}}) > 20.5$ (see Table 1). For both sets of $N(\mathrm{H_{tot}})$, $[\mathrm{N/H}] = 0.5\,[\mathrm{N/H}]_\odot$. Errors in f-values of 30% could account for the difference in the values for O/H, since the two sets of observations involve different lines (Table 1). A number of lower limits for N(N I) are higher than the line representing solar abundances, so [N/H] may be higher for $N(\mathrm{H_{tot}}) > 10^{20.5}$.

Variations of 25%–50% in the integrated [N/O] values for different lines of sight are allowed by the data; however, the three cases with the smallest error bars agree with constant abundance of N I to within 25%: log[N(N I)/N(H I)] is −4.36, −4.27, and −4.36 in λ Sco [$N(\mathrm{H_{tot}}) = 1.7 \times 10^{19}$], κ Ori [$N(\mathrm{H_{tot}}) = 3.5 \times 10^{20}$], and δ Sco [$N(\mathrm{H_{tot}}) = 1.4 \times 10^{21}$] respectively. For log[O/H], the corresponding numbers are more divergent (−3.63, −3.17, and −3.33 respectively). Note that reddening, $E(B-V)$, and mean density ($\bar{n}_\mathrm{H} = N(\mathrm{H_{tot}})/d$, where d = the distance to the star) are well correlated with $N(\mathrm{H_{tot}})$ (Bohlin, Savage, and Drake 1978), so that our statements with regard to $N(\mathrm{H_{tot}})$ apply with regard to $E(B-V)$ and $\bar{n}_\mathrm{H}$ as well.

These computations neglect H, N, and O atoms in ionized states. Since the ionization potentials of N I and O I are greater than that of H I (by 0.94 and 0.19 eV respectively), O II and N II are expected to make a negligible contribution to the total oxygen and nitrogen

TABLE 1

LOGARITHMIC COLUMN DENSITIES OF O I, N I, AND HYDROGEN

Star	Class	N I	O I	H_{tot}[a]	*b*(N I)
ε CMa	2	> 14.0[b]	> 14.3	< 18.77	< 3
α Vir	...	14.6–14.9[c]	15.5–15.7[c]	19.00	4.0
λ Sco	...	14.77–14.97[d]	15.5–15.7[d]	19.23	2.5
υ Sco	2	> 15.5:	> 15.5	< 19.26	2:
β Cen	...	15.05–15.35[e]	15.7–16.0[f]	19.52	> 3.8
γ^2 Vel	3	15.88–6.17	< 17.1	19.78	> 1
α^1 Cru	2	15.4–15.6	> 16.1	19.85	3–5
ε Cen	2	15.35–15.60	16.15–16.7	19.90	> 5
ζ Pup	...	15.80–16.15[e]	...	19.99	5–7
ζ Cen	2	15.5–15.8	> 15.9	20.02	1.8–2.8
δ Cru	2	15.30–15.70	> 16.1	20.04	1.6–3.5
η Cen	3	15.80–15.95	< 17.0	20.11	> 0.3
ι Ori	3	15.85–16.15	< 16.8	20.15	> 1
γ Cas	3	15.85–16.00[g]	< 16.8	20.16	> 2
λ Lep	2	> 15.8	> 16.3	20.17	< 6
δ Lup	2	15.6–16.1	> 16.3	20.18	2.8–4.0
γ Lup	2	15.1–15.8	> 16.1	20.23	> 3
δ Ori	3	15.80–15.92	< 16.7	20.23	> 2
64740	3	< 17.2	< 18.5	20.26	> 0.3
59 Cyg	1	> 17.2	< 18.5	20.34	0.3–0.6
μ^1 Sco	3	< 16.5	< 17.3	20.40	> 0.3
μ Cen	2	> 15.5	> 16.4	20.40	1.4–6
ε Ori	3	15.92–16.40	< 16.8	20.45	0.8–4.0
κ Vel	3	< 16.1	< 18.1	20.48	> 0.3
ε Per	3	16.10–16.43	17.20–17.50	20.51	0.5–2.0
σ Ori	3	16.5–16.9:[g]	< 17.2	20.52	2:
α Pyx	3	< 17.2	< 19.0	20.52	> 0.3
κ Ori	3	16.18–16.33	17.30–17.40	20.52	> 4.0
10 Lac	3	...	...	20.72	> 2.0
χ Car	3	< 17.2	< 18.5	20.74	> 0.3
λ Ori	3	16.47–16.75[g]	17.40–17.75	20.80	1–2
φ Ori	3	> 16.9	< 18.3	20.84	< 1.3
139 Tau	1	17.2–17.60	< 18.4	20.95	> 2.0
188209	1	> 17.6	< 18.8	21.00	0.6–2.0
σ Cas	1	> 16.8	...	21.04	0.4–1.4
1 Cas	1	> 17.2	17.5–18.6	21.07	0.5–5.0
κ Aql	1	> 17.2	> 17.7	21.08	0.3–2.0
α Cam	1	16.9–17.6	> 17.8	21.09	> 0.9
135591	1	> 16.6	> 17.7	21.12	> 0.5
θ Mus	1	> 16.6	> 17.8	21.13	> 0.3
β^1 Sco	1	16.85–17.10	17.70–17.80	21.14	1.0–1.6
δ Sco	1	16.70–16.90	17.70–17.95	21.16	> 1.1
ν Sco	1	...	> 17.5	21.19	...
1 Sco	1	> 16.9	17.7–18.7	21.20	> 1.1
ζ Per	1	> 17.4	17.2–18.1	21.20	0.6–1.8
o Per	1	16.75–17.05	17.62–17.85	21.21	> 4
40 Per	1	> 16.7	> 17.9	21.23	> 0.4
ω^1 Sco	1	17.0–17.5	17.75–18.20	21.24	> 1.0
15 Sgr	1	> 16.8	> 18.0	21.25	> 0.4
ξ Per	1	...	> 17.6	21.30	...
χ Oph	1	> 16.9	> 18.0	21.35	> 0.8
σ Sco	1	> 17.3	> 18.1	21.37	0.5–1.6
ρ Oph	1	> 16.8	> 18.0	21.86	> 0.7

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[a] Bohlin *et al.* 1978; Bohlin *et al.* 1982.

[b] Based on 1 σ upper limit of 2.5 mÅ at 952 Å. Lines reported by Bohlin *et al.* 1982.

[c] York and Kinahan 1979.

[d] York 1982.

[e] Lugger *et al.* 1978.

[f] York and Matheson 1983.

[g] Apparent multicomponent curve of growth (York 1976; Lugger *et al.* 1978).

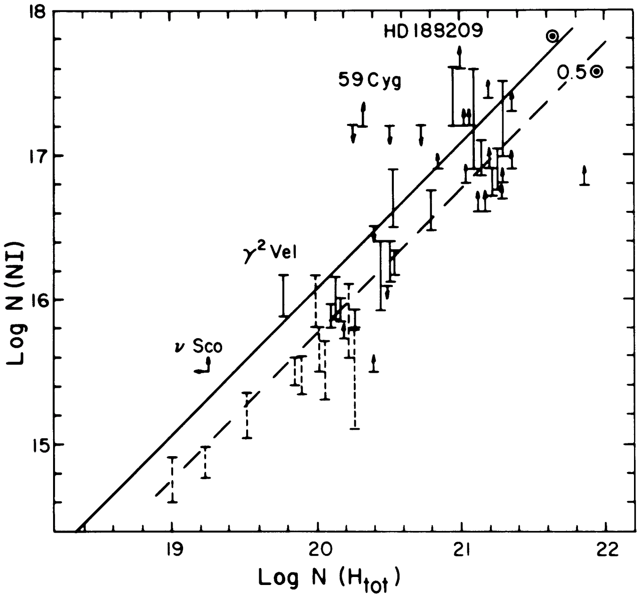

FIG. 2

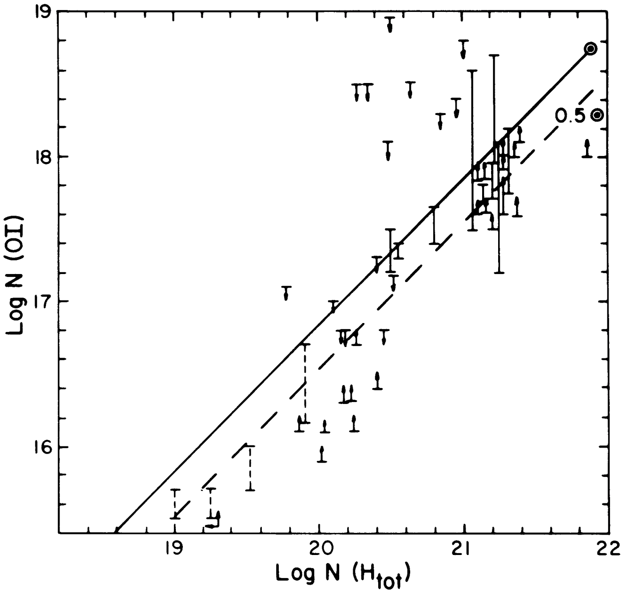

FIG. 3

FIG. 2.—Shown are log N(N I) vs. log $N(\mathrm{H_{tot}})$. Solar abundance and one-half solar abundance lines are shown. Solid bars refer to class 1 or 3 stars, where N I λ1159.817 is used to obtain abundances. Dashed bars are for class 2 stars, based on the triplet at 952 Å. A few points which are inconsistent with near-solar abundances are labeled with the name of the star observed.

FIG. 3.—Shown are log N(O I) vs. log $N(\mathrm{H_{tot}})$. Values are based on W_λ (O I λ1355.598) and b(N I) from Table 1 for stars with log $N(\mathrm{H_{tot}}) > 20$ (*solid bars*) and on the 988 Å triplet for lower values of log $N(\mathrm{H_{tot}})$ (*dashed bars*). For both Figures 2 and 3, the errors in log $N(\mathrm{H_{tot}})$ are $\lesssim 0.1$ dex.

column densities in the neutral hydrogen regions we are discussing. For example, the components producing the dominant contribution for neutral N I lines have N(N II)/N(N I) < 0.1 for λ Sco (York 1983), δ Per, and ε Per (Martin and York 1982).

IV. DISCUSSION

Depletion of elements heavier than neon exists even in lightly reddened lines of sight (Savage and Bohlin 1979; York and Kinahan 1979; York 1983; Morton 1978). Thus grains are presumed to exist in clouds of both low and high reddening. According to Spitzer (1978), the mass fraction of interstellar material in grains is at least 0.006. To try to ascertain the amount of different elements in the mix that constitutes the grains, we show, in Table 2, the mass fractions (f) attributable to C, N, O, and all elements heavier than neon in grains. Values are listed for all atoms in a gas of solar abundance, for N and O from this *Letter*, for carbon as referenced, and for elements heavier than neon from York and Kinahan (1979) and Snow (1975).

Observations for lines of sight with $N(\mathrm{H_{tot}}) > 10^{20.5}$ imply a total mass fraction of missing gas of $\gtrsim 0.007$ compared with 0.006 based on generalized grain models that produce the observed extinction. However, for the average of all stars observed, the mass fraction in missing gas is somewhat higher still than the minimum required to produce the observed selective extinction. This latter result, if true, could imply the existence of grains too large to cause selective extinction. On the other hand, the mass fractions we deduce to be locked in grains may be too large, if the solar abundances are higher than the true interstellar abundances of C and O in gas and solid phase. (See Joss 1974 who also discusses this possibility.)

Mathis, Rumpl, and Nordsieck (1977) constructed grain models that adequately explain the observed extinction based on carbon and on oxides of Si, Fe, etc., but including no ice coatings. They predict, for the gas phase, $[\mathrm{O/H}] = 0.75\,[\mathrm{O/H}]_\odot$ and $[\mathrm{C/H}] \geqslant 0.3\,[\mathrm{C/H}]_\odot$, in agreement with our observations for cases with $N(\mathrm{H_{tot}}) > 10^{20.5}$. De Boer (1981) analyzed data for oxygen for eight stars including the 1356 Å line in o Per from Bohlin *et al.* (1982). He argued that the derived oxygen abundances are consistent with the Mathis *et al.* model. On the other hand, our results for all stars would be consistent with some additional oxygen depletion, which could be in the form of ices (Hong and Greenberg 1980). Ferlet (1981) analyzed published data for N I in 21 stars and found, on average, $\log[\mathrm{N/H}] = -4.21$, with no systematic depletion as a function of $E(B-V)$.

Since none of the three elements (C, N, and O) show evidence for systematically greater depletion as reddening increases and since all three show some depletion, the main mass in grains may be an amorphous mixture

1983ApJ...266L..55Y

TABLE 2

MASS OF ATOMS POSSIBLY IN GRAINS

Parameter	f_C	f_N	f_O	f > Ne	Totals
Fraction available[a]	0.0034	0.0010	0.0071	0.0026	0.014
$N(H_{tot}) > 10^{20.5}$[b]	0.0024[c]	0.0005	0.0020	$\gtrsim 0.0020$[d]	$\gtrsim 0.0069$
$N(H_{tot}) < 10^{20.5}$[b]	(?)	0.0005	0.0043	0.0020[e]	(> 0.0068)
All $N(H_{tot})$[b]	0.0024	0.0005	0.0031	$\gtrsim 0.0020$	$\gtrsim 0.0080$

[a] Total mass fraction available for C, N, etc., in a gas of solar abundances.

[b] Observed values from this work unless otherwise noted.

[c] Hobbs, York, and Oegerle 1982 use C II] 2326 Å and find [C/H] = 0.3 $[C/H]_\odot$ for δ Sco. Jenkins, Jura, and Lowenstein 1983 find [C/H] = 0.2–0.5 $[C/H]_\odot$ for 20 of 23 lines of sight, based on C I observations.

[d] Snow 1976.

[e] York and Kinahan 1979; f > Ne = 0.002 for 90% depletion of Fe, Si, Al, Ca, 80% depletion of Mg, and no depletion of Ne or S.

of C, N, and O. Such grains would have to be well mixed with gas and would have to have similar makeup independent of the radiation or density environment. In this case, the decrease of [Fe/H] with increasing reddening, noted earlier, poses problems. Conceivably, Fe ions could accumulate on grains more rapidly (i.e., be released from grains less rapidly) than O I or N I or compounds containing O or N. Then one might expect a measurable increase of depletion of Fe but not of N and O in the relatively denser clouds, which have presumably formed relatively recently. Slight differences of destruction rates from region to region could also explain the more variable Fe depletions. Fe is so highly depleted compared with C, N, and O that destruction of 10% of the grains drastically modifies [Fe/H] without affecting [O/H], [N/H], or [C/H] appreciably. There may be, on the other hand, interpretive problems with the Fe II data. The published iron depletions do not allow for the possibility that b(Fe II) < 0.2 km s^{-1} in cold clouds that produce thermally broadened line profiles: some iron may thus be hidden.

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