

THE HIGH TEMPERATURE EXCITATION OF HELIUM

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Summary

The relative populations of the helium ground state, the singlet and triplet states of principal quantum number 2 and 3, and the ionized state are obtained for an atmosphere isothermal at one of a number of kinetic temperatures in the range 10^4 – 10^5 °K.

It is shown that the non-appearance of the D_3 line of helium in the solar Fraunhofer spectrum may be reconciled with the simultaneous appearance of the infra-red $\lambda 10830$ line, provided the mean kinetic temperature of the chromosphere is not too great. From an analysis of observations of the D_3 emission of the solar chromosphere, it is concluded that the mean kinetic temperature of the lower chromosphere is most probably in the range 10^4 – 1.25×10^4 °K.

I. INTRODUCTION

The suggestion by Redman (1942) that the solar chromosphere has a high kinetic temperature ($\sim 30,000$ °K) has in recent years stimulated studies of the excitation of and emission of radiation from high temperature atmospheres, with particular reference to the solar chromosphere and various related features such as prominences and flares. Attention so far has been confined largely to the excitation of hydrogen since it is the most abundant element in stellar systems and the simplest to consider theoretically and because most of the relevant atomic excitation processes have been studied. The data so obtained have been applied by the author (1955) to determine the physical conditions in prominences, and it is clearly desirable that such computations should be extended to other elements so as to check results found for hydrogen and to allow interpretation of observations where the results for hydrogen are either lacking or equivocal.

In this paper the excitation of helium is considered for a number of kinetic temperatures in the range 10^4 – 10^5 °K, this range being of considerable interest in astrophysics. The choice of helium as the next element for consideration after hydrogen lies in its importance in the solar flash spectrum and its high excitation potential which should make the emission quite sensitive to small changes in kinetic temperature. Further, the interpretation of helium spectra from the Sun is likely to be more straightforward than for hydrogen, as the effects of self-absorption should be far smaller. The rather curious and variable behaviour of helium eclipse spectra also makes its study of interest, as it is felt that an explanation of such features could assist considerably in solving problems of chromospheric structure.

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In order to test Redman's (1942) suggestion of a high chromospheric temperature, Miyamoto (1951) considered the excitation of helium in a model solar chromosphere at 35,000 °K and showed that, at such a high temperature, one would expect strong He I and He II absorption lines in the solar disk spectrum, contrary to observation.

We shall consider here the excitation of helium in a high temperature, horizontally stratified, isothermal atmosphere of which helium is a constituent. The presence of other elements in the atmosphere is taken to influence the helium excitation only by increasing the electron concentration and so increasing the rate of collisional excitation; heavy particle collisions are assumed of negligible importance. In general the most important element present, at least in astrophysical situations, is hydrogen, and the numerical illustrations given here are limited to cases where the atmosphere is composed of hydrogen and helium, generally with an abundance ratio 5:1. In these cases, the electrons result mainly from ionization of hydrogen. The theory, however, is developed using the electron concentration N_e as a parameter and so may be applied to any atmosphere.

Excitations and de-excitations of the atoms are also caused by radiative transitions involving absorption or emission of radiation. Since applications will be mainly to solar phenomena, numerical results are confined to the case of an atmosphere irradiated by hemispherical black-body radiation at 6000 °K, corresponding to solar photospheric radiation. This irradiation will only be significant in those parts of the spectrum where the optical depth of the atmosphere is small. Elsewhere radiative excitation is due to the radiation field built up by the atmosphere itself.

As for hydrogen, which was treated by Jefferies and Giovanelli (1954),* the problem for helium may be formulated in terms of a set of simultaneous equilibrium equations which state that the rate of entry into an atomic level equals the rate of leaving, together with a set of second order differential equations whose solutions give the intensities in each spectral line and continuum. As the solution of such a set is formidable, recourse is made to an approximate treatment using a restricted number of energy levels, namely, the ground and ionized states together with the singlet and triplet states of principal quantum numbers 2 and 3. The fine structure splitting will be ignored; where necessary we shall suppose these states to be populated in the ratios of their statistical weights.

Intercombination transitions between an excited singlet and a triplet level will also be ignored. Optically forbidden radiative transitions of this type are known to be weak in comparison with the corresponding optically allowed transitions. Collisional transitions will be neglected for simplicity, but this neglect will not cause much error as the singlet and triplet levels are quite strongly linked through the ionized state. Further these intercombination collision transitions are unlikely to be more frequent than the transitions between states of equal multiplicity, and, since we can hardly do better than guess these latter rates, the order of accuracy of the results will not be greatly affected by the

* This paper will be referred to throughout as paper A.

neglect of intercombination transitions. Transitions between the ground state and the triplet 2 and 3 states, whose cross sections are quite well known, are, however, taken into account.

II. THE EXCITATION RATES

The total rate of excitation per unit volume from state j to state l is denoted $P_{jl}N_j$, where N_j is the population of the j state. P_{jl} may be dissected into a radiative component A_{jl} and an electron collisional component R_{jl} , which contains the electron concentration N_e as a factor. The rates of collision excitation

TABLE 1
HELIUM COLLISION CROSS SECTIONS (πa_0^2)

Transition	Cross Section
1^1S-2^1S	$3 \times 10^{-2} (E_0/E)$
1^1S-2^1P	$1.5 \times 10^{-1} (E-E_0)/(E_m-E_0); E_m=50 \text{ eV}$
1^1S-3^1S	$3 \times 10^{-3} (E_0/E)$
1^1S-3^1P	$3 \times 10^{-2} (E-E_0)/(E_m-E_0); E_m=100 \text{ eV}$
1^1S-3^1D	$8 \times 10^{-4} E_0/E$
1^1S-2^3S	$4 \times 10^{-2} (E_0/E)^2$
1^1S-2^3P	$3 \times 10^{-2} (E_0/E)^3$
1^1S-3^3S	$2 \times 10^{-3} (E_0/E)^2$
1^1S-3^3P	$1 \times 10^{-2} (E_0/E)^3$
1^1S-3^3D	$8 \times 10^{-4} (E_0/E)^4$

follow, assuming a Boltzmann distribution of energy among the electrons, from the absolute values and energy dependence of the collision cross sections. For collisions from the ground state this information is available for most transitions—Bates *et al.* (1950)—and the values adopted here are shown in Table 1 together with our idealized energy dependence. For the optically allowed transitions 1^1S-2^1P , 3^1P , a linear energy dependence is assumed here up to a maximum

TABLE 2
ADOPTED VALUES OF q

Transition	2S-3S	2S-3P	2S-3D	2P-3S	2P-3P	2P-3D
q (eV)	10	100	5	10	10	150

cross section at E_m . Owing to the high values of E_m compared with kT , the value of the excitation rate is effectively independent of the cross section beyond E_m . For transitions between excited states some reasonable guess must be made as no data are available. It has been assumed that, for corresponding singlet-singlet and triplet-triplet transitions, the cross sections are equal and of the form $q\pi a_0^2/E$; the adopted values of q obtained from comparison with corresponding data for hydrogen are shown in Table 2.

The resultant collisional excitation rates between states of given principal quantum numbers are shown in Table 3 for a number of kinetic temperatures.

The rates of super-elastic collision and of collision ionization are found in a straightforward manner by the method used by Giovanelli (1948). The rates of photoelectric ionization and of spontaneous recombination are also computed

TABLE 3
RATES OF COLLISION EXCITATION ($N_e N_n$ CM⁻³ SEC⁻¹)

T (10 ⁴ °K)	1-2 ¹	1-3 ¹	2-3	1-2 ³	1-3 ³
1.00	3.5×10^{-19}	2.2×10^{-21}	1.0×10^{-7}	7.5×10^{-19}	5.3×10^{-21}
1.25	4.2×10^{-17}	3.4×10^{-19}	1.4×10^{-7}	6.5×10^{-17}	9.0×10^{-19}
1.50	1.0×10^{-15}	1.0×10^{-17}	1.8×10^{-7}	1.3×10^{-15}	2.6×10^{-17}
2.00	6.3×10^{-14}	8.4×10^{-16}	2.2×10^{-7}	5.6×10^{-14}	1.8×10^{-15}
2.50	7.2×10^{-13}	1.0×10^{-14}	2.5×10^{-7}	4.9×10^{-13}	2.2×10^{-14}
5.00	1.2×10^{-10}	1.8×10^{-12}	2.8×10^{-7}	3.7×10^{-11}	3.3×10^{-12}
10.00	1.8×10^{-9}	2.4×10^{-11}	2.4×10^{-7}	2.7×10^{-10}	3.2×10^{-11}

by a similar method using the Gaunt formula for the continuous absorption coefficient, as modified by Menzel (1931).

$$\alpha(n, \nu) = 2^6 \pi^4 m Z^4 \epsilon^{10} / 3 \sqrt{3} c h^6 \nu^3 n_{\text{eff}}^5,$$

where n_{eff} is the effective principal quantum number for the level.

Rates of spontaneous transitions between bound states may be computed from tables given by Bates and Damgaard (1949) and are shown in Table 4.

TABLE 4
SPONTANEOUS TRANSITION RATES (N_j CM⁻³ SEC⁻¹)

Transition $j-l$..	2 ¹ -1	3 ¹ -1	3 ¹ -2 ¹	3 ³ -2 ³
Rate	1.62×10^9	2.15×10^8	4.27×10^7	4.60×10^7

Of the intercombination lines, one would expect the most important to be the extreme ultraviolet line resulting from the transition 2³P-1¹S. Its transition probability, however, seems to be very small, as can be inferred from photographs given by Hopfield (1930) and we shall ignore it here in comparison with other processes removing atoms from the triplet 2 state. It should, however, be pointed out that this intercombination line is likely to be important in very diffuse atmospheres only faintly illuminated from outside, since in such cases it is likely to be the predominant transition from the triplet 2 state.

III. THE POPULATIONS OF THE GROUND AND IONIZED STATES

Using excitation rates found as in Section II, we may formulate six equilibrium equations for the populations of the 1, 2¹, 3¹, 2³, 3³, and 4 states, the last representing the ionized state, He II. This set may be solved for the ratios of populations of any two states; for absolute values we need, of course, one

further piece of information which will usually be the total concentration of helium atoms and ions.

The Lyman type radiation arising from the transitions 2^1-1 , 3^1-1 , and $4-1$ will be denoted here by $L\alpha$, $L\beta$, and $L\gamma$. Since we shall be dealing solely with helium radiation, no confusion with the Lyman radiation of hydrogen should result.

Arrivals in the ionized, 4, state are due to:

- (i) ionizations from 1,
- (ii) ionizations from 2^1 and 3^1 ,
- (iii) ionizations from 2^3 and 3^3 .

If the atmosphere is optically thin to $L\alpha$ and $L\beta$, the contributions from (ii) are negligible compared with (i). Ionizations from the triplet states, however, are not negligible since, following the collision excitations $1-2^3$, $1-3^3$ the most probable result is an ionization, since the rates of the super-elastic collision 3^3-1 , 2^3-1 are much less than the corresponding rates of ionization. The ionizations (i) and (iii) are balanced by recombinations to the ground and excited singlet levels; any recombination to the triplet levels resulting in a subsequent ionization. It follows then that

$$(R_{14} + R_{12^3} + R_{13^3})N_1 = (P_{41} + P_{42^1} + P_{43^1})N_4,$$

or

$$\frac{N_1}{N_4} = \frac{P_{41} + P_{42^1} + P_{43^1}}{R_{14} + R_{12^3} + R_{13^3}} \quad \dots \dots \dots (3.1)$$

Excited singlet levels have a high probability of returning direct to the ground state emitting a quantum of radiation. If, however, the atmosphere is optically thick to $L\alpha$ and $L\beta$, this quantum is immediately reabsorbed in the atmosphere and the process is repeated until an ionization occurs. Thus nearly all collisions from the ground state result eventually in ionizations, which together with the ionizations from the ground state are balanced by recombinations to the ground state only, since a recombination to any excited level will result in a subsequent ionization in the great majority of cases. For high opacity in $L\alpha$ and $L\beta$ therefore

$$\frac{N_1}{N_4} = \frac{P_{41}}{P_{14} + R_{12^1} + R_{13^1} + R_{12^3} + R_{13^3}} \quad \dots \dots \dots (3.2)$$

If the atmosphere is optically thin in $L\gamma$, P_{14} may be replaced by R_{14} and hence

$$\frac{N_1}{N_4} = \frac{P_{41}}{\sum_l R_{1l}} \quad \dots \dots \dots (3.3)$$

The values of N_1/N_4 shown in Table 5 are obtained on inserting numerical values into (3.1) and (3.3).

If the optical thickness in $L\gamma$ is not small, P_{14} in (3.2) cannot be replaced by R_{14} , i.e. account must be taken of the effect of $L\gamma$ absorption on the populations N_1 and N_4 . Applying the method used in paper A for the corresponding problem for hydrogen it is found that, for high opacity in $L\alpha$, $L\beta$, and $L\gamma$,

$$\frac{N_1}{N_4} = \lambda_{14} \frac{P_{41}}{\sum_l R_{1l}}, \quad \dots \dots \dots (3.4)$$

TABLE 5
THE RATIO N_1/N_4

T (10^4 °K)	Atmospheres Thin in $L\alpha$, $L\beta$, $L\gamma$ Eqn. (3.1)	Atmospheres Thick in $L\alpha$, $L\beta$ and Thin in $L\gamma$ Eqn. (3.3)
1.00	4.3×10^5	2.4×10^5
1.25	4.4×10^3	2.2×10^3
1.50	1.9×10^2	8.8×10^1
2.00	3.1	1.4
2.50	2.6×10^{-1}	1.1×10^{-1}
5.00	9.3×10^{-4}	4.5×10^{-4}
10.00	5.0×10^{-5}	2.2×10^{-5}

where λ_{14} is the scattering parameter for $L\gamma$ radiation, whose value is found, using the general method given by Giovanelli and Jefferies (1954), to be given approximately by the relation

$$\lambda_{14} = \frac{\alpha'(P_{423} + P_{433}) + \alpha(P_{421} + P_{431})}{P_{41}}, \quad \dots\dots\dots (3.5)$$

where $\alpha' = R_{231}/P_{234}$ and $\alpha = R_{211}/P_{214}$.

Expressions for λ_{14} in terms of N_e are shown in Table 6.

TABLE 6
THE SCATTERING PARAMETER FOR $L\gamma$ RADIATION

T (10^4 °K)	λ_{14}
1.00	$7.6 \times 10^{-14} N_e / (1 + 3.7 \times 10^{-13} N_e)$
1.25	$6.4 \times 10^{-14} N_e / (1 + 1.0 \times 10^{-12} N_e)$
1.50	$6.3 \times 10^{-14} N_e / (1 + 1.6 \times 10^{-12} N_e)$
2.00	$5.2 \times 10^{-14} N_e / (1 + 3.3 \times 10^{-12} N_e)$
2.50	$4.8 \times 10^{-14} N_e / (1 + 5.0 \times 10^{-12} N_e)$
5.00	$3.8 \times 10^{-14} N_e / (1 + 1.1 \times 10^{-11} N_e)$
10.00	$3.4 \times 10^{-14} N_e / (1 + 1.5 \times 10^{-11} N_e)$

Optical depths for an isothermal atmosphere of temperature T are given below. The values refer to the line centres for $L\alpha$ and $L\beta$ and to the head of the continuum for $L\gamma$.

$$\tau_{L\alpha} = \frac{4.5 \times 10^{-12}}{\sqrt{T}} \int_0^\infty N_1 dz,$$

$$\tau_{L\beta} = \frac{4.7 \times 10^{-13}}{\sqrt{T}} \int_0^\infty N_1 dz,$$

$$\tau_{L\gamma} = 6.2 \times 10^{-18} \int_0^\infty N_1 dz.$$

Thus for a model atmosphere of thickness 2×10^8 cm, electron concentration 5×10^{11} cm $^{-3}$, and kinetic temperature $T = 10^4$ °K in which the H : He abundance ratio is 5 we find, since the hydrogen is nearly all ionized—paper A—while the helium atoms are nearly all in the ground state, that $N_1 \sim 10^{11}$ cm $^{-3}$, and

$$\begin{aligned}\tau_{L\alpha} &\sim 9 \times 10^5, \\ \tau_{L\beta} &\sim 9 \times 10^4, \\ \tau_{Lc} &\sim 10^2,\end{aligned}$$

while for the same atmosphere at 5×10^4 °K, $N_1 \sim 5 \times 10^7$ and

$$\begin{aligned}\tau_{L\alpha} &\sim 2 \times 10^2, \\ \tau_{L\beta} &\sim 2 \times 10^1, \\ \tau_{Lc} &\sim 6 \times 10^{-2}.\end{aligned}$$

IV. THE POPULATIONS OF THE EXCITED STATES

The equilibrium equations for the excited singlet or triplet states may be written

$$\left. \begin{aligned}P_{42}N_4 + P_{32}N_3 + P_{12}N_1 &= T_2N_2, \\ P_{43}N_4 + P_{23}N_2 + P_{13}N_1 &= T_3N_3,\end{aligned} \right\} \dots\dots\dots (4.1)$$

where T_2 and T_3 represent the total rates per atom for departure from the 2 and 3 states and, since the equations apply to either singlet or triplet levels, distinguishing symbols have been omitted.

The solutions of (4.1) are

$$\left. \begin{aligned}N_2 &= \frac{T_3K_2 + P_{32}K_3}{T_2T_3 - P_{23}P_{32}}, \\ N_3 &= \frac{T_2K_3 + P_{23}K_2}{T_2T_3 - P_{23}P_{32}},\end{aligned} \right\} \dots\dots\dots (4.2)$$

where

$$\begin{aligned}K_2 &= P_{42}N_4 + P_{12}N_1, \\ K_3 &= P_{43}N_4 + P_{13}N_1.\end{aligned}$$

If the atmosphere is optically thin in the 2-3 radiation, the radiative component A_{23} of the transition rate P_{23} is found from the intensity of the radiation incident on the atmosphere. If it is not optically thin, A_{23} is found from the intensity of the radiation inside the atmosphere, which varies from depth to depth and may be computed in the manner indicated in paper A. The following remarks apply to an atmosphere optically thin in 2-3 radiation, although the modifications necessary for a thick atmosphere are straightforward.

For high opacity in the Lyman type lines, we replace the transition rates P_{12} , P_{21} , P_{13} , P_{31} by their corresponding collisional transition rates and obtain, neglecting some small terms, and assuming $P_{23} > P_{24}$, which will be so for cases of interest here,

$$\left. \begin{aligned}N_{21} &\simeq \frac{K_{21} + K_{31}}{P_{214}}, \\ N_{31} &\simeq \frac{P_{2131}}{P_{3121}} N_{21}.\end{aligned} \right\} \dots\dots\dots (4.3)$$

The triplet populations N_{2^3} and N_{3^3} are also given by equations of the form (4.3) owing to the assumption of no radiative intercombination between the ground and triplet levels.

If the atmosphere is optically very thin in $L\alpha$ and $L\beta$ solutions (4.2) become, for the singlet states,

$$\left. \begin{aligned} N_{2^1} &\simeq \frac{R_{12^1}N_1 + P_{42^1}N_4}{P_{2^11}}, \\ N_{3^1} &\simeq \frac{R_{13^1}N_1 + P_{43^1}N_4}{P_{3^11}}, \end{aligned} \right\} \dots\dots\dots (4.4)$$

TABLE 7
POPULATIONS OF THE SINGLET AND TRIPLET 2 STATES

T (10^4 °K)	N_{2^1}/N_1N_e (cm^3)	N_{2^3}/N_1N_e (cm^3)
1.00	$\frac{3.5 \times 10^{-19} + 7.2 \times 10^{-14}N_4/N_1}{2.5 \times 10^4 + 8.8 \times 10^{-9}N_e}$	$\frac{7.5 \times 10^{-19} + 2.4 \times 10^{-13}N_4/N_1}{1.4 \times 10^4 + 5.5 \times 10^{-9}N_e}$
1.25	$\frac{4.2 \times 10^{-17} + 6.1 \times 10^{-14}N_4/N_1}{2.5 \times 10^4 + 2.0 \times 10^{-8}N_e}$	$\frac{6.6 \times 10^{-17} + 2.0 \times 10^{-13}N_4/N_1}{1.4 \times 10^4 + 1.4 \times 10^{-8}N_e}$
1.50	$\frac{1.0 \times 10^{-15} + 5.3 \times 10^{-14}N_4/N_1}{2.5 \times 10^4 + 3.5 \times 10^{-8}N_e}$	$\frac{1.3 \times 10^{-15} + 1.8 \times 10^{-13}N_4/N_1}{1.4 \times 10^4 + 2.5 \times 10^{-8}N_e}$
2.00	$\frac{6.4 \times 10^{-14} + 4.3 \times 10^{-14}N_4/N_1}{2.5 \times 10^4 + 7.3 \times 10^{-8}N_e}$	$\frac{5.8 \times 10^{-14} + 1.4 \times 10^{-13}N_4/N_1}{1.4 \times 10^4 + 5.3 \times 10^{-8}N_e}$
2.50	$\frac{7.3 \times 10^{-13} + 3.4 \times 10^{-14}N_4/N_1}{2.5 \times 10^4 + 1.1 \times 10^{-7}N_e}$	$\frac{5.1 \times 10^{-13} + 1.2 \times 10^{-13}N_4/N_1}{1.4 \times 10^4 + 8.2 \times 10^{-8}N_e}$
5.00	$\frac{1.2 \times 10^{-10} + 2.0 \times 10^{-14}N_4/N_1}{2.5 \times 10^4 + 2.4 \times 10^{-7}N_e}$	$\frac{4.0 \times 10^{-11} + 6.9 \times 10^{-14}N_4/N_1}{1.4 \times 10^4 + 2.0 \times 10^{-7}N_e}$
10.00	$\frac{1.8 \times 10^{-9} + 1.1 \times 10^{-14}N_4/N_1}{2.5 \times 10^4 + 3.4 \times 10^{-7}N_e}$	$\frac{3.0 \times 10^{-10} + 3.7 \times 10^{-14}N_4/N_1}{1.4 \times 10^4 + 2.8 \times 10^{-7}N_e}$

which are much smaller than the values given by (4.3). For intermediate optical depths in $L\alpha$ and $L\beta$ approximations to the ratios N_{2^1}/N_1 and N_{3^1}/N_1 may be found by the method indicated in paper A. We outline the method for N_{2^1}/N_1 ; the procedure for N_{3^1}/N_1 is analogous.

Provided the optical depth in $L\alpha$ is not too low,

$$\frac{N_{2^1}}{N_1} \simeq \frac{A_{12^1}}{A_{2^11}} \simeq \frac{J_\alpha}{\rho_\alpha}, \dots\dots\dots (4.5)$$

where $\rho_\alpha = \frac{8\pi h \nu_\alpha^3}{c^2} \frac{\omega_1}{\omega_2}$, ω_1 and ω_2 are the statistical weights, and J_α is the total intensity at the level in the atmosphere where the ratio N_2/N_1 is required. The value of J_α is found as in paper A; for a homogeneous atmosphere with no incident radiation at the top and total reflection at the base,

$$J = \frac{4\pi b}{\lambda} \left[1 - \frac{\exp(-\sqrt{3\lambda}\tau) + \exp[\sqrt{3\lambda}(\tau - 2\tau_1)]}{1 + 2\sqrt{\lambda/3} + (1 - 2\sqrt{\lambda/3}) \exp(-2\sqrt{3\lambda}\tau_1)} \right], \dots (4.6)$$

where the source function b and the scattering parameter λ may be found, in terms of the transition rates, from the method given by Giovanelli and Jefferies (1954).

The ratios N_{2^1}/N_1 and N_{2^3}/N_1 computed from (4.3) and so applying, for the singlet states, only to high opacities in $L\alpha$ and $L\beta$, are given in terms of N_e and N_4/N_1 in Table 7.

V. DISCUSSION AND APPLICATIONS TO THE SOLAR CHROMOSPHERE

Comparison of the ratios of the population of the ground state to that of the ionized state in helium and hydrogen shows that they are of the same order for a temperature T_1 in H as for a temperature $2T_1$ in He. This is as expected since the ionization potentials differ by a factor 2.

We shall now consider some aspects of solar helium emission. In the visible part of the spectrum of the undisturbed disk no trace of He absorption or emission lines is found even in the case of the strong D_3 transition, though the 2^3S-2^3P infra-red line at $\lambda 10830$ appears in absorption, indicating very different optical depths in these lines.

The optical thickness in the D_3 , 3^3D-2^3P , line may be obtained from well-known expressions for the Doppler broadened absorption coefficient and, at the line centre, is given by

$$\tau(D_3) = \int_0^\infty \frac{8.4 \times 10^{-11}}{\sqrt{T}} N_{2^3P} dz, \quad \dots \dots \dots (5.1)$$

the integration extending throughout the chromosphere. For the $\lambda 10830$ line,

$$\tau(10830) = \int_0^\infty \frac{1.4 \times 10^{-10}}{\sqrt{T}} N_{2^3S} dz. \quad \dots \dots \dots (5.2)$$

We shall consider firstly the ratio of the optical depths in D_3 and $\lambda 10830$. For simplicity we have throughout assumed the states of principal quantum number 2 to be degenerate. In fact this is not so; the 2^3S and 2^3P states have an energy difference of 1.14 eV and so the two populations are not in the ratio of their statistical weights. The relative populations are maintained primarily by radiative transitions, so that if the radiation in the atmosphere corresponds at $\lambda 10830$ to black-body radiation at a temperature T °K diluted by a factor κ it follows that

$$\frac{N_{2^3P}}{N_{2^3S}} \simeq \frac{\omega_{2^3P}}{\omega_{2^3S}} \frac{\kappa}{\exp(E_0/kT) - 1}, \quad \dots \dots \dots (5.3)$$

where $E_0 = 1.14$ eV. With $T = 6000$ °K and $\kappa = \frac{1}{2}$, the ratio of the optical depths given by (5.1) and (5.2) becomes

$$\frac{\tau(D_3)}{\tau(10830)} \simeq \frac{1}{10}. \quad \dots \dots \dots (5.4)$$

According to Mohler *et al.* (1950) $\lambda 10830$ is depressed about 5 per cent. below the local continuum, meaning that the chromospheric optical depth in this line is

~ 0.05 . From (5.4), the optical depth in D_3 should then be ~ 0.005 which is too small to allow D_3 absorption to be seen.

The magnitudes of the optical depths may be used to derive an estimate of the chromospheric temperature. In the solar chromosphere the concentration and distribution of helium is poorly known. To estimate optical depths, we use the homogeneous model defined in Section III, which should give results of roughly correct order. For $T=10^4$, 1.25×10^4 , and 1.5×10^4 °K the optical depths in D_3 and $\lambda 10830$ are then found, taking $N_{2S}=N_2/4$ and using (5.4), to be as shown in Table 8. This table shows that at temperatures above about 1.1×10^4 °K absorption lines should appear in $\lambda 10830$ and at about 2000 °K higher they should appear in D_3 .

TABLE 8
OPTICAL DEPTHS IN D_3 AND $\lambda 10830$ FOR THE MODEL IN SECTION III

T (10^4 °K)	$\tau (D_3)$	$\tau (10830)$
1.00	2×10^{-4}	2×10^{-3}
1.25	4×10^{-2}	4×10^{-1}
1.50	4×10^{-1}	4

While these results indicate that the mean kinetic temperature of the regions responsible for helium emission in the lower chromosphere is of the order of 1.25×10^4 °K or less, the shortcomings of the model make this estimate a rather crude one. A better indication of the temperature can be obtained from measurements of the helium emission in the chromospheric spectrum such, for example, as those of Perepelkin and Melnikov (1935) on the D_3 line. According to these authors, the emission of D_3 at a height of 1000 km above the solar limb is approximately 10^{-4} ergs $\text{cm}^{-3} \text{sec}^{-1}$. The population N_{3^3D} of the upper level of D_3 is then given by

$$Ah\nu N_{3^3D} \sim 10^{-4}, \dots\dots\dots (5.5)$$

where A ($=7.2 \times 10^7 \text{sec}^{-1}$) is the spontaneous transition probability for D_3 . From (5.5) we find

$$N_{3^3D} \sim 4 \times 10^{-1} \text{cm}^{-3}. \dots\dots\dots (5.6)$$

This result may be used, as follows, to infer a value of the kinetic temperature in the solar chromosphere at a height of 1000 km above the solar limb. At this height the electron concentration is, from observation, $\sim 2 \times 10^{11} \text{cm}^{-3}$. We assume that these electrons arise entirely from ionization of hydrogen and that the H:He abundance ratio is 5. From expressions, derived in paper A, for the degree of ionization of hydrogen at various temperatures, and with similar expressions for helium obtained here, the ground state population of helium, N_1 , may be found as a function of temperature. Using the triplet analogue to (4.3) we can then compute N_{3^3} and hence $N_{3^3D} = (5/9)N_{3^3}$. In this way the values of N_{3^3D} shown in Table 9 have been obtained. Results are shown for both high

and low opacity in the Lyman type continuum although the former almost certainly applies at 1000 km in the solar chromosphere if the mean kinetic temperature is of the order of 1.5×10^4 °K or less.

Comparison of the values of N_{3^3D} in Table 9 with the result (5.6) indicates that the mean temperature is not much higher than 10^4 °K. Owing to the rapid variation of N_{3^3D} with temperature, only gross changes in the data could materially affect this result.

TABLE 9
POPULATIONS OF THE 3^3D STATE

T (10^4 °K)	N_{3^3D} (cm $^{-3}$)	
	$\tau_c \gg 1$	$\tau_c \ll 1$
1.00	4×10^{-1}	1×10^{-2}
1.25	4×10^1	1
1.50	1×10^3	2×10^1
2.00	6×10^4	6×10^3

Whether or not this temperature estimate is a unique one depends on the corresponding values of N_{3^3D} below 10^4 °K. These cannot be obtained directly from the computations here or in paper A as these do not extend below 10^4 °K. We can, however, estimate the trend as follows. At 5×10^3 °K, the various populations should be the order of magnitude given by the Saha relation. With $N_e = 2 \times 10^{11}$ cm $^{-3}$ and the abundance ratio used above, it is found that $N_{3^3D} \sim 5 \times 10^{-8}$ cm $^{-3}$ at 5×10^3 °K. It follows that, for a constant electron concentration, N_{3^3D} decreases quite rapidly below 10^4 °K, and that the observations are uniquely satisfied by a temperature close to 1.0×10^4 °K.

Perepelkin and Melnikov's observations, on which the above has been based, are of considerable interest in showing a maximum emission of D_3 at a height of 2000 km above the solar limb. It seems probable that this is due to an increase of kinetic temperature with height and the results could be analysed to determine this temperature gradient from the helium abundance. An attempt along these lines using reasonable values of the latter two parameters has been made, but indicates little beyond the fact that the mean temperature in the first 4000–5000 km of the solar chromosphere is in the range 10^4 – 1.5×10^4 °K if the helium abundance at the base is of the order of 5×10^{10} cm $^{-3}$.

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