THE RELATIVE INTENSITIES OF LINES FROM BeI-LIKE IONS IN THE SOLAR SPECTRUM

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1. Introduction

The permitted transitions $2s^2\ {}^1S$–$2s2p\ {}^1P$ and $2s2p\ {}^3P$–$2p^2\ {}^3P$ in the BeI-like ions CIII, NIV and OV have been observed for some years in the solar spectrum (Hall *et al.*, 1963). Recently, intensity data have also been obtained for the intercombination line $2s^2\ {}^1S$–$2s2p\ {}^3P_1$ in these ions (Burton *et al.*, 1970). A large number of excitation rate coefficients are needed before the intensity ratios of these transitions can be computed and compared with those observed. These excitation cross-sections are now becoming available (Osterbrock, 1970; Eissner, private communication), and the present paper gives the results of an analysis of the intensity data. Figure 1 shows a partial term scheme for the BeI-like ions and the observed transitions.

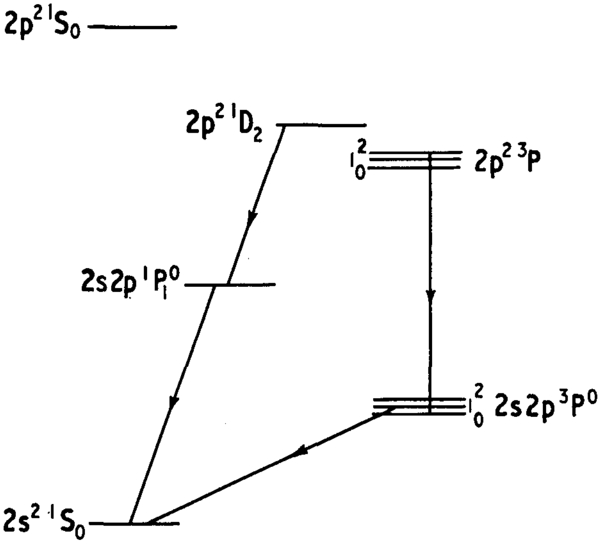

Fig. 1. Partial term scheme for BeI-like ions, with observed transitions indicated.

2. Method

The populations of the $2s2p\ {}^1P$ and $2s2p\ {}^3P_{0,1,2}$ levels have been computed as a function of density and temperature by solving the equation of statistical equilibrium for each level. The following processes have been included in the calculations;

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collisional excitation from $2s^2\,{}^1S$ to $2s2p\,{}^1P$, $2s2p\,{}^3P$, $2p^2\,{}^1D$, $2p^2\,{}^1S$, $2p^2\,{}^3P$,
collisional excitation from $2s2p\,{}^3P$ to $2s2p\,{}^1P$, $2p^2\,{}^1D$, $2p^2\,{}^1S$, $2p^2\,{}^3P$,
collisional de-excitation from $2s2p\,{}^3P$ to $2s^2\,{}^1S$,
radiative decay of $2s2p\,{}^1P$, $2s2p\,{}^3P_{1,2}$, $2p^2\,{}^3P$, $2p^2\,{}^1D$, $2p^2\,{}^1S$,
collisional excitation and de-excitation between the levels of the $2s2p\,{}^3P$ term.

The most important processes in determining the level populations are;

for $2s2p\,{}^1P$, collisions from $2s^2\,{}^1S$ and spontaneous radiative decay to $2s^2\,{}^1S$.

for $2s2p\,{}^3P$, collisions from $2s^2\,{}^1S$; spontaneous radiative decay from $2s2p\,{}^3P_1$ to $2s^2\,{}^1S$; mixing through collisions between the $2s2p\,{}^3P$ levels and through collisions to $2p^2\,{}^3P$ followed by radiative decay back to $2s2p\,{}^3P$; loss through collisions to $2s2p\,{}^1P$.

for $2p^2\,{}^3P$, collisions from $2s2p\,{}^3P$, and spontaneous radiative decay to $2s2p\,{}^3P$.

The equations for the relative intensities of the three observed multiplets are given below, omitting terms contributing a total of less than 10% to the total rates.

$$\frac{E({}^3P\text{–}{}^3P')}{E({}^1S\text{–}{}^1P)} = \frac{\lambda({}^1S\text{–}{}^1P)}{\lambda({}^3P\text{–}{}^3P')}\cdot\frac{\Sigma N({}^3P)}{N({}^1S)}\cdot\frac{\Sigma C({}^3P\text{–}{}^3P')}{C({}^1S\text{–}{}^1P)} \tag{1}$$

$$\frac{E({}^1S\text{–}{}^3P_1)}{E({}^1S\text{–}{}^1P)} = \frac{\lambda({}^1S\text{–}{}^1P)}{\lambda({}^1S\text{–}{}^3P_1)}\cdot\frac{N({}^3P_1)}{N({}^1S)}\cdot\frac{A({}^3P_1\text{–}{}^1S)}{N_eC({}^1S\text{–}{}^1P)} \tag{2}$$

where E is the intensity in erg/cm^2/sec, λ is the wavelength, N is the population, A is the spontaneous transition probability, C is the collisional excitation rate coefficient, and the $2p^2\,{}^3P$ level is designated by ${}^3P'$.

Thus the two parameters derived from the observations and which may be compared with calculated values are

$$\Sigma N({}^3P)/N({}^1S) \quad \text{and} \quad N({}^3P_1)/N({}^1S)\,N_e.$$

3. Data Used

Table I gives the intensity data and some of the atomic data used in the analysis. The intensities are from Hall *et al.* (1963), Burton *et al.* (1970) and Freeman and Jones (1970). The permitted transition probabilities are from Wiese *et al.* (1966) and the forbidden transition probabilities are from Garstang and Shamey (1967). The collision strengths have been derived from Osterbrock (1970), from Eissner (private communication) and for the transitions between the levels of the $2s2p\,{}^3P$ terms, from the results of Saraph *et al.* (1969) for the $2p^2\,{}^3P$ term of the same charge.

4. Results

The computed values of the parameters $\Sigma N({}^3P)/N({}^1S)$ and $N({}^3P_1)/N({}^1S)\,N_e$ in C III, N IV and O V are given in Figures 2, 3 and 4, as a function of density and temperature.

The results of the comparison between the theoretical values and those derived from observations are given in Table II.

TABLE I

Data

Ion	Transition	λ (Å)	Intensity erg cm^{-2} sec^{-1}	Ω	A sec^{-1}
C III	$2s^2\ {}^1S - 2s2p\ {}^1P$	977	0.023	3.75	
	$2s^2\ {}^1S - 2s2p\ {}^3P_1$	1909	0.015	1.1	1.9×10^2
	$2s2p\ {}^3P - 2p^2\ {}^3P$	1175	0.012	23.3	
	$2s2p\ {}^3P_0 - 2s2p\ {}^3P_1$			0.38	
	$2s2p\ {}^3P_0 - 2s2p\ {}^3P_2$	$\sim 10^6$		0.21	
	$2s2p\ {}^3P_1 - 2s2p\ {}^3P_2$			0.95	
N IV	$2s^2\ {}^1S - 2s2p\ {}^1P$	765	0.006	3.5	
	$2s^2\ {}^1S - 2s2p\ {}^3P_1$	1487	< 0.0019	0.55	9.2×10^2
	$2s2p\ {}^3P - 2p^2\ {}^3P$	923	0.0032	17.7	
	$2s2p\ {}^3P_0 - 2s2p\ {}^3P_1$			0.28	
	$2s2p\ {}^3P_0 - 2s2p\ {}^3P_2$	$\sim 10^6$		0.16	
	$2s2p\ {}^3P_1 - 2s2p\ {}^3P_2$			0.64	
O V	$2s^2\ {}^1S - 2s2p\ {}^1P$	630	0.024	3.1	
	$2s^2\ {}^1S - 2s2p\ {}^3P_1$	1218	0.0011	0.35	3.6×10^3
	$2s2p\ {}^3P - 2p^2\ {}^3P$	760	0.0016	16.7	
	$2s2p\ {}^3P_0 - 2s2p\ {}^3P_1$			0.24	
	$2s2p\ {}^3P_0 - 2s2p\ {}^3P_2$	$\sim 10^5$		0.12	
	$2s2p\ {}^3P_1 - 2s2p\ {}^3P_2$			0.58	

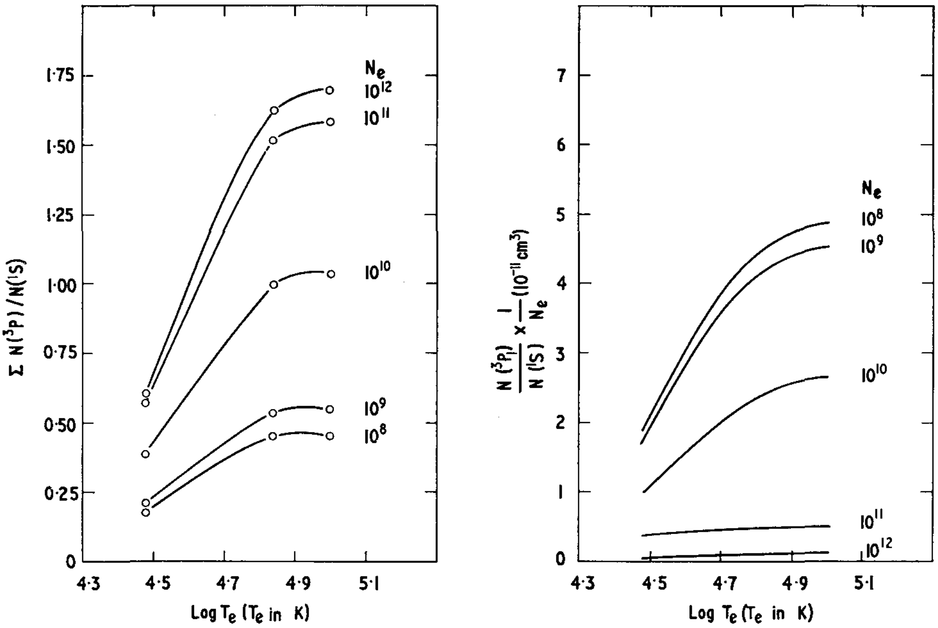

Fig. 2. The variation of $\Sigma N(^3P)/N(^1S)$ and $(N\,^3P_1)/N(^1S)\,(1/N_e)$ with N_e and T_e for C III.

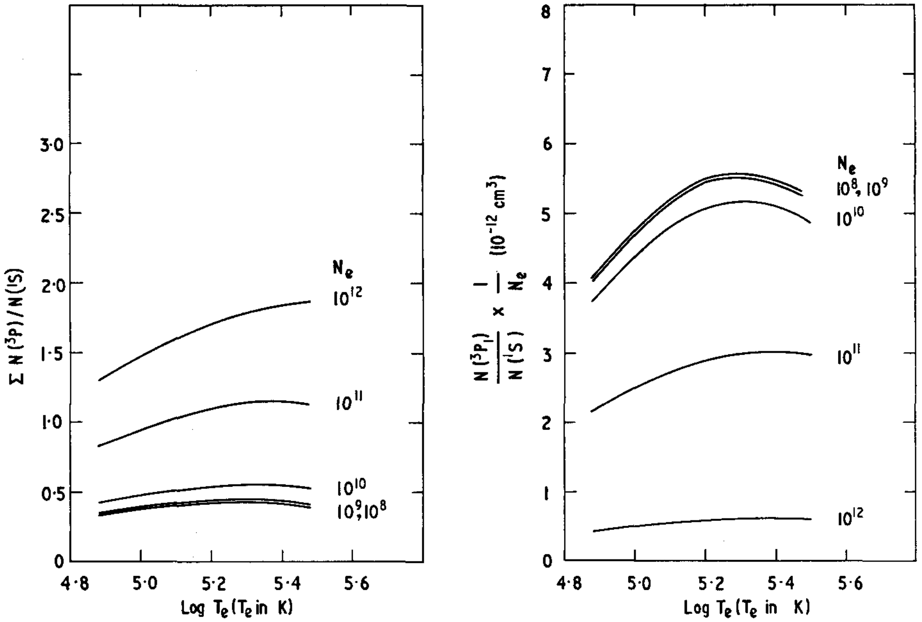

Fig. 3. As for Figure 2, for N IV

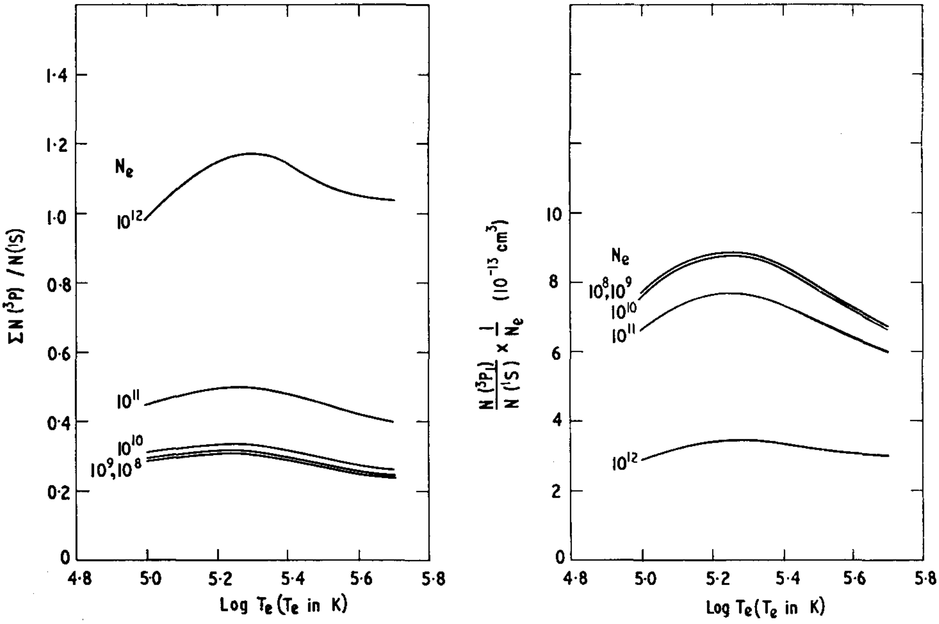

Fig. 4. As for Figure 2, for O V.

TABLE II

Results

T_e Ion		$\Sigma N(^3P)/N(^1S)$	N_e cm^{-3}	$(N(^3P_1)/N(^1S))\ (1/N_e)$		$\Sigma N(^3P)N(^1S)$	N_e cm^{-3}	$(N(^3P_1)/N(^1S))\ (1/N_e)$
	10^5 K	Equation (1)		Equation (2)	Equation (1)	From	EUV	model
C III	0.56	0.73	5.3×10^9	8.5×10^{-11}	3.0×10^{-11}	0.87	1.0×10^{10}	2.2×10^{-11}
N IV	1.52	1.0	8.5×10^{10}	$< 1.5 \times 10^{-11}$	3.0×10^{-12}	0.47	3.7×10^9	5.2×10^{-12}
O V	2.3	0.11	$< 10^6$	5.2×10^{-13}	$\sim 8.6 \times 10^{-13}$	0.31	2.5×10^9	8.6×10^{-13}

The temperature tabulated for each ion is that at which the function

$$\int_{\Delta T} N_e^2 \frac{N(\text{ion})}{N(E)} T_e^{-1/2} \left(\frac{dh}{\mathrm{d} \log T} \right) e^{-W/kT_e} \, \mathrm{d} \log T$$

has its maximum value, where $N(\text{ion})/N(E)$ is the ionization equilibrium population ratio, taken from Jordan (1969); T_e is the electron temperature; $(\mathrm{d}h/\mathrm{d} \log T)^{-1}$ is the logarithmic temperature gradient; W is the energy of the transition in eV; N_e and $\mathrm{d}h/\mathrm{d} \log T$ are taken from the model of the solar atmosphere derived by Jordan (1965) from the absolute intensities of EUV lines. If results with an accuracy of only about 10% are required, the same temperature can be used for each transition in an ion.

The values of $\Sigma N(^3P)/N(^1S)$ derived from Equation (1) and the above temperatures, and the electron densities derived from these ratios are given in Table II.

The values of $N(^3P_1)/N(^1S)\,N_e$ derived from Equation (2), and from the above values of $\Sigma N(^3P)/N(^1S)$ and N_e are also tabulated. The values of these parameters expected from the EUV model of Jordan (1965) are given for comparison.

A. C III RESULTS

From Table II it can be seen that the agreement between the 'observed' and 'predicted' values of $\Sigma N(^3P)/N(^1S)$ and N_e is entirely satisfactory. However, there is a difference of about a factor of 3 in the values of $N(^3P_1)/N(^1S)\,N_e$ derived from Equations (1) and (2). Allowing for the integration over the atmosphere in calculating the intensities, instead of taking the same temperature for both lines, would reduce this to a discrepancy of a factor of 2.5. A satisfactory solution cannot be obtained by changing the temperature at which the lines are formed. It is unlikely that either $A(^3P_1{-}^1S)$ or $C(^1S{-}^1P)$ is incorrect by a factor of three. The most likely source of error is the intensity data used because of the wide separation in the wavelengths of the $^1S{-}^3P_1$ and $^1S{-}^1P$ transitions. Each intensity is expected to be correct to within a factor of two, so a factor of three does lie within the upper limit to the expected error.

The calculations for C III may also be used to interpret the changes in the $E(^3P{-}^3P')/E(^1S{-}^1P)$ ratio from quiet to active regions as observed from OSO IV by Noyes *et al.* (1970). For the two active regions for which data are available the ratio changes by a factor of about 1.35. At a constant temperature of 5.6×10^4 K and $N_e(\text{quiet}) = 1 \times 10^{10}$ cm^{-3}, this corresponds to an increase of a factor of 8 in electron density from the quiet Sun to the active regions.

B. N IV RESULTS

The results for N IV, given in Table II, show that the ratio of $\Sigma N(^3P)/N(^1S)$ derived for the observations is a factor of 2 larger than that predicted by the calculations and the EUV model. Considering the weakness of the $^3P{-}^3P'$ multiplet and the possible blending with a member of the Lyman series this agreement is satisfactory. The N IV lines do not provide a sensitive method of determining electron density.

Only an upper limit is available for the intensity of the intercombination transition.

The difference between the values of $N(^3P_1)/N(^1S)\ N_e$ derived from Equations (1) and (2) is then a factor of 5.

C. O V RESULTS

The value of $\Sigma N(^3P)/N(^1S)$ derived from $E(^3P\text{–}^3P')/E(^1S\text{–}^1P)$ is a factor 2.9 smaller than that predicted by the calculations and the EUV model. Since the $^3P\text{–}^3P'$ multiplet is weak the origin of the difference is probably the relative intensity data.

The value of $N(^3P_1)\ N(^1S)\ N_e$ derived from Equation (2) is a factor of 1.7 smaller than that predicted by the EUV model; this agreement is satisfactory.

The change of a factor ~1.1 in the ratio $E(^3P\text{–}^3P')/E(^1S\text{–}^1P)$ observed by Noyes *et al.* (1970) from quiet to active regions implies a density increase of about a factor of 5, taking $N_e(\text{quiet}) = 2.5 \times 10^9\ \text{cm}^{-3}$.

The transition $2s\,2p\ ^1P\text{–}2p^2\ ^1D$ is also observed in O V at 1317 Å. The computed value of $E(^1P\text{–}^1D)/E(^1S\text{–}^1P)$ is 0.0092, a factor of 2.7 smaller than the observed value of 0.024. This factor is just within the expected accuracy of the intensity data.

5. Conclusions

For C III, N IV and O V, the observed ratios $E(^3P\text{–}^3P')/E(^1S\text{–}^1P)$ agree with those predicted by the model derived from total fluxes and the theoretical excitation rate coefficients, within the expected accuracy of the intensity data.

The intercombination line $^1S\text{–}^3P$ in C III, is stronger than expected from the observed ratio of the $^1S\text{–}^1P$ and $^3P\text{–}^3P'$ transitions, but the intensity data used are not sufficiently reliable to conclude that the errors lie in the theoretical calculations of the populations and intensities.

Acknowledgement

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References

Burgess, A.: 1964, AERE Report-4818, UKAEA, Harwell.
Burton, W. M., Jordan, C., Ridgeley, A., and Wilson, R.: 1971, *Phil. Trans. Roy. Soc. A.* **270**, 81.
Freeman, F. F. and Jones, B. B.: 1970, *Solar Phys.* **15**, 288.
Garstang, R. H. and Shamey, L. J.: 1967, *Astrophys. J.* **148**, 665.
Hall, C. A., Damon, K. R., and Hinteregger, H. E.: 1963, *Space Res.* **3**, 745.
Jordan, C.: 1965, Ph.D. Thesis, London University.
Jordan, C.: 1969, *Monthly Notices Roy. Astron. Soc.* **142**, 501.
Noyes, R. W., Withbroe, G. L., and Kirshner, R. P.: 1970, *Solar Phys.* **11**, 388.
Osterbrock, D. E.: 1970, *J. Phys. B.* [2], **3**, 149.
Saraph, H. E., Seaton, M. J., and Shemming, J.: 1969, *Phil. Trans. Roy. Soc. London*, **A264**, 77.
Wiese, W. L., Smith, M. W., and Glennon, B. M.: 1966, NSRDS-NBS-4, U.S. Govt. Printing Office, Washington, D. C.

DISCUSSION

E. Trefftz: In which direction is the derived electron density for C III wrong by a factor of three? Is it too high?

C. Jordan: No, the density derived using the intersystem line and resonance line is too low.

E. Trefftz: Could this be due to a process not included in the calculation?

C. Jordan: No, another process would not help as it is essentially the $^3P_1$ population compared with the total ^3P population which gives the low density. Even bringing the ^3P relative populations up to a Boltzmann distribution would only change the result by about twenty percent.