Observations of the Interstellar Gas with the Copernicus Satellite

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Observations of the interstellar gas with the Copernicus satellite

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Recent results are summarized on interstellar H I, D I, H_2, HD, and heavy elements whose absorption lines have been measured in the far ultraviolet.

The ultraviolet scanning spectrometer of the Copernicus satellite telescope has been described by Rogerson *et al.* (1973). Since the launch on 1972 August 21, the spectra of some 90 stars have been scanned in selected regions between 920 and 3100 Å† with resolutions up to 11 km s^{-1} f.w.h.m. for the study of interstellar absorption lines. To date we have detected one or more ions of H, D, C, N, O, Mg, Al, Si, P, S, Cl, Ar, Mn, Fe, Cu and Zn, as well as the molecules H_2, HD and CO in the interstellar gas. In addition, more complete lower resolution scans have been used by York *et al.* to extend the interstellar extinction curve to 1000 Å. The steepness of the curve at the shortest wavelengths implies some scattering particles with radii smaller than 350 Å.

The strength of the interstellar Lyman α absorption line gives a direct measurement of the column density towards any star in which the stellar feature is separated easily, or is not important. Preliminary results confirm the analysis of the OAO-2 data by Savage & Jenkins (1972) and Jenkins & Savage (1974) who reported wide differences in various directions. Spitzer *et al.* (1973) found an average volume density of $n_{\text{H I}} \approx 2$ cm^{-3} over the 57 pc‡ towards σ Sgr, compared with 0.09 cm^{-3} over 460 pc to δ Ori. Rogerson & York (1973) obtained 0.14 cm^{-3} for the 80 pc to β Cen. (Distances were taken from Lesh 1968, 1972.) The higher concentrations occur where reddening indicates the presence of a moderately dense interstellar cloud. A more accurate analysis of the Lα profiles is now underway by Bohlin, who has developed a scheme for eliminating the stray light described by York *et al.* (1973). The interstellar absorption superposed on the Lα emission line in cool stars provides important information on H I densities near the Sun. Linsky, Moos, Henry & McClintock (1974) found $n_{\text{H I}}$ lies between 0.02 and 0.1 cm^{-3} over 11 pc to α Boo.

Rogerson & York (1973) found that the H I lines in β Cen are sufficiently weak that the D I lines of Lβ, Lγ, Lδ and Lε were measurable about 0.26 Å shortward of the H I centres, giving a ratio of D/H $= (1.4 \pm 0.2) \times 10^{-5}$ by number in the interstellar gas. Colgate (1973) has suggested that this deuterium could be formed in supernovae explosions, though Epstein, Arnett & Schramm (1974) have argued that the same process would produce more of the principal isotopes of Li, Be, and B than found. Deuterium can be produced in a big bang, but the amount decreases rapidly with increasing density, as shown by Reeves, Audouze, Fowler & Schramm (1973). The observed D/H requires a universe with a present density $\rho_0 = 4.7 \times 10^{-31}$ g cm^{-3} if there were no burning of deuterium in stars and $\rho_0 = 1.5 \times 10^{-31}$ g cm^{-3} if the present D/H is increased by a factor 6.4 to account for the expected processing through stars. For comparison

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† 1 Å = 0.1 nm = 10^{-10} m.
‡ 1 pc = 3.09×10^{16} m.

$\rho_0 = 4\times10^{-30}$ if the universe is closed and $H_0 = 50$ km s^{-1} Mpc^{-1}. Thus the measurement of D I implies an open universe unless some alternate source for the interstellar deuterium proves to be reasonable. Observations are now under way to test whether D/H is constant in various directions.

The number of hydrogen nuclei in the form of H_2 towards reddened stars often is comparable with the number of H atoms, as shown by the analysis of Spitzer *et al.* (1973). Weak H_2 lines also have been found in the spectra of stars with relatively little interstellar reddening, but the column densities are much smaller. Glassgold & Langer (1974) and Jura (1974) have shown how this pattern is consistent with the ideas of Hollenbach, Werner & Salpeter (1971), in which H_2 is formed on grains and dissociated by absorption of u.v. photons with $\lambda \approx 1000$ Å. Such photons can excite a high state in the second electronic level which can decay into the vibrational continuum of the ground state. In dense clouds self shielding and absorption by grains protects the H_2, while the molecular densities towards the unreddened stars represent the equilibrium between formation and destruction with no protection. Spitzer & Cochran (1973) and Spitzer, Cochran & Hirshfeld (1974) have examined the population of the excited rotational levels in the lowest vibrational state of the ground state. For 13 stars with $N(H^2, J = 0) > 10^{17}$ cm^{-2} the relative number of molecules in $J = 0$ and $J = 1$ corresponds to a Boltzmann distribution with temperatures $T = 81 \pm 13$ K, close to the kinetic temperatures derived from 21 cm observations. Dalgarno, Black & Weisheit (1973) have noted the high rate coefficient for excitation between $J = 0$ and 1 by charge-exchange collisions with protons, so that the kinetic temperature of the gas is quickly reflected in the populations. In these stars, the populations of the levels from $J = 3$–6 correspond to higher temperatures, from 180 to 390 K. In the case of stars with relatively small column densities, $N(H_2, J = 0) < 10^{15}$, a single temperature between 216 and 1100 K can explain the populations of all J levels. Aannested & Field (1974) have shown that a shock wave at 13 km s^{-1} could produce an excitation temperature of 660 K, but the lack of any velocity separation greater than 2 km s^{-1} between $J = 0$–3 and $J = 4$–6 in ζ Oph shows that a shock is not the explanation for this star. Further discussion of the excitation of the higher rotational levels will be given by Dalgarno.

Spitzer, Cochran & Hirshfeld (1974) observed HD lines in 13 stars with $N(\mathrm{HD}) \approx 10^{14}$ cm^{-2} and $\mathrm{HD}/H_2 \approx 10^{-5}$ to 10^{-6} by number. HD can be destroyed much more easily than the H_2 because the strongest absorption lines occur at different wavelengths, avoiding the shielding by the more abundant H_2. However, Watson (1973) and Black & Dalgarno (1973) have noted that HD can be formed easily by the process

$$\mathrm{H^+ + D \rightarrow H + D^+},$$

$$\mathrm{D^+ + H_2 \rightarrow HD + H^+},$$

since the right-hand side of the second reaction has lower energy. Black & Dalgarno (1973), Jura (1974) and O'Donnell & Watson (1974) have used the observations of H I, D I, H_2, HD and D/H to estimate the H^+ density in clouds and the ionizing flux needed to produce the H^+. Jura (1974) made a realistic calculation of the stellar radiation field and found a hydrogen ionization rate $\zeta_H = 5\times10^{-17}$ s^{-1} per H nucleus due to X-rays or cosmic rays.

The inital analysis of reddened stars (Morton *et al.* 1973), for which the line of sight should pass through one or more interstellar clouds, showed evidence for depletion of several heavy elements in the gas when compared with solar abundances. A more detailed investigation of ζ Oph by Morton (1974) has indicated depletions of C, N, O, Mg, Al, Si, P, Mn, Fe, Ni and Cu by factors of 10 or more while S appears close to normal. Measurements in the visible have shown that Ca and Ti also are depleted, and so are Li, Na and K if their ionization can be estimated from the electron density $n_e = 0.4 \text{ cm}^{-3}$ derived from Ca I/Ca II. Abundance determinations from the strong u.v. lines can depend critically on the choice of the internal velocity parameter b. The visible lines of Na I and K I easily can be ionized to a higher state, while Ca is strongly depleted and therefore cannot be considered representative. Hobbs (1974) has shown that $N(\text{K I})$ varies as $N(\text{H I})^2$ implying that neutral K is more prevalent where n_e is high and thus is not expected to be distributed in the same way as the dominant species C II, N I, etc., seen in the u.v. Other neutrals such as C I, Na I and Fe I should be similar to K I. In the case of ζ Oph there are enough lines of such elements to determine an empiral curve of growth, so that the derived abundances should not depend significantly on the distribution over clouds at various velocities. Furthermore the absence of damping wings on most profiles places important upper limits on column densities. Details of the Fe II curve of growth for ζ Oph have been reported by de Boer, Morton, Pottasch & York (1974), who found an effective b of 7 km s^{-1} and Fe/H with 0.01 the abundance by number in the Sun. The ratio Mn/H was depressed to 0.05 the solar value. In contrast, de Boer & Morton (1975) concluded that b for C I is 1 km s^{-1}, indicating this atom must be concentrated in the cloud with the majority of the Na I and K I which require similar b values according to de Boer & Pottasch (1974) and Hobbs (1973).

Since Jenkins *et al.* (1973) found that $\text{CO/H} = 4\times10^{-7}$ or less by number towards four stars and that several other likely molecules were not detectable in ordinary clouds, the missing material probably is in grains rather than molecules. In fact, it is reasonable to expect a certain fraction of the heavy elements in clouds to be absent from the gas to provide the material for the grains. Field (1974) has noted that the trend of increasing depletion with increasing condensation temperature supports the idea of the formation of the grains by chemical equilibrium in the atmosphere or nebula of a cool star which is returning matter to the interstellar medium. Some later accretion of C, N and O in a dense cloud seems necessary to explain these depletions, but a general accretion of all elements on grains appears to be ruled out. One difficulty with Field's scheme is the low abundance of interstellar boron found by Morton, Smith & Stecher (1974). They concluded that in the gas towards ζ Oph, B/H by number is less than 0.02 the abundance expected from the ratio of B/Si in carbonaceous chondrites. Interstellar boron ought to be relatively normal since its condensation temperature has been estimated to be around 700 K, close to that of S. The carbonaceous chondrites may not be a suitable standard because they contain boron with an abundance 6–9 times the upper limit for the solar atmosphere. Any nuclear burning of boron would require an unexpected amount of mixing early in the Sun's history.

The four stars α Eri, α Leo, υ Sco and λ Sco with very little reddening were analysed by Rogerson *et al.* (1973) to determine the properties of the intercloud medium. Recently Spitzer *et al.* (1974) have found H_2 towards similar stars such as 20 Tau and μ Col with $E_{B-V} = 0.02$, implying that some cloud material can be present almost anywhere. A significant depletion of Fe towards α Vir and β Cen has been reported by de Boer *et al.* (1974). In α Vir, York (1974) also has found depletion of Mg, Si, Ca and Mn, but not C, N, O and S consistent with a picture of fractionation by chemical processes without the later accretion of the lighter elements. It has been argued that a heat source is needed in the intercloud medium in addition to the known u.v. and X-ray fluxes to produce $n_e = 0.03 \text{ cm}^{-3}$ deduced from the pulsar dispersion measures. An X-ray spike (Weisheit 1973) at 100 eV is inconsistent with the observed relative populations of ion states, while the HD abundance in clouds shows that neither X-rays nor cosmic rays can be important. More likely candidates seem to be various types of hot stars whose u.v. flux is not entirely absorbed by clouds so that the intercloud medium could be mainly H II with a few small H I clouds.

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