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Analysis of the Far-ultraviolet Silicon Lines in G Dwarf Stars

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Summary. The structure of the outer stellar regions is investigated for four G type dwarfs observed with the IUE satellite. Line fluxes of the Si II lines at 1817 Å, 1808 Å, and 1309 Å and Si III at 1206 Å are used to obtain temperatures and electronic densities. A temperature of 16,000 K is found from the lines at 1817 Å and 1808 Å, 26,000 K from the 1309 Å line and 50,000 K from that at 1206 Å. Predicted fluxes are compared with the observed ones. The significance of the results is discussed in terms of line formation regions.

Key words: G dwarf stars – ultraviolet spectra – emission lines

Table 1. Characteristics of stars observed

	$\varkappa$ Cet	β CVn	β Com	η Cas
IUE Image No.	1926	1925	1901	1902
Exp. time	35 min	50 min	32 min	26 min
Spec. type	G 5 V	G 0 V	G 0 V	G 0 V
log *g*	4.4	4.3	4.3	4.7
Distance (pc)	9.53	9.26	8.33	5.49
(Fe/H)	0.08	0.08	0.27	−0.20

Table 2. Observed flux (10^{-14} erg cm^{-2} s^{-1})

λ	$\varkappa$ Cet	β CVn	β Com	η Cas
1817	43.6	0.9	26.4	6.6
1808	9.3	—	11.9	0.5
1309	8.9	—	7.7	—
1206	6.3	4.1	14.2	—

1. Introduction

The main sources of information about the outer regions of intermediate and late type stars arise from observations of the Ca II K emission line, Mg II h and k emissions and recently from far UV observations. The weak continuum in this region allows the observation of spectral lines originating in outer regions, but it makes stellar observation difficult. For instance, only 0.11% of the observations with the S2/68 experiment aboard the TD1 satellite were of G type stars (Marcau et al., 1978).

We have carried out observations between $\lambda\lambda$ 1100–1900 Å of dwarf stars $\varkappa$ Cet (G 5), β Com (G), β C Vn (G 0), and η Cas (G 0). Three of these stars, $\varkappa$ Cet, β Com, and η Cas were included by Zirin (1976) in a program of He I λ 10,830 Å line observations; this line, considered as an existence indicator of the outer stellar regions, was identified only in $\varkappa$ Cet.

The whole sample was also observed by Wilson et al. (1956) in the context of their Ca II emission researches. They found a K emission intensity of 3 in $\varkappa$ Cet, 1 in β Com, and 0 in the other two stars. Nevertheless we have identified K emission in β CVn, although with a lower intensity than β Com K emission. This line exhibits a behaviour similar to that we have observed in h and k emission from these stars (1978a). On the other hand, the identifications that we have carried out in $\varkappa$ Cet (1978b) and β CVn (1978c) have revealed the similarity between the behaviour of Si II resonance lines λ 1817 and λ 1808 and Ca II and Mg II emissions. Si II line intensities are related with solar activity (Brueckner et al., 1976), appearing stronger in the active spectral regions than in the quiet sun spectrum.

In this paper we present an analysis of the Si II lines λ 1817 Å, λ 1808 Å, and λ 1309 Å and the Si III line λ 1206 Å in order to study the physical characteristics of line formation regions and to make emission predictions for them. We assumed that for expected densities and temperatures, collisional processes will be the most important mechanisms populating excited levels.

Atmospheric parameters and metallic abundances used in $\varkappa$ Cet, β Com, and β CVn analyses were determined by Hearnshaw (1971) from high resolution spectra. For η Cas these parameters were obtained by Bell (1971) using photometric methods. Silicon abundances, not computed for the star sample in earlier papers, have been determined from silicon solar abundances taking into account relative metallic abundances.

2. Observations

Observations in the range $\lambda\lambda$ 1100–1900 Å were made in a low resolution mode with the SWP camera aboard the IUE satellite. These observations were supplied after a scanning which provided the IUE net flux, *FN*, as a function of wavelength. Noise was corrected by VILSPA equipment for treatment of the information. Intensities in absolute units were computed by means of the relation $F_\lambda = S_\lambda^{-1} FN/t$, where S_λ^{-1} corresponds to the mean values listed

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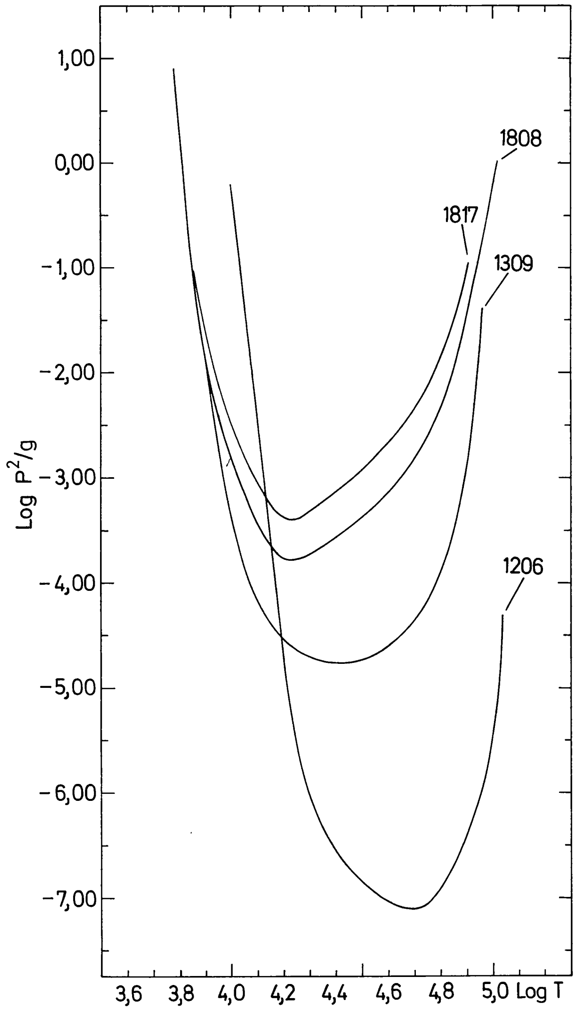

Fig. 1. Values of P^2/g versus temperature for $\varkappa$ Cet

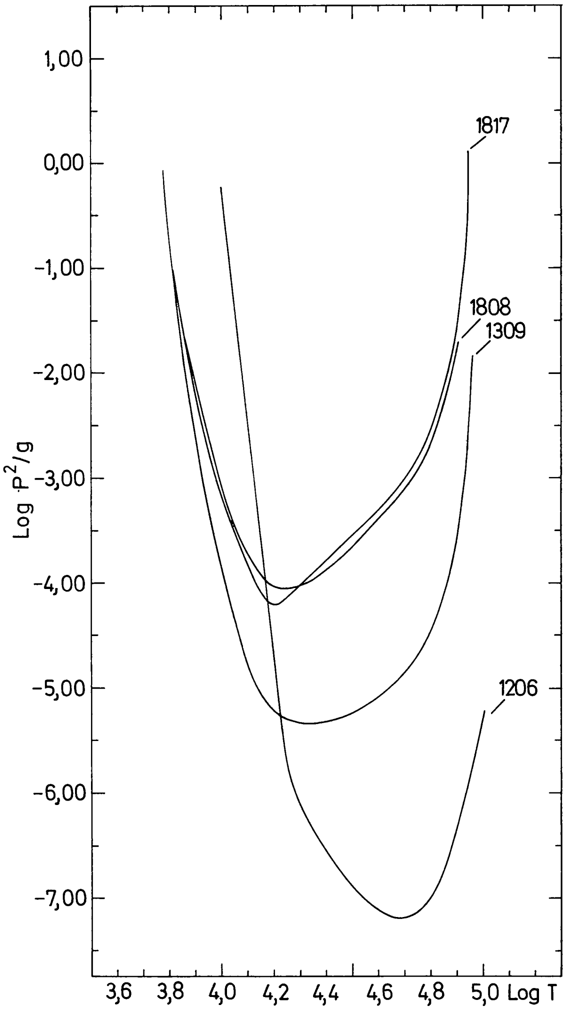

Fig. 2. Values of P^2/g versus temperature for β Com

Table 3. Mass column and electronic density

	$\varkappa$ Cet			β CVn			β Com			η Cas		
λ	$\log P^2/g$	$\log T_m$	N_e	$\log P^2/g$	$\log T_m$	N_e	$\log P^2/g$	$\log T_m$	N_e	$\log P^2/g$	$\log T_m$	N_e
1817	−3.38	4.2	2.64(12)	−4.34	4.2	7.56(11)	−4.24	4.2	9.53(11)	−4.49	4.2	7.02(11)
1808	−3.80	4.2	1.62(12)	—	—	—	−4.04	4.2	1.00(12)	−5.37	4.2	2.26(11)
1309	−4.70	4.4	1.96(11)	—	—	—	−5.32	4.3	1.12(11)	—	—	—
1206	−7.10	4.7	6.55(9)	−7.50	4.7	3.63(9)	−7.20	4.7	5.13(9)	—	—	—

Table 4. Predicted fluxes from β Com (10^{-14} erg cm^{-2} s^{-1})

	η Cas		β CVn		$\varkappa$ Cet	
λ	F_{obs}	F_{pred}	F_{obs}	F_{pred}	F_{obs}	F_{pred}
1817	6.6	19.4	0.9	4.1	43.6	3.1
1808	0.5	1.5			9.3	2.1
1309	—	—			8.9	3.1
1206	—	—	4.1	7.4	6.3	5.3

in the IUE calibration memo for low dispersion images issued September 21. Table 1 lists observations and stellar parameters.

Measurements of line energy fluxes are strongly affected by the low resolution and the observed signal-to-noise ratio, which is different for each star spectral range. The Si II λ 1206 Å profiles are well defined. Si II λ 1808 Å appears in the λ 1817 Å wing, but its profile can be well restored. The β Com spectrum exhibits a good signal-to-noise relation, but Si II λ 1817 Å is weak and stands out slightly on the continuum. In η Cas, Si II λ 1817 Å is weak although well defined, but Si II λ 1808 Å is weaker and blended as

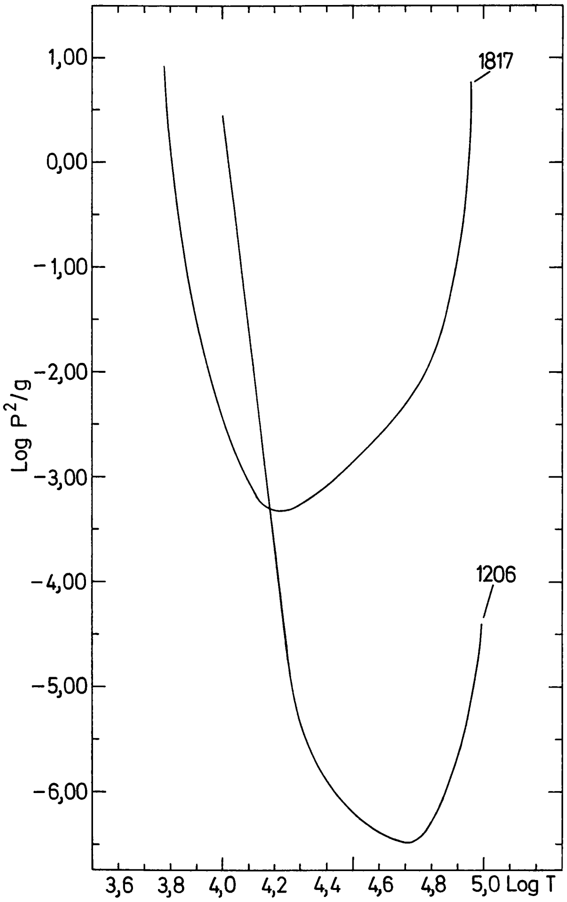

Fig. 3. Values of P^2/g versus temperature for β CVn

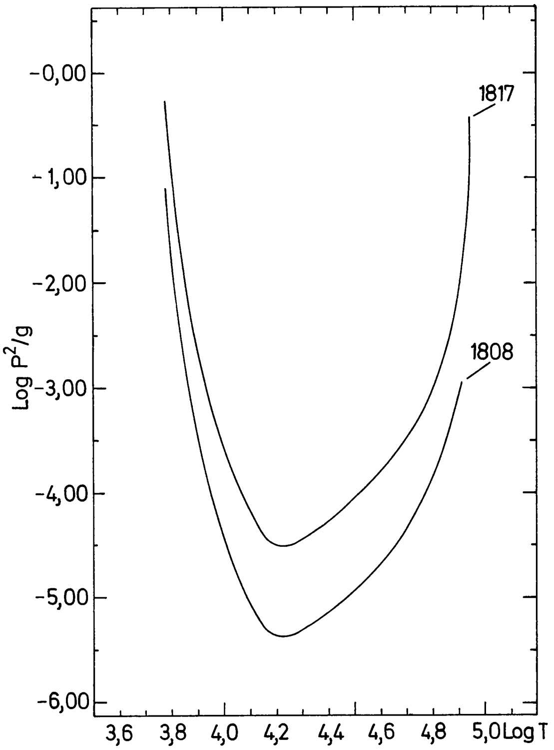

Fig. 4. Values of P^2/g versus temperature for η Cas

in earlier cases. Below λ 1650 Å the continuum decreases strongly in η Cas and the signal-to-noise ratio is lowest.

In all cases the λ 1206 Å profile is affected by the Lyman α line, which also disturbs the continuum in this region. The signal-to-noise ratio is lower in this case and the uncertainty in the adopted continuum becomes up to 20%. Table 2 shows the observed line fluxes for each star.

3. Results and Discussion

The spectroscopic observations from active and quiet solar regions have revealed the existence of a chromosphere in which temperature rises slowly, followed by a transition region showing a temperature gradient and a corona where the temperature is higher than in the chromosphere (Goldberg, 1974). The main difference among these regions is due to the various terms determining the total energetic balance.

The emitted flux in the lines arising from the transition and coronal regions has been determined from simplified models tested by solar observations (Gerola et al., 1974). Although these models do not account for magnetic fields and spatial inhomogeneities, the results are, nonetheless, in good agreement with solar observations. We use this type of model for analysing the outer regions of the star sample, which being G 0 and G 5 type will present no important physical differences with the outer solar regions.

Transition and coronal line fluxes were determined assuming that the line formation takes place in a plane-parallel isothermal region in hydrostatic equilibrium and that the lines are optically thin.

The observed flux on Earth is

$$F=G\frac{P^2}{g}\,b(T) \tag{1}$$

where G is a gain geometrical factor taking into account the stellar radius and the distance, P/g is the mass column density (where P is the pressure at the base of the considered region, and g is gravity) and $b(T)$ a function of temperature depending on the collisional excitation rate, the abundance and the temperature ionization rate. If G and $b(T)$ are incorporated into Eq. (1), we find

$$F=4.17\;10^{15}\left(\frac{R/R_\odot}{d(\mathrm{pc})}\right)^2\frac{1}{\lambda(\text{Å})}\,\frac{N_{\mathrm{elem}}}{N(\mathrm{H})}\,C_{\mathrm{lu}}\,\frac{P^2}{gT} \tag{2}$$

$N_{\mathrm{elem}}/N(\mathrm{H})$ include both the silicon abundance and the temperature ionization rate. One of the critical parameters in this analysis is the collisional cross section which has been obtained theoretically, since no experimental values are available. So, C_{lu} values were calculated for a temperature ranging between 6000 and 100,000 K for all Si II and Si III lines, using the relation established by Seaton (1964), where the collisional cross section is proportional to the oscillator strength value.

$$C_{\mathrm{lu}}=1.7\;10^{-3}f_{\mathrm{lu}}\langle g\rangle\,W_{\mathrm{lu}}^{-1}T_e^{-1/2}\exp\left(-W_{\mathrm{lu}}/kT\right). \tag{3}$$

The f-values used have been obtained from Weiss (1969) and for the λ 1817 Å line from Weiss (1976). The $N_{\text{ion}}/N_{\text{atom}}$ relation was obtained from the Jordan (1969) tables for the same temperature range. Incorporating the observed fluxes into Eq. (2) we have determined P^2/g, which is given in Table 3, and plotted as a function of temperature in Figs. (1)–(4). A temperature ranging between 16,000 and 30,000 K was found for the Si II formation region and a temperature of 50,000 K was obtained for the Si III line. This last value was found for all stars in the sample. The Si II values are slightly lower than those obtained by Weinstein (1977) from the Arcturus spectrum whereas the Si III values are similar to ours.

A test for the model used can be made by predicting the observed line fluxes from mass column density values (Gerola et al., 1974).

We have computed the emitted fluxes from the observed lines in η Cas, $\varkappa$ Cet, and β CVn using P^2/g values corresponding to β Com. Table 4 lists the results obtained. The predicted fluxes are close to the observed ones, except in the case of $\varkappa$ Cet Si II λ 1817 Å. For this time the discrepancies could be due to the measurements of observed fluxes, metallic abundances and simplified model assumptions.

From P^2/g values, we have obtained the pressure and electronic density corresponding to the line formation region. The results are given in Table 4; they are in good agreement with those obtained by Evans et al. (1975) using semiempirical models for similar star types, and also with electronic densities given by Okjelseth et al. (1977) for Si III.

According to our results we can conclude that the formation layer temperature of the Si II and Si III lines considered does not exceed 50,000 K, a noticeably lower value than normally taken for the corona ($3\ 10^5\ \text{K} < T_c < 6\ 10^6\ \text{K}$) (Evans et al., 1975; Athay, 1976).

If an approximate range of temperature from $5\ 10^4$ K to $5\ 10^5$ K is attributed to the solar transition region, then the silicon lines considered could be formed either in a solar like transition region or in a high region of the chromosphere.

Predicted fluxes obtained from β Com agree quite well with those observed in η Cas, β CVn, and for all the observed lines in $\varkappa$ Cet except Si II λ 1817 Å. The discrepancy for Si II λ 1817 Å could be explained by the existence in the line formation of mechanisms similar to those taking place in the active solar regions. Thus the K emission variations in $\varkappa$ Cet (Wilson, 1978) could be also produced in Si II λ 1817 Å, and obviously in the Mg II h and k emission. More sphisticated models, a synthetic spectrum and new observations are needed to complete and confirm the above results.

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