THE MOTION OF GASES IN THE SUN'S ATMOSPHERE
PART IV

ON THE OCCURRENCE OF HIGHLY STRIPPED ATOMS IN THE CORONA

By A. K. DAS

AND

Y. P. RAO

(Received for publication, May 2, 1942)

ABSTRACT. It has recently been announced by Edlen that the hitherto unexplained emission lines in the coronal spectrum are due to forbidden transitions in very highly stripped iron, nickel and calcium atoms The conditions of temperature and pressure in the corona are insufficient to ionise these atoms to such a great degree. The idea developed in the earlier papers of this series, that the material of the solar atmosphere is coming from the core of the sun, is applied to the coronal problems also. Eddington has shown in another connection that material in convection will not attain the equilibrium ionisation of the layer through which it is passing, if the convective velocity exceeds a critical value. The critical velocity for the breakdown of convective equilibrium in a region (26,000 km. below the photosphere) where iron atoms are stripped of the first fourteen outer electrons is computed as 300 km /sec. approximately From the available observational evidence it is shown that matter responsible for the coronal emission lines can have a velocity exceeding 300 km./sec at a depth of 26,000 km. in the interior. This explains how the ionised atoms reach the corona retaining the ionisation acquired in the interior.

INTRODUCTION

Although the chromosphere and the prominences had been visually observed for only a little over a century and the existence of the corona as an aureole of light around the sun during total eclipses had been known from antiquity, when the method of spectrum analysis was discovered it was applied first to the prominences instead of the corona. It was in 1868 that the spectroscope was for the first time employed for the study of the corona. During the total eclipse which happened in that year, only one observer, Tennant, pointed his spectroscope towards the corona, but he saw nothing more than a continuous spectrum. A year later during the eclipse of August 7, 1869, three famous solar observers, Young, Harkness and Lockyer, observed a single bright line in the green (superpoeed upon a continuous background) in the spectrum of the solar corona. This was the beginning of the study of the nature and composition of the corona. During the seventy odd years that have elapsed since the discovery of the green coronal line, eclipse observers have not let slip a single opportunity of studying the outer atmosphere of the eclipsed sun ; but the total time that has been available for the necessary observations is little over an hour. The surprising thing is not that the problem of the corona is still very far from solution, but that a great deal of observational data of varied types has been collected about the corona. The coronagraph invented and perfected by Lyot during the last few years will no doubt increase rapidly our knowledge about the lower parts of the corona ; but for gathering information about the finer details of structure of the outer corona and about the spectral composition of its light we shall still have to depend upon the rare and precious moments of the total solar eclipse.

THE BRIGHT-LINE SPECTRUM OF THE CORONA

The emission line λ 5303 being the brightest coronal line and being situated in a region of the spectrum to which the human eye is most sensitive was naturally the first line to be observed. In later years through the persistent efforts of some of the greatest solar observers and by the use of varied types of spectroscopes and spectrographs, with slit and without slit, many more lines have been discovered in the bright-line spectrum of the corona extending from the near infra-red to well into the ultra-violet. In 1918 Campbell and Moore summarised all the information gathered from about half a century of eclipse observation. They listed forty lines observed by various authorities during totality as possibly of coronal origin. More than half of these have since been expunged from the coronal list as they are now known to belong to the chromosphere. After the 1930 eclipse Mitchell catalogued the wave-lengths and intensities of lines which were then believed to be truly coronal in origin ; there are, in all, nineteen lines in Mitchell's list which is reproduced below, but Mitchell thinks that one or two lines of this list may still be suspicious.

TABLE I

Wave-length in A.U.	Intensity	Wave-length in A.U.	Intensity	Wave-length in A.U.	Intensity
3328.00	8	4086.29	6	5302.91	20
3387.96	20	4231.40	8	5536.00	1
3454.13	8	4311.00	2	6374.28	12
3600.97	10	4359.00	4	6704.00	2
3642.87	3	4567.80	4	6776.00	8
3800.77	3	4586.00	2	—	—
3986.88	8	5117.00	2	—	—

The above list has been supplemented in later years by the discovery of new lines. Particularly noteworthy are the following infra-red lines discovered by Lyot by his new method of observing the corona without a solar eclipse (see Table II). Some observers have contended also that a few lines previously believed to be of chromospheric origin really belong to the corona. For instance, Righini[1] considers that the emission line at λ 5354.2 previously attributed to the chromosphere is a truly coronal line. Similarly, Sekiguti[2] argues that his and Tanaka's observations during the 1936 eclipse require that the line at λ 4725.3, which had been rejected from the coronal list as being insufficiently supported should be restored. He points out further that this line and several other lines observed in the emission spectrum of the corona by the Japanese observers are close to, if not identical with, certain lines in the spectra of nebulae and novae now known to be forbidden lines in the spectrum of N II. But mere coincidence between certain coronal lines and certain N II lines can scarcely be regarded as proof of the existence of nitrogen in the solar corona. In fact, astronomical literature abounds in instances in which astronomers have been temporarily misled by coincidences in wave-lengths into believing that certain substances have been identified in astronomical bodies. Many have been the attempts at identification of the coronal emission lines and several workers have found remarkable coincidences between these lines and certain lines of familiar elements, but in the long run such coincidences and identifications based on them have proved to be illusory. Fresh hopes were, however, raised when in 1927 Bowen made his great discovery that the so-called "nebulium" lines were caused by certain forbidden transitions of the oxygen and nitrogen atoms ; and numerous attempts were made to identify the coronal lines as originating in similar forbidden transitions of known atoms, in neutral and ionised conditions, but all these efforts were singularly unsuccessful and the old riddle of the "coronium" remained unsolved.

TABLE II

Wave-length in A U.	Intensity
7059.62	4
7891.94	20
8024.21	13
10746.80	240
10797.95	150

EDLEN'S IDENTIFICATION OF CORONAL LINES

In the afore-mentioned attempts at identification of the coronal lines only the possible forbidden transitions of neutral atoms or of atoms which had lost at most three or four of the outer electrons were considered. But very recently Edlen of Uppsala, who has been studying the ultra-violet and X-ray spectra of highly stripped atoms, has advanced strong reasons justifying the conclusion that most of the prominent coronal lines arise from forbidden transitions of iron, nickel and calcium atoms from which a large number of electrons have been torn off. No copy of Edlen's original publication is available to us, but we understand that his identifications have been accepted by the astronomical spectroscopists of Harvard and by H. N. Russell whose authority in such matters must be regarded as deserving of the highest respect. In *Scientific American*, August, 1941, Russell specifically mentions the following identifications :

TABLE III

Wave-length of coronal line (in A U.)	Origin
5303	Fe XIV
10798, 10747, 3388	Fe XIII
7892	Fe XI
6374	Fe X
3601	Ni XVI

Several other observed lines can also be accounted for by iron, nickel and calcium ; but some predicted accessible lines of potassium, chromium, manganese and cobalt are not observed. It is to be noted in this connection that a little while ago D. N. Kundu[3] suggested that the line at λ 4359 may be due to Co^{+14}. Edlen's identifications of the coronal lines are not based on actual observation of the lines of Fe XVI and Ni XVI in laboratory spectra, but upon an extrapolation from some ions earlier in the sequence. The method is, however, regarded as highly satisfactory ; it was used some time ago in the successful identification of nine forbidden lines of Fe VII in the spectrum of Nova Pictoris.

ORIGIN OF HIGHLY STRIPPED ATOMS

If the identifications proposed by Edlen are correct, then the most important question, which requires an answer before anything else, is "How do such highly stripped atoms originate in the solar corona ?" In Edlen's scheme the energies of ionisation involved amount to hundreds of volts. If the extreme state of ionisation of the coronal atoms were due to the temperature of the corona, then the corona would have to be some twenty times as hot as the photosphere. The temperature of the inner corona is however believed, for very good reasons, to be of the order of only 3000°. An equally paradoxical situation arises if one tries to associate the temperature of the corona with the widths of the three prominent lines λ5303, λ6384, λ6704 which, according to Edlen, are due to iron. The equivalent widths of these lines as measured by Lyot[4] are 0.80 A, 0.97 A, and 1.07 A respectively : if these widths are taken to be due to Doppler effect arising from the random motion of the emitting particles, then the average velocity of the particles works out to be 32 km. per second. Now, if we identify this velocity with the mean square velocity of thermal agitation, then a very simple calculation shows that the temperature of the corona must be of the order of 2.3 million degrees, which is inconceivable. The only conclusion to be drawn from these paradoxes is therefore that here we have nothing to do with the temperature of the corona. One might imagine that the observed widths of the lines might arise from the mutual collisions (*i.e.*, pressure effect of the particles of the corona, but that would require the density of coronal matter to be absurdly high and quite inconsistent with the low-pressure criterion of the production of forbidden lines. The unquestionably low density of coronal matter also precludes the possibility of the broadening of the spectral lines arising out of Stark effect due to intense electrical fields. The simplest, and the most probable, explanation of the observed breadths of the coronal lines is therefore that the emitting particles are actually endowed with an average velocity of the order of 30 km /sec., but this velocity is quite unconnected with the temperature and the electrical state of the corona. This points to the source of the highly stripped atoms of the corona being located somewhere other than the corona itself ; but we do not get from this any idea of the process responsible for producing the extreme state of ionisation of the atoms. Evidently one can imagine more than one process capable of meeting the situation. For instance, M. N. Saha[5] has suggested that "it is quite possible that stripped iron and nickel atoms are produced in the chromosphere or somewhat lower as a result of some type of nuclear reaction, analogous to uranium fission, and are projected upwards with energies amounting to millions of electron-volts." We do not know how far this view harmonises with the facts of solar observation ; but in private correspondence Prof. Saha has told one of us that he is preparing a paper in which he is giving a detailed working out of the above idea. A. K. Das[6] on the other hand has suggested, from entirely different considerations, an alternative process which is also capable of accounting for the presence of highly stripped atoms in the solar corona. While awaiting the details of Saha's investigation and without claiming that Das's suggestion is in any way better than the view-point advocated by Saha, we work out in the present paper some details of the former suggestion. The process here considered is roughly as follows: The highly stripped atoms of the corona which are responsible for its bright-line spectrum originally formed part of the deep interior of the sun where the conditions of temperature, pressure and density are such that most of the outer electrons of atoms like iron, nickel, cobalt, calcium, etc., are torn off. Probably through local rises in radiation pressure these highly ionised atoms are ejected outwards and eventually reach different levels of the solar envelope depending upon their velocity of ejection. So long as the velocity of outward travel remains below a certain *critical velocity*, the state of ionisation of the atoms is determined at each level by the local thermodynamical conditions. But as soon as the outward velocity of the atoms exceeds the critical velocity, the ionisation of the ejected atoms departs materially from what would be expected from convective and thermodynamical equilibrium. It is postulated that at some level in the interior of the sun this is precisely what happens and thereafter the atoms capture no more electrons, so that they finish their journey in some level of the outer envelope in a state of ionisation quite inconsistent with the physical conditions of the layer where they are observed. It is to be expected, of course, that the critical level will be different for different elements. We now proceed to see how far this picture is supported by quantitative calculations in the case of iron, which we take as a typical case.

ESTIMATION OF CRITICAL VELOCITY

In the ordinary theory the state of ionisation of stellar material is calculated under equilibrium conditions. The ionisation equilibrium is however reached rather slowly, so that the state of ionisation of convecting matter must depend very greatly upon the speed of convection. This point has been clearly brought out in a recent paper by Sir A. S. Eddington[7] who has shown that for quite small speeds of convection the state of ionisation fails to keep pace with the changing pressure and temperature of the material. In our calculation of the critical velocity at which ionisation equilibrium in the case of the highly stripped iron atoms ejected from the deep interior of the sun breaks down, we have followed Eddington's method : we give below an outline of the method.

Consider two layers, A and B, in the interior of the sun, the latter being the deeper. A particular type of atom with a critical ionisation frequency ν loses $p-1$ electrons at A and p electrons at B. T_a and T_b are the temperatures and P_a and P_b are the pressures in the two layers. The ionisation in the column of material comprised between the two layers is regarded as being produced (directly or indirectly) by the photons entering at the base of the column; so that an increase in the degree of ionisation can only be produced by a difference between the number of competent photons entering and leaving. By Planck's law the numbers of photons n, with frequency equal to or greater than ν, contained in a cubic centimetre of radiation at the temperatures T_a and T_b are calculated. Then, under equilibrium conditions, $\frac{1}{4}n_a c$ and $\frac{1}{4}n_b c$ ionising photons per sq. cm. and per sec. will pass outwards across the layers A and B respectively,

c being the velocity of light. Therefore the number of ionising photons available per sec. for a column of unit cross-section bounded by the two layers will be $\frac{1}{4}c\,(n_b - n_a)$. The total number of atoms in the column is estimated from the difference in pressure between the two layers by making some reasonable assumption with regard to the relative abundance of the elements. If this number is N, then the time necessary for ionisation equilibrium to be established is $N/\frac{1}{4}c\,(n_b - n_a)$ and the critical velocity is $d/N.\frac{1}{4}c\,(n_b - n_a)$, where d is the distance between the layers.

In principle, the above procedure can be used for calculating the critical velocity of convecting matter at which ionisation equilibrium breaks down in any region in the interior of the sun, although the result, on account of the neglect of collision excitation and ionisation, should be regarded only as approximate. It has been found in the earlier papers of this series that many of the important features of prominences, dark markings, the chromosphere, the reversing layer, etc., can be quantitatively understood on the assumption that the matter taking part in these phenomena is supplied continually from the core which roughly corresponds to a sphere of $\frac{1}{8}$ of the radius of the sun. We therefore assume that the material of the corona also is derived from the same source. It is of particular interest to judge first in what state of ionisation atoms of iron would be if they came from the core and reached the corona without losing their ionisation.

On the basis of the theory of polytropic gas spheres, the temperature, pressure and density at the centre of the sun are 39×10^6, 124.8×10^{15} dynes/cm.^{2} and 76.7 respectively, taking the polytrope index $n = 3$, $\mu = 2.1$ and $\beta = 0.9501$ (the notation adopted is the same as that in Eddington's *Internal Constitution of Stars*). At a point distant $R\odot/3.45$ from the centre, the temperature, pressure and density (derived with the help of Emden's tables) are respectively 23×10^6, 14.4×10^{15} dynes/cm^2 and 15.19. The ionisation of iron atoms in this layer computed from the formula

$$\log \frac{1-x}{x} = \frac{0.4343\psi}{RT} + \log \frac{\rho}{\mu T^{3/2}} + 8.3925 \qquad \ldots \quad (1)$$

is presented in Table IV. $\frac{1-x}{x}$ is the ratio of the number of atoms with $p-1$ electrons missing to the number with p electrons missing, ψ is the ionisation potential of the pth electron, ρ and T are the density and temperature in the layer, and R is the Boltzmann constant. The mean atomic weight, μ, is taken to be 2.1 in all these computations.

It is clear from Table IV that 95% of the iron atoms in the layer under consideration have lost 24 or more of the outer electrons. If some of these stripped atoms are ejected with velocities high enough to bring about a complete break-down of ionisation equilibrium in the expelled mass of atoms, then the

TABLE IV

p	Ionisation potential expressed as critical wave-length, λ	$\frac{1-x}{x}$	Ratio of atoms with p electrons missing	% of atoms with p electrons missing
26	1.35	1.5	351	18.24
25	1.43	1.0	526	27.34
24	6.15	0.045	1000	51.98
23	6.57	0.042	45	2.34
22	7.15	—	2	0.10

Note—The ionisation potentials given here are different from the potentials for removing K, L etc. electrons as obtained from X-ray experiments, which refer to the case of knocking out the particular electron from a complete atom. The potentials given here refer to an ion from which the outer electrons have already been removed

corona may be expected to contain iron atoms which have only one or two of the normal 26 outer electrons. The fact that so highly ionised iron atoms are not detected in the corona would of course be no proof of their non-existence, because their spectrum lines are quite inaccessible to astronomical spectroscopy. But we think that iron atoms in such extreme states of ionisation really do not exist in the corona, and for reasons which will be apparent from the following considerations. If we calculate the critical velocity for the layer about $R_\odot/3$ away from the centre of the sun, we get a value of the order of 10^5 km./sec., which is far too great to be exceeded by the actual velocity with which atoms may be ejected, so that in reality there will be no break-down of ionisation equilibrium. We have calculated the critical velocity for other layers progressively farther away from the centre of the sun and have obtained similar results. Then we have tried a region where the 14th electron of the iron atom is torn off : the boundaries chosen are at distances of $\frac{6.63}{6.90}R_\odot$ and $\frac{6.68}{6.90}R_\odot$ from the centre. The corresponding pressures, temperatures and densities are given in Table V. The states of ionisation at the two boundaries have been calculated with the help of equation (1) and presented in Table VI.

TABLE V

Boundary	Temperature*	Pressure	Density
$\frac{6.63}{6.90}R_\odot$	4.7×10^6	2.59×10^9	0.0001325
$\frac{6.68}{6.90}R_\odot$	3.9×10^6	1.25×10^9	0.0000767

TABLE VI

p	Ionisation potential in critical wave-lengths	% of atoms with p electrons missing	
		Upper boundary	Lower boundary
16	25.8	—	3.3
15	28.4	0.7.	19.4
14	31.7	10.2	41.3
13	35.3	36.5	28.5
12	41.1	40.5	7.4
11	44.1	10.5	—
10	49.5	1.5	—

On account of the closeness of the ionisation potentials for successive electrons it is not possible to find a sharp boundary with a characteristic degree of ionisation. The difference in ionisation between the two boundaries can be summed up as follows : 31% of the iron atoms which have lost 12 electrons at the upper boundary lose the 13th and the 14th electrons at the lower boundary ; 8% which have lost 13 electrons lose also the 14th and the 15th ; 10% which have lost 11 electrons lose the 12th, 13th, 14th and 15th electrons.

The difference in pressure between the two boundaries is 1.34×10^9 dynes./cm.^{2}. Taking the mean value of gravity to be 2.929×10^4 cm /sec.^{2}, the mass of a column of unit cross-section enclosed between the two boundaries is 4.5×10^4 gm. The whole of this mass is, however, not due to iron. According to ideas underlying the present series of papers the material of the solar envelope is derived from the interior of the sun, so that there is no special reason to suppose that the material of the interior is essentially different in composition from the material of the envelope. We therefore take the composition of the envelope as given by Russell to be valid for the interior. From Russell's mixture we get the proportion of metals to the total mass as 32 : 132 and the ratio of iron to the metals by weight as 1000 : 4184. The mass of iron in the column under consideration is 2.65×10^3 gm. and the number of iron atoms in the column is therefore 2.86×10^{25}.

Now by Planck's law the density of radiation in a thermodynamical enclosure at temperature T is $\frac{8\pi h\nu^3}{c^3} \cdot \frac{1}{e^{h\nu/kT} - 1}$. For the very short wave-lengths under consideration this may be written as $\frac{8\pi h\nu^3}{c^3} \cdot e^{-h\nu/kT}$. The density (*i.e.*, number/cm.^{3}) of photons of frequency equal to ν or greater than ν is therefore given by

$$\int_{\nu}^{\infty} 8\pi \frac{\nu^2}{c^3} \cdot e^{-h\nu/kT} d\nu = \frac{8\pi}{c^3} e^{-h\nu/kT} \left[\nu^2 \frac{kT}{h} + 2\left(\frac{hT}{h}\right)^2 \nu + 2\left(\frac{kT}{h}\right)^3 \right]$$

Consequently,

$$\frac{1}{4} nc = \frac{2\pi}{c^2} e^{-h\nu/kT} \left[\nu^2 \frac{kT}{h} + 2\left(\frac{kT}{h}\right)^2 \nu + 2\left(\frac{kT}{h}\right)^3 \right]. \qquad \ldots \quad (2)$$

From (2) we get for the value of $\frac{1}{4}$ nc for the lower and upper boundaries 2.985×10^{26} and 5.428×10^{25} respectively for wave-lengths shorter than 41.1A. Hence the number of photons available per second for ionising the column is 2.44×10^{26}.

From Table VI it will be seen that the critical ionisation wave-lengths for the different stages of ionisation vary between 28.4 A for the 15th electron and 41.1 A for the 12th electron. For wave-lengths below 28.4 A the value of log ($\frac{1}{4}$ nc) at the lower boundary is 25.3278, while for $\lambda = 41.1$ A, it is 26.4749 ; the margin of variation is more than ten times. The absorption of photons by the iron atoms to attain equilibrium ionisation is as follows :

18% absorb below 28.4 A
49% absorb below 31.7 A
41% absorb below 35.3 A
10% absorb below 41.1 A

Thus the absorption is greater below $\lambda = 31.7$. To allow for this we take the total number of effective photons to be one-fifth of the value for $\lambda = 41.1$ A. Before proceeding to the estimation of the critical velocity, another important factor has to be considered. So far it has been tacitly assumed that all the photons are available for the ionisation of iron atoms ; this assumption is certainly not justified. In the layer under consideration the ionisation of most elements (other than hydrogen and helium) is incomplete, so that the atoms of these elements will naturally use up some of the available ionising photons. It may reasonably be assumed that the photons will be distributed among the different elements in accordance with their relative abundance. According to Russell's estimate the proportion of metallic atoms to all atoms (except H and He) is 1 14 : 3.14 and the ratio of iron atoms (atomic weight 55.84) to the metallic atoms (mean atomic weight 28) is $\frac{\cdot 100}{55.84} \cdot \frac{4\,18}{28}$ or 1 791 ; 14.930. The proportion of ionising photons available to the iron atoms is therefore 0.04355, and accordingly the total number of photons available for ionising the iron atoms in the column under consideration is $2.44 \times 10^{26} \times 0.2 \times 0.04355$ or 21.25×10^{23}. The total number of photons required for equilibrium ionisation of the iron atoms is $\frac{2.86 \times 10^{25} \times 118}{100}$ or 3.37×10^{25}. Now the number of photons available per second is 21.25×10^{23}. Therefore the time required for ionisation equilibrium is 15.86 seconds. The distance between the two boundaries is 5039 km., and consequently the critical velocity for the break-down of ionisation equilibrium is 318 km./sec. This means that iron atoms travelling outwards with a velocity of the order of 300 km./sec. at a depth of about 26000 km. below the photosphere will have a good chance of reaching the corona with 11 to 15 of their outer electrons missing. We may note here that 300 km./sec. is quite a moderate speed compared to the scale of velocities sometimes observed even on the surface of the sun.

DISCUSSION AND CONCLUSIONS

Now the question is : " Is there any evidence to justify the conclusion that particles ejected from the interior of the sun actually travel with velocities of the order of 300 km./sec. or more at a depth of about 26000 km. below the photosphere?" Naturally there can be no direct evidence, but the evidence available, though indirect, appears to be decidedly in favour of this conclusion. The spectrum of the corona shows the Fraunhofer lines in addition to the emission lines superposed upon a faint continuous background. This Fraunhofer spectrum of the corona can only be the result of scattering of the disc spectrum by the particles in the higher reaches of the corona. From measurements of the plates secured during the 1922 and 1932 eclipses, Moore[8] comes to the conclusion that the scattering particles have an outward velocity of the order of 15 to 25 km./sec. Of course this velocity cannot be regarded as very accurate, but it may be taken to represent the right order of magnitude. There seems to be some doubt as to the identity of the scattering particles. According to a view expressed by Grotrian[9] which seems at present to be rather widely accepted, they must be considerably larger than ordinary molecules. If Grotrian's view is correct, these particles could not have come as such from the interior, and therefore they would have acquired their outward velocity through bombardment by other particles coming from below the corona. If we identify these latter with the particles ejected from the interior of the sun, then we must expect them to possess, when they reach the corona, a velocity considerably higher than 15 to 25 km./sec. When one considers the retarding forces which must operate upon particles travelling from the depth of some 26000 km. below the photosphere to a height of 10′ to 20′ above the limb (where the above velocity has been measured), a diminution of the initial velocity by a factor of 10 or more seems entirely probable. Thus the depleted Fe atoms ejected from the deep interior of the sun may very well have a velocity of 300 km./sec. or higher during their outward travel through the

26000 km. level. Of course, on account of the nature of the data available for the calculations, the position of the critical level should be regarded only as a rough estimate, but the significant point is that the calculations indicate the existence of such a level for the Fe^{+13} and Fe^{+12} atoms.

The boundary at which ionisation equilibrium fails will be different for different atoms depending upon the ionisation potentials, the atomic weights and the abundances of the different species. The ionisation potentials for the 14th electron of Fe, the 15th electron of Co and the 16th electron of Ni are as 29 : 32 : 36. These are so close to each other that ionisation equilibrium for all these three atoms will break down in a fairly thin layer not very far from the 26000 km. level calculated above. This helps us to understand to some extent at least why the lines of these atoms appear prominently in the coronal spectrum. Another point which looks favourable to the process imagined in the present paper is that the lines identified by Edlen as being due to Fe^{+13} and Fe^{+12} are stronger than those which arise from less highly ionised iron atoms. The intensity of any emission line in the corona will depend upon the abundance of the appropriately ionised atoms and the probability of the transition which gives rise to the line. If ionisation equilibrium breaks down in the region considered above, then the number of Fe^{+10} and Fe^{+9} atoms in the corona will be much less than the number of Fe^{+13} and Fe^{+12} atoms. This may partly explain the greater intensity of the Fe^{+13} and Fe^{+12} lines over the Fe^{+10} and Fe^{+9}.

The outer parts of the corona which scatter the Fraunhofer spectrum are believed to consist of particles much larger than ordinary molecules. In fact, according to Grotrian, the sun is surrounded by a dust-cloud (perhaps of meteoric origin) which is composed of particles having about 3 times the size of an ordinary molecule. Observational data show that the Fraunhofer lines of the corona are displaced with respect to those of the disc spectrum in a way which shows that the dust-cloud is moving outwards with a velocity of 15 to 25 km./sec.; also the coronal Fraunhofer lines are not wider than the ordinary Fraunhofer lines, showing that the scattering particles are not endowed with any extraordinary random motion. At the same time the widths of the emission lines λ5303, λ6374 and λ6704 show that the emitting Fe atoms have a random velocity of the order of 32 km./sec. These observational facts are just what one would expect from the process imagined in the present paper as will be seen from the following considerations. The particles coming from the interior would have to possess a velocity of 50 km./sec. or more outside the photosphere in order that they may reach the outer corona; this follows from a rough calculation based on the equations of motion derived in the earlier parts of this series of papers. These particles will, through impact, impart an outward velocity to the heavier particles of the dust-cloud which will therefore show an expansive velocity of a smaller magnitude than the velocity of the particles coming from the interior. The impinging particles will, on the other hand, be slowed down and deflected through collisions ; this will appear as an average random velocity which will show itself as a broadening of the emission lines.

Finally, we may also mention the general correspondence which exists between solar activity as judged from sunspots, prominences, eruptive phenomena, etc., and the intensity of the coronal emission lines. Solar activity is admittedly due to some deep-seated variations in the interior of the sun, and therefore the above correspondence points to the interior as the probable place of origin of the highly stripped atoms of the corona. The same indication is given by the fact that some of the prominent coronal lines are observed also in certain novæ.

Note added in proof

Soon after the present paper was sent out for publication Prof. Saha's paper entitled "On a physical theory of the solar corona" appeared in the *Proc. Nat. Inst. of Sc. of India*, Vol. VIII, pp. 99-126. The standpoints of the two papers are so fundamentally different from each other that it does not seem profitable yet to compare them. Both theories require to be developed much further and given greater definiteness before it can be possible to form a reliable judgment in favour of one to the exclusion of the other.

SOLAR PHYSICS OBSERVATORY,
KODAIKANAL, SOUTH INDIA.

REFERENCES

[1] Abetti, *The Sun*, p. 253 (1938).
[2] Sekiguti, *Nature*, **140**, 724 (1937)
[3] Kundu, *Science and Culture*, **7**, 364 (1942).
[4] Lyot, *Bull. Sc. Astr. de France*, **51**, 203 (1937).
[5] Saha, *Science and Culture*, **7**, 251 (1941)
[6] Das, *Science and Culture*, **7**, 357 (1942).
[7] Eddington, *M.N R.A.S.*, **101**, 177 (1941).
[8] Moore, *P.A S.P.*, **35**, 333 (1923).
[9] Grotrian, *Zeit. f. Astrophys.*, **8**, 124 (1934).