INTERSTELLAR LINES AND ABUNDANCES FROM THE FAR-U.V.

K. S. DE BOER

Kapteyn Astronomical Institute, University of Groningen, The Netherlands

Résumé. — Plus de 200 lignes d'absorption de H₂ et C°, formées dans les nuages interstellaires, contiennent une information sur la densité et la température du gaz. Les autres lignes métalliques donnent l'abondance des éléments dans le milieu interstellaire très proche de 0,5 kpc. Cette contribution discute aussi des difficultés rencontrées dans l'interprétation des intensités des raies.

Abstract. — Over 200 lines from H₂ and C°, formed in interstellar clouds, contain information on the density and the temperature of the gas. Other lines from metals give the abundance of the elements in the solar neighbourhood. Problems with the interpretation of line intensities are discussed.

1. Introduction. — Since the early seventies we face a big step forward in our knowledge on interstellar absorption lines. After the indication of N, O and Si and the discovery of the molecule H₂ (Carruthers, 1970 [9]) in rocket spectra, the TD I satellite gave the first quantitative results on metals such as Mg I, Mg II, Mn II and Fe II (de Boer et al. 1972 [4]). The high quality observations with Copernicus have shown the existence of almost every element which is reasonable abundant in interstellar space. After the presentation of the preliminary results on a few stars in the Astrophysical Journal in May 1973, the first detailed analysis was of the well-known interstellar line star ζ Oph [14] followed by several other stars [16], [25], [20], [21].

2. Spectral resolution, reduction techniques. — After the pioneering work of Hobbs (1969) [10], who observed the visual NaID lines at very high spectral resolution, it has become clear that the interstellar medium is full of velocity structure. Clouds can be recognized by radial velocity differences down to the characteristic width of 1-2 km.s⁻¹ for many clouds. Therefore, detailed observations require a spectral resolution ∆λ/Δλ ≥ 10⁵, compared to ≈ 10³ for TD I and rocket spectrographs. Even Copernicus and IUE with 3 × 10⁴ have insufficient resolution for very reliable interstellar line studies.

The reduction to column densities is complicated by curve of growth problems. The first warnings came with the preliminary Copernicus results, and ζ Oph was the first star for which these problems were tackled for the neutral species [6]. For ζ Oph the three different curves of growth needed in the interpretation were collected into one picture by Spitzer and Jenkins (1975) [22]. With such ambiguities on the optical depth, the column densities derived from only 1 or 2 lines available for some elements are very uncertain. In fact the same simple analysis as what was common from 1935-1970 is applied frequently, hence the results often are misleading. This is in particular true for column densities in individual stars derived from one line only (e. g. TD 1) ; in particular for C⁺ and to a lesser degree for N⁺ and O° from observations with Copernicus. If all lines discovered of C° (> 100), Fe° (14), O° (13) and Si⁺ (?) are observed indeed, strong limits are available as to what the optical depth relation is.

3. Molecular hydrogen, neutral carbon, excitation. — Lines of H₂ are seen in large numbers in the spectra, e. g. Morton (1975) reported on 118 in ζ Oph. From the distribution over the levels, a temperature of excitation can be derived provided the excitation is governed by collisions. The population of the J = 0 and 1 levels probably refers to the densest gas. From the results in 13 stars Spitzer and Jenkins (1975) [22] find an average excitation temperature of 80 K. This compares well with temperatures found from H I 21 cm absorption profiles. From various models on H₂ formation it follows then that n_H = 10² - 10³ cm⁻³ [23].

The other element with a large number of lines is neutral carbon. In ζ Oph over 100 lines are seen with about 25 usable ones from each level in the 3P ground state. The analysis proved to be laborious as only a few transition probabilities were known. Half of the lines were used by de Boer and Morton (1974) [6] to solve for column densities, f-values and the curve of growth, and de Boer (1974) [4] showed that C° follows the same optical depth relation as Na°. A recent refinement (ζ Pup, [7]) confirms the earlier results in spite of transition probabilities which differ from laboratory measurements. With excitation cross
sections for $C^0-H^0$ collisions of Launay and Roueff (1977) [13] one can explain the level populations. For $\zeta$ Oph $T_{\text{ze}} = 70$ K and $n_H = 150$ cm$^{-3}$ is found (excluding the earlier high density solution).

The C I data give about the same temperatures as found from H$_2$ but point to lower densities. Also the H$_2$ lines seem to have a larger velocity spread than the C I lines. But with the uncertainties in observations, reductions and the models used, the agreement is satisfactory.

4. Molecules, 0 VI, extinction. — Many other species have been detected in the far-U.V. The metals are not discussed here in detail. From some ion ratios one may calculate $n_e$. Only 3 molecules were discovered, H$_2$, HD and CO, the latter being the only molecule detected by optical and radio means. In particular the observations to $\zeta$ Oph have led Black and Dalgarno (1977) [2] to construct a detailed model for the line of sight to $\zeta$ Oph, including predictions on the abundances and detectabilities of many other molecules.

It was a surprise to find 0 VI in many spectra. Jenkins and Meloy (1974) [12] studied this and they noted that the absence of lines from N V, Si IV and S IV points to gas of corona like temperatures $T \geq 3 \times 10^5$ K. This temperature was consistent with the observed doppler widths of the 0 VI lines. There has been some dispute if the 0 VI was formed very close to the stars, but the appearance of that ion also in somewhat later type stars made it clear that the hot gas occupied a large volume in the interstellar space, possibly at low density, and it may be the source of the widespread diffuse soft X-ray background as well.

Recently Savage et al. (1977) [18] have shown that the amount of molecular hydrogen correlates well with extinction. For $E_{B-V} < 0.1$ the amount of H$_2$ is well below $10^{19}$ cm$^{-2}$, for larger $E_{B-V}$ mostly $N_{H_2} > 10^{20}$ cm$^{-2}$. Consequently the fraction of molecules to total hydrogen jumps from very small values to between 5 and 50 % if $E_{B-V} > 0.1$. The ratio of hydrogen to extinction gives

$$(N_{H_2} + 2N_{H_0})/E_{B-V} = 5.5 \times 10^{21} \text{ at.cm}^{-2} \text{.mg}^{-1},$$

or somewhat larger for small fractions of H$_2$, and reverse. The ratio may be compared with what has been found to globular clusters i. e.

$$5.1 \times 10^{21} \text{ at.cm}^{-2} \text{.mg}^{-1}$$

and with the amount of equivalent H atoms deduced from the attenuation of soft X-rays by Ryter et al. (1975) [17], $6.8 \times 10^{21} \text{ at.cm}^{-2} \text{.mg}^{-1}$.

5. Abundances. — With all the column densities derived, and allowing for the possible ionization stages, the abundance of an element can be calculated. The depletion of metals was evident from the first U.V. measurements on and similar to what was known from elements observed in the visual (Na, Ca, K, Ti). As young stars show almost the same abundances as the sun the depletion is real. Following old suggestions that dust comprises the non-free metals we now can deduce the composition of the dust. Calculations on the fractionation of protoplanetary matter (review by Barshay and Lewis, 1976 [1]) hint to a relation of the amount of depletion of free elements with the condensation temperature. With well determined average abundances from the visual [8], [11], [24] and for Mn and Fe from TD 1 [5] the high temperature part of the curve seems to be well established. Snow (1975) [19] suggested that grains grow just due to high density. The ions have to stick, but the energy released at recombination in the encounter would more easy push the high ionization potential elements off.

Following cooling theories, first Perovskite (CaTiO$_3$) should form followed by large amounts of Enstatite and Olivine (Mg-silicates). The average abundances seem to be near normal for $T_c < 10^3$ K. And so in the gas in the solar vicinity the dust represents about 0.5 % of the interstellar matter.

The U.V. observations, requiring high spectral resolution, had to be restricted to bright stars, $m_V < 5$. So B stars were closer than 500 pc and some O type stars may be observed by Copernicus out to 1 kpc. There also will be a bias to stars with only little reddening. The U.V. data do reflect conditions and abundances in the solar neighbourhood only. No U.V. data whatsoever are available from really dense clouds with star formation of from H II regions. Therefore the U.V. and the I. R. inform us on different parts of the interstellar medium.
References