12. IONIZATION IN THE SOLAR CHROMOSPHERE*

§1

It has been known for a long time that the high-level chromosphere is generally distinguished by those lines which are relatively more strengthened in the spark than in the arc, and which Lockyer originally styled as enhanced lines. The following list taken from Mitchell's[1] list of chromospheric lines, along with the respective intensities of the line in the arc and the spark, illustrates the case:—

TABLE I[2]

Element	Wave-length of the line in A.U.'s.	Chromospheric level reached in Kms.	Intensity. Arc.	Intensity. Spark.
Calcium	3968 (H)	14000	300	500 L
	3933 (K)		500	1000 L
Strontium	4216	6000	500	500 L
	4078	6000	1000	1000 L
Barium	4994	750	500	1000 L
	4554	1200	1000	1000 L
Scandium	4247	6000	50	1000 L
Titanium	3685.4	6000	8	100
	3741.8	1500	3	10
	3759	6000	10	20 L
	3761	6000	6	10 L
	3900	1600	5	50 L
	3914	2000	5	20 L
	4290	1300	2	10 L
	4294	1200	3	8 L
	4300	1200	3	8 L
	4395	2500	10	10 L
	4444	1600	4	15 L
	4468	1500	4	15 L
	4501	1600	4	15 L
	4563	1200	3	10 L
	4572	1200	5	20 L

This table makes it quite clear that generally only those lines occur in the highest levels which are relatively more strengthened in the spark discharge spectrum. We can add to the above table a list of the high-level iron and other lines, but the conclusion would be the same.

It appears that no satisfactory explanation of this fact, as well as of the extraordinary height reached by these lines, has yet been offered. It is intimately connected with the physical mechanism of the arc and the spark. In this connexion, it is well to recall Lockyer's original hypothesis, which, however, does not seem to have been, at any time, much in favour with the physicists. According to Lockyer, the passage from the arc to the spark means a great, though localised, increase of temperature, to which mainly the enhancement of the lines was to be ascribed. But, apart from its physical incompleteness, Lockyer's theory launches us amidst great difficulties as far as the interpretation of solar phenomena is concerned. It would lead us to the hypothesis that the outer chromosphere is at a substantially higher temperature than the photosphere, and the lower chromosphere; and that the temperature of the sun increases as we pass radially outwards. This hypothesis is, however, quite untenable and is in flagrant contradiction to all accepted theories of physics.

A much more plausible explanation is that the lines in question are not due to radiations from the normal atom of the element, but from "an ionized atom, *i.e.,* one which has lost an electron." The high-level chromosphere is, according to this view, the seat of very intense ionization. Let us see briefly how this hypothesis has grown up.

Modern theories of atomic structure and radiation leave little doubt that the "enhanced lines" are due to the ionized atom of the element. As a concrete example, let us take the case of the Calcium H, K, and *g* lines. The "H, K" lines are of the enhanced type, while "*g*" is of the normal type. The "H, K" are the leading members of the principal pair-series of the system of double lines of Calcium, while the "*g*" line is the first member of the system of single lines of Calcium. Lorenser and Fowler[3] have shown that the series formula of the double lines is of the type

$$\nu = 4N \left[\frac{1}{\{f(m)\}^2} - \frac{1}{\{\phi(n)\}^2} \right],$$

while the series formula of the single lines is of the type

$$\nu = N \left[\frac{1}{\{f'(m)\}^2} - \frac{1}{\{\phi'(n)\}^2} \right],$$

where $f(m)$, $\phi(n)$ are functions of the form $m + \alpha$, according to Rydberg, and $m + \alpha + \beta[t(m)]$, according to Ritz, $t(m)$ being a function of m which vanishes with increasing values of m.

In other words, in the series formula of the enhanced lines, the spectroscopic constant is 4N instead of the usual Rydberg number N. In the light of Bohr's theory, this is to be understood in the sense that, during the emission of the enhanced lines, the nucleus, and the system of electrons

(excluding the vibrating one) taken together behave approximately as a double charge, so that the spectroscopic constant, $=\dfrac{2\pi^2 e^2 E^2 m}{h^3}$, becomes 4N, as E=2e. This means that if the nuclear charge is n, the total number of electrons is $(n-1)$, and the system has been produced by the removal of one electron from the normal atom.

What has been said of the Calcium lines H and K is also true of the Strontium pair 4216 and 4078, and the Barium pair 4934 and 4554, i.e., they are due to the ionized atom of these elements. The principal lines of the system of single lines of these elements also occur in the flash spectrum, but the following table shows that they reach a much lower level:—

TABLE II.

Element	Lines due to the Ionized Atom	Chromo-spheric level	Lines due to the Normal Atom	Chromo-spheric level
Ca	(H) 3968 (K) 3933	14000	(g) 4227	5000
Sr	4216 4078	6000	4607	350
Ba	4934 4554	750 1200	5536	400

N.B.—The lines chosen are the fundamental lines or the first lines of the principal series, having the symbolic formula $\nu=(1.S)-(2.P)$.

No satisfactory series formula is known for the other high-level chromospheric elements, viz., Titanium, Scandium, Iron, and other elements. But the recent remarkable work of Kossel and Sommerfeld[4] makes it quite clear that the spark-lines of these elements are due to the ionized atom. The spark-lines of alkalies have not been much investigated and lie in the ultraviolet beyond 3000, so that, even if they are present in the high-level chromosphere, we shall have no means of detecting them[5].

As regards Hydrogen, ionized Hydrogen would mean simply the hydrogen core, and this probably by itself would be incapable of emitting any radiation. But as H_α and H_β lines occur high in the chromosphere, we have to admit that hydrogen probably is not much ionized in the chromosphere.

The case of helium is very interesting. It is well known that the Fraunhofer spectrum does not contain any helium lines, which are obtained only in the flash spectrum. But these lines are all due to normal helium, and the highest level reached by the second line of the so-called principal series is some 8500 kms.[6], while the better-known D_3 reaches a level of 7500 kms. The lines due to ionized helium are represented by the general series formula

$$\nu=4N\left[\frac{1}{m^2}-\frac{1}{n^2}\right],$$

and the best known of them, in the visible range, are the Rydberg line 4686 and the Pickering system

$$\nu=N\left[\frac{1}{2^2}-\frac{1}{(m+\frac{1}{2})^2}\right]$$

once ascribed to "cosmic hydrogen." Mitchell[7] states that 4686 occurs in the flash spectrum, and reaches a level of 2000 kms. If the identification be all right, helium would present a seemingly anomalous case, for, whereas other elements are ionized in the upper strata, it is ionized in the lower strata of the chromosphere.

The above sketch embodies, in short, the problems before us. The alkaline earths and the heavier elements are ionized throughout the whole of the solar atmosphere, but the ionization is complete in the chromosphere, which seems to contain no normal atom at all. But hydrogen and helium are probably unionized throughout the whole chromosphere, and in the case of helium we have probably some slight ionization in the lower parts—a rather anomalous case.

The explanation of these problems, and some other associated problems of solar physics, will be attempted in this paper. The method is based upon a recent work of Eggert[8]— "On the State of Dissociation in the Inside of fixed Stars." In this problem, Eggert has shown that by applying Nernst's formula of "Reaction-isobar,"

$$K=\frac{p_M^{\nu m} p_N^{\nu n} \cdots}{p_A^{\nu A} p_B^{\nu B} \cdots},$$

to the problems of gaseous equilibrium in the inside of stars, it is possible to substantiate many of the assumptions made by Eddington[9] in his beautiful theory of the constitution of stars. These assumptions are that in the inside of stars the temperature is of the range of 10^5 to 10^6 degrees and the pressure is about 10^7 Atm., and the atoms are so highly ionized that the mean atomic weight is not much greater than 2. This method is directly applicable to the study of the problems sketched above. The equation of the Reaction-isobar is

$$\log K=\log\frac{p_M^{\nu m} p_N^{\nu n}\cdots}{p_A^{\nu A} p_B^{\nu B}\cdots}=-\frac{U}{4\cdot571T}+\frac{\Sigma\nu C_p}{R}\log T+\Sigma\nu C, \quad (1)$$

where K=the Reaction-isobar,
U=heat of dissociation,
C_p=specific heat at constant pressure,
C=Nernst's Chemical constant,

and the summation is extended over all the reacting substances. The present case is treated as a sort of chemical reaction, in which we have to substitute ionization for chemical decomposition. The next section shows how U is to be calculated. The equation will be resumed in §3.

[4]Kossel and Sommerfeld, Ber. d. d. Phys. Gesellschaft, Jahrgang 21, p. 240.

[5]Kossel and Sommerfeld, loc. cit. p. 250.

[6]This line is masked by the strong hydrogen line Hζ.

[7]Mitchell, loc. cit. pp. 490-491.

[8]Eggert, Phys. Zeitschrift, Dec. 1919.

[9]Eddington, M. N. R. A. S. vol. lxxvii. pp. 16 and 596.

§2.

We may regard the ionization of a calcium atom as taking place according to the following scheme, familiar in physical chemistry,

$$Ca \underset{\longleftarrow}{\longrightarrow} Ca_+ + e - U. \ldots \ldots \ldots \ldots \ldots \ldots (2)$$

Where Ca is the normal atom of calcium (in the state of vapour), Ca_+ is an atom which has lost one electron, U is the quantity of energy liberated in the process. The quantity considered is 1 gm. atom.

The value of U in the case of alkaline earths, and many other elements, can easily be calculated from the value of the ionization potential of elements as determined by Franck and Hertz, MacLennan[10], and others. Let V=ionization potential. Then, to detach one electron from the atomic system, we must add to each atom an amount of energy equivalent to that acquired by an electron falling through a potential difference V, where V (in volts) is given by the quantum relation,

$$\frac{eV}{300} = h\nu_0, \qquad \cdot \qquad \cdot \qquad \cdot \qquad \cdot \qquad (3)$$

ν_0 being the convergence frequency of the principal series, i.e., (1, s) in Paschen's notation[11]. If this quantity be multiplied by the Avogadro number N, and expressed in calories, we obtain U.

Thus if V=1 volt, we have

$$U = \frac{eV.N}{J.300} = \frac{9645.10^8}{4.19 \times 10^7} = 2.302.10^4 \text{ calories.}$$

Table III. contains for future use the values of the ionization potentials[12] as far as known, and the calculated value of U. Here I wish to remark that an element may have more than one ionization potential, depending upon the successive transfer of the outer electrons one by one to

TABLE III.

Element	Ionization Potential	U in Calories
Mg	7.65	$1.761 \cdot 10^5$
Ca	6.12	1.409 ,,
Sr	5.7	1.313 ,,
Ba	5.12	1.178 ,,
Ra	?	?
Na	5.112	1.177×10^5
K	4.318	.994 ,,
Rb	4.155	.957 ,,
Cs	3.873	.892 ,,
Zn	9.4	2.164×10^5
Cd	9	2.072 ,,
Hg	10.45	2.406 ,,

[10]MacLennan, 'Proceedings of the Physical Society of London,' Dec. 1918.

[11]Paschen uses the symbol (1.5, s), but following Sommerfeld (loc. cit. p. 243), I have taken off .5 and used (1, s).

[12]MacLennan, loc. cit. p. 18.

infinity, or the simultaneous existence of two more constitutions of the normal atom (e.g. helium and parhelium). The ionization potential given in the table corresponds to the case when only one electron is transferred to infinity leaving an excess of unit positive charge in the atom. We have made it clear in the introduction that the high-level alkaline earth-lines are due to the atoms with one plus charge in excess.
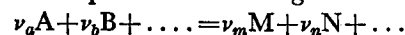
The cases of hydrogen and helium will be taken up later on.

§3. Equation of the Reaction-isobar for Ionization.

As mentioned in the introduction, the equation of gaseous equilibrium proceeds according to the equation,

$$\log K = -\frac{U}{4.571T} + \frac{\Sigma \nu C_p}{R} \log T + \Sigma \nu C, \ldots (1)$$

where the reaction proceeds according to the scheme,

$$\nu_a A + \nu_b B + \ldots = \nu_m M + \nu_n N + \ldots$$

and K is the "Reaction-isobar",

$$\frac{p_M^{\nu_m} p_N^{\nu_n} \ldots}{p_A^{\nu_a} p_B^{\nu_b} \ldots}$$

$p_M^{\nu_m}, p_N^{\nu_n} \ldots$ being the partial pressures of the reacting substances—M, N, etc.

In the present cases, viz., for a reaction of the type,

$$Ca \underset{\longleftarrow}{\longrightarrow} Ca_+ + e - U, \quad \ldots \ldots \ldots \ldots (2)$$

we have

$$\Sigma \nu C_p = (C_p)_{Ca+} + (C_p)_e - (C_p)_{Ca}.$$

We can take

$$(C_p)_{Ca} = (C_p)_{Ca+},$$

and $(C_p)_e = \frac{5}{2}R$, the electron being supposed to behave like a monatomic gas.

Eggert calculates the chemical constant from the Sackur-Tetrode-Stern relation,

$$C = \log \frac{(2\pi M)^{\frac{3}{2}} k^{\frac{5}{2}}}{h^3 N^{\frac{5}{2}}} = -1.6 + \frac{3}{2} \log M, \quad \ldots \ldots (4)$$

where M=molecular weight, the pressure being expressed in atmospheres.

Now C has the same value for Ca and Ca_+. For the electron $M = 5.5 \times 10^{-5}$, and $C = -6.5$.

We have thus

$$\Sigma \nu C = -6.5 \qquad \cdot \qquad \cdot \qquad \cdot \qquad \cdot \qquad (5)$$

To calculate the "Reaction-isobar" K, let us assume that P is the total pressure, and a fraction x of the Ca-atoms is ionized.

Then we have

$$\log K = \log \frac{x^2}{1-x^2} P = -\frac{U}{4.571T} + 2.5 \log T - 6.5. \ldots (1')$$

This is the equation of the "reaction-isobar" which is throughout employed for calculating the "electron-affinity" of the ionized atom.

Ionization of Calcium, Barium, and Strontium.

With the aid of formula (1), the degree of ionization for any element, under any temperature and pressure, can be calculated when the ionization potential is known. As a concrete example, we may begin with Calcium, Strontium, and Barium.

A glance at equation (1') shows that pressure has a very great influence on the degree of ionization, which does not seem to have been anticipated. This is due to the occurrence of P in the first power in the expression for the "Reaction-isobar." A reduction in the value P is attended with greatly enhanced ionization. This will become apparent from an inspection of the following tables, which show the ionization of Calcium, Strontium, and Barium under varying conditions of pressure and temperature.

TABLE IV.

Ionization of Calcium (in per cents).
$U = 6\cdot12$ volts $= 1\cdot40.10^5$ calories approximately.
Pressure in atmospheres—Temperature on the Absolute Scale.

Pressure / Temp.	10.	1.	10^{-1}.	10^{-2}.	10^{-3}.	10^{-4}.	10^{-6}.	10^{-8}.
2000°					5.10^{-4}	$1.4.10^{-3}$		
2500					2.10^{-2}	7.10^{-2}		
3000					3.10^{-1}	1	9	
4000				2.8	9	26	93	
5000		2	6	20	55	90		
6000	2	8	26	64	93	99		
7000	7	23	68	91	99			
7500	11	34	75	96.5				
8000	16	46	84	98.5				
9000	29	70	95					
10000	46	85	98.5					
11000	63	93						
12000	76	96.5						
13000	84	98.5						
14000	90							

(Region to the right: Complete Ionization.)

TABLE V.

Ionization of Strontium (in per cents.).
$U = 1\cdot3 \times 10^5$ calories.

Pressure / Temp.	10.	1.	10^{-1}.	10^{-2}.	10^{-3}.	10^{-4}.	10^{-6}.	10^{-8}.
2000°					$1.2.10^{-2}$	4.10^{-3}		
2500					6.10^{-2}	2.10^{-1}		
3000			7.10^{-3}	2.10^{-2}	7.10^{-3}	2.5		
4000				1.6	5	15	45	98.5
5000	1	3.2	11	32	73	96		
6000	4	13	37	78	97			
7000	10	32	73	96				
7500	15	45	84	98.5				
8000	22	58	91	99				
9000	38	79	97.5					
10000	56	90	98.5					
11000	71	95						
12000	82	97.5						
13000	89	98.5						
14000	93							
15000	96							

(Region to the right: Complete Ionization.)

TABLE VI.

Ionization of Barium (in per cents.).
$U = 1\cdot2.10^5$ calories approximately.

Pressure / Temp.	10.	1.	10^{-1}.	10^{-2}.	10^{-3}.	10^{-4}.	10^{-6}.	10^{-8}.
2000°						6.10^{-3}	2.10^{-2}	2.10^{-1}
2500						$1.8.10^{-1}$	7.10^{-1}	6
3000						1.6	5	46
4000			1	3	9	28	68	99
5000		1.7	5.5	17	48	86	98	
6000	6.2	19	52	88	99			
7000	15	43	83	98				
7500	22	57	91					
8000	30	70	94					
9000	47	85						
10000	65	93						
11000	97							
12000	99							

(Region to the right: Complete Ionization.)

We are not aware how the temperature and the pressure (partial pressure for a particular element) vary with height in the solar atmosphere. According to F. Biscoe[13], the temperature of the photosphere is about 7500°K., while the pressure in the reversing layer varies, according to different investigators, from 10 to 1 atmospheres. If we suppose that the variation in temperature is entirely caused by radiation, the temperature of the upper layers should tend to the limit $\dfrac{7500}{2^{\frac{1}{4}}}$[14] or a little more than 6000°K.

The partial pressure may be supposed to vary from 10 atmospheres in the reversing layer to 10^{-12} atmosphere in the outermost layers.

An examination of Tables IV., V., VI. shows that, under the above-mentioned assumptions, about 34 per cent. of the Ca-atoms are ionized on the photosphere. When the pressure falls to 10^{-4} atmosphere, almost all the atoms get ionized, so that up to this point in the solar atmosphere, we shall get combined emission of the H, K, and the g-line, but above this point, we shall have only the H, K lines. This is in very good agreement with observed facts.

In the case of strontium and barium, owing to their comparatively low ionization potential, ionization at 6000° is practically complete at 10^{-3} atmosphere, and the heights shown by the lines of the unionized atoms of these elements are still lower. Compare the Tables IV., V., VI.

The results of the flash-spectrum observations are thus seen to be very satisfactorily accounted for on the basis of our theory.

Laboratory experiments also, as far as they go, are in qualitative agreement with our theory. It is well known that in the flame, the flames due to the ionized atom either do not occur at all, or even if they do occur they are extremely faint compared with the lines of the unionized atom.

[13] F. Biscoe, The Astrophysical Journal, vol. xlvi. p. 355.
[14] Schwarzschild, Gott. Nachrichten, p. 41 (1906).

As the temperature is increased, the "enhanced lines" begin to strengthen, until at the temperature of the arc they are comparable in intensity to the lines of the normal atom.

We give below the results of King[15] on the relative intensity of the "enhanced" and ordinary lines of the alkaline earths in vacuum-tube furnaces at varying temperatures. Unfortunately, the pressure, which is a vital point, is not mentioned. The last line shows the percentage of the ionized atoms under a pressure of 10^{-4} atmosphere, or ·1 mm. of mercury.

The tables show that an increase of temperature causes an increase of ionization and the proportion of emission centres of the enhanced lines. The increasing intensities of the double lines are mainly to be ascribed to this fact. These become comparable in intensity to the principal lines of the normal atom only when the degree of ionization is rather large (comp. the figures at 4000°). Comparing the relative intensities of the corresponding lines of the calcium and barium group, we find that for the same temperature the enhanced lines of barium are relatively stronger than the calcium lines; and this, according to our theory, is due to the comparatively lower ionization potential of barium.

The objection may be raised whether the proportion of ionized atoms at low temperatures, as given by the theory, is not rather too low. The tables show that at 2000° K., only 1 in 10^5 calcium atoms is ionized. Is this small number of ionized atoms capable of affecting the photographic plate by the emission of the H and the K lines?

No definite answer can be given to this point. We may, however, point out that, according to Ladenburg and Loria[16], when a hydrogen vacuum tube at a pressure of a few mms. of mercury is excited by a spark, only 1 atom in 50,000 is found to be radiant, i.e., capable of emitting $H\alpha$ and $H\beta$. A very low proportion of radiant centres may therefore affect the photographic plate. It should also be remembered that at low temperatures the principal line of the normal atom is not only relatively more intense, but very broad and diffuse, when the enhanced lines are extremely narrow in addition to being faint.

A reduction in pressure will cause the relative intensity of the H-K line to increase, but not the absolute intensity, because the total available number of radiant particles will now decrease. I am not aware whether there is any laboratory experiment for testing this point.

§ 4. *Hydrogen in the Sun.*

It has been mentioned in the introduction that hydrogen is not appreciably ionized at even the highest levels of the solar chromosphere. We should add to this the fact that hydrogen exists in the Sun only in the atomic state, for, if there were molecular hydrogen in the Sun, we could have detected some at least of the lines of the secondary spectrum. But this is not the case; hydrogen enters into chemical combination with calcium and magnesium in the sun-spot, but does not probably form molecules of its own.

TABLE VII.

Element.	Line.	Actual Approx.	1923 2000	2273 2500	2623 3000	Arc. 4000	Photosphere 7500	Chromosphere. 6000
					Intensity.			
Ca	4227 (g)		300	500	1000	500	20	25
Ca+	3968 (H)		18	25	50	350	700	80
	3933 (K)		20	30	60	400	1000	100
Proportion of ionized atoms in per cents.			$1{\cdot}4.10^{-3}$	7.10^{-2}	1	26	75 ($P=10^{-1}$)	93 ($P=10^{-3}$)
Sr...	4607		300	400	600	600	1	2
Sr +	4216⎫ 4078⎭		6 12	15 25	30 40	400 400	5 8	40 40
Proportion of Sr+ in per cents.			4.10^{-3}	2.10^{-1}	2.5	45	84 ($P=10^{-1}$)	97 ($P=10^{-3}$)
Ba	5536		400	500	1000	1000	2	1
	4934⎫ 4554⎭		50 70	60 80	70 100	700 1000	7 8	12 20
Proportion of Ba+ in per cents.			2.10^{-2}	7.10^{-1}	5	68	91 ($P=10^{-1}$)	98 ($P=10^{-3}$)

N.B.—The intensity scale under the headings photosphere and chromosphere is different from the scale in King's furnace spectra.

[15] King, 'The Astrophysical Journal,' vol. xlviii. p. 13.   [16] Ladenburg and Loria, Ber. d. D. Phys. Gesellschaft, 1908.

We shall consider in this section whether these facts are reconcilable with our theory. This requires a knowledge of the heat of molecular combination and the ionization potential of hydrogen.

These data already lie available in a recent paper by Franck[17] and others. They find evidences of the following chemical and electronic reactions:—

$$H_2 = H + H + 3 \cdot 5 \text{ volts } (= 84{,}000 \text{ calories}), \tag{A}$$
$$H_2 = (H_2)_+ + e + 10 \cdot 6 \text{ volts}, \tag{B}$$
$$H = H_+ + e + 13 \cdot 6 \text{ volts } (= 3 \cdot 2.10^5 \text{ calories}), \tag{C}$$
$$H_2 = H_+ + H_+ + 2e + 30 \cdot 7 \text{ volts } (= 7 \cdot 2.10^5) \tag{D}$$

The first is a purely chemical reaction, and the heat of molecular combination has been directly measured by Langmuir[18] and found to be 82,000 calories. The ionization voltage 13·6 in (C), can be calculated from the relation $V = \dfrac{h\nu_0}{e}$, taking $\nu_0 =$ convergence frequency of the Lyman series $\nu = N\left[\dfrac{1}{1^2} - \dfrac{1}{m^2}\right]$, i.e., $\nu = N$. The actual occurrence of this process in the ionization of H_2 is indicated by a sudden increase of ionization at 17·1 volts (13·6+3·5 volts). The ionization voltage 30·7 in process (D) $= 2.13 \cdot 7 + 3 \cdot 5$, corresponding to the complete breaking up of the H_2-molecule into 2 atoms, and of these again into the core and the electron.

Let us first consider reaction (A)—dissociation of the molecule into atoms. Taking the equation of the reaction-isobar,

$$\log K = -\frac{U}{4 \cdot 571 T} + \frac{\Sigma \nu C_p}{R} \log T + \Sigma \nu C,$$

we have $\Sigma \nu C_p = 2(C_p)_H - (C_p)_{H_2} = \dfrac{3R}{2}$,

$$C_{H_2} = -3 \cdot 40,[19] \quad C_H = -1 \cdot 6, \quad \Sigma \nu C = \cdot 2,$$
$$U = 8 \cdot 2.10^4 \text{ calories}.$$

$K = \dfrac{x^2}{1 - x^2} P$, where $P =$ total pressure, and a fraction x has been dissociated. We have thus

$$\log \frac{x^2}{1 - x^2} P = -\frac{8 \cdot 2.10^4}{4 \cdot 571 T} + 1 \cdot 5 \log T + \cdot 2.$$

Table VIII. shows the dissociation of hydrogen under different pressures and temperatures (in per cents.):— .

TABLE VIII.
Dissociation of the H_2-molecule.

Pressure Temp.	1.	10^{-1}.	10^{-2}.	10^{-3}.	10^{-4}.
2000°	1	3	9	29	70
2500	11	35	75	97	
3000	46	85	98.5		
3500	85	98.5			
4000	96.5		Complete Ionization		
5000	100				

[17]Franck and others, *Ber. d. D. Phys. Gesellschaft*, vol. xxi.
[18]Langmuir, *Zeits. f. Elektrochemie*, vol. xxiii. p. 217 (1917) no. 20.
[19]Reiche, *Ann. d. Physik*, vol. lviii. p. 657, and Leon Schames, *Phys. Zeits.* vol. xxi. p. 41.

The table shows that under the conditions prevailing in the Sun the dissociation is complete. Even in the umbra of sun-spots, assuming that the temperature is 4000°K. and the pressure is of the order of 1 atmosphere, the dissociation is almost *complete* (96·5 per cent).

Ionization of Hydrogen.

For a rigorous treatment of the case, we should start with the process (D). But since in the Sun the hydrogen is entirely in the atomic state, we may use the process (C). The results will be but approximate, for the equation which follows does not hold over the whole range of temperature.

The case is quite analogous to the ionization of calcium. We have only to put $U = 3 \cdot 2 \times 10^5$ calories (approximately) corresponding to 13·6 volts. We have then

$$\log \frac{x^2}{1 - x^2} P = -\frac{3 \cdot 2.10^5}{4 \cdot 571 T} + \frac{5}{2} \log T - 6 \cdot 5$$
$$= \bar{6} \cdot 020 \text{ for } T = 7500$$
$$= \bar{9} \cdot 279 \text{ for } T = 6000$$

These figures show that at a point where $T = 6000°$, hydrogen can be completely ionized if $P = 10^{-11}$ atmosphere. Thus only at the highest points of the chromosphere, where the partial pressure falls to 10^{-11} atmosphere, can the ionization be complete, and the vanishing of the H-lines be expected.

Helium.

The previous work on the ionization of H atoms will have made it clear that the higher the ionization potential of an element is, the less will be its degree of ionization under a given thermal stimulus. This is best exemplified in the case of helium, which has got the highest ionization potential of the elements so far investigated.

The experimental results, however, are rather discordant. According to Bohr, the ionization potential should be 29 volts, while most investigators have detected the commencement of a distinct ionization at 20·5 volts. Some investigators have detected two distinct stages of ionization, one at 20·5 and another at 25 volts. In addition to this last, Rau detected a rather strong ionization when the potential is raised by 54·6 volts, i.e., to about 80 volts.

These processes probably take place according to the following schemes:—

$$He = He_+ + V_1 \tag{A}$$
$$Parhe = He_+ + V_2 \tag{B}$$
$$He = Parhe + V_1 - V_2 \tag{C}$$
$$He_+ = He_{++} + e + V_3 \tag{D}$$
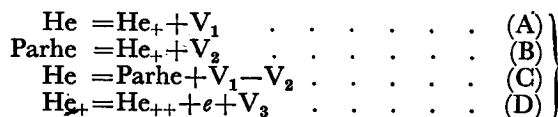
The distinction between He and the so-called parhelium is taken as one of relative configuration of the steady orbits

of the two electrons[20]. V_2 may be identified with 20·5 volts, V_1 with 25 volts, and V_3 with 4.13·6 = 54·6 volts[21].

Taking V_2 = 20·5 volts, $U = 4·8 \times 10^5$ calories approximately, we have the following table for the first step ionization of parhelium. If the ionization voltage be taken = 25 volts, the degree of dissociation will become still less:—

TABLE IX.
Ionization of Helium (in per cents.)
$U = 4·8.10^5$ calories (approximately).

Pressure Temp.	1.	10^{-1}.	10^{-2}.	10^{-3}.	10^{-4}.	10^{-6}.
6000°	5.10^{-6}	$1·7.10^{-6}$	5.10^{-5}	$1·7.10^{-4}$	5.10^{-4}	5.10^{-3}
7000	1.10^{-4}	$3·6.10^{-4}$	1.10^{-3}	$3·6.10^{-3}$	1.10^{-2}	1.10^{-1}
7500	4.10^{-4}	$1·2.10^{-3}$	4.10^{-3}	$1·2.10^{-2}$		
8000	$1·2.10^{-3}$	$3·7.10^{-3}$	$1·2.10^{-2}$	$3·7.10^{-2}$	$1·2.10^{-1}$	$3·7.10^{-1}$
9000	7.10^{-3}	$2·3.10^{-2}$	7.10^{-2}	$2·3.10^{-1}$	7.10^{-1}	7
10000	3.10^{-2}	1.10^{-1}	3.10^{-1}	1	3	31
11000	1.10^{-1}	$3·4.10^{-1}$	1	3·4	11	72
12000	3.10^{-1}	1	3	10	28	93
13000	7.10^{-1}	2	7	22	58	
14000	1.5	4	15	43	83	
15000	3	10	28	68	94	
16000	6	17	47	85		

The table shows clearly the ionization of helium is too slight under the conditions in the solar atmosphere, both in the reversing layer (T = 7500°, pressure = 1 atm.), as well as in the high-level chromosphere (T = 6000°, $p = 10^{-6}$ atmos.). But somewhere between the two (T = 7000°, $p = 10^{-3}$ atm.), there may be some slight ionization (1 in 10,000) which may account for the occurrence of the line of ionized helium $\lambda = 4686$, which has been detected by Mitchell. The calculations are, of course, of the roughest nature.

The investigation also incidentally shows that the Pickering lines $\nu = N \left[\dfrac{1}{2^2} - \dfrac{1}{(m+\frac{1}{2})^2}\right]$ and the Rydberg line 4686 can occur as absorption-lines only in stars having the highest temperature, exceeding 16,000° K. This seems to be independently borne out by the investigations of Eddington and Russell.

The application of the method and the results obtained in the present paper to the problems of temperature radiation of elements and of the different spectral types of stars

naturally suggest themselves, and will be taken up in a future communication.

Summary

1. In the present paper it has been shown from a discussion of the high-level chromospheric spectrum that this region is chiefly composed of ionized atoms of Calcium, Barium, Strontium, Scandium, Titanium, and Iron. In the lower layers both ionized and neutral atoms occur.

2. An attempt has been made to account for these facts from the standpoint of Nernst's theorem of the "Reaction-isobar," by assuming that the ionization is a sort of reversible chemical process taking place according to the equation $Ca \rightleftarrows Ca_+ + e - U$. The energy of ionization U can be calculated from the ionization-potential of elements as determined by Franck and Hertz, and MacLennan. For determining Nernst's chemical constant and the specific heat, the electron has been assumed to be a monatomic gas having the atomic weight of $\dfrac{1}{1836}$.

3. The equation shows the great influence of pressure on the relative degree of ionization attained. The almost complete ionization of Ca, Sr, and Ba atoms in the high-level chromosphere is due to the low pressure in these regions. The calculated values are in very good accord with observational data and the laboratory experiments of King.

4. Hydrogen has been shown to be completely dissociated into atoms at all points in the solar atmosphere.

5. It has also been shown that the greater the ionization potential of an element, the more difficult ionization will be for that element under a given thermal stimulus. Calculations have been made in the case of hydrogen (V = 13·6 volts) and helium (V = 20·5 volts), which show that these elements cannot get ionized anywhere in the Sun to an appreciable extent. Helium can have appreciable ionization only in stars having the highest temperature (> 16,000°K.), which only are therefore capable of showing the Rydberg line 4686 and the Pickering lines $\nu = N \left[\dfrac{1}{2^2} - \dfrac{1}{(m+\frac{1}{2})^2}\right]$.

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[20]See a paper by Lande, *Ber. d. D. Phys. Gesellschaft*, 1919.

[21]It is not possible to deduce V from the quantum relation $eV = h(1, s)$, for the fundamental term $(1, s)$ is unknown both for helium and parhelium. What are generally called the principal series of helium are really the series $\nu = (2, s) - (m, p)$ (the leading lines being 10380, for He and 20587 for parhelium).