THE IDENTIFICATION OF THE CORONAL LINES

(*George Darwin Lecture, delivered by Professor Bengt Edlén on* 1945 *October* 12)

The coronal emission lines are superimposed on the continuous radiation of the inner parts of the solar corona, the region of their appearance extending from the top of the chromosphere to a height generally not exceeding 10 minutes of arc (half a million kilometers) from the Sun's limb. The lines are responsible for only a small fraction of the total intensity of the corona.

The coronal line spectrum has been studied by most eclipse expeditions since 1869, when the first line was discovered by Young and Harkness. During the last decade Lyot's ingenious invention of the coronagraph, described by him in the George Darwin Lecture of 1939 *, has greatly improved and extended the observations, especially for the infra-red part of the spectrum. At present, as a net result of all observations, the wave-lengths of some twenty coronal emission lines have been established. Six of these lines are much stronger than the rest. These conspicuous lines are: λ 3388, λ 5303, λ 6374, λ 7892, λ 10747 and λ 10798. None of the coronal lines has been observed in a laboratory light-source and there is no real coincidence with any of the Fraunhofer lines nor with any line in the chromospheric spectrum. The coronal lines were in fact a unique feature of the solar corona until in 1932 a number of them showed up in the spectrum of the recurrent nova RS Ophiuchi. Recently the coronal lines have reappeared in Nova Ophiuchi at the outburst of 1942 and have also been observed in T Pyxidis in 1945.

The explanation of "coronium", which will form the subject of this lecture, has a close resemblance to Bowen's solution of the nebulium problem inasmuch as the lines are in both cases caused by transitions from low, metastable levels in various ions of cosmically abundant elements, transitions normally forbidden and able to appear only in sources of very low density. While, however, the carriers of the strongest nebulium lines are found among the light elements, especially oxygen, nitrogen and neon, the coronium lines are due to heavier elements. Thus, the six outstanding lines just mentioned are all due to iron. Another difference is that most of the coronal transitions occur between levels within the ground term, whereas the nebular transitions take place between levels of different terms. The main difference, however, is caused by the much higher stage of ionization of the coronal atoms, which are shown to have lost from 10 to 15 electrons.

Turning to the details of the identification †, I will first mention that the starting-point was Grotrian's discovery of the coincidence between the level separations within the ground terms of the spectrum *Fe*X and *Fe*XI with the wave-numbers of the coronal lines λ 6374 and λ 7892 respectively. The ground state of *Fe*X is a ^{2}P term arising from the electron configuration $3s^2 3p^5$. If supposed to be real, the first mentioned coincidence means that the red coronal line is emitted when iron atoms 9 times ionized pass from the metastable level $^2P_{\frac{1}{2}}$ which has an energy of 1·94 electron volts, to the ground level $^2P_{\frac{3}{2}}$. The level separations of *Fe*X and *Fe*XI were obtained directly from the extreme ultra-violet spectrum of these ions. Table I contains the significant data relating to these identifications as well as to two additional identifications with similar transitions in the ions of *Ca*XII and *Ca*XIII.

* *M.N.*, **99**, 580, 1939.

† The full description is in *Z. Astrophys.*, **22**, 30, 1942; see also *Ap. J.*, **98**, 116, 1943.

TABLE I

The Experimental Basis for the Direct Identification of Coronal Lines

Transitions in the Extreme Ultra-Violet	λ and Intensity in the Vacuum Spark	ν cm.$^{-1}$	Level Separations	Corona
*Fe*X $3s^2 3p^5 - 3s^2 3p^4 4s$:				
$^2P_{\frac{3}{2}} - {}^2P_{\frac{1}{2}}$	95·338 (1)	1 048 900	15 714	
$^2P_{\frac{1}{2}} - {}^2P_{\frac{1}{2}}$	96·788 (2)	1 033 186		
$^2P_{\frac{3}{2}} - {}^2P_{\frac{3}{2}}$	96·122 (4)	1 040 345	15 660	
$^2P_{\frac{1}{2}} - {}^2P_{\frac{3}{2}}$	97·591 (0)	1 024 685		
Average	...	...	15 687	15 683
*Fe*XI $3s^2 3p^4 - 3s^2 3p^3 4s$:				
$^3P_2 - {}^3D_2$	87·025 (1+)	1 149 095	12 667	
$^3P_1 - {}^3D_2$	87·995 (0)	1 136 428		
$^3P_2 - {}^3S_1$	89·185 (1+)	1 121 265	12 679	
$^3P_1 - {}^3S_1$	90·205 (1)	1 108 586		
Average	...	...	12 673	12 668
*Ca*XII $2s^2 2p^5 - 2s 2p^6$:				
$^2P_{\frac{3}{2}} - {}^2S_{\frac{1}{2}}$	141·036 (8)	709 039	30 028	30 039
$^2P_{\frac{1}{2}} - {}^2S_{\frac{1}{2}}$	147·273 (6)	679 011		
*Ca*XIII $2s^2 2p^4 - 2s 2p^5$:				
$^3P_2 - {}^3P_2$	161·748 (1d)	618 246	24 464	24 465
$^3P_1 - {}^3P_2$	168·412 (00d)	593 782		

The lines λ 6374 and λ 7892 belong to the six strongest coronal lines previously mentioned. The strength of these lines combined with the absence of the analogous transitions of *Fe*VII, well known from their prominent appearance in Nova Pictoris, indicates that the most abundant ionization stages of iron might be found more likely above than below *Fe*X and *Fe*XI. A search for these higher stages, however, has to be based on extrapolations, as the relevant spectra in the extreme ultra-violet could not be analysed with the sufficient accuracy and completeness to fix the ground level separations. Preliminary extrapolations showed that transitions analogous to those of *Fe*X and *Fe*XI should be looked for within the configurations $3s^2 3p$, $3s^2 3p^2$, $3s^2 3p^4$ and $3s^2 3p^5$ of the elements of the iron group. Of these elements iron is by far the most abundant, next followed by nickel.

The difference between the two levels of the ^{2}P term of the configurations $3s^2 3p$ and $3s^2 3p^5$ is conveniently extrapolated by means of the regular doublet law. As shown in Table II, the fourth root of the level separation increases more and more linearly along the sequences of the iso-electronic ions starting with *Al*I and *Cl*I. The extrapolation through the *Al*I sequence to *Fe*XIV suggests unambiguously the origin of the green coronal line.

The extrapolation to *Fe*XIV is rather extended and naturally somewhat precarious. As a decisive confirmation of the identification of both the green and the red line, however, coronal lines of medium strength are found at exactly the predicted positions for the corresponding transitions in *Ni*XII and *Ni*XVI. The latter positions are predictable with great precision as soon as the coronal wave-numbers are accepted for iron.

In the configurations $3s^2 3p^2$ and $3s^2 3p^4$ several types of transitions are possible, as shown in Fig. 1.

These transitions are not so simply extrapolated as the coupling changes considerably along the sequences. Using the known formulæ for intermediate coupling it is possible, however, to follow a procedure consisting essentially of a transformation of the ^{3}P-

TABLE II

Comparison of the Ground-Term Splittings in the Iso-electronic Sequences $3s^2 3p$ (*Al*I, *Si*II, . . .) *and* $3s^2 3p^5$ (*Cl*I, *A*II, . . .); $\zeta = \frac{2}{3}\Delta\nu$

Atomic Number Z	Ion	$^2P_{\frac{3}{2}} - {}^2P_{\frac{1}{2}}$ cm.$^{-1}$	$\sqrt[4]{\zeta}$	Diff.	Ion	$^2P_{\frac{1}{2}} - {}^2P_{\frac{3}{2}}$ cm.$^{-1}$	$\sqrt[4]{\zeta}$	Diff.
13	*Al*I	112·04	2·939	0·781				
14	*Si*II	287·3	3·720	·675				
15	*P*III	559·6	4·395	·622				
16	*S*IV	950·2	5·017	·599				
17	*Cl*V	1 492	5·616	·579	*Cl*I	881	4·923	0·636
18	*A*VI	2 210	6·195	·564	*A*II	1 432	5·559	·603
19	*K*VII	3 131	6·759	·560	*K*III	2 162	6·162	·589
20	*Ca*VIII	4 305	7·319	·552	*Ca*IV	3 115	6·751	·576
21	*Sc*IX	5 759	7·871	·543	*Sc*V	4 325	7·327	·567
22	*Ti*X	...	...		*Ti*VI	5 825	7·894	·558
23	*V*XI	...	...		*V*VII	7 657	8·452	·553
24	*Cr*XII	...	...		*Cr*VIII	...	...	
25	*Mn*XIII	...	...		*Mn*IX	...	...	
26	*Fe*XIV	18 852·5 * (λ 5303)	10·588	0·538	*Fe*X	15 683·2 * (λ 6374)	10·112	0·545
27	*Co*XV	...	...		*Co*XI	...	...	
28	*Ni*XVI	27 762 * (λ 3601)	11·664		*Ni*XII	23 626 * (λ 4231)	11·203	

* Wave-numbers of coronal lines.

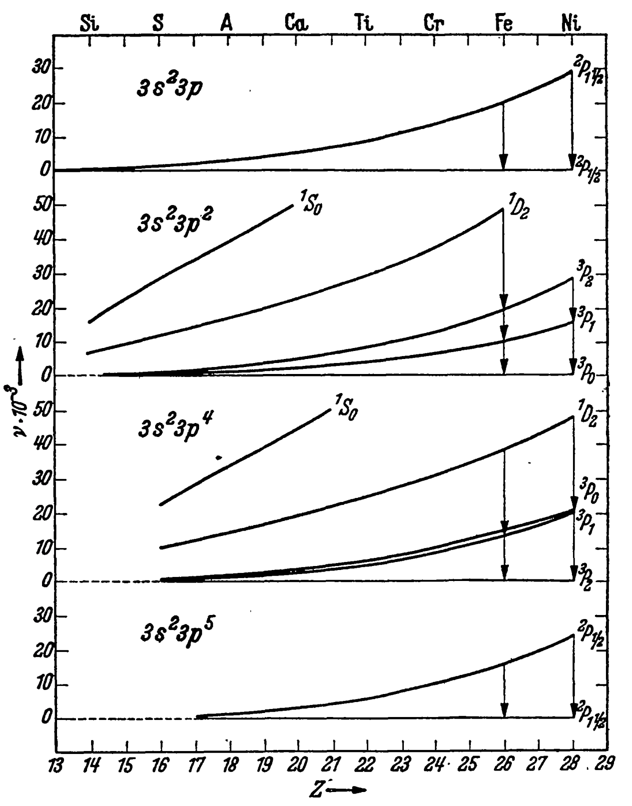

FIG. 1.

TABLE III

Comparison of the Ground-Term Splittings in the Iso-electronic Sequences

$3s^2 3p^2$ (*Si*I, *P*II, . . .)

Ion	$^3P_2 - {}^3P_0$	$\sqrt[4]{\zeta}$		$^1D_2 - {}^3P_2$	*F* cm.$^{-1}$	
*Si*I	223·3	3·489	712	6 076	5 121	2 000
*P*II	470·3	4·201	642	8 402	7 121	1 821
*S*III	832·5	4·843	609	10 488	8 942	1 727
*Cl*IV	1 341	5·452	590	12 425	10 669	1 669
*A*V	2 028	6·042	573	14 269	12 338	1 635
*K*VI	2 924	6·615	567	16 046	13 973	1 626
*Ca*VII	4 075	7·182	556	17 796	15 599	
*Sc*VIII	5 506	7·738		...	...	
*Ti*IX	...	...		...	...	
*V*X	...	...	547	...	...	1 583
*Cr*XI	...	...		...	...	
*Mn*XII	...	...		...	...	
*Fe*XIII	18 561 *	10·475		29 507 *	25 098	
			541	(λ 3388)		
*Co*XIV	...	...		...	...	
*Ni*XV	27 376 *	11·558		u. violet	...	

$3s^2 3p^4$ (*S*I, *Cl*II, . . .)

Ion	$^3P_1 - {}^3P_2$	$\sqrt[4]{\zeta}$		$^1D_2 - {}^3P_1$	*F* cm.$^{-1}$	
*S*I	397	4·441	661	8 843	7 523	1 871
*Cl*II	697	5·102	619	10 955	9 394	1 765
*A*III	1 112	5·721	599	12 898	11 159	1 701
*K*IV	1 673	6·320	582	14 713	12 860	1 657
*Ca*V	2 407	6·902	572	16 424	14 517	1 629
*Sc*VI	3 350	7·474	562	18 047	16 146	1 612
*Ti*VII	4 535	8·036	555	19 592	17 758	
*V*VIII	6 006	8·591		...	...	
*Cr*IX	...	...	550	...	...	1 580
*Mn*X	...	...		...	...	
*Fe*XI	12 668 *	10·240		25 075 *	24 079	
	(λ 7892)			(λ 3987)		
Co XII	...	...	543	...	...	1 538
*Ni*XIII	19 541 *	11·326		27 443 *	27 155	
	(λ 5116)			(λ 3643)		

* From coronal lines.
18 561 = sum of wave-numbers of λ 10747 and λ 10798,
27 376 = „ „ „ λ 6702 and λ 8024.

intervals into the "magnetic" parameter ζ and the intervals of the type $^1D - {}^3P$ into the "electrostatic" parameter F. These parameters are convenient for an extrapolation, the former being proportional to Z^4 and the latter to Z (Z = atomic number). The intervals and the variation in the corresponding parameters are shown in Table III.

These data lead to the identification of the remaining strong coronal lines, λ 3388, λ 10747 and λ 10798. As before, the presence of fainter coronal lines at the accurately predictable positions for the corresponding nickel transitions support the identifications. In both Tables II and III the numbers inserted for *Fe* and *Ni* are the wave-numbers of coronal lines or in the case of $3s^2 3p^2\ {}^3P_2 - {}^3P_0$ the sum of two such wave-numbers.

The extrapolations leading to the *Fe* and *Ni* identifications are perhaps more clearly illustrated by the diagrams in Figs. 2 and 3, representing in a condensed form the

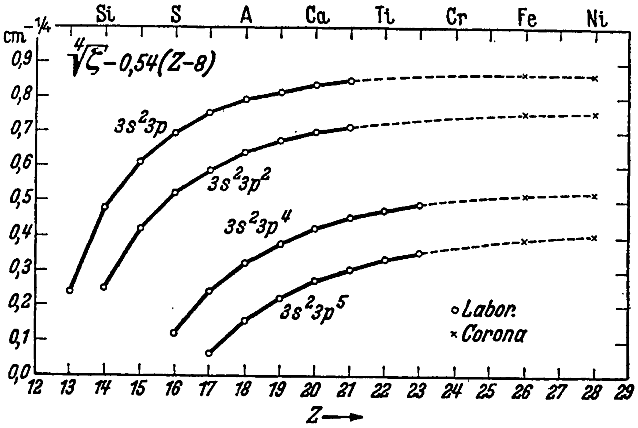

FIG. 2.

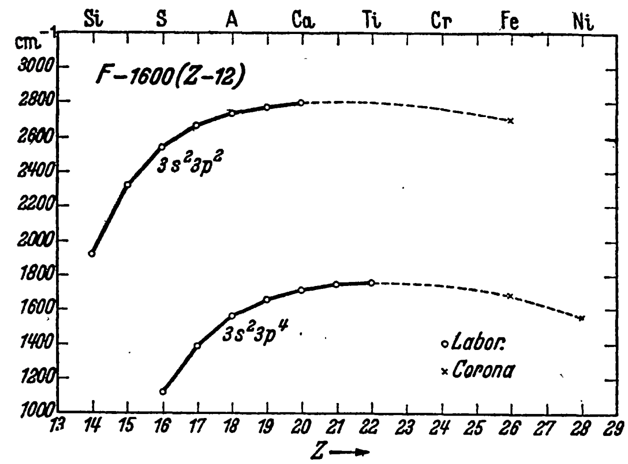

FIG. 3.

variation of the parameters ζ and F. Thus, Fig. 2 gives the evidence for the identification of the five strong iron lines, $\lambda\lambda$ 5303, 6374, 7892, 10747 and 10798, and of the five corresponding nickel lines, while Fig. 3 illustrates the identification of λ 3388 and two fainter lines.

In this way altogether 13 coronal lines, comprising all the strong lines and more than 95 per cent. of the total intensity of the line emission, have been identified with transitions in *Fe* and *Ni* ions. The origin of the various lines is again illustrated by Fig. 4.

After this exposition of the numerical coincidences of wave-numbers we shall turn to a discussion of the intensities to be expected for various transitions.

The number of quanta emitted through a particular transition is evidently proportional to the number n of ions reaching the initial level of this transition. It is further proportional to the probability A_1 of this transition divided by the sum of the probabilities of all possible ways of de-excitation from the same level. The intensity, *i.e.* number of quanta × energy per quantum, is then expressed in arbitrary units by

$$I = \nu n \frac{A_1}{A_1 + A_2 + A_3 + \ . \ . \ . \ + B + C},$$

if A_n stands for the probabilities of spontaneous radiation transitions to lower levels, B for de-excitation by collisions, and C for de-excitation by radiation absorption.

The probabilities A_n of the forbidden transitions here in question can be easily calculated on the basis of recent theoretical work. As a general result it is found (1) that

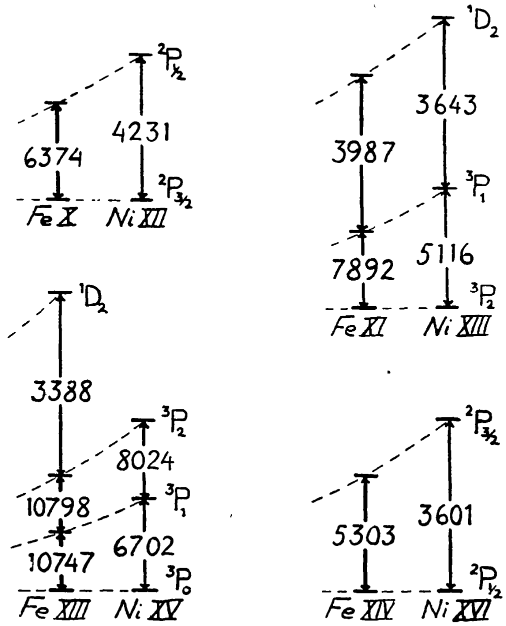

FIG. 4.

magnetic dipole transitions are by far more probable than transitions of the electric quadrupole type, the coronal lines being all of the former type, (2) that the probabilities of the coronal transitions are on the average very much greater than those of the nebular transitions. While, for instance, the main nebular lines of OIII have transition probabilities about 0·01 per second and those of the OII lines λ 3726–29 are much smaller still (about 0·00003 sec.$^{-1}$), the coronal transition probabilities range from 10 to 500 sec.$^{-1}$.

With regard to the spectral structure of the coronal ions and to the intensity distribution in the solar spectrum the process of de-excitation by radiation absorption, represented by C in the intensity formula, should be insignificant. The quantity B, representing the probability of de-excitation through collisions, depends on partly unknown parameters. Theoretical considerations indicate, however, that B should in most cases be smaller than ΣA by a factor of perhaps 1 or 2 powers of ten and thus might be preliminarily neglected in comparison with ΣA. This result seems to be confirmed by the observed intensity ratios of coronal lines belonging to *Fe*XIII. For the discussion of excitation processes in the corona a wave-mechanical calculation of the collisional cross-sections of the ions involved would be very welcome.

The further discussion of line intensities requires a knowledge of the relative number n of ions arriving in a certain metastable level, and we are now forced to decide by what kind of mechanism the ions are transferred into these levels. In this case it is tempting to compare with the similar, thoroughly investigated case of the nebulæ. It was originally assumed by Bowen and has later been confirmed that the metastable levels of the nebular ions are reached through excitation from the ground level by means of electron collisions. Probably the same process is dominant also in the corona, but it should be remembered that the physical conditions are in some respects quite different and other excitation mechanisms, negligible in the nebulæ, may well be of importance. For instance the intensity of even the strongest coronal lines is an extremely small fraction of the solar radiation of the same wave-length, and consequently an appreciable part of the line emission could well be thought of as a fluorescence excited through the absorption of solar radiation. Such a mechanism is the more likely as the transition probabilities of the "forbidden" coronal lines are comparatively very large.

In order to ascertain that the identifications of coronal lines were at all acceptable with regard to intensities, an attempt was made to calculate what the relative intensities of the identified transitions should be under certain simplified conditions. It was assumed that electron collisions are the cause of the excitation of the metastable levels and de-excitation by means other than spontaneous radiation is negligible. The number of ions arriving in a given level was derived in analogy with the treatment by Menzel, Aller and Hebb * of the similar case of forbidden *O*III in nebulæ. On further assumptions regarding the collisional cross-sections, the electron temperature ($=250\,000^\circ$) and the relative abundance of elements (*Fe* : *Ni* = 100 : 5·2), the intensity in arbitrary units of any one of the coronal transitions in the various *Fe* and *Ni* ions could be expressed as a product of a calculable factor and the unknown percentage R of the particular ionization stage.† The figure for the electron temperature is rather a guess, but it should be remarked that the result is very little affected as long as the temperature is assumed to be very high, an assumption which is supported by several independent facts. The calculation could be much improved, however, if the theoretical values for the collisional cross-sections were available.

Table IV

"Calculated" and Observed Intensities ‡

Configuration	Transition	Iron				Nickel			
		Ion	I'	I (obs.)	I (obs.)/I'	Ion	I'	I (obs.)	I (obs.)/I'
$3s^23p^5$	$^2P_{\frac{1}{2}}-{}^2P_{\frac{3}{2}}$	*Fe*X	43	8·1 (18)	0·19 (0·42)	*Ni*XII	3·1	2·6 ...	0·84 ...
$3s^23p^4$	$^1D_2-{}^3P_1$	*Fe*XI	14	0·7 ...	0·05 ...	*Ni*XIII	0·5	faint ...	... ...
	$^3P_1-{}^3P_2$	,,	70	... (13)	... (0·19)		5·2	4·3 (2·2)	0·83 (0·42)
$3s^23p^2$	$^1D_2-{}^3P_2$	*Fe*XIII	87	16 ...	0·18 ...	*Ni*XV	4·5	u. violet ...	... ...
	$^3P_2-{}^3P_1$	,,	89	... (35)	... (0·39)		5·6	... (0·5)	... (0·09)
	$^3P_1-{}^3P_0$	,,	160	... (55)	... (0·34)		12	5·4 (2·0)	0·45 (0·17)
$3s^23p$	$^2P_{\frac{3}{2}}-{}^2P_{\frac{1}{2}}$	*Fe*XIV	100	100 (100)	1 (1)	*Ni*XVI	7·2	2·1 ...	0·29 ...

In Table IV the factors I' thus calculated are collected and these "calculated intensities" are compared with the observed intensities of the coronal lines. With regard to the considerable uncertainty in both calculations and observations, the agreement is satisfactory. The table contains only the observed transitions, but it should be pointed out that the absence of the other possible transitions within the same configurations is in accord with negligible values for the calculated intensities.

* *Ap. J.*, **93**, 230, 1941.

† See *Z. Astrophys.*, **22**, 30, 1942.

‡ The observed intensities are taken from Grotrian or based on Lyot's observations (figures in parentheses).

The ratio $I(\mathrm{obs.})/I'$ should be proportional to the abundance R of the different ionization stages and thus provide a quantitative indication as to the degree of ionization of the coronal gas. The result is illustrated by Fig. 5 where this ratio is plotted for selected pairs of *Fe* and *Ni* lines. The relative abundance of ions evidently increases from *Fe*X to *Ni*XII, reaches a maximum around the XIII ionization stage and decreases again from *Fe*XIV to *Ni*XVI. It should be remarked here that lines of *Fe*XII cannot be expected because of unfavourable positions of the metastable levels in that ion.

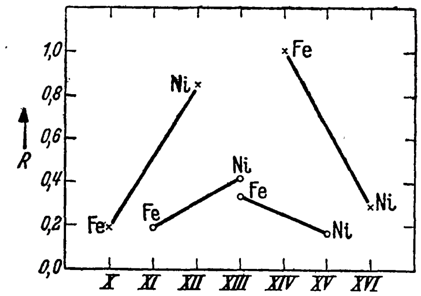

FIG. 5.

This discussion shows in any case that the identifications of the iron and nickel lines are compatible with calculable transition probabilities and known cosmic abundances of these elements.

A few words may be said about some additional identifications. In the first place we have to consider ions of the configurations $2s^2 2p^n$ analogous to those of $3s^2 3p^n$ already treated. In the sequence *F*I, *Ne*II, etc., with the electron configuration $2s^2 2p^5$ the splitting of the ground term ^{2}P is directly determined from measurements in the extreme ultra-violet spectrum of the vacuum spark up to *Ca*XII as shown in Table V.

TABLE V

Ground-Term Splittings in the Iso-electronic Sequence $2s^2 2p^5$ (FI, NeII, . . .); $\zeta = \frac{2}{3}\Delta\nu$

Z	Ion	$^2P_{\frac{1}{2}} - {}^2P_{\frac{3}{2}}$ cm.$^{-1}$	$\sqrt[4]{\zeta}$	Diff.
9	*F*I	404·0	4·051	
10	*Ne*II	782	4·778	0·727
11	*Na*III	1 364	5·491	·713
12	*Mg*IV	2 226	6·207	·716
13	*Al*V	3 440	6·920	·713
14	*Si*VI	5 097	7·635	·715
15	*P*VII	7 268	8·343	·708
16	*S*VIII	10 081	9·054	·711
17	*Cl*IX	13 641	9·765	·711
18	*A*X	(18 063)	...	·710
19	*K*XI	23 475	11·185	
20	*Ca*XII	30 028	11·895	0·710

As previously mentioned, the *Ca*XII transition has been identified with the coronal line λ 3328. Furthermore, the separation interpolated for *A*X fits exactly with the wave-number of coronal line λ 5536. There is, however, no trace of a coronal line corresponding to the separation of *K*XI. As the conditions for an appearance of this line should be more favourable than for other possible transitions in potassium, this element is evidently not present in the coronal spectrum. The absence of potassium was rather puzzling with regard to the abundance ratio $K : Ca = 1{\cdot}2$ from Russell's well-known analysis of the solar atmosphere. On the other hand a ratio $K : Ca = 0{\cdot}12$ corresponding to the average composition of meteorites (Goldschmidt) would explain the absence of potassium and consequently I was led in my first note on the coronal lines to suggest a meteoric origin for the coronal matter. Recently, however, Bengt Strömgren found with a refined method exactly the meteoric ratio 0·12 for the solar atmosphere.* The argument for a meteoric origin of the coronal matter is therefore no longer valid. Indeed, several facts rather suggest that the figures from the analyses of meteorites could be generally accepted as the most accurate representation of the cosmic distribution of metals.

TABLE VI

Relative Atomic Abundance of Metals in Meteorites

Z	19	20	22	24	25	26	27	28
Atom	*K*	*Ca* *	*Ti*	*Cr*	*Mn*	*Fe* *	*Co*	*Ni* *
Abundance	0·8	6·4	0·5	1·3	0·7	100	0·4	5·2

* Observed in the corona.

The collection of these abundance data in Table VI, comprising all elements heavier than potassium that are present in meteorites by more than 1 atom per 1000 iron atoms, gives an obvious reason for the selection of elements observed in the corona.

TABLE VII

The Emission Lines in the Solar Corona: Observational Data and Identifications

λ	ν cm.$^{-1}$	Intensity		Identification		A_m sec.$^{-1}$	E.P.	I.P.
3 328	30 039	1·0	...	*Ca*XII	$2s^2 2p^5$, $^2P_{\frac{1}{2}} - {^2P_{\frac{3}{2}}}$	488	3·72	589
3 388·1	29 507	16	...	*Fe*XIII	$3s^2 3p^2$, $^1D_2 - {^3P_2}$	87	5·96	325
3 454·1	28 943	2·3	...		...	...	...	...
3 601·0	27 762	2·1	...	*Ni*XVI	$3s^2 3p$, $^2P_{\frac{3}{2}} - {^2P_{\frac{1}{2}}}$	193	3·44	455
3 642·9	27 443	...	...	*Ni*XIII	$3s^2 3p^4$, $^1D_2 - {^3P_1}$	18	5·82	350
3 800·8	26 303	...	...		...	...	...	...
3 986·9	25 075	0·7	...	*Fe*XI	$3s^2 3p^4$, $^1D_2 - {^3P_1}$	9·5	4·68	261
4 086·3	24 465	1·0	...	*Ca*XIII	$2s^2 2p^4$, $^3P_1 - {^3P_2}$	319	3·03	655
4 231·4	23 626	2·6	...	*Ni*XII	$3s^2 3p^5$, $^2P_{\frac{1}{2}} - {^2P_{\frac{3}{2}}}$	237	2·93	318
4 311	23 190	...	...		...	...	...	...
4 359	22 935	...	...	?*A*XIV	$2s^2 2p$, $^2P_{\frac{3}{2}} - {^2P_{\frac{1}{2}}}$	108	2·84	682
4 567	21 890	1·1	...		...	...	...	...
5 116·03	19 541·0	4·3	2·2	*Ni*XIII	$3s^2 3p^4$, $^3P_1 - {^3P_2}$	157	2·42	350
5 302·86	18 852·5	100	100	*Fe*XIV	$3s^2 3p$, $^2P_{\frac{3}{2}} - {^2P_{\frac{1}{2}}}$	60	2·34	355
5 536	18 059	...	...	*A*X	$2s^2 2p^5$, $^2P_{\frac{1}{2}} - {^2P_{\frac{3}{2}}}$	106	2·24	421
5 694·42	17 556·2	...	1·2	?*Ca*XV	$2s^2 2p^2$, $^3P_1 - {^3P_0}$	95	2·18	814
6 374·51	15 683·2	8·1	18	*Fe*X	$3s^2 3p^5$, $^2P_{\frac{1}{2}} - {^2P_{\frac{3}{2}}}$	69	1·94	233
6 701·83	14 917·2	5·4	2·0	*Ni*XV	$3s^2 3p^2$, $^3P_1 - {^3P_0}$	57	1·85	422
7 059·62	14 161·2	...	2·2	*Fe*XV	$3s3p$, $^3P_2 - {^3P_1}$	...	31·7	390
7 891·94	12 667·7	...	13	*Fe*XI	$3s^2 3p^4$, $^3P_1 - {^3P_2}$	44	1·57	261
8 024·21	12 458·9	...	0·5	*Ni*XV	$3s^2 3p^2$, $^3P_2 - {^3P_1}$	22	3·39	422
10 746·80	9 302·5	...	55	*Fe*XIII	$3s^2 3p^2$, $^3P_1 - {^3P_0}$	14	1·15	325
10 797·95	9 258·5	...	35	*Fe*XIII	$3s^2 3p^2$, $^3P_2 - {^3P_1}$	9·7	2·30	325

Table VII gives the complete set of coronal lines with observational data and identifications. The columns contain: wave-length λ, wave-number ν, intensity according to Grotrian and Lyot, identified transition in the usual spectroscopic notation, transition probability A_m, excitation energy E.P. in electron volts, and ionization energy I.P. for the next preceding ion.

The line λ 5694, tentatively identified as *Ca*XV, deserves a special remark. This

* *Festskrift för Elis Strömgren*, Copenhagen, 1940.

line was first observed by Lyot and is normally very faint, but on one occasion it was observed by Waldmeier over a large active spot group with an intensity three times greater than that of the green coronal line. This exceptional behaviour of λ 5694 could well be compatible with the proposed identification, which implies an ionization potential (>800 volts) decidedly higher than for any of the other ions identified. To prove the identification, however, a second transition in the same ion must appear with the same behaviour and a similar intensity within the visible spectrum. Such a line has not yet been observed.

According to the explanation now described the essential part of the coronal lines is due to iron, nickel, calcium and argon atoms deprived of 10 to 15 electrons, *i.e.* about half of their normal electron envelope. The discovery of this enormously high stage of ionization has obviously introduced a new argument in the discussion of solar phenomena. Several attempts to give the established facts a physical explanation have already been made.

Let us first recall some of the more obvious arguments for the existence of a very high temperature in the corona:

1. The high mean stage of ionization as revealed by the emission lines.
2. The breadth of the emission lines, if due to thermal Doppler effect. The broadening of the lines might also be caused by macroscopic irregular motions (turbulence) or radial motions of the matter.
3. The blurring out of the Fraunhofer lines in the continuous spectrum of the inner corona, assumed to be an effect of the velocities of the scattering electrons.
4. The absence of the Balmer lines in the emission line spectrum of the corona, explained by the electrons being too fast to be captured by the protons.
5. Dynamical considerations showing that great thermal velocities are necessary to balance the gravitational forces in order to explain the observed density gradient of the corona.

All these observations point to temperatures higher than a quarter of a million degrees.

Independently of the identification of the coronal lines, Alfvén * came to the conclusion that the corona might consist altogether of particles with very high energy and derived from the density function a temperature of about one million degrees. On certain assumptions Alfvén finds that the energy necessary to maintain this high temperature of the corona would be about 10^{-5} of the total energy radiated by the Sun, and that the total energy contained in the corona would be produced in about two hours. The "heating" mechanism conceived by Alfvén is described in the following way:

"Motion of solar matter in magnetic fields on the Sun, especially the vortical motion in a sunspot must bring about potential differences between different points of the solar surface, and it was shown [in a previous paper] that under certain conditions this gives rise to discharges above the surface of the Sun. Calculations indicate that the electromotive force can be as high as 10^7 volts, so that even if charged particles are usually accelerated only by a small fraction of this potential, they attain rather high energies.

"The process is most conspicuous in the prominences, where consequently we can expect a very intense production of high energy particles. As the mechanism is of a very general character the same process is likely to take place very frequently on a smaller scale. If—as many authors mean—we can regard the chromosphere as a multitude of small prominences, it is likely that a production of high energy particles takes place almost everywhere on the solar surface or in some layer above it."

A different view on the origin of the highly ionized particles in the corona was taken by Menzel † by the suggestion that the coronal matter was ejected from the hot interior of the Sun through holes and cracks in the solar surface. A somewhat similar opinion

* *Arkiv Mat. Astr. Fys.*, 27 A, No. 25, 1941.
† *The Telescope*, **8**, 65, 1941.

is expressed by Vegard * in a recent paper. According to his theory "the highly ionized 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".

Finally, a quite different explanation has been put forward by Saha †, who suggests that the highly ionized atoms emitting the coronal lines are the fragments of a kind of nuclear fission, similar to the uranium fission, occurring somewhere near the solar surface.

Before the various suggestions have been more thoroughly examined it would be unwise to judge in favour of the one or the other. In that respect the physical explanation of the solar corona still remains a problem.

Appendix

As mentioned above the starting-point for the identification of the coronal lines was given by Grotrian. His letter of 1937 February 13 reads (in translation) as follows:—

Dear Dr. Edlén,

According to your latest article on the spectra of highly ionized atoms, the separation of the ground levels of the *Fe*X-spectrum is $15{\cdot}69 \times 10^3$ cm.$^{-1}$. The wave-number of the well-known red coronal line λ 6374·75 is 15 682·3 cm.$^{-1}$. Thus, the wave-numbers agree within the limits of error of your present measurements. This may naturally be a chance coincidence. However, I would like to ask: would it be possible for you to increase the accuracy of your measurements so far as to make possible the decision whether the coincidence has a real significance or not?

Also the separation of the ground levels $^3P_2 - {}^3P_1$ of the *Fe*XI-spectrum, for which you give the value $12{\cdot}68 \times 10^3$ cm.$^{-1}$, agrees within the limits of error with the wave-number of the infra-red coronal line λ 7891·6; $\nu = 12\ 668{\cdot}2$, recently observed by Lyot. Other forbidden transitions of this spectrum, which may be expected, are obviously not manifested as coronal lines. Thus I am very sceptical whether the above-mentioned numerical agreements mean more than chance coincidences. Perhaps it will be worth while, however, to investigate the question. I should be glad to hear your opinion on this matter and remain with my best greetings,

Yours sincerely,

W. Grotrian.

* *Geofys. Publ.*, 16, No. 1, 1944.

† *Proc. Phys. Soc.*, 57, 271, 1945; see also P. Swings, *P.A.S.P.*, 57, 117, 1945.