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ELECTRON DENSITIES IN STELLAR ATMOSPHERES DETERMINED FROM *IUE* SPECTRA

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ABSTRACT

An EUV spectroscopic method is described for determining the electron density in solar and stellar plasmas for densities less than $\sim 10^{11}$ cm^{-3} and for temperatures near $\sim 5 \times 10^4$ K. The method is applied to *IUE* spectra of α Aur, HR 1099, and λ And. Preliminary results give densities of $\sim 10^{10}$ cm^{-3} for α Aur and λ And, and $\sim 2 \times 10^9$ cm^{-3} for HR 1099.

Subject headings: stars: atmospheres — stars: chromospheres

I. INTRODUCTION

The wavelength range 1200–2000 Å contains a number of solar transition-zone intercombination lines that can be used to determine electron densities in solar and stellar atmospheres. Among the strongest of these lines are O V 1218 Å, O IV 1401 Å, O III 1666 Å, Si III 1892 Å, and C III 1909 Å. Their behavior as a function of electron density is given in the following papers: for O IV and O V see Feldman, Doschek, and Rosenberg (1977); for C III and O III see Doschek *et al.* (1978); and for Si III see Nicolas (1977). A summary of all of the above results except for Si III is given in Doschek, Feldman, and Mason (1978). The sources of the atomic data used in the calculations are Dufton *et al.* 1978 and Nussbaumer and Storey 1978 (C III), Nussbaumer 1976 (O IV), and Malinovsky 1975 and Dufton *et al.* 1978 (O V). All of these lines are useful for determining electron densities, but the upper levels of the lines, with the exception of C III, reach a pseudo-Boltzmann equilibrium with the ground state at electron densities $\gtrsim 10^{10}$ cm^{-3}. However, the C III 1909 Å line approaches a pseudo-Boltzmann equilibrium below an electron density of 10^9 cm^{-3}. Because of this sensitivity to lower densities, we show that it is possible to use the C III line, combined with the intensity of the Si III 1892 Å line, to determine electron densities in the upper atmospheres of the stars observed by Linsky *et al.* (1978) with the *International Ultraviolet Explorer* (*IUE*).

II. THE METHOD

The power (ergs s^{-1}) emitted from the atmosphere of a star in an optically thin emission line is given by

$$P = h\nu A_{UL} N_U V \, , \qquad (1)$$

where $h\nu$ is the photon energy, A_{UL} is the spontaneous decay rate from the upper level U to the lower level L, N_U is the average number density of ions in level U, and V is the volume over which the ions are distributed. Equation (1) is an approximation to the local line emission integrated over the volume of the atmosphere over which the line is formed. For the lines discussed here the emission is restricted to a narrow temperature range and the approximation is valid. The quantity N_U can be expressed as

$$N_U = \frac{N_U}{N_{\text{ion}}} F(T) A_{\text{el}}(0.8) N_e \, , \qquad (2)$$

where N_{ion} is the total number density of the ion, $F(T)$ is the ratio of the number density of the ion to the number density of the element, A_{el} is the elemental abundance relative to hydrogen, 0.8 is the ratio of the hydrogen number density to the electron number density, and N_e is the electron number density. For ionization equilibrium, which is assumed in this discussion, the functions $F(T)$ have been calculated by Jordan (1969).

Equation (1) can be rewritten as

$$P = 0.8 h\nu A_{UL} F(T) A_{\text{el}} N_e^2 V J / N_e \, , \qquad (3)$$

where $J \equiv N_U / N_{\text{ion}}$. The function J depends primarily on the electron density of the plasma.

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For an allowed line emitted at solar densities (10^8–10^{13} cm^{-3}), the coronal approximation applies and $J = \beta N_e$, where β is a constant containing temperature and atomic factors. For an intersystem line at sufficiently high electron densities such that the upper level is in pseudo-Boltzmann equilibrium with the ground level, $J = \gamma$, where γ is a constant that contains temperature and atomic factors. For densities intermediate between the low- and high-density limits, J is not a constant, but the proportionality is not as strong as N_e. The function J is evaluated for the above-mentioned intersystem lines in the papers cited.

The ratio of the power in two emission lines can be written as

$$\frac{P_1}{P_2} = \frac{[h\nu A_{UL}F(T)]_1}{[h\nu A_{UL}F(T)]_2}\,\frac{(J/N_e)_1}{(J/N_e)_2}\,\frac{(A_{\rm el}N_e{}^2V)_1}{(A_{\rm el}N_e{}^2V)_2}\,. \tag{4}$$

For two allowed lines, the first and second terms on the right are constants that can be derived from known atomic physics. In this case the intensity ratio of the two lines is a constant times the product of the ratio of the abundances and the ratio of the emission measures ($N_e{}^2V$). However, if line 1 originates from a metastable level or a level approaching pseudo-Boltzmann equilibrium and line 2 is an allowed line, then the second term will be proportional to $1/N_e$, or will approach this proportionality. In this case the electron density can be determined if the first and third terms are known. In practice two lines are chosen that are emitted at nearly the same temperature. Then the ratio of emission measures is close to unity, and if the relative element abundances are known, the third term can be easily evaluated.

III. SOLAR AND STELLAR ELECTRON DENSITIES

In Figure 1 we present the relative intensities of three allowed lines from different solar regions and from four stars observed with *IUE*. The lines are the resonance transitions in Si IV ($T_e = 7 \times 10^4$ K), C IV ($T_e = 1 \times 10^5$ K), and N V ($T_e = 2 \times 10^5$ K), and the intensities have been plotted relative to the Si IV line. The solar data are from Feldman and Doschek (1978) and Feldman *et al.* (1976). The stellar data are from Linsky *et al.* (1978). As can be seen from the figure, the relative intensities from the solar regions and the stars are constant to within the uncertainties of the measurements to about a factor of 2. Thus, at each temperature in the range 7×10^4–2×10^5 K, the ratio $(A_{\rm el}N_e{}^2V)_1/(A_{\rm el}N_e{}^2V)_2$ is the same. This means that while the absolute value of the quantity $A_{\rm el}N_e{}^2V$ may change for different stars, the slope of this quantity plotted as a function of temperature is always the same within the stated temperature limits.

We note in particular that the ratio of $(A_{\rm el}N_e{}^2V)_1/(A_{\rm el}N_e{}^2V)_2$ in Figure 1 is the same in very different regions of the solar atmosphere. The electron pressure in the particular coronal hole studied was found to be $N_eT_e \approx 10^{15}$ cm^{-3} K (Doschek *et al.* 1978), while in the June 15 flare the pressure is $N_eT_e \gtrsim 10^{18}$ cm^{-3} K (Feldman, Doschek, and Rosenberg 1977). Since we assume that the ratio of element abundances $A_{\rm el}$ is the same in the different solar plasmas, we can conclude that the ratio of emission measures $(N_e{}^2V)_1/(N_e{}^2V)_2$ in the 7×10^4 K to 2×10^5 K region is a property of the plasma that is not very sensitive to the atmospheric conditions.

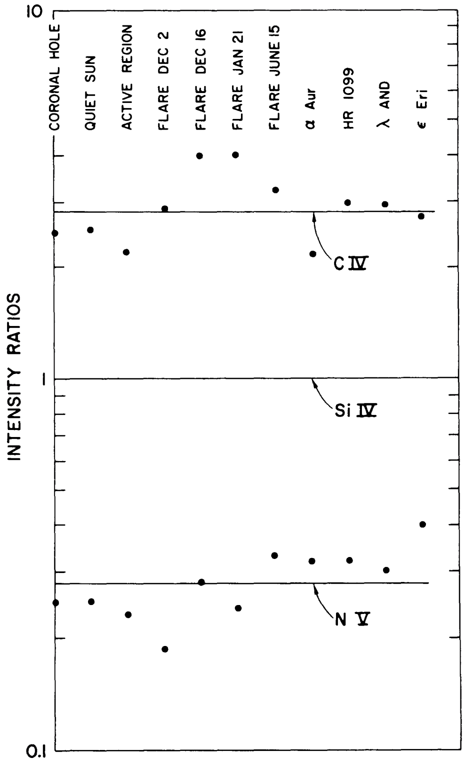

FIG. 1.—Intensity ratios of C IV (1550 Å) and N V (1242 Å) relative to Si IV (1403 Å) for different solar regions and for the stars indicated.

In fact, the similarity in the shape of the differential emission measure curve, i.e., ratios of emission measures determined from allowed lines, appears to hold down to temperatures as low as 4×10^4 K for very different regions of the solar atmosphere. The 4×10^4 K emission measure is determined from the intensity of the $3s$–$3p$ lines of Al III near 1860 Å. Relatively small variations in the slope between 4×10^4 K and 2×10^5 K are observed due to variations of relative line intensities by factors of about 2. It is possible that the shape of the differential emission measure depends primarily on the radiative cooling properties of plasma (as a function of temperature). If this is true, we would expect the shape of the differential emission measure to be independent of atmospheric conditions and to depend only on atomic properties of the plasma.

If we assume that the differential emission measure curve has a shape that is independent of atmospheric conditions, and if the shapes of the stellar curves are the same as the solar curve, then we can conclude that the stellar abundance ratios of C, N, and Si are close

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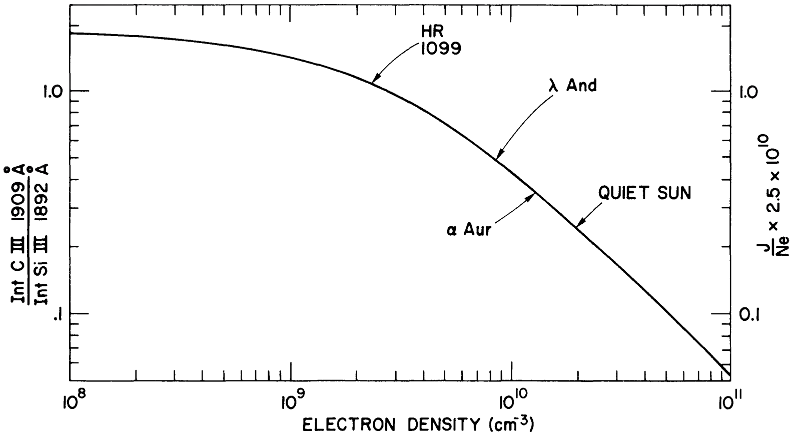

FIG. 2.—The intensity ratio of C III (1909 Å) to Si III (1892 Å), calculated as described in the text. The function J/N_e is also shown. The arrows show the value of the ratio for each source indicated.

to the solar abundance ratios. From Figure 1 this is seen to be the case for the stars discussed by Linsky *et al.* (1978). It is known from independent investigations that the abundances in Capella and the Sun are quite close (Wright 1954).

A more difficult question is whether the differential emission measure curve is similar to the solar curve down to 4×10^4 K for the stellar atmospheres considered. Unfortunately, the Al III lines do not appear in the Capella spectrum and are too weak for reliable measurement in the spectra of λ And and HR 1099. We therefore stress that the results of our method applied to the stars discussed by Linsky *et al.* (1978) are to be regarded as preliminary. The *IUE* spectrograph was not optimized when these data were obtained, and we can expect improved spectra of these stars and others as well in the near future. We emphasize the basis of the method rather than the results. We assume in the subsequent discussion that the differential emission measure of the stellar atmospheres is similar to the solar case down to a temperature of about 4×10^4 K.

If the shape of the emission measure distribution between stars and the Sun is assumed to be the same down to 4×10^4 K, we can compare the ratio of the C III 1909 Å line and the Si III 1892 Å line with the solar ratio and obtain the second term on the right in equation (4). This is possible provided the stellar densities are less than about 10^{11} cm^{-3}. In this case the 1892 Å line behaves like an allowed line, i.e., $J \propto N_e$. In Figure 2 we have plotted the ratio of C III 1909 Å to Si III 1892 Å as a function of electron density in the range 10^8–10^{11} cm^{-3}. At densities above 10^{11} cm^{-3} the Si III 1892 Å line begins to change from an allowed to a metastable line, i.e., collisional depopulation of the upper level begins to compete with spontaneous radiative decay. The plot has been normalized to the ratio observed for the quiet Sun. Thus, because of the assumed similarity of the slope of the quantity $A_{\rm el} N_e^2 V$ between the solar and stellar atmospheres, the observed stellar line ratio can be used with Figure 2 to determine the electron density. For cases in which the products of the emission measure and the abundances deviate from the solar behavior, we have included a scale for the quantity J/N_e for the 1909 Å line. This, coupled with an emission measure estimate at the temperature of formation of the 1909 Å line, can be used to determine an electron density. We have chosen to compare Si III 1892 Å with C III 1909 Å because of the proximity of the two lines in intensity, wavelength, and temperature of formation. The proximity in wavelength should eliminate problems due to uncertainties in the instrumental calibration and the wavelength dependence of interstellar absorption.

Using the data published by Linsky *et al.* (1978), we obtain the preliminary results that at $T_e \approx 5 \times 10^4$ K the electron densities for α Aur, λ And, and HR 1099 are 1.4×10^{10} cm^{-3}, 8×10^9 cm^{-3}, and 2×10^9 cm^{-3}, respectively.

Kelch *et al.* (1978) have derived a semiempirical chromospheric model for α Aur. They found an electron pressure at 2×10^4 K of between 3.6×10^{13} and 1.1×10^{14} cm^{-3} K. If we assume a constant pressure between 2×10^4 K and 5×10^4 K, our result implies an electron pressure at 2×10^4 K of 5×10^{14} cm^{-3} K, somewhat higher than the Kelch *et al.* results. Our pressure is, however, more than a factor of 10 lower than the 1.5 dyn cm^{-2} total gas pressure estimated by Haisch and Linsky (1976) on the basis of a simple energy balance argument.

We believe that the electron density determination for α Aur is better than for the other two stars. The estimated error in the C III to Si III line ratio is 17%, 62%, and 26%, for α Aur, λ And, and HR 1099, respectively. The C III line is in fact quite weak in λ And, and we suggest that both λ And and HR 1099 be reobserved with longer exposures.

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