LINE ABSORPTION STUDIES
OF THE INTERSTELLAR GAS NEAR 10^{15} Hz

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Abstract. The *Copernicus* satellite now opens up the ultraviolet region for inspection, and the number of resonance lines which may be studied has increased from 6, seen in the visible, to more than 30. The distribution and properties of an important constituent of the interstellar gas, molecular hydrogen, can be studied in detail using this instrument. A more comprehensive picture may now be developed for element depletion factors, electron densities, and sources of ionization (UV photons, low energy cosmic and X-rays).

I. General Perspective

In studying the interstellar medium, one of the fundamental questions we can explore is, "What is its composition?" Aside from the merits of answering this question for its own sake, a comprehension of the relative abundances of the primary constituents of the interstellar material plays an important role in our understanding of the different physical and chemical phenomena which may occur in space. As a starting point, we could maintain the premise that the distribution of elements conforms to cosmic abundances and then ascertain the apportionment of these elements into various ions, atoms, free radicals and molecules, or solid particles. Until some evidence compels us to think otherwise, this assumption seems reasonable since the cosmic abundances are consistent with the composition of the atmospheres of B type stars which have recently formed out of the interstellar material (Traving, 1966).

In its atomic form, the presence of the most abundant element, hydrogen, is easily detected by line emission and absorption at 21 cm. As many of the contributions in this symposium volume attest, the study of this radiation has provided us with extensive information on the distribution, kinematics and temperature of interstellar H I. Microwave emissions from a wide variety of molecules have been detected, although most of the molecules are in appreciable abundance only in very dense concentrations of gas. In many H II regions, information on the abundances of ionized H, He, N, O and Ne has come from observations of emission lines at radio and optical wavelengths, resulting from recombinations and collisional excitations (Churchwell, 1974; Osterbrock, 1970). For the measurement of interstellar atoms and ions in the general H I regions, however, we must rely upon absorption lines appearing in the visible and ultraviolet spectra of O and B type stars. (Although high-level recombination lines have been detected from H I regions, they are difficult to interpret quantitatively.) A survey of the conclusions from these optical absorption line studies will be covered in the discussion which follows.

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II. Studies at Visible Wavelengths

Let us consider the principal atoms and ions we might expect to find in the interstellar gas. For all elements having a cosmic abundance greater than 10^{-8} that of hydrogen, the diagram in Figure 1 shows a vertical slot whose width is proportional to the logarithm of the abundance (deuterium has been shown explicitly). This width serves as a crude but reasonably realistic measure of the strengths of lines which may appear,

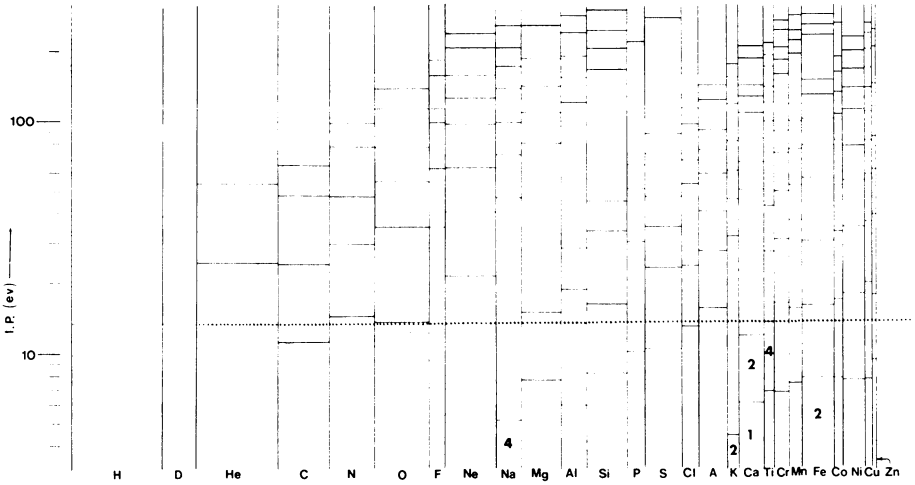

Fig. 1. A representation of the more cosmically abundant ions and atoms. The width of each column is proportional to log (element abundance relative to hydrogen) -8; if this quantity is negative the element is omitted. The columns are partitioned vertically into segments which represent successively higher levels of ionization, starting with neutral atoms at the bottom. The upper boundaries for each ion are positioned according to their respective ionization potentials. The ionization potential of hydrogen is continued across the diagram as a dotted line because of its significance in determining the dominant stage of ionization of H I regions. The numbers in the boxes indicate the number of interstellar absorption lines detected in the visible spectra of stars.

as well as an indication of the importance of an element's contribution to the composition of the interstellar material. Each of the slots is divided vertically into boxes which represent the successive stages of ionization. The boundaries of the boxes are placed at heights which correspond to the appropriate ionization potentials in each case. These energies are relevant to the principal phenomena which are responsible for distributing an element into various levels of ionization.

Ionization by starlight is the dominant means for ionizing atoms in space. Photons at wavelengths between the Lyman limit and the soft X-ray region cannot penetrate H I regions, and hence starlight will not produce ions requiring more energy than 13.6 eV. For most elements (a notable exception is calcium) the recombination with free electrons is so much slower than the ionization that most of the atoms are found in the stage intersected by the horizontal dotted line in the diagram. For instance, carbon should be predominantly singly ionized in the interstellar medium; less than 1% of it would be neutral in the ordinary, low density H I regions.

Virtually none of the interstellar atoms and ions would have excited electronic levels (except for fine structure states), and thus all absorption lines must originate from the ground state. A recent compilation of such transitions, with their *f*-values if known, has been given by Morton and Smith (1973). As shown in Figure 1, relatively few of the more abundant elements have strong enough transitions of this sort to be seen as interstallar lines in the visible region of the spectrum. The numbers in the boxes show how many transitions have been detected by ground-based telescopes over many decades of observing. Not shown are a number of atoms or ions sought after with negative results; these have led to upper limits for the abundances, sometimes below the cosmic values. Except for Ti II all of the transitions observed are from levels of ionization which may be ionized by starlight (i.e., they are below the dotted line at 13.6 eV in Figure 1). Thus total element abundances may be derived only after solving for the ionization equilibrium. The most extensively studied lines in the visible are the Na I D lines and H and K lines of Ca II. The results have shown that, regardless of uncertainities in the corrections for ionization, the abundances of calcium and titanium are far below their cosmic values, while sodium is moderately below normal. The abundance of potassium is relatively close to the cosmic value. Habing (1969) has summarized and discussed many of the results on abundances from various studies of visual interstellar lines.

In addition to investigating abundances, the early surveys established that the distribution of gas was not uniform, and distinct concentrations of material, often referred to as clouds, moved about at their own peculiar velocities. A statistical description of the dispersion of cloud velocities, as well as a specification for the number of clouds per unit volume in our region of the Galaxy evolved from these data. Conclusions of this sort have been summarized by Spitzer (1968) and Heiles (1974).

III. Ultraviolet Research

Soon after the launch of the *Copernicus* satellite in August 1972, we were able to realize a manyfold increase in the number of lines which could be analyzed. This instrument was designed to record absorptions from just above the Lyman limit (912 Å) to 3100 Å where our atmosphere becomes transparent. There is a lack of coverage from about 1450 to 1600 Å, and longward of 1600 Å the effective sensitivity of the spectrometer is somewhat reduced by the high noise level resulting from cosmic rays and trapped radiation interacting with the near UV detectors. However, the greatest wealth of lines occurs at the shorter wavelengths where instrument performance has been excellent. Figure 2 summarizes, in a format identical to that of Figure 1, the number of transitions and the ions detected during the first year in orbit.

Not only has *Copernicus* allowed us to measure the most abundant ion states of 13 elements (and also deuterium, see Section VII), but in many cases we have had the opportunity to examine the relative distribution over a range of different ionization

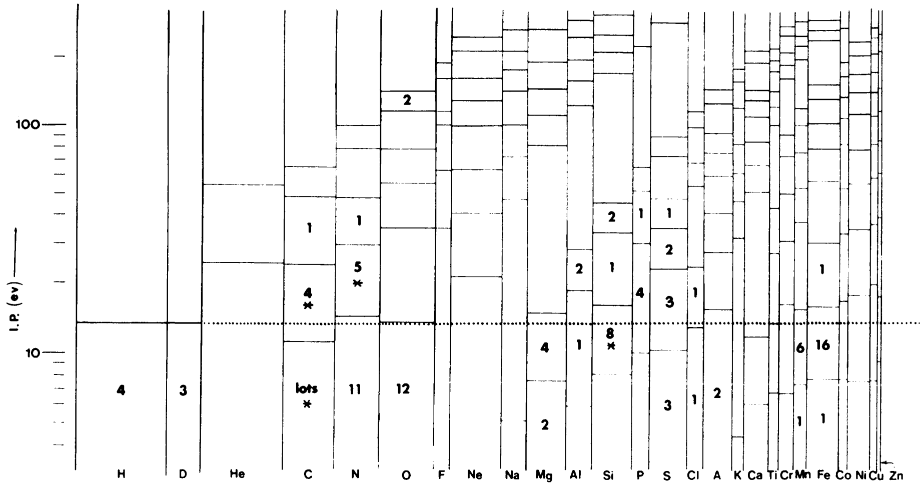

Fig. 2. Same as Figure 1 except the numbers denote how many transitions for a given atom or ion have been observed in the ultraviolet spectra of stars recorded by the *Copernicus* instrument.

stages. The populations of ions above those intersected by the 13.6 eV line allow us to assess the importance of ionizations by X-rays and cosmic rays. When an element is predominantly ionized (by starlight), the amount in neutral form will provide an indication of the electron density if we know the ambient starlight flux and the cross sections for ionization and recombination, provided the ions and atoms reside in the same regions of space. An analysis of this sort has already been successfully derived from the ground-based observations of the Ca I to Ca II ratio; for instance, White (1973) derived electron densities in clouds which are consistent with the general results $n_e \approx 0.03$ cm^{-3} from pulsar dispersion measures (Guélin, 1974).

The asterisks within some of the boxes in Figure 2 identify those atoms or ions for which interstellar absorptions from fine-structure excited levels have been observed. These levels, which arise from the *J* splitting of the ground state, can be populated under interstellar conditions by collisions at typical H I temperatures (~60 K) when the densities are sufficiently high (generally 10 to 100 cm^{-3}). The creation of these excitations is balanced with collisional and radiative de-excitation. One can arrive at an estimate for various combinations of temperature and density of the gas by evaluating this equilibrium and relating it to the observed relative populations (Bahcall and Wolf, 1968; Dalgarno and McCray, 1972). The infrared radiation from these excited levels is a principal source of heat loss for the interstellar gas; a measurement of the number density of excited atoms or ions, when multiplied by the infrared transition's energy and Einstein A coefficient, provides a direct indication of the cooling rate by this mode.

IV. Element Abundances

Although it is evident from Figure 2 that a good coverage of the more important elements has been obtained by studying ultraviolet spectra, there are some significant gaps. There are no lines available from the ground state of helium which have a wavelength longward of the Lyman limit. This deficiency is not too serious since helium abundances are available from both optical and radio observations of recombinations occurring in H II regions. Many lines of neutral oxygen have been observed, but all of the oxygen ions except O VI are undetectable. If a reasonable fraction of the oxygen is singly ionized, as somewhat to our surprise we find for nitrogen, we would underestimate the oxygen abundances. Another significant omission is Ne; once again the optical studies of emissions for H II regions can fill this need.

For most stars, a substantial fraction of the observed lines are saturated, and we must rely upon a curve-of-growth analysis to determine a column density. We are fortunate enough in some cases to have at our disposal a large collection of lines with appreciably different oscillator strengths. N I, O I, Si II and Fe II are particularly favorable in this respect. On the other hand there are several astrophysically important species, such as C III, N II, N III, Al II, and Si III for which only one line has been available for measurement. (Although Figure 2 lists five lines for N II, all but one are from the excited levels for a single multiplet.) When one is confronted with a single line which may be saturated, one may derive a column density either by using the curves of growth for other elements or ionization stages, or one may derive a curve of growth from high resolution data taken in the visible, such as the Na I and Ca II line scans of Hobbs (1969) and Marschall and Hobbs (1972). It must be remembered, however, that the velocity profiles of various species along a line of sight to a star may not all be the same. This may be especially true for different levels of ionization of a single element, which may have markedly different distributions in space.

The initial results from *Copernicus* were reported in a series of six articles (which are given in the references and will be referred to as Papers I through VI). In addition to information on element abundances and relative ionizations, these articles discussed the observations of interstellar H_2, HD and CO and also the far UV extinction properties of dust grains. Paper I gave a basic description of the instrument and its performance. Papers II and III indicated that elements are depleted from the interstellar gas phase in both interstellar clouds and in the intercloud medium (the distinction between the two cases was based purely on the amount of reddening toward the stars). Figure 3, taken from Paper II, exemplifies this depletion for five stars which have a moderate amount of reddening. Although there is a significant variability from one star to the next for the depletion of a given element, the overall indication is that the deficiencies are a general phenomenon.

It has often been suggested that the interstellar dust grains are responsible for the depletion of various elements. It is not at all unreasonable that interstellar dust represents a significant fraction of the heavy element material available: Jenkins and Savage (1974) estimate that the ratio of the mass of dust to that of hydrogen in the interstellar medium is 0.006 while the cosmic ratio of heavy elements (excluding He) to hydrogen is 0.022 (from the results of Withbroe, 1971). Field (1973) has estimated the characteristic (maximum) temperature at which various elements would form compounds and could condense onto, or actually form, dust grains. He then examined

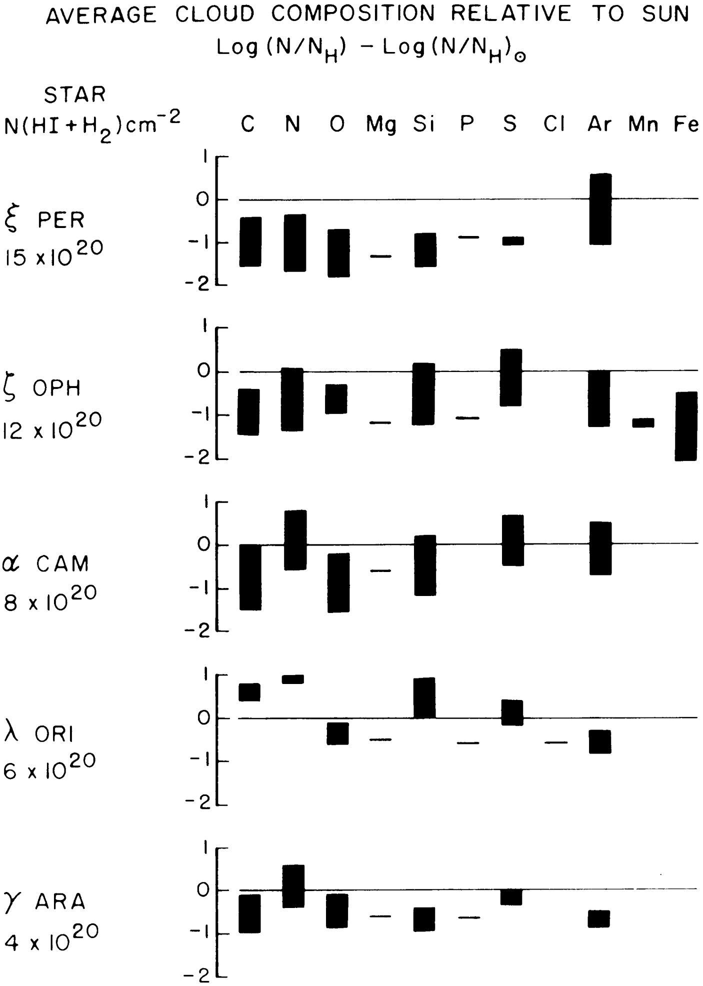

Fig. 3. Relative interstellar gas abundances of elements, in all observable levels of ionization, compared with solar abundances. The tops and bottoms of the bars are the upper and lower error limits, respectively. The less certain values (depicted with tall bars) are for elements whose lines are on the flat portion of the curve of growth; the velocity dispersions of the material are not known accurately. This figure is adopted from Paper II of the original *Copernicus* series, except for the correction of mistakes in the drawing of the bars for Si toward ζ Oph and C toward λ Ori (Reproduced by courtesy of *The Astrophysical Journal*, University of Chicago Press, publisher. © 1973. American Astronomical Society. All Rights Reserved).

the general pattern for the depeletion of elements in the direction of ζ Orph, based on the results from visual lines and the ultraviolet lines observed by *Copernicus*, and showed that the depletion was strongest for elements having the higher condensation temperatures. Grain growth, he concluded, could begin in the outer layers of stellar atmospheres where densities are large, and result in a strong depletion of the more refractory elements. Then, as the gas is ejected and spreads into space where the densities and temperatures become progressively lower, the other elements condense but the depletion is not as complete.

Future observations by the *Copernicus* instrument may help to clarify the involvement of element depletion with the formation of dust. For instance, it would be interesting to ascertain whether or not excesses and deficiencies in the ratio of extinction to the amount of hydrogen present (in the form of both molecules and atoms) correlates with any elemental deficiencies. Alternatively, it might be profitable to see whether or not differences in the character of the extinction correlate with any changes in the overall pattern of depletion. A few stars have markedly atypical extinction curves in the far ultraviolet (Bless and Savage, 1972). A discussion by Greenberg (1974) emphasizes the possibility that the extinction shortward of 1400 Å may be caused by very small silicate grains, and when mantles of ice and other volatile compounds form on these grains the extinction in the visible increases. One could check the compatibility of this hypothesis with the comparison of depletion patterns and the ratios of far ultraviolet to visual extinctions. Strom (1973) has emphasized the possible importance of the value for $\lambda_{\max}$, the wavelength where maximum interstellar polarization occurs, as a determinant of the character of dust grains.

V. Degrees of Ionization

An immediate conclusion from the results of Paper III was that relatively few of the atoms were to be found in very high stages of ionization. For instance, upper limits for the intercloud abundances of N v, Si IV, and S IV generally ranged from 10^{-2} to 10^{-3} of the respective total element abundances. Meszaros (1973) concluded the observed amounts of C III and N III were too small to be consistent with the presence of a large enough flux of low energy galactic X-rays or cosmic rays to explain the high apparent ionization rate in H I regions, as deduced from various measures of interstellar electron densities. Such hypothetical large fluxes have also been suggested as a means for supplying enough heat gain to sustain the observed temperature of the H I gas (Goldsmith *et al.*, 1969). On the other hand, the *Copernicus* data on the ionization structure seem consistent with the presence of the *observed* diffuse X-ray flux down to 100 keV, which may be sufficient to explain the heating of the intercloud medium (with $n_H = 0.2$ cm^{-3}) but not the observed electron densities (Grewing and Walmsley, 1974).

A fundamental difficulty in measuring the abundances of highly ionized atoms in H I regions is separating out the contributions from each (observed) star's own H II region. In reducing the *Copernicus* data, we are just now achieving enough accuracy and confidence in our wavelength scales to identify lines of differing radial velocity. In some favorable cases the velocity of the gas within the star's Strömgren sphere will differ enough from the intervening H I material to allow a distinction to be made. The relative importance of the H II regions can also be reduced by choosing stars having both large distances and low effective temperatures.

VI. Molecules

Over the past decade there has been a dramatic series of discoveries of new molecules in space which has followed from line-radiation observations at centimeter and millimeter wavelengths (Rank *et al.*, 1971). These radio studies have probed very dense clouds where a variety of moderately complex compounds could form rapidly and be protected from destruction by ultraviolet starlight. The large extinctions through these clouds, even at visible wavelengths, precludes our studying these rich molecule regions optically. In less dense areas, which are more representative of the 'general' interstellar medium, lines from the ground states of CH, CH^+ and CN have been observed in the visible spectra of some early-type stars. The observed abundances of these diatomic molecules at times exceed 10^{-9} that of hydrogen, a pattern which seems consistent with recent theoretical discussions by Watson and Salpeter (1972) and Solomon and Klemperer (1972). Measurements of absorption (or lack thereof) from the lowest rotationally excited levels of these molecules have helped to confirm that the cosmic background radiation indeed conforms to a 3 K black-body curve at millimeter wavelengths (Bortolot *et al.*, 1969).

The most abundant molecule in space, molecular hydrogen, has eluded detection until only recently. Except for pressure induced dipole transitions and some very weak quadrupole lines, this molecule does not have any resonance lines from the ground state at wavelengths longward of about 1100 Å (Field *et al.*, 1966). Hence visual and radio astronomical techniques have been unable to answer any questions concerning the distribution of H_2 in space, and even many of the early rocket and satellite ultraviolet experiments were not capable of observing the strong absorption by the Lyman bands because of insufficient sensitivity below about 1150 Å. Carruthers (1970) accomplished the first detection of interstellar H_2 features in his rocket observation of the spectrum of ξ Per. The ability to measure the transitions of H_2 was an important objective for the *Copernicus* telescope and was a strong justification for having a system sensitivity which extended well below 1100 Å. Shortly after the launch of *Copernicus* a survey of many stars was carried out to determine not only the abundances of H_2 but also the distribution of the molecules in various stages of rotational excitation.

The results of the initial H_2 survey were given in Paper IV of the original series of *Copernicus* articles. The most striking property of the abundances was that for most cases either a significant fraction of the atoms appeared in molecular form ($>10\%$) or else less than 10^{-7} of the atoms were bound in H_2. Figure 4 illustrates this bistable situation for the stars reported in Paper IV, where the H_2 column densities are plotted against the $B-V$ color excesses of the stars. The $E(B-V)$ values are a good representation of the total amount of interstellar material present. The data clearly show that concentrations of H_2 are found preferentially in regions of space where the gas (and dust) density is above a certain amount.

The qualitative features of the contrasting H_2 abundances are in accord with theoretical expectations. Stecher and Williams (1967) pointed out that when H_2 is excited into the $B_1\Sigma_u^+$ state by starlight photons in the Lyman bands, a significant fraction of the subsequent decays ends up in the vibrational continuum of the ground state, and the molecule is destroyed. Hollenbach *et al.* (1971) investigated the importance of self-shielding by H_2 in the Lyman bands and absorption by dust. They concluded that while destruction by unattenuated starlight can keep the equilibrium fractional abundance of H_2 at around 2×10^{-7}, when dense enough concentrations of material are present there is a fairly rapid shift toward much of the hydrogen being in molecular form.

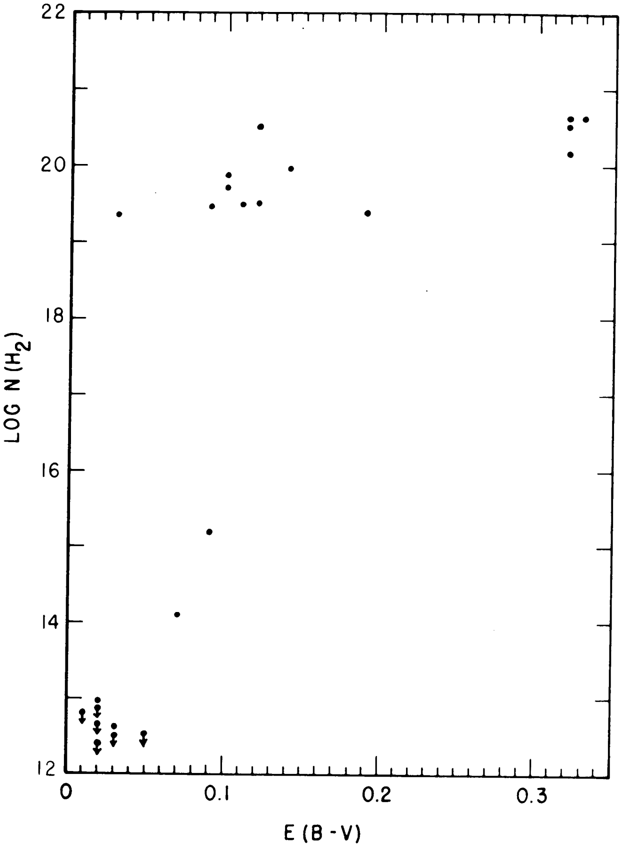

Fig. 4. A plot of measured H_2 column densities (or their upper limits) against interstellar reddening for the 23 stars reported in Paper IV of the original series of articles on the *Copernicus* results.

Paper IV also discussed the observation of lines from rotationally excited H_2, with absorptions appearing for molecules up to $J = 6$. In a followup on this finding, Spitzer and Cochran (1973) measured the various column densities $N(J)$ for a number of stars. They found that $N(1)/N(0)$ was generally consistent with a temperature of 80 K if $N(0)$ exceeded 10^{17} molecules cm^{-2}. Collisions with protons can be effective in transferring H_2 between these two levels (Dalgarno *et al.*, 1973), and hence the level populations are strongly coupled to, and a good measure of, the kinetic temperature of the gas. For the higher *J* levels ($J > 3$), the temperatures abruptly increase to values ranging from 180 to 390 K. Figure 5 illustrates the two temperatures for observations toward ξ Per. This pattern is rather typical of cases where $N(0) > 10^{17}$ molecules cm^{-2}. The high *J* molecules have a rapid enough radiative decay to preclude their

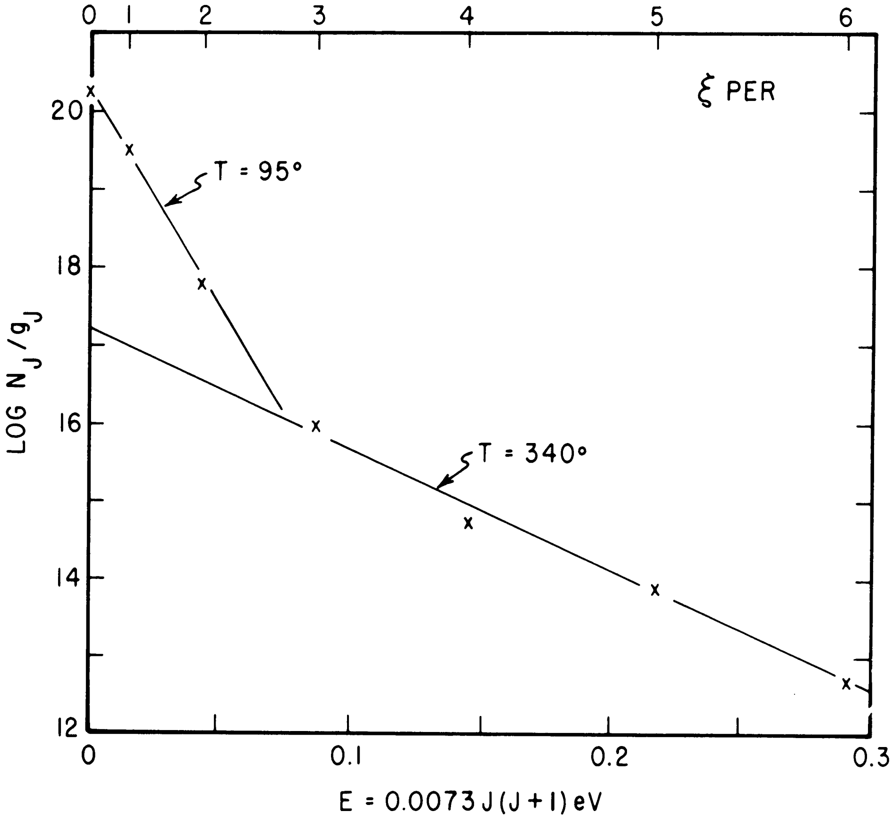

Fig. 5. An illustration of the two rotation temperatures of H_2 observed toward ξ Per, a star which shows the typical pattern found for large H_2 column densities. The ordinate of each point is the log column density of molecules in a particular rotation level *J* divided by the level's statistical weight, $2J+1$ or $3(2J+1)$ for even and odd *J*, respectively. The abscissa represents the energy of each level, with the *J* values identified at the top.

coming into equilibrium with the kinetic temperature, unless the total densities are somewhat higher than normal. Spitzer and Cochran also noted that the velocity dispersion (as deduced from the line widths) increased as the higher *J* levels were reached. They suggested the large rotational and translational excitation could be attributed to newly formed molecules. In addition, molecules which were not dissociated during the decay following an absorption of a Lyman-band starlight photon would usually cascade to a high *J* level. Aanestad and Field (1973) have explored the possibility that shocks in the interstellar gas could be responsible for the observed high rotation temperatures.

VII. Deuterium

The abundance of deuterium is of special interest because of the hypothesis that it may all be produced in the early stages of the big bang of the Universe. Unlike some other elements which are also produced in the primordial fireball, deuterium has a cosmic abundance which depends critically upon the present average density of the Universe, and hence a measurement of D/H is a useful discriminant of this quantity. A summary of various determinations of the cosmic D/H ratio has been prepared by Reeves *et al.* (1973), but the methods generally suffer from either giving rather high upper limits or indirect values based upon measurements with uncertain corrections. Observations of deuterium in the interstellar medium would aid in narrowing the uncertainty in the cosmic D/H ratio.

Paper IV listed a number of reasonably accurate determinations of the column densities of HD. Unfortunately, the ratios of HD to H_2 (generally around 10^{-6}) give us little insight on the actual abundance of deuterium. Two effects significantly alter the HD/H_2 ratio from that of the total D/H. First, by virtue of its lower abundance, HD is much less effective in protecting itself against dissociation in the Lyman lines. To compensate for this difference, corrected HD/H_2 ratios were derived in Paper IV which were higher than the observed values by factors of about 10^4. The second important effect, which works in the opposite sense to the first (and was not treated in Paper IV), arises from the importance of the exchange reaction, $H_2 + D^+ \rightarrow HD + H^+$. This reaction is exothermic owing to the difference in the zero-point vibrational energies of H_2 and HD. Hence, with other exchange reactions and the fractional ionization rate for H and D being equal, the one-sidedness of this reaction at interstellar temperatures favors a relative enrichment of HD, to an extent which is not too certain (Watson, 1973; Black and Dalgarno, 1973). Recent radio measurements of the DCN/HCN ratio (Jefferts *et al.*, 1973) also suffer from the difficulty of having to correct for the chemical fractionation effect (Solomon and Woolf, 1973).

The ideal measurement for a deuterium abundance in the interstellar medium is the ratio of atomic deuterium to atomic hydrogen in regions where no molecules are present. Although the separation of the H and D Lyman lines is only about $\frac{1}{4}$Å, it is possible to distinguish the two in Ly-β and higher order lines when the hydrogen column densities are not too large. From an analysis of the interstellar Ly-β, -γ and -δ lines in the spectrum of β Cen, a star which is bright at short wavelengths (due to the negligible reddening) and which has no H_2 in the line of sight, Rogerson and York (1973) found a D/H number ratio of 1.4×10^{-5}.

After a correction for the deuterium consumption by stars during the age of our Galaxy, the aforementioned result implies a primordial abundance which is consistent with a present density of 1.5×10^{-31} g cm^{-3} for the Universe. This density is somewhat above the estimate by Shapiro (1971) of 5×10^{-32} g cm^{-3} (with H revised to 50 km s^{-1} Mpc^{-1}) for the amount of *visible* material present, but is considerably smaller than the critical density of 4×10^{-30} needed to close the Universe. There is some uncertainty in the magnitude of the correction for consumption by stars, but even if the effect is neglected altogether – a most conservative stance – the deuterium measure would still not be consistent with a closed Universe. Colgate (1973) has suggested that significant deuterium production may occur in supernova shocks. Some indication of whether or not this possibility may be an important source of deuterium may be accomplished by looking for a variability in the abundance ratio over various lines of sight or, better yet, by looking for an enhancement in the amount of deuterium along a path through a young supernova remnant.

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DISCUSSION

Zuckerman: The Copernicus results appear reasonably consistent with ionization by starlight in H I clouds plus a contribution from the H II regions that surround the observed stars. There is no apparent reason to invoke a non thermal (i.e., X-ray or cosmic ray) source of ionization for the intercloud medium which might, therefore, be an extended very low density H II region. Interpretation of the diffuse radio recombination line radiation also suggests that much of space may be filled with very low density H II regions. Thus, except possibly for the 21-cm emission results, there appears to be no observational evidence for a hot partially ionized (H I) intercloud medium. Perhaps the broad 21-cm lines observed at high latitudes are due to a blend of relatively hot H I clouds having a fairly wide dispersion of velocities rather than the 'intercloud' medium.

Jenkins: I would tentatively agree with your remarks. We are improving our wavelength scale to a point where we can separate with some confidence gas clouds of different velocities. For some of the data now being analyzed we can differentiate between absorption lines produced by the star's H II region and lines arising from the intercloud regions.

Heiles: If you look at stars in some high-latitude regions you may expect not to find any intercloud medium because there is a great big region up in positive latitudes where all the intermediate and high velocity gas is concentrated and where all the local-velocity gas disappears. I think this is shown most beautifully in the slides van Woerden showed in Sydney, and also I see it in my profiles. So if you ever look at a star and see only 0.02 cm^{-3} along the line of sight to the star, you should check if this star is in that particular region, which occupies a very large solid angle in the sky, and, if it does, then all it tells you is that the intercloud medium in that particular region has been disturbed by the energetic events which have produced the intermediate and high velocity gas.

van Woerden: The low-velocity hole at high northern latitudes is not *empty* of hydrogen; the column density there, for $-20 < V < +15$ km s^{-1}, is still about 0.9×10^{20} H cm^{-2} (Wesselius and Fejes, *Astron. Astrophys.* **24** (1973), 25, Figs. 6 and 7). Takakubo (in preparation) has found that the hole is prominent for narrow components ($\sigma < 7$ km s^{-1}), but absent for the wide components ($\sigma > 7$ km s^{-1}), which may be identified with the intercloud medium. Thus, here as almost everywhere, observations are consistent with a smooth intercloud medium.

Heiles: I agree.