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THE EXCEPTIONALLY VACANT LINE OF SIGHT TO BETA CANIS MAJORIS

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ABSTRACT

Copernicus UV data on interstellar lines in the spectrum of β CMa are analyzed to study the physical conditions in the (nearby) interstellar medium in this direction. The derived abundances indicate a very weak neutral component which, from comparison with other results concerning the nearby ISM, appears to be confined to the first few parsecs, with a density of 0.1 cm^{-3}. Furthermore, the ionized gas appears to be more abundant than the neutral gas. It has a density also around 0.1 cm^{-3} (derived from the excited level of C II) and ionization ratios consistent with a collisional equilibrium temperature of 25,000 K, filling 20%–45% of the line of sight. A marginal detection of O VI indicates the presence of very diffuse coronal gas. The location of the ionized phases as well as the ionizing mechanisms are not yet clear and need to be further discussed through model comparisons.

Subject headings: interstellar: abundances — interstellar: matter — stars: individual — ultraviolet: spectra

I. INTRODUCTION

The local interstellar medium can be probed using *Copernicus* observations of bright B stars (see, for example, York 1983; York and Kinahan 1979; Ferlet *et al.* 1980). Studies to date have revealed that gas within 100 pc of the Sun includes temperatures in the range 6000 K to 4×10^5 K. Observations of H_2 and Na I suggest that there are some cool clouds ($T < 100$ K) in these regions. Soft X-ray emission which fairly uniformly fills the sky may come from gas with $T > 10^6$ K in the 100 pc region near the Sun (McCammon *et al.* 1983), but the origin of this emission is still ambiguous.

The presence of warm neutral gas is not yet clearly defined in current models. There are several sources of heating of cloud edges (e.g., cosmic rays, shocks, UV radiation), but it is difficult to say which is most important or applicable in a given part of space. It is therefore important to obtain good observational definition of the filling factors and locations of the various phases.

Consequently, interstellar lines in all bright unreddened B stars within 150–200 pc have been observed with *Copernicus*. This paper presents the results for β CMa, a B1 III star, 200 pc away from the Sun, the line of sight to which passes through the nearly empty region surrounded by Gould's belt.

Section II presents the column density and velocity analysis; § III includes an analysis of the separate physical regions present.

This particular line of sight is remarkable for its low mean densities. We find $\bar{n}_{\rm H\,I} \approx 0.002$ cm^{-3}, $\bar{n}_{\rm H\,II}$ ($T < 50{,}000$ K) ≈ 0.02 cm^{-3}.

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II. LINE PROFILE ANALYSES

a) Measurements

The measurements used in this analysis were all obtained with the *Copernicus* satellite in the 900–1300 Å range, which is particularly rich in atomic and ionic resonance lines. Except for the deuterium and hydrogen Lyman lines, observed from

TABLE 1
LINES USED WITH THEIR WAVELENGTHS AND OSCILLATOR STRENGTHS

Element	λ (Å)	f
H I	1025.722	7.9×10^{-2}
	972.537	2.9×10^{-2}
D I	1025.442	7.9×10^{-2}
	972.272	2.9×10^{-2}
N I	1134.415	2.7×10^{-2}
	1134.165	1.3×10^{-2}
	1199.549	1.3×10^{-1}
	1200.711	4.4×10^{-2}
O I	1302.169	4.9×10^{-2}
Si II	1190.416	2.5×10^{-1}
S II	1250.586	5.4×10^{-3}
	1253.812	1.1×10^{-2}
	1259.520	1.6×10^{-2}
S III	1012.504	3.6×10^{-2}
	1190.206	2.2×10^{-2}
Si III	1206.510	1.7×10^{0}
C II*	1037.018	1.3×10^{-1}
N II	1083.990	1.0×10^{-1}
O VI	1031.928	1.3×10^{-1}
	1037.619	6.5×10^{-2}

NOTE.—Sources: Morton and Smith 1973; Morton 1978.

TABLE 2

CHARACTERISTICS OF THE COMPONENTS

Species (1)	Observations[a] N (cm^{-2}) (2)	b (km s^{-1}) (3)	V (km s^{-1}) (4)	N (cm^{-2}) Expected[b] (5)
H I	1–2.2 × 10^{18}	13.5–14.3	0.5–2.5	...
D I	1.5–2.3 × 10^{13}	9–12	0.5–2.5	...
N I	6–8.2 × 10^{13}	6.5–8	0.6–4.3	5–14 × 10^{13}
S II	1.7–2.2 × 10^{14}	6–8	4.4–6.2	2.9 × 10^{13}
S III	0.9–1.6 × 10^{13}	7–8	5–8	7 × 10^{7}
Si II	> 1.9 × 10^{13}	...	5–8	6 × 10^{12}
Si III	1.2–1.7 × 10^{12}	7–8	5–8	4 × 10^{10}
N II	1–50 × 10^{14}	7–8	5–8	5 × 10^{12}
O I	3.8–16.8 × 10^{14}	6–8	3.2–4.5	5.7–14.5 × 10^{14}
C II*	0.8–1.3 × 10^{13}	7–8	5–7	...

[a] Derived from absorption profiles. Ranges listed are those for which a statistically acceptable fit to the profile results.

[b] Predicted abundances in the H I region where N(H I) = (1–2.2) × 10^{18} cm^{-2} and T = 11,000–12,500 K.

1980 December 23 to December 25, all the data have been obtained from 1973 January 22 to January 26. The spectral lines used in this study are listed in Table 1. The wavelengths and f-values were taken from the compilation of Morton and Smith (1973), including some improvements provided by Morton (1978), for the wavelengths of O VI and the f-value of Si II 1190.416. Note that some elements, in particular N I and S II, are observed through lines of different oscillator strengths, which allows a more precise determination of the gas phase parameters.

To derive the column density $N(Z)$, the b-value $b(Z)$, and the velocity $V(Z)$ of every element Z investigated here, we used the profile fitting program described by Vidal-Madjar *et al.* (1977) and Ferlet *et al.* (1980). An iterative process, based on the least-squares principle, fits the observed profiles with one or several interstellar components simultaneously with a stellar component defined as a third-order polynomial interpolated from the continuum on both sides of the line. The analysis was affected by the presence in the spectrum of many relatively narrow stellar lines ($V \sin i$ = 35 km s^{-1}), reducing sometimes (see Figs. 2*b* and 2*c*) to a few points the adjacent stellar continuum used to define the stellar contribution to the profile. Yet, letting the polynomial parameters vary together with the interstellar component parameters, we obtained good fits of all observed interstellar lines by considering only one component in the line of sight. Fits were also performed with two and three components without any formally better results.

The resulting central velocities, b-values, and column densities are listed in Table 2 as the highest and smallest acceptable values before a measurably poor fit results. In Figures 1 and 2 the observed spectrum is plotted for each line together with one of the computed one-component profiles that best fit it.

b) *Velocities*

The velocities listed in Table 2 are with respect to the local standard of rest and are accurate to ±2 km s^{-1} (1 σ) in absolute terms. Relative velocity errors are included in the ranges quoted in Table 2 (i.e., ∼ ±1 km s^{-1}).

From Table 2, one can see that the neutrals have rather lower velocities than ionized species. H I, D I, and the weakest lines of N I show a LSR velocity of about 0.5–2.5 km s^{-1}, whereas the S II, S III, N II, Si III, and C II lines imply a velocity of 5–8 km s^{-1}. The strongest N I line at 1199.5 Å and the strong O I line at 1302.2 Å are intermediate, with 4 km s^{-1}. As we mentioned previously, these differences may be due to the uncertainty when placing the stellar continuum, but in view of the systematic nature of the shifts with respect to ionization, they more probably suggest the presence of two different components in the line of sight: one containing almost all the neutral gas near +2 km s^{-1}, and the other being almost entirely ionized and moving at a different radial velocity of 7 km s^{-1}.

c) H I *Abundance*

The total neutral hydrogen column density was found to be less than 5 × 10^{18} cm^{-2} by Bohlin (1975). This is confirmed here by the Lyman-β profile, which shows no damping wings (see Fig. 1). With a reasonable choice of the stellar line, the fit gives N(H I) = (1–2.2) × 10^{18} cm^{-2}, and a rather high b-value: b(H I) = 13.5–14.3 km s^{-1}.

d) D I *Abundance*

The deuterium feature in Lyman-γ is detectable, and an upper limit for its equivalent width was found to be 5.3 mÅ (by the method described by Jenkins *et al.* 1973). This value lies at the top of the linear part of the curve of growth, and we could thus derive N(D) < 2.5 × 10^{13} cm^{-2}. Furthermore, the Lyman-β deuterium line was fitted together with the hydrogen line, and this gave a deuterium column density in the range N(D) = (1.5–2.3) × 10^{13} cm^{-2}. The ratio of deuterium to hydrogen in this line of sight is thus N(D)/N(H) = (0.7–2.3) × 10^{-5}.

e) *Other Species*

1. N I.—From the three weakest lines (1134.165 Å, 1134.415 Å, 1200.711 Å), the column density of N I is found in the range N(N I) = (6–8) × 10^{13} cm^{-2}, independent of the b-value which can lie between 3 and 7 km s^{-1}. This is consistent with the stronger 1199.549 Å line, which provides the formal additional constraint that b(N I) > 6.5 km s^{-1}, though this b-value is probably affected by the presence of two components, one from H I gas and one from H II gas.

2. S II.—The S II column density is also well determined, being found with the help of three different lines (1250.586 Å, 1253.812 Å, and 1259.520 Å): N(S II) = (1.7–2.2) × 10^{14} cm^{-2}.

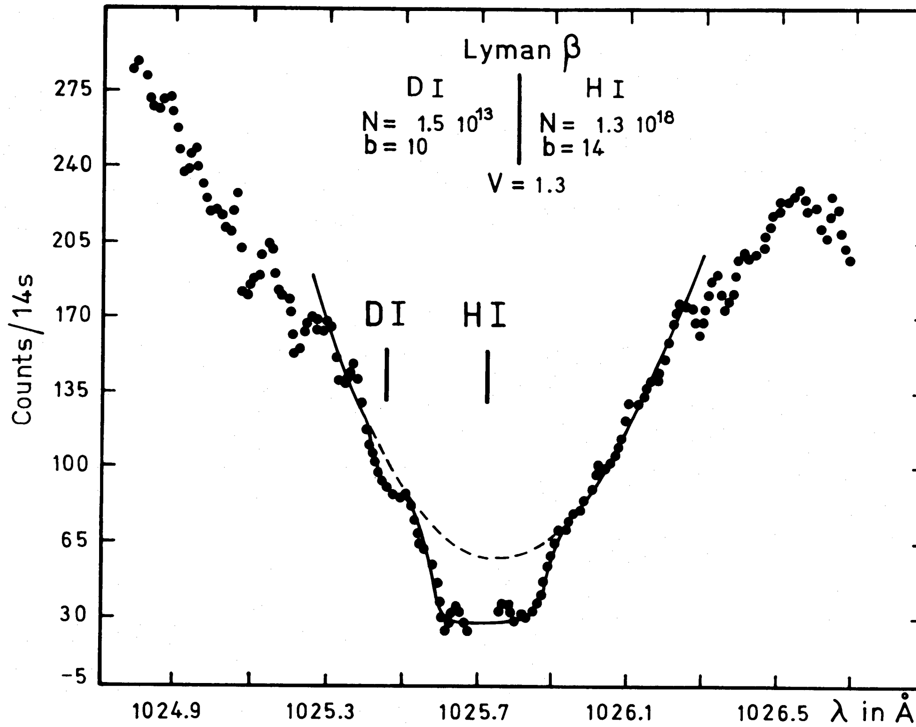

FIG. 1.—H and D Lyman-β profiles. The dots are the data obtained with the *Copernicus* U1 Spectrometer at a resolution of 0.045 Å. The theoretical profile (*continuous line*) is obtained by a least-squares fitting program which optimizes simultaneously the stellar contribution (*dotted line*) and the interstellar component (defined by N, b, V). In this case the shape of the profile excludes the possibility of a smaller stellar contribution; furthermore, the low amount of interstellar matter is evidenced by the absence of damping wings in the interstellar part of the hydrogen profile.

3. The column densities of the other species (Si III, S III, N II, C II*, O I, and Si II) are somewhat less precise, each being derived from only one line which can be blended with stellar features. One of the S III lines, λ1190.205, has no detectable interstellar component, giving only an upper limit for N(S III)—which is, however, determined more accurately from λ1012.504.

On the other hand, the adjacent Si II 1190.416 line could not be fitted due to the lack of continuum on the red side of the profile (see Fig. 2*e*). A very rough estimate of the equivalent width gives a lower limit to the Si II column density of about 1.9×10^{13} cm^{-3}.

4. As for the two O VI lines, only the stronger (1031.928 Å) might be marginally detected at a velocity of about 5 km s^{-1} (see Fig. 2*m*). The program failed to fit it properly due to the erratic shape of the stellar profile, which makes even the identification of the O VI absorption uncertain. Moreover, the line could be very wide, and probably much wider than shown by the b-value given on Figure 2*m*, hiding part of the absorption. It should also be noted that an eventual O VI component with a velocity higher than 100 km s^{-1} would fall outside the wavelength range scanned and would thus be invisible.

III. DISCUSSION: THE NATURE OF THE INTERSTELLAR MEDIUM IN THE LINE OF SIGHT

a) The Neutral Gas

The H I column density is very low for a 200 pc line of sight; it is comparable to the column densities found toward much closer stars. In fact, observations of nearby stars, as well as evaluations made locally inside the solar system, lead to a local neutral hydrogen density of about n(H I) = 0.1 cm^{-3} (see, e.g., Vidal-Madjar *et al.* 1978; Dupree, Baliunas, and Shipman 1977; McClintock *et al.* 1978; Anderson and Weiler 1978). Adopting this value, neutral hydrogen extends only 5 pc along the line of sight to β CMa. This is in perfect agreement with observations toward the star α CMa B which lies 2.7 pc away from the Sun and only 0.3 pc out of the line of sight to β CMa.

The line of sight to α CMa B has been discussed by Kondo *et al.* (1978) and by Bruhweiler and Kondo (1982). From the observation of the 1260 Å Si II line, and by comparison with the results obtained in the direction of other nearby white dwarfs, they claim a neutral hydrogen column density of 8.5×10^{17} cm^{-2}. This value is half of what we found for β CMa and is indeed what we expect if α CMa B lies half way between the Sun and the end of the H I cloud in the direction of β CMa, i.e., if this cloud has an extension of 5 pc in this direction.

From the b-value of the H I line, supposing it to represent thermal broadening, we derive a temperature of 11,000–12,500 K. This value of the temperature is in very good agreement with that inferred from observations of Lyman-α and He 485 Å radiation produced by the flow of interstellar matter into the solar system (Bertaux *et al.* 1976; Cazes and Emerich 1977; Adams and Frisch 1977; Weller and Meier 1981).

The expected contributions to the N I, O I, S II, S III, Si II, and Si III absorption lines of such a region (with an H I column density of $(1–2.2) \times 10^{18}$ cm^{-2} and a temperature of 11,000–12,500 K) have been evaluated and added to Table 2 for comparison with the observed column densities. For each of these elements, Z, we have assumed a mean interstellar abundance: $\log (N/H)_I \approx -4.3$, $\log (O/H)_I \approx -3.18$, $\log (S/H)_I \approx -4.8$, $\log (Si/H)_I \approx -4.48$ (Spitzer and Jenkins 1975; Ferlet 1981; York *et al.* 1983), and we have made the assumption that the medium is in collisional equilibrium, using the computations of

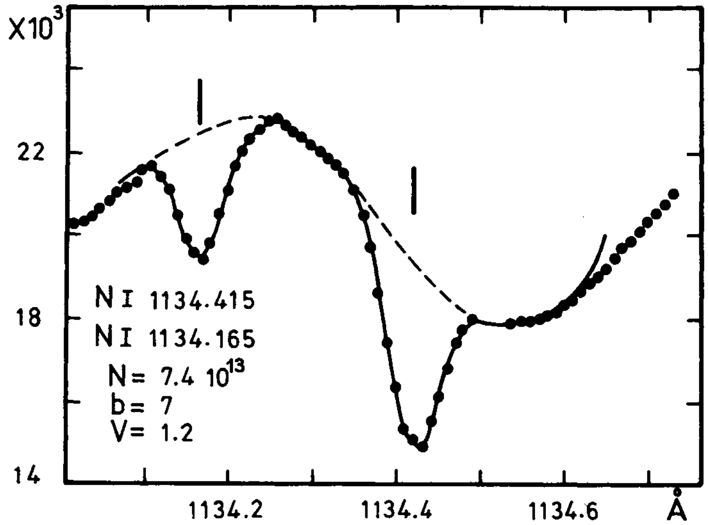

FIG. 2*a*

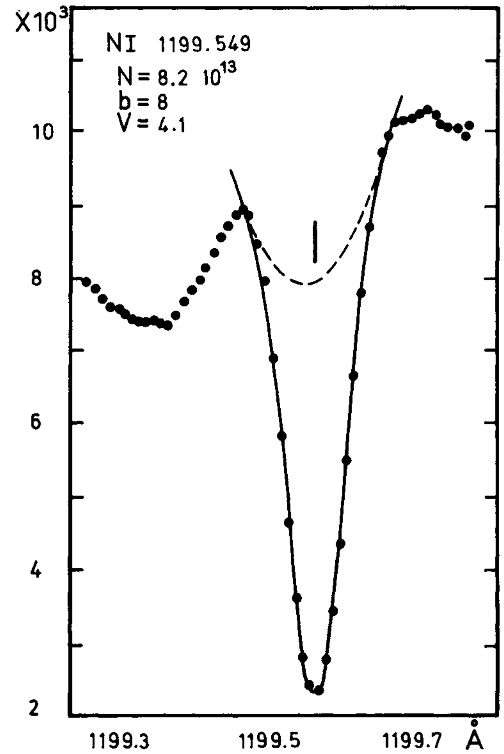

FIG. 2*b*

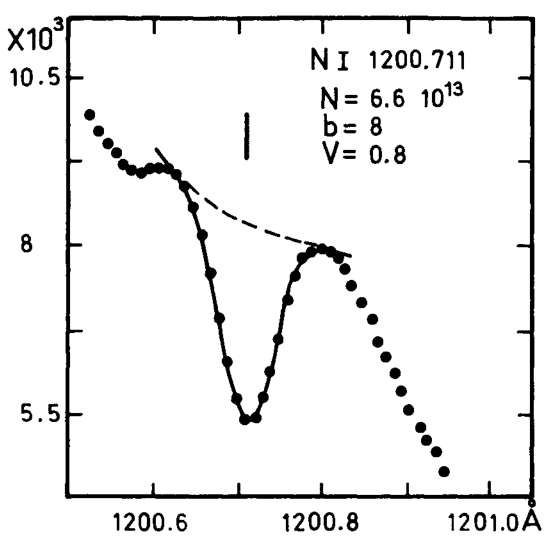

FIG. 2*c*

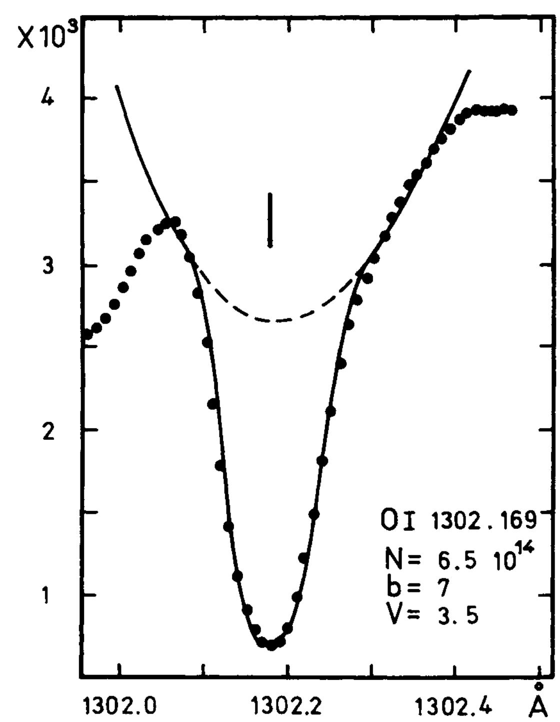

FIG. 2*d*

FIG. 2.—Observed profiles (*dots*) of all lines used in this study, shown here together with a theoretical profile (*continuous line*) which is the combination of a stellar absorption (*dotted line*) and an interstellar component (with the characteristics noted on each plot) that produces the best fit. The ordinates are in 10^3 counts per 14 s.

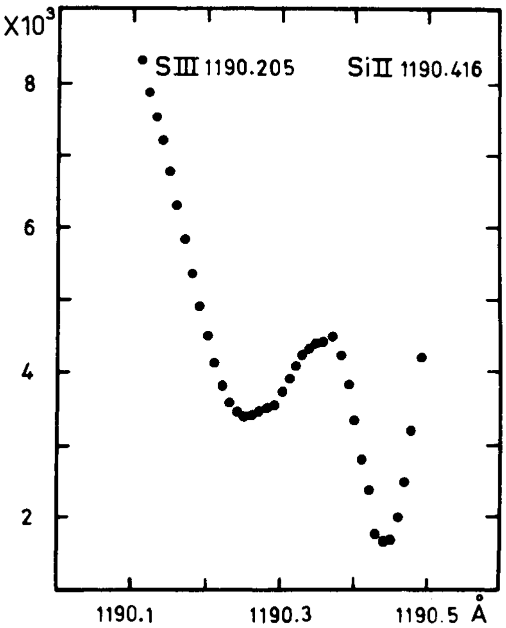

FIG. 2e

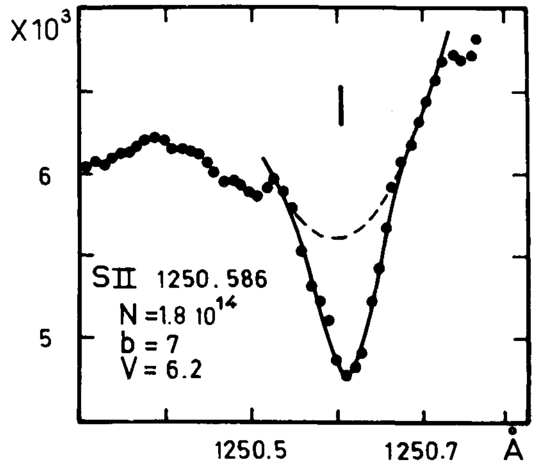

FIG. 2f

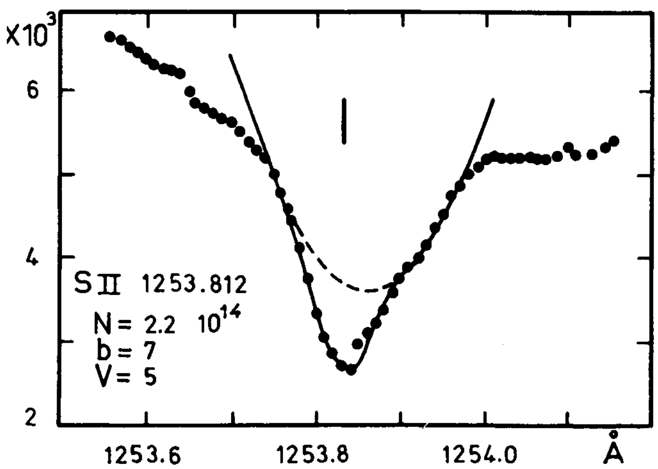

FIG. 2g

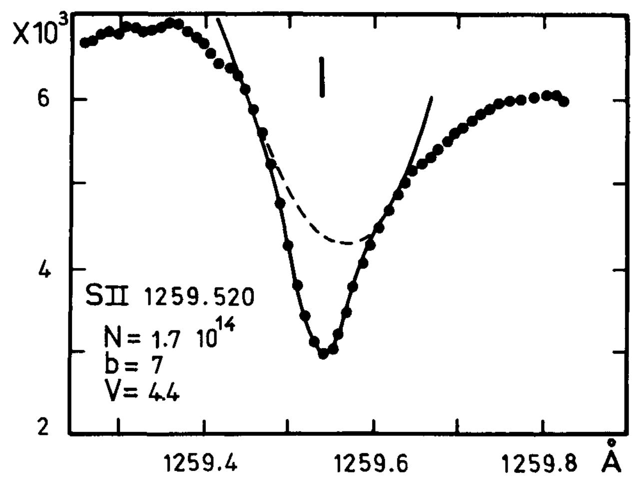

FIG. 2h

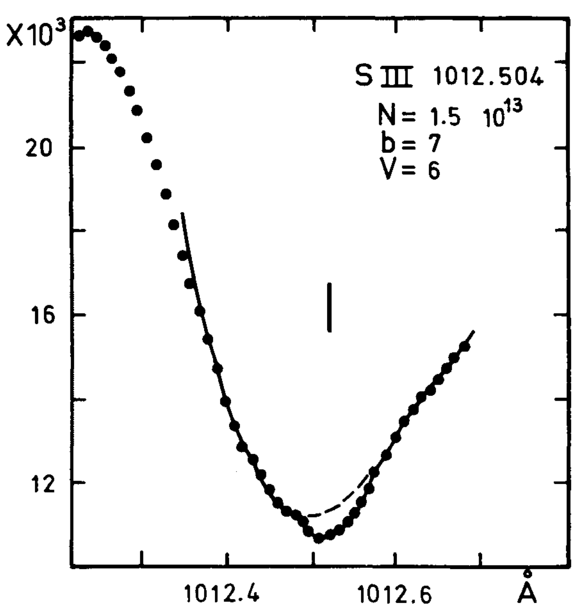

FIG. 2i

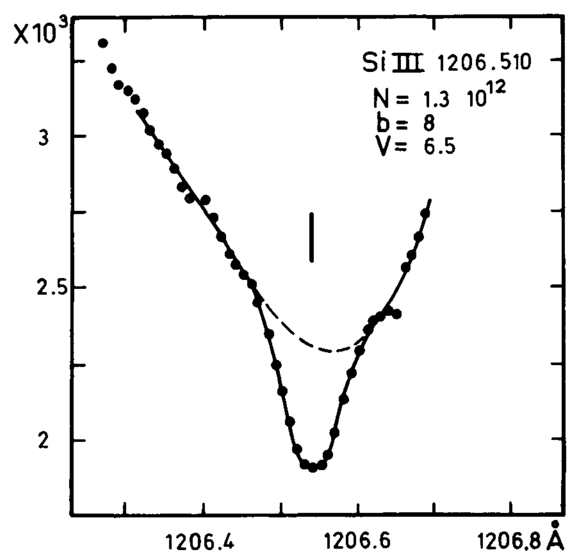

FIG. 2j

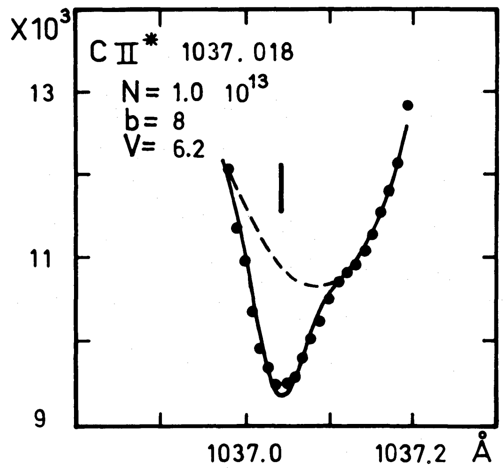

FIG. 2k

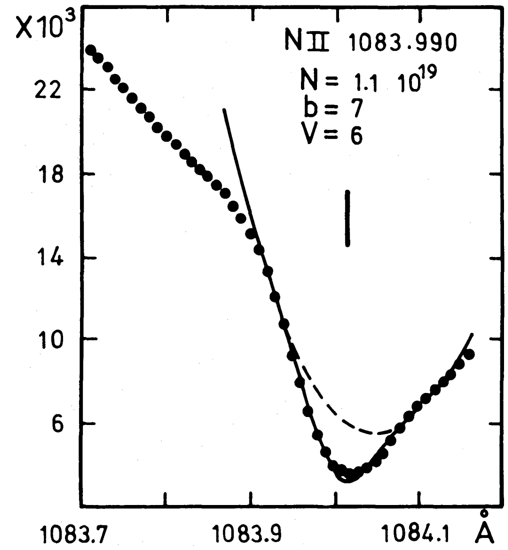

FIG. 2l

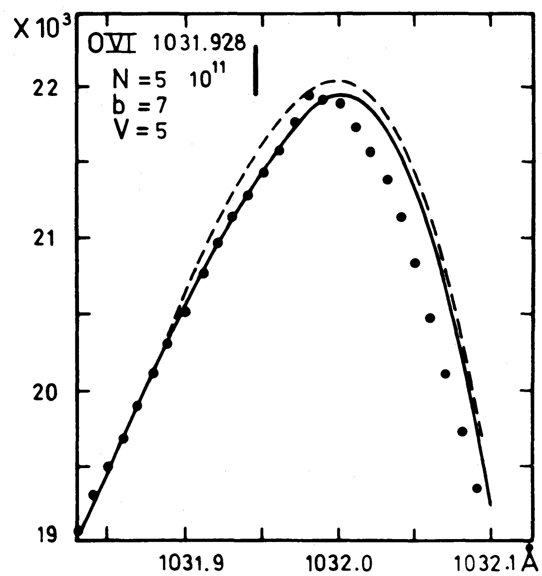

FIG. 2m

Shull and Van Steenberg (1982) for the ionization fractions $\log (Z^i/Z)_T$ of the element Z at a given temperature T. The expected column density $N(Z^i)$ in the neutral region where $N(\text{H I}) = (1\text{–}2.2) \times 10^{18}$ cm^{-2} and $T = T_1$ may be derived from

$$\log (Z^i/\text{H I})_{T_1} = \log (Z^i/Z)_{T_1} + \log (Z/\text{H})_I - \log (\text{H I}/\text{H})_{T_1} .$$

Comparison of columns (2) and (5) of Table 2 provides evidence for the fact that the region producing the H I absorption produces most or all of the observed neutral abundances (N I and O I) but cannot account for the abundances of the ionized species as S II, S III, and Si III. This confirms the idea suggested by the velocity analysis (§ II), that the ionized species belong to a separate physical region.

In conclusion, in addition to the neutral gas (which has a density of about 0.1 cm^{-3} and extends out to only 5 pc), the line of sight contains ionized gas which shows up in the lines of elements in low ionization states.

b) *The Ionized Regions*

The properties of the H II region have to be derived by different means from those of the H I region. The electron density in this region can be evaluated from the excited fine structure of C II (York and Kinahan 1979). On the other hand, the temperature cannot be derived from the *b*-values which, due to the high mass of the observed elements (N, S, Si, and C), may include a more important relative contribution of nonthermal broadening.

If we assume a solar sulfur abundance, the total hydrogen column density in the ionized region derived from the S II and S III column densities is $N(\text{H}^+) \approx (1.6\text{–}2) \times 10^{19}$ cm^{-2}. Since the ratio C/S can be assumed to be solar for this unreddened line of sight, we find a C II column density of about $(3.7\text{–}5) \times 10^{15}$ cm^{-2}. From Table 2, $N(\text{C II*}) \approx (0.8\text{–}1.3) \times 10^{13}$ cm^{-2}; thus $N(\text{C II*})/N(\text{C II}) \approx (1.6\text{–}3.5) \times 10^{-3}$. From Table 4 of York and Kinahan (1979), this implies collisional excitation of the ground term of C II by electrons in a medium with density $n_{\text{H*}} = n_e = 0.07\text{–}0.14$ cm^{-3}. Thus the H II region has a density comparable to that of the neutral region. It extends over 40–90 pc and fills 20%–45% of the line of sight.

The remaining space in the line of sight is probably filled with gas from which the O VI absorption arises, which implies a temperature higher than 2×10^5 K.

It is possible, in view of the similarity of the densities, that the H II region is adjacent to the H I region, being a transition zone between the neutral cloud ($T \approx 12{,}000$ K) and the hot diffuse gas ($T > 2 \times 10^5$ K). However, this possibility cannot be confirmed before comparison is made with model calculations of the ionization structure of a low-density gas under various hypotheses for the ionization mechanism. This latter can, for example, be photoionization by the UV radiation of the star β CMa itself or photoionization by the general interstellar UV radiation field. or heating by the propagation of a shock and radiative cooling, or evaporation into a hot diffuse gas.

We will not discuss here in detail the ionizing (or heating) mechanisms which can produce the H II and coronal regions since this involves extensive calculations and model comparison; yet we made a few estimations to fill out our picture of the line of sight.

If we suppose that the region is in collisional ionization equilibrium, the temperature can be deduced directly from the knowledge of any two ionization stages of a given element: S II/S III being between 10.6 and 24.4 indicates an equilibrium temperature between 22,500 K and 25,000 K (Shull and Van Steenberg 1982). This temperature is obviously quite high, given that radiative cooling is generally found to be very efficient for gas above 10,000 K.

Yet is it striking that, as we checked, this range of temperatures can account for all observed line intensity ratios. The silicon in this case would be depleted by a factor of 4–10, similar to values found in several other unreddened lines of sight (e.g., Morton 1978; York and Kinahan 1979; Morton and Bhavsar 1979), and this model is also consistent with the N I absorption contribution being shared between the H I and the H II regions.

On the other hand, this model omits the UV radiation emitted by the star β CMa (B1 III), a possibly important source of ionization.

The extension of the ionized region R_S (Strömgren sphere) around the star depends on the total number of ionizing stellar photons, S, and of the surrounding density n_0: $R_S = (S/n_0{}^2 1/\alpha 3/4\pi)^{1/3}$, where α is the recombination coefficient of H^+ to all excited states; for an electron temperature of about 10,000 K, $\alpha = 2.6 \times 10^{-13}$ (Kaplan and Pikelner 1970). Thus with an ionizing flux for a B1 III star of $S = 7.4 \times 10^{45}$ (Panagia 1973) and a density of $n \approx 0.1$, we find $R_S \approx 30$ pc. This figure is marginally consistent with the 40–90 pc length found above the observed H II region.

Consequently, the star β CMa is able to produce the ionization of the observed 0.1 cm^{-3} density gas only if this gas is close to the star. This eventuality requires the presence just around β CMa of a second cloud with the same density as the nearby natural one and an extent of a few tens of parsecs. If the gas lies further toward us from the star, the depth of the Strömgren region must be reduced considerably just because of the geometric dilution of the photon flux, and β CMa could not then be considered the cause of the ionization any longer.

IV. CONCLUSION

With the analysis of the *Copernicus* data of the line of sight to β CMa we have obtained a tentative picture of the interstellar medium in this direction.

It seems to be made up of three regions with distinct properties. The regions are not necessarily unconnected.

1. Immediately next to the Sun lies a warm (about 12,000 K) neutral region of density close to 0.1 cm^{-3}, extending over a few (~ 5) pc toward the star.
2. Moderately ionized gas (the ionization ratios correspond to a collisional equilibrium temperature of about 25,000 K), with roughly the same density as the H I region, but a velocity of about 5 km s^{-1} higher, fills 40–90 pc of the line of sight, possibly just next to the H I region.
3. Finally the rest of the space might be occupied by very diffuse coronal gas.

The ionization mechanisms involved in this line of sight are not yet clarified. In any case, their investigation is fundamental not only for the knowledge of this particular line of sight but also more generally for the comprehension of the local interstellar medium. In addition, it may contribute to the study of the structure and interaction of the different components of the ISM, study facilitated here by the scarcity of clouds in this portion of space.

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