CORONAL PHENOMENA AND THEIR RELATION TO SOLAR AND TERRESTRIAL PROCESSES

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§ 1. Some properties of the solar corona.

During a total solar eclipse the sun is seen to be surrounded by a white halo called the solar corona.

The intensity of the coronal luminescence decreases outwards but at a comparatively slow rate, with the result that the luminescence may be traced to distances from the photosphere which are many times the radius of the sun.

Another peculiar property of the corona is its great variability with regard to form, structure, and extension. As a rule the corona shows a radiant structure, while its extension may be very different in different directions and its form and extension vary with the solar activity. At sun-spot maxima we have a dense and concentrated corona fairly equally developed in all directions; at sun-spot minima the corona has comparatively small intensity near the sun's edge, and very small extension in the polar region. In the equatorial region, however, the corona — often in the form of streamers — may extend much further away from the sun than during sun-spot maxima.

The outer region of the corona gives a continuous spectrum intersected by Fraunhofer lines, practically equal to that of ordinary sunlight. The inner corona has a continuous spectrum without the Fraunhofer absorption lines, and in addition a number of emission lines. These "coronal lines" are typical of the coronal light and until quite recently none of them could be indentified with any of those lines which were found from stellar or terrestrial sources.

The sun is a gas ball composed of atoms in an ionised state and free electrons in a number sufficient to neutralise the charge of the positive ions. A mixture of atoms, molecules, ions and electrons is often called a "plasma". The degree of ionisation increases rapidly towards the sun's centre. We are therefore naturally led to regard the sun's atmosphere as being composed of a "plasma". If all positive electricity is carried by atomic nuclei, *a plasma in equilibrium under the influence of the sun's gravitational field is found to give a too rapid fall of density outwards to explain the large extension and luminosity distribution of the corona.* A plasma consisting of electrons and positrons, which would give a rate of fall of density outwards similar to that of the corona, is not possible under the physical conditions present in the sun's atmosphere.

We shall therefore have to assume that forces and processes which counteract gravitation are in operation within the corona. It has usually been assumed by astronomers that the coronal matter is driven to large distances from the sun through light pressure.

But although the light pressure connected with the absorption lines of a gas — as shown by MILNE[1] may play an important part in solar physics and in the theory of stellar constitution, it appears to be of minor importance in connection with the theory of the solar corona.

A light pressure theory does not explain the structure and variability of the corona, and the fact that the coronal lines are not to be detected in absorption; but the most weighty argument against it lies in the fact that the light pressure is not wanted at all for the explanation of the coronal properties. This is evident from the very fact that coronal structures are found in systems where the light pressure is insignificant and would act in the same direction as the gravitational force.

[1] E. A. MILNE, The Equilibrium of the Calcium Chromosphere. Monthly Not. 85, 111, 1925.

§ 2. The terrestrial corona and the zodiacal light.

Through investigations on the auroral spectrum combined with height measurements of the aurorae, it was found that molecular nitrogen with quite noticeable density appears up to altitudes of say 800—1000 km above the ground. A calculation of the pressure of nitrogen by means of the barometric height formula showed that the density of nitrogen should have practically vanished at altitudes of less than 150 km.

Thus the auroral studies show that on the top of the earth's atmosphere there is a layer were the density decreases outwards much more slowly than in an atmosphere in equilibrium under the action of gravitation. In other words — in the auroral region we are operating in an atmospheric layer quite similar to that constituting the solar corona.

Thus not only the sun, but also a planet with an atmosphere is surrounded by a coronal structure forming the terminal aspect of its atmosphere towards cosmical space.

The observational data which showed the existance of a terrestrial corona, were obtained in 1923 and were immediately followed by a theoretical explanation, which appeared to have far reaching consequences for the understanding of a number of solar and terrestrial phenomena and their relationships.[1]

The theory is based on the assumption that the sun, in addition to the ordinary sunlight (thermic radiation), emits radiations of very short wave-length of the X-ray type. When the upper atmospheric layer is struck by these rays, electron rays of high energy will be emitted through photo-electric action. The electron rays will in their turn ionise the atmosphere. Those which have a velocity component directed downwards will soon be absorbed, while those directed upwards pass towards decreasing density and traverse a much longer distance before they stop. In this way the layer struck will be left behind with a surplus of positive electricity, while higher up there is a surplus of negative electricity due to the electrons. — The result is that the positive gas layer will be subject to an upwards directed electric field which will drive the matter against gravitation towards larger altitudes.

[1] Cfr. L. VEGARD, Phil. Mag. 46, 193, 577, 1923, Z. S. f. Phys. 16, 367, 1923.

The matter driven upwards will be continually bombarded by X-rays from the sun, and new electron rays are emitted. The negative electron rays take the lead in the motion upwards, and the positively charged matter left behind will follow behind on account of the electrostatic attraction.

The motion of the electrons will be retarded partly by absorption and partly by the electric field produced.

The largest density and extension of the terrestrial corona is usually found on the day side of the earth, and to some extent it is concentrated in the plane of the magnetic equator. *After sunset the terrestrial corona can be directly seen as zodiacal light due to scattering of sunlight in the coronal matter.*

The terrestrial corona forms the essential part of the "ionosphere", and as shown in a number of papers,[2] and also in a previous article in the "Scientia", *our theory of the upper atmosphere gives a simple explanation of the layers of maximum ionisation which reflect the electric radio waves.*

§ 3. Application to the solar corona.

It is evident that our theory of the state of the upper atmosphere may be directly transferred to the solar corona.[3] The essential condition for the formation of the terrestrial corona is that the extreme limit of the atmosphere towards space should be hit by X-rays from the sun and brought to emit electron rays of high velocity.

Now these solar X-rays must have a similar effect when they pass through the upper layers of the sun's atmosphere, and in order to explain the formation of the solar corona, we have merely to repeat what has been said about the formation

[2] L VEGARD, Geofys. Publ. V 9, No. 11, 1932; 12, No. 5 1938. Ergebnis. d. Exakt, Nat.wiss. XVII, 229, 1938.

[3] Cfr. L. VEGARD, Result from the Solar Eclipse in Norway, June 29, 1927 and the Constitution of the Solar Corona and Sunspots. Norsk Vid.-Akad. Skr. I, No. 2, 1928.

L. VEGARD, Die Korona der Erde und Sonne und ihre Beziehung zu kosmischen Erscheinungen. Gerlands Beiträge zur Geophys. 32, 288, 1931.

L. VEGARD, Results of Investigations of the Auroral Spectrum during the years 1921—26. Geofys. Publ. IX, No. 11, 1932.

of the terrestrial corona. Electron rays of high velocity will continually leave the sun and positive ions will follow on account of the electro-static field, which results from the electric separation produced by the electron rays of high energy. Whatever may be the way in which the high speed electron rays are produced, they will give rise to the formation of cororal streamers.

Just as in the case of the terrestrial corona, the electron rays will sooner or later stop or be forced to return. The height they reach will depend on the position of the point of departure, and the initial velocity and its direction.

From the point of view of our theory the properties of the solar corona are easily explained. The radiant structure means that the electron rays have a tendency to follow certain directions, determined e. g. by local magnetic fields existing at the sources. The different length of the streamers means that the different sources give rays of different velocities.

The way in which the density of matter varies with solar altitude, depends on the distribution of velocities in the electron ray bundles and on the specific charge (charge to mass ratio) of the positively charged particles. High speed electrons and large specific charge give long streamers with a slow diminution of density with increasing altitude.

During sun-spot maxima we have intensive sources giving nearly the same velocity distribution spread almost evenly over the surface of the sun. The result is a dense corona fairly evenly developed in all directions, but of comparatively small extension.

At sun-spot minima the sources are very weak in the polar regions, while the sources near the equator, although not strong, produce electron rays of greater velocity than at times of sun-spot maxima. The result is a corona which is very little pronounced at the poles, but developing weak, though very long streamers near the equator.

Now the bundles of electric solar rays which produce the aurorae and certain types of magnetic disturbances have a similar constitution to the coronal streamers.

These ray bundles — which are more or less occasional occurrences — and which are emitted from sources associated with the sun-pots, produce electron rays of much higher velocity than those of the ordinary coronal streamers.

When a bundle of swift electrons passes through the coronal plasma, it may be electrostatically neutralised by positive ions drawn from the surroundings, and especially if the electron ray bundle strikes a celestial body of large electrostatic capacity, the electrons may continue to pass without being counteracted by an electro-static field due to accumulation of negative charge (volume charge). We have a cathode ray bundle passing through a plasma of very much the same constitution as that we observe in a discharge tube, where the negative charge is neutralised by the positive ions (plasma) formed by the discharge. Thus in the case of the ray bundles producing aurorae and polar magnetic storms, the negative charge carried through the cross section in unit time may be much greater than the positive charge carried by the positive ions. The result is that the bundle produces a magnetic field in its surroundings and may penetrate into the atmosphere as if it were mainly composed of negative electrons.[1]

The current density *(i)* is given by an expression of the form:

$$i = \sum_r N_r n_r e U_r - NeV$$

N_r is the number of positive ions of group *(r)* contained in unit volume, U_r is the velocity and $n_r e$ the electric charge of an ion of the same group. V is the velocity and Ne the volume charge of the electrons. When the bundle is electro-statically neutral:

$$\sum_r N_r n_r = N$$

and when U_r is very small compared with V the last term of equation (1) will dominate.

It is of interest to notice that a certain type of aurora with a red bottom edge and for which the lowest altitides are observed, seems to occur during sun-spot minima. Thus the ray bundles which produce the aurorae should also obtain the highest velocity near sun-spot minima.

[1] L. VEGARD, Det norske Vid.-Akad. Skr I, No. 2, p. 33, 1928.

L. VEGARD, The Aurora Polaris and the Upper Atmosphere. Physics of the Earth, Vol. VIII. Edited by J. A. Flemming.

§ 4. The X-ray sources on the sun.

In connection with the coronal theory the writer[1] also suggested a possible explanation of the formation of the sources of X-rays on the sun.

Through the vortex motion, which is attached to the sun-spot activity, masses from the interior are supposed to be brought up towards the surface. These masses have a large store of energy and are highly ionised. Through the re-combination process which takes place near the surface, light of very short wave-length — of the type of X-rays — will be produced, and electrons of high speed will result through photo-electric effect.

The emitted electrons escape in the form of bundles because the effective source is limited, and because the electrons will have a tendency to follow the lines of force of the local magnetic field of the sun-spots. The highly ionised masses pumped up to the surface store much energy and may last during several revolutions of the sun, thus explaining the fact that strong magnetic storms and aurorae appear after 26 days and may continue to do so after several revolutions and after any visible trace of the original sun-spot-group has disappeared.

The granulation of the photo-sphere indicates that similar vortices are distributed on the whole surface of the sun, and in the way described they form the sources of the emission of those X-rays which cause the coronal streamers, and which are softer than the aurora-producing rays connected with the sun-spot vortices.

According to our theory the solar corona consists of a mixture of electrons and positive ions, a plasma, but it is not a plasma in equilibrium in a gravitational field. *The coronal state at any given moment, is a result of processes and motions continually going on.*

In addition to the electrons, *the corona should preferably be composed of positive ions which have a large specific charge and which are present in great abundance in the solar atmosphere.*

Thus a great deal of the coronal matter no doubt consists of protons, and in addition we may expect to find He^{+} ions and α-particles, further atoms of *Ca*, *Na*, *Fe* and *Ni* in a highly ionised state.

From the investigations on the auroral spectrum the writer found, some years ago, that the upper strata of the atmosphere were exposed to showers of hydrogen.[2] *This would mean that coronal streamers composed of protons and electrons reach the earth.*

The yellow sodium line which appears particularly strong in the twilight spectrum, is found to originate from the higher strata of the atmosphere — above 60 km.[3] Its intensity appears to fluctuate and it seems likely that sodium atoms coming from the sun also enter into the earth's atmosphere. *This would mean that coronal streamers containing sodium atoms — probably highly ionised — occasionally reach the earth.*

§ 5. The continuous spectrum of the corona.

The current opinion among astronomers regarding the origin of the continuous spectrum of the corona is that it is simply due to sunlight scattered by the coronal matter, and the absence of the Fraunhofer absorption lines in the lower part of the corona should be due to a great Doppler-effect, resulting from a very high temperature in the lower coronal layers.

The problem of the origin of the continuous coronal spectrum has been treated by Wilhelm Anderson.

On theoretical grounds he holds that the continuous light is partly scattered sunlight and partly light resulting from a thermic emission of his electron gas. The ratio of the intensity of thermic emission to that of scattered light should increase downwards, and in the lower part the thermic emission should dominate.

According to Anderson the absence of Fraunhofer lines in the lower corona should be partly due to thermic emission and partly to Doppler-effect.

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[1] L. VEGARD, Det norske Vid.-Akad. Skr. I, No. 2, p. 33, 1928.
L. VEGARD, The Aurora Polaris and the Upper Atmosphere. Physics of the Earth, Vol. VIII. Edited by J. A. Flemming.

[2] L. VEGARD, Geof. Publ. V. XII, No. 14, 1940. Nature 144, 1089, 1939.

[3] L. VEGARD and E. TØNSBERG: Geof. Publ. V. XIII, No. 1, 1940; Gerlands Beitr. z. Geoph. 57, 289, 1941. Geof Publ. V. XIII, No. 5, 1941.

This view of the continuous coronal spectrum may with certain modifications be applied to our theory. The coronal matter is in very rapid motion, which should account for a great Doppler effect which might broaden the Fraunhofer lines. This motion, however, is due to photo-electric effect and the resulting influences of electro-static fields, and is not to be regarded as a thermic motion in the strict sense of the word.

The continuous light of the photo-sphere may be explained as due to a re-combination of positive ions and electrons. Electrons with a continuous energy distribution are captured by ions, and light quanta are emitted in accordance with the equation:

$$E_j^{+n} + E_e^{-1} = E_j^{+(n-1)} + h\nu$$

E_j^{+n} and $E_j^{+(n-1)}$ are the energies of the ions before and after the re-combination and E_e^{-1} the Kinetic energy of the electron.

Accordingly to our theory the corona consists of electrons and positive ions moving rapidly away from the photo-sphere, and the re-combination process in the photo-sphere continues to take place in the corona with diminishing intensity outwards. This continuous coronal spectrum, being emitted above the reversing layer, shows no Fraunhofer absorption lines. The intensity of the emitted continuous light relative to that of the scattered sunlight increases downwards, and thus, in the lower part of the corona, the scattered light may be masked by emitted continuous light ("thermic emission").

§ 6. The origin of the coronal lines.

In the paper already referred to dealing with the solar eclipse of June 1927, and with the new coronal theory, the following suggestion was made regarding the origin of the coronal lines:[1]

"With our present knowledge of the structure of matter and the light process we need not assume that the coronal lines are due to some unknown element. Under the conditions on the sun the atoms may exist in ionized states and under conditions that we are not able to reproduce in laboratory experiments. Especially when the light process takes place in a system of such extremely small density as that of the corona, the re-combination leading to emission of spectral lines may follow another course than when it takes place in vacuum tubes, where the course is disturbed by collisions. In this connection it is of interest to mention that I. S. Bowen (Nature 1927, p. 473) will explain the nebular lines in this way, by supposing that they are due to electronic jumps, which under ordinary conditions are forbidden by the selection rule or prevented because the metastable state from which the electron jumps take place is disturbed by collisions."

Such an interpretation would fall into line with our theory, because according to this theory coronal matter should consist of electrons and positive ions.

Our suggestion regarding the possible origin of the coronal lines has been confirmed by the interpretation of coronal lines recently given by Edlén. At the same time his interpretation gives most important support to our coronal theory.

Following a suggestion by Grotrian, Edlén[2] has shown that the more prominent coronal lines originate from transitions between the metastable ground states of the highly ionised atoms of *Fe*, *Ni*, *Ca* and *A*. The strongest coronal line is found to originate from Fe-atoms which have lost 13 electrons.

Thus we see that the coronal lines — in accordance with our theory — are emitted from ions of large specific charge, and (perhaps with the exception of Argon) from elements present in great abundance in the sun's atmosphere.

In Table I are given the lines interpreted by Edlén and the ions from which each of them originates. The last column contains the specific charge (e/m) relative to that of hydrogen. The specific charge, which is seen to vary between 0,16 and 0,30, is of about the same magnitude as that of the He^+ ion.

Thus the ions emitting the coronal lines and forming part of the coronal matter should be quite as easily driven away from the sun as the light helium ion.

In accordance with our view of the sources of the coronal streamers Edlén's identification of the coronal lines shows that highly ionised atoms must form an essential part of the

[1] L. Vegard, Det norske Vid.-Akad. Skr. I, No. 2, 1928, p. 33.

[2] Bengt Edlén, Nordisk Astron. Tidsskrift 1943, Fra Fysikkens Verden 4, 199, 1943.

Table I.

Ion	Coronal lines	e/m
Ca XII	3328	0,28
Ca XIII	4086,3	0,30
Ni XII	4231,4	0,19
Ni XIII	3642,9; 5116,0	0,20
Ni XV	6701,8; 8024,2	0,24
Ni XVI	3601,0	0,26
Fe X	6374,5	0,16
Fe XI	3986,9; 7891,9	0,18
Fe XIII	3388,1; 10747; 10798	0,21
Fe XIV	5302,9	0,23
Fe XV	7059,6	0,25
A X	5536	0,23

coronal matter. The presence in the corona of highly ionised atoms necessarily involves that the sun, through the re-combination process, must emit rays of the X-ray type, *and consequently the interpretation of the coronal lines has proved the correctness of the assumption which forms the very basis of our coronal theory.*

§ 7. On the presence of Na-ions in the corona.

As already mentioned and as pointed out in an article recently published in the Norwegian journal "Fra Fysikkens Verden", we should expect the coronal streamers to contain also highly ionised *Na*-atoms. This is first of all suggested by our coronal theory, because we know from the solar spectrum that the solar atmosphere contains considerable quantities of sodium, and secondly the sodium *D*-line, which is emitted from the terrestrial ionosphere, shows considerable intensity fluctuations. These fluctuations which are found for the sodium line in the twilight spectrum as well as in the spectrum of the aurorae, indicate that sodium coming in from space, enters the higher strata of our atmosphere, and we are led to the assumption that coronal streamers containing *Na*-ions may reach the earth.

The question arises whether any of the coronal lines may originate from the metastable ground states of highly ionised *Na*-ions.

As far as I know, the term values of the metastable ground states of highly ionised sodium have not been directly determined from observations of the *Na*-spectra. We shall have to try the same method as that used by EDLÉN in his interpretation of the coronal lines, and take advantage of the fact that for a series of ions with the same number of bound electrons (Isoelectronic series) the term values vary as a monotonous function with atomic number. From the knowledge of the term values of ions of the lighter elements *C*, *N*, *O*, *F* and *Ne* the term values for the ground states of *Na* may be found approximately by extrapolation.

The material at my disposal regarding term values of the elements *C*, *N*, *O*, *F* and *Ne* is that tabulated in BACHER and GOUDSMIT's book[1] but even from this somewhat incomplete material, we have been able to derive some interesting results regarding the lines originating from the ground states of the *Na*-ions.

We first consider the isoelectronic series:

a: *OI*, *FII*, *NeIII*, *NaIV*,
b: *NI*, *OII*, *FIII*, *NeIV*, *NaV*,
c: *CI*, *NII*, *OIII*, *FIV*, *NeIV*, *NaVI*.

In the case of the first series *(a)* the term values of the metastable ground states are only given for oxygen. From the rate of increase of the term differences with increasing atomic number found for other iso-electronic systems, we may conclude that the lines of *NaIV* which correspond to the red and green auroral lines *OI* ($^3P_{2,0,1}$—$^1D_2$) and *OI* ($^1D_2$—$^1S_0$) will be situated in the observable region, probably somewhere in the region 3700—3900 Å. As a matter of fact some faint coronal lines appear in this region, which have not been identified by EDLÉN.

In the case of the iso-electronic series *(b)* beginning with *NI*, we have to consider the transitions ($^4S_{3/2}$—^2D), ($^4S_{3/2}$—$^2P^0$) and ($^2D^0$—^2P). It can easily be estimated that the two first of these transitions give lines so far into the ultra violet that they would be completely absorbed in the atmosphere.

From BACHER and GOUDSMIT we find for *NeIV*: $^2D_{5/2}$—$^2P_{3/2}$=21216. The terms $^2D_{3/2}$ and $^2P_{1/2}$ are not given.

In the case of *FIII* only the mean value of each doublet term is given. In order to extrapolate from the value of $^2D_{5/2}$—$^2P_{3/2}$ given for neon to the corresponding frequency for sodium, we therefore take the mean value of the doublet terms $^2D_{5/2,\,3/2}$ and $^2P_{3/2,\,1/2}$ in the case of *OII* and *NI*.

[1] R. H. BACHER and GOUDSMIT, Atomic Energy States, London, 1932.

The values of $^2D_0$—$^2P^0$ thus found are given in Table II.

Table II.

Electron states: $1\,s^2\;2\,s^2\;2\,p^3$ ($^4S_{3/2}$, $^2D_{3/2,\,5/2}$, $^2P_{1/2,\,3/2}$).

Ion	$^2D^0-{}^2P^0$	Δ	Δ^2	Δ^3
NI	9610,7			
		4032,1		
OII	13642,8		—212,9	
		3819,2		+157,7
FIII	17462		— 55,2	
		3754		+157,7
NeIV	21216		+102,5	
		3856,5		
NaV	25072,5			

Table III.

Electron states: $1s^2\;2s^2\;2p^2$ ($^3P_{0,\,1,\,2}$, $^1D_2$, $^1S_0$).

Ion	$^3P_2-{}^1D_2$	Δ	Δ^2	$^1S_0-{}^1D_2$	Δ	Δ^2
CI	10150			11455		
		5036			5917	
NII	15186		—255	17372		—376
		4781			5541	
OIII	19967		(—255)	22913		(—376)
		(4526)			(5165)	
FIV	(25393)		(—255)	(28078)		(—376)
		(4271)			4789	
NeV	(29664)		(—255)	(32867)		(- 376)
		(4016)			(4413)	
NaVI	(33680)			(37280)		

We assume that the relation between the frequency (ν) and the atomic number (Z) is approximately represented by an expression of the form:

$$\nu = A + BZ + CZ^2 + DZ^3$$

This means that the third difference Δ^3 should be constant. On the basis of this assumption the frequency ($^2D_{5/2}$—$^2P_{3/2}$) for *NaV* is found to be 25072,5, which corresponds to the wave-length:

$$\lambda = 3987{,}3\ \text{Å}.$$

Among the coronal lines we find a fairly strong one with the wave-length $\lambda = 3986{,}9$. Taking into account the possible errors in the determination of the energy states $^2D^0$ and $^2P^0$ of the elements *Ne* and *F*, and the possible error introduced through the extrapolation, the agreement is quite surprisingly good; *thus within the limit of error the coronal line 3986,9 coincides with the sodium line NaV* ($^2D^0{}_{5/2}$—$^2P^0{}_{3/2}$).

In the case of the iso-electronic series (*c*) BACHER and GOUDSMIT only give the term values of the ground states for *CI*, *NII* and *OIII*. The frequencies which might come into consideration are given in Table III.

The extra-polation to the corresponding *NaVI*-frequencies through several steps must be subject to considerable errors. From the frequencies of *CI*, *NII*, *OIII*, we only obtain the differences Δ and Δ^2 and not Δ^3. If the variation of frequency with atomic number in this case follows a similar law to that in the case of the previous series beginning with *NI*, it would follow that Δ^3 is positive and that consequently Δ^2 increases algebraically with increase of *Z*.

The frequencis of *NaVI* given in Table III, which are obtained by putting Δ^2=constant, are therefore too small. The corresponding wave-length values are 2968 Å and 2682 Å, and the true values are still smaller. Thus the lines fall outside the observable spectral region.

If we regard the transition between states with different resultant quant number (*L*), we thus find that *Na*-ions which have lost more than 4 electrons will emit lines which are completely absorbed by the earth's atmosphere.

Transitions between multiple states which only differ by the quant number *j* give lines too far in the infra-red region to be observed.

Remembering that the *NaII* and *NaIII*-ions have no metastable ground states it appears that only the transitions *NaIV* (^3P—$^1D_2$) ($^1D_2$—$^1S_0$) and *NaV* ($^2D^0$—$^2P^0$) *may possibly give coronal lines in the observable region.*

For the coronal line 3986,9 EDLÉN gives the interpretation:

$$FeXI\ 3\,s^2\,3\,p^4\ (^1D_2—{}^3P_1).$$

I am not in possession of such observational data as would be necessary for the evaluation of the degree of uncertainty which might still be attached to the interpretation suggested by EDLÉN. On account of the great importance attached to the question of the possible appearance of sodium lines in the coronal luminesence a further discussion of the origin of this line on the basis of the observational data will be of particular interest.

At present we may state that the wave-length of the coronal line 3986,9 agree remarkably well with the value 3987,3 calculated for the line

$NaV\ 2s^2\ 2p^3$ ($^2D_{5/2}$—$^2P_{3/2}$). The specific charge of NaV is 0,174, while that of $FeXI$ is 0,179. Thus as regards specific charge our interpretation is almost equally favourable to that given by EDLÉN.

§ 8. Theoretical considerations regarding the intensity variation of coronal lines with solar altitude.

According to our coronal theory the highly ionised heavy ions present in the corona come from the sun's deeper layers and are driven away from the sun at great speed through the electric fields resulting from photo-electric effect produced by soft X-rays. It is therefore legitimate to assume that when an ion passes from the chromosphere into the coronal region it is in an excited state, which means that a considerable fraction of the ions will be in one of the upper levels of the ground state.

In this way our coronal theory gives a simple explanation of the fact that no lines of the ordinary spectrum of the ions are to be found among the coronal lines, but only lines connected with the metastable states. This means that owing to the extremely small density of the coronal matter the probability of new excitations through collisions or capture of electrons is so small that the resulting spectral lines would be too weak to be detected.

In other words *the transfer of the ions to the upper metastable states of the ground configuration is mainly effected somewhere below the upper limit of the chromosphere and the appearance of the emission lines in the corona is due to the long lifetime of the metastable states and the great radial velocity of the ions.*

Under these conditions we can determine how the light intensity of a coronal line of known origin will vary with solar altitude. We consider a group of ions with the same atomic number and with (n) bound electrons. Let the metastable ground states beginning with the upper one be indicated by 1, 2, 3 . . . . and the average lifetimes by τ_1, τ_2, τ_3 . . . . At a section (S_0) across the streamers, e. g. at the bottom of the corona, the number of ions in unit volume in the states 1, 2, 3 . . . . is indicated by A_0, B_0, C_0 . . . . and at a section (S) at a height (x) from (S_0) by A, B, C . . . .

To simplify matters, all ions of this group are supposed to have the same radial velocity (v) and the number of ions passing through unit cross section at (S) in unit time will be

$$Av,\ Bv,\ Cv\ .\ .\ .\ .\ .$$

When the ions with (n) bound electrons pass through a distance from x to $x+dx$ the number of ions per unit volume in a given metastable state will change owing to the following causes:

1. The number of ions in the state considered diminishes through transitions to lower metastable states or to the normal ground state.
2. If the ion is not in the upper metastable state the number increases through transitions from higher levels.

For the reasons mentioned, we neglect the increase in the number of excited ions which may occasionally result from excitation or disturbance of the metastable states due to collisions within the coronal region. The intensity of the coronal line considered is proportional to the number of transitions per unit length along the coronal streamer.

The number of ions in a certain state passing a section (S) in unit time is Av. In the time (dt) the number of transitions performed is $\left(\frac{1}{\tau} Av.\,dt\right)$ and these transitions will be distributed over a distance $dx = vdt$. Only a certain fraction α of these transitions go to the state (r) and contribute to the intensity of the line considered. The contribution (di) delivered on the way dx to the energy of the line, will be:

$$di = \frac{\alpha\ A}{\tau_1} vdt \text{ or}$$

$$\frac{di}{dx} = I = \frac{\alpha\ A}{\tau_1} \qquad (1)$$

We first consider the simplest case that the coronal line corresponds to a transition from the upper metastable state to the lower state (r). In order to determine the variation of the intensity (I) of the line with solar altitude, we have to determine A as a function of (x).

In the simplest case when A is the number of ions in the upper metastable state, we have:

$$d(Av) = -\frac{1}{\tau_1} Av.dt = -\frac{1}{\tau_1} A\ dx \text{ and}$$

$$A = A_0\, e^{-\frac{x}{v\tau_1}} \qquad (2\text{ a})$$

and from equation (1)

$$I = \frac{\alpha A_0}{\tau_1} e^{-\frac{x}{v\tau_1}} = I_0 e^{-\frac{x}{v\tau_1}} \qquad (2\text{ b})$$

If we were able to measure the diminution of I with the solar altitude, we could determine the quantity $v\tau_1$.

If further we knew the average life time of the upper metastable state, we could find the velocity of the ions. Suppose we measure the intensities of the line I_1 and I_2 corresponding to the solar altitudes x_1 and x_1+l, then:

$$v\tau_1 = \frac{l}{lognat \frac{I_1}{I_2}} \qquad (3)$$

If during a total eclipse we let the image of the corona fall on the slit of a spectrograph in such a way that the slit is perpendicular to the surface of the sun, then the intensities (I_1) and (I_2) corresponding to a known distance *(l)* could be found from the intensity distribution along the spectral line, and by such observations we should be able to measure the product $v\tau_1$.[1]

If our interpretation of the coronal line 3986,9 is correct, this line corresponds to a transition from the upper metastable state of *NaV*, and the intensity should diminish with solar altitude in accordance with equation (2). If we knew the average lifetime of the upper metastable state (^2P) of *NaV*, we might use this line for the determination of the velocity *(v)* of the *NaV*-ions.

When the line is emitted through a transition from one of the lower states, the problem of finding the variation of intensity with altitude is more complicated. but may be solved in any actual case.

As in the case already treated, the number of ions in the level of start will diminish, on account of transitions to lower levels, but it is increased from transitions to the level of departure from still higher levels.

To simplify matters we assume that the increase only results from transitions from one upper level. Let e. g. the line considered correspond to transition from $2 \rightarrow 3$.

[1] In exact measurements we must take it into account that ions of the same group may have different velocities, and that the light entering the slit comes from coronal layers of a certain thickness. Still equation (3) might give the right order of magnitude of $v\tau$.

If a fraction α of the transitions from state (1) pass to state (2), and a fraction β from state (2) pass to state (3), then according to equation (1):

$$I = \frac{\beta B}{\tau_2} \qquad (1')$$

The differential equation now takes the form:

$$d(Bv) = \frac{\alpha A}{\tau_1} vdt - \frac{B}{\tau_2} vdt$$

or

$$\frac{dB}{dx} = \frac{\alpha A}{\tau_1 v} - \frac{B}{\tau_2 v}$$

From equation (2 a) we have:

$$A = A_0 e^{-\frac{x}{v\tau_1}}$$

and

$$\frac{dB}{dx} = \frac{\alpha A_0}{v\tau_1} e^{-\frac{x}{v\tau_1}} - \frac{B}{v\tau_2} \qquad (4)$$

The integral is of the form:

$$B = a.\, e^{-\frac{x}{v\tau_1}} + b.\, e^{-\frac{x}{v\tau_2}} \qquad (5\text{ a})$$

If $B = B_0$ for $x = o$, we find

$$a + b = B_0$$

$$a = \alpha A_0 \frac{\tau_2}{\tau_1 - \tau_2}$$

and

$$B = B_0\, e^{-\frac{x}{v\tau_2}} + \frac{\alpha A_0 \tau_2}{\tau_1 - \tau_2}\left(e^{-\frac{x}{v\tau_1}} - e^{-\frac{x}{v\tau_2}}\right)$$

From equation (1), we get:

$$I = \frac{\beta B_0}{\tau_2} e^{-\frac{x}{v\tau_2}} + \frac{\alpha\beta A_0}{\tau_1 - \tau_2}\left(e^{-\frac{x}{v\tau_1}} - e^{-\frac{x}{v\tau_2}}\right) \qquad (6\text{ a})$$

We see that $x = o$ gives $I = I_0 = \frac{\beta}{\tau_2} B_0$

Putting $\alpha\beta A_0 = A'_0$ we get:

$$I = I_0\, e^{-\frac{x}{v\tau_2}} + \frac{A'_0}{\tau_1 - \tau_2}\left(e^{-\frac{x}{v\tau_1}} - e^{-\frac{x}{v\tau_2}}\right) \qquad (6\text{ b})$$

This formula (6 b) corresponds to the case where the upper metastable state of the transition considered only receives contributions from one higher state; but even in this case the intensity variation follows a fairly complicated law, in spite of the simplifying assumptions on which the equation (6 b) is based. When several higher states contribute to the number of ions in the upper metastable state of the transition considered, the expression for the variation of intensity with solar altitude will become still more complicated.

Although an accurate quantitative comparison between theory and observation is difficult, especially in the more complicated cases of higher metastable states, the comparison may give us some estimates of the ionic velocities and the lifetime of the metastable states engaged in the formation of any particular line. It may also be useful as a criterion for the correctness of identifications or for choosing between several possible interpretations.

In this way we might, for instance, decide whether the coronal line 3987 originates from *NaV* in the way suggested in this paper, or from *FeXI* as proposed by Edlén. In the case of *NaV* the upper metastable level of the transition is the highest one, and the intensity should vary with solar altitude in the way characterised by the equation (2 b).

According to Edlén the line 3987 should originate from the transition *FeXI* ($^1D_2$ $^3P_1$) and and there is a metastable $^1S_0$-level above the $^1D_2$-state. Consequently the intensity variation with altitude should be characterised by the equation (6).

At any rate a study of the intensity variations of the coronal lines with solar altitude in the way here indicated may give us valuable information regarding the light processes connected with the emission of the coronal lines.

Summary.

1. The coronal theory dealt with in this and previous papers follows as a consequence of the physical conditions of the upper terrestrial atmosphere, as they have been revealed through the study of the auror spectrum combined with measurements of the position in space of the aurorae.
2. Coronal phenomena are not restricted to the sun and the stars, but are common to all planitary systems and to all planets or comets which are either surrounded by an atmosphere or are in a gaseous state, provided the sun (or the central star) emits a radiation of the X-ray type.
3. The terrestrial corona which is most highly developed on the day side of the earth and has its greatest extension near the plane of the ecliptic, is directly seen as zodiacal light after sunset and as "Gegenschein" before sunrise.
4. The constitution and formation of the coronal streamers gives at the same time an idea of the constitution of those electric ray bundles which produce the aurorae and certain magnetic disturbances.
5. The essential condition for the formation of a coronal structure is the emission of high speed electrons. In the case of the terrestrial corona these electron rays must be produced by rays from the sun of the X-ray type. The same rays will act on the sun and produce the streamers which form the solar corona. Any process on the sun, however, resulting in the emission of cathode rays, will produce coronal streamers.
6. The X-ray sources on the sun were explained by assuming that matter in a highly ionised state is brought through the turbulent motions from the interior towards the surface. The X-rays are emitted through the re-combination process which takes place near the sun's "surface".
7. The granulation on the sun's surface is probably an indication of turbulent motions which bring active matter towards the surface, so the X-rays will be emitted more or less from all parts of the sun. In this way we explain the fact that the solar corona extends in all directions and forms a continuous luminous halo around the sun.
8. In the sun-spot region, where the turbulent motion is particularly strong, matter is pumped up to the surface from very deep layers. The ions are consequently still more highly ionised than those driven up through the turbulence of granulae. The X-rays resulting from the re-combination have a higher frequency and they produce electron rays of higher speed. These electron rays produce coronal streamers which may reach the earth, where they produce aurora and magnetic disturbances.
9. According to our theory the coronal matter is a plasma consisting of electrons and of positive ions which have a great spesific charge, and which is present in great quantities in the surface layers of the sun. Thus

we may expect to find protons, He-ions and highly ionised ions of the elements *Na, Ca, Fe* and *Ni.*

). The presence of protons in the coronal matter is supported by the great fluctuation in the intensity of hydrogen lines in the auroral spectrum. These fluctuations indicate that every now and then showers of hydrogen coming from the sun penetrate into the upper layers of our atmosphere.

.. The sodium D_1D_2 — doublet which appears with great intensity in the twilight spectrum and also but weaker in that of the aurora is shown to be emitted from the highest region of our atmosphere above 56 km. The *Na*-doublet also shows considerable intensity fluctuations, indicating that the *Na*-atoms are of cosmical origin and that they probably come from the sun.

?. The continuous spectrum of the photo-sphere is due to re-combination of ions and electrons. Electrons of varying Kinetic energy are captured by an ion and the energy loss is emitted in the form of photons. This re-combination process also goes on in the mixture of positive ions and electrons which constitute the corona, but as the light is emitted above the reversing layer the Fraunhofer lines are absent. This re-combination spectrum ("thermic emission") is particularly strong in the lower part of the corona. Some of the continous light is due to scattering, but in the lower part the Fraunhofer lines are partly masked by the "thermic emission", partly by Doppler effect.

}. In accordance with our theory EDLÉN has found that all the stronger coronal lines originate from highly ionised ions of the elements *Ca, Fe, Ni* and *A*, and they are referred to forbidden transitions between the metastable ground states of these elements.

!. None of the lines identified by EDLÉN is referred to *Na*. For the reasons mentioned, however, we should expect to find lines from the metastable ground states of *Na*-ions represented among the coronal lines. Through extrapolation within the iso-electronic series *NI, OII, FIII, NeIV, NaV* it was found that the line *NaV* ($^2D_{5/2}$—$^2P_{3/2}$) has a wave-length 3987,3 which within the limit of error coincides with the coronal line 3986,9 which EDLÉN refers to *FeXI* ($^1D_2$—$^3P_1$). We are not in possesion of sufficient data to decide which of these interpretations is the correct one.

15. Our coronal theory may explain the reason why only lines corresponding to forbidden transitions between the metastable ground states appear in the coronal spectrum. This means that the metastable states are excited before they reach the coronal region, and owing to the small density in the corona the upper ionic states of very short lifetime, giving the ordinary line spectra, are not produced to any marked degree.

16. On the assumption that the coronal lines are emitted from ions in the metastable ground states leaving the chromosphere at a high velocity, the intensity variation of the line with solar altitude may be calculated. If we could measure the intensity variation with altitude, we might calculate the quantities $(v\tau)$ where (τ) is the average life time of the metastable state and (v) a kind of average velocity of the ion. The intensity distribution with solar altitude might also give us a means of testing the correctness of the interpretations of the lines.

17. EDLÉN's interpretation of the coronal lines shows that matter in a highly ionised state is present in the higher strata of the solar atmosphere and rays of the X-ray type must be emitted from the sun. Thus the interpretation of the coronal lines has proved the correctness of the assumption which forms the very basis of our coronal theory.

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