RECENT PROGRESS IN ASTROPHYSICS

EDLÉN'S IDENTIFICATION OF THE CORONAL LINES WITH FORBIDDEN LINES OF *Fe* X, XI, XIII, XIV, XV; *Ni* XII, XIII, XV, XVI; *Ca* XII, XIII, XV; *A* X, XIV[1]

For seventy years the line spectrum of the solar corona has been observed at practically all eclipse expeditions. Since 1936 it has been also obtained with coronagraphs. There are more than twenty lines present in the inner corona, some of them quite conspicuous, especially a green line (λ 5303), two red ones (λ 6375 and λ 6702), two in the infrared (λ 10,747 and λ 10,798), and one in the ultraviolet (λ 3388). The green line is the strongest of all. These lines have been measured very often; they are not as sharp as the nebular lines but have rather a diffuse character. Their behavior has been examined at different eclipses; the monochromatic images of the corona in various wave lengths have been compared; the intensity decrease of the lines with increasing distance from the limb is not identical for all lines; and, finally, certain coronal lines have been observed in Nova RS Ophiuchi in 1932 and in 1942. From all these observations the coronal lines have been classified in a number of groups, probably belonging to specific excitations. The most reliable of such groupings was made by Lyot.[2] Yet, despite the considerable amount of data accumulated on the coronal lines, no satisfactory identification was available until quite recently. All possibilities based on the usual (i.e., normal or ionized once, twice, or three times) atoms or molecules had failed. Neither forbidden lines, Raman effects, nor peculiar types of excitation could provide an interpretation of the corona.[3] After Bowen had succeeded in 1927 in interpreting the strongest nebular radiations, the coronal lines remained the most spectacular spectroscopic mystery in astronomy. This problem has now been solved by the Swedish physicist B. Edlén.[1] Among the other less spectacular unidentified astronomical spectra, several have been interpreted in the course of the last four years: sharp interstellar absorption lines as due to molecules of *CH*, *CN*, and CH^+; the λ 4050 group of emission features in comets as due to CH_2; and numerous lines in early-type objects as due to permitted or forbidden transitions in *Fe* III, V, VI, and VII. Hence, at the present time the only important spectroscopic features which still remain unidentified are the diffuse interstellar absorption lines and certain emission bands of supernovae. The present review is concerned with Edlén's discovery. It has appeared to me that some historical remarks might not be out of place since I have collaborated with Edlén in several other spectroscopic investigations and since the first list of coincidences with coronal wave lengths was communicated to me by Edlén in June, 1939. Edlén had been thinking of the corona problem for many years. In 1934 we had spent three months together discussing all possibilities existing at that time. In 1937 we started our joint investigation of the *Fe* III spectrum with a slight hope that it might be of some help in identifying the coronal lines! In 1939 W. Grotrian[4] pointed out[5] that the term separations $3s^23p^5\,{}^2P_{1/2}-{}^2P_{1\frac{1}{2}}$ of *Fe* X and $3s^23p^4\,{}^3P_1-{}^3P_2$ of *Fe* XI, as determined in the extreme ultraviolet by Edlén,[6] coincide

[1] B. Edlén, *Arkiv f. Matem., Astr. och Fys.*, **28**, B, No. 1, 1941; *Zs. f. Ap.*, **22**, 30, 1942.

[2] *C.R.*, **202**, 1259, 1936; *ibid.*, **203**, 1327, 1936; *L'Astronomie*, **51**, 203, 1937; *C.R.*, **206**, 648, 1938; *M.N.*, **99**, 580, 1939.

[3] P. Swings, *Scientia*, **33**, 69, 1939.

[4] *Naturwiss.*, **27**, 214, 1939.

[5] Throughout this review the levels are named in the order: initial level minus end level, as in Edlén's paper.

[6] *Zs. f. Phys.*, **103**, 536, 1936; *ibid.*, **104**, 188 and 407, 1937.

with the wave numbers of the two coronal lines λ 6374 and λ 7892. This remark by Grotrian came at about the time Edlén was preparing his report on the spectra of novae in their nebular stages which was to be presented at the Paris conference on novae. Edlén became deeply interested in Grotrian's remark. From his unpublished measurements of the spectra of *Ca* XII and *Ca* XIII he found that the separations in the $2s^22p^5$ and $2s^22p^4$ configurations of these two ions also coincided within the experimental errors with two fainter coronal lines (λ 3328 and λ 4086). Assuming the identifications of *Fe* X and XI, *Ca* XII and XIII, to be correct, Edlén proceeded with the prediction of the forbidden lines of *Fe* XIII, XIV, *Ni* XII, etc., and found a number of coincidences which at that time (June–July, 1939) already seemed too remarkable to be due purely to coincidences. I had the privilege of seeing this first table and of discussing it with Edlén

TABLE 1

THE EXPERIMENTAL BASIS FOR THE DIRECT IDENTIFICATION OF CORONAL LINES

Transitions	λ (Vacuum Spark)	ν Cm⁻¹	Level Separations	ν Corona
Fe X $3s^23p^5-3s^23p^44s$:				
$^2P_{1\frac{1}{2}}-{}^2P_{\frac{1}{2}}$..........	95.338 (1)	1,048,900	15,714	
$^2P_{\frac{1}{2}}-{}^2P_{\frac{1}{2}}$..........	96.788 (2)	1,033,186		
$^2P_{1\frac{1}{2}}-{}^2P_{1\frac{1}{2}}$.........	96.122 (4)	1,040,345	15,660	
$^2P_{\frac{1}{2}}-{}^2P_{1\frac{1}{2}}$.........	97.591 (0)	1,024,685		
Av...........	....	....	15,687	15,683
Fe XI $3s^23p^4-3s^23p^34s$:				
$^3P_2-{}^3D_2$..........	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		
Av...........	....	....	12,673	12,668
Ca XII $2s^22p^5-2s2p^6$:				
$^2P_{1\frac{1}{2}}-{}^2S_{\frac{1}{2}}$..........	141.036 (8)	709,039	30,028	30,039
$^2P_{\frac{1}{2}}-{}^2S_{\frac{1}{2}}$..........	147.273 (6)	679,011		
Ca XIII $2s^22p^4-2s2p^5$:				
$^3P_2-{}^3P_2$..........	161.748 (1d)	618,246	24,464	24,465
$^3P_1-{}^3P_2$..........	168.412 (00d)	593,782		

in June–July, 1939, while he was spending a few weeks in my laboratory in Belgium on his way to and from the Paris meeting. Yet he refrained from mentioning his results at the conference even when he was questioned on the problem of coronal lines in novae: modestly, he wanted to study the matter further. The first announcement in a scientific periodical appeared in 1941 under the title "An Attempt To Identify the Emission Lines in the Spectrum of the Solar Corona."[1] A complete account has now been published in the *Zeitschrift für Astrophysik*, **22**, 30, 1942. A few typewritten copies of this last paper have been received in this country from the author.

I. WAVE-NUMBER COINCIDENCES WITH DIRECTLY OBSERVED TERM SEPARATIONS

The coincidences between the level separations of *Fe* X and XI and *Ca* XII and XIII, as determined in the laboratory by Edlén[6] and the wave numbers of coronal lines, are listed in Table 1.

The level separations are necessarily rather uncertain, since they are determined through lines of very short wave lengths. Other transitions of *Fe* X and XI of longer wave lengths may eventually provide better laboratory values of the ground-term separations. As for the calcium lines of Table 1, they represent the largest wave lengths in which the ground terms are involved.

Although the coincidences of Table 1 are rather impressive, they cannot quite make the identification conclusive, owing to the present unavoidable relatively wide tolerances. The decisive fact is that, assuming the identifications of λλ 6374 (*Fe* X), 7892 (*Fe* XI), 3328 (*Ca* XII), and 4086 (*Ca* XIII) to be correct, an almost complete identification of the coronal spectrum can be consistently carried through, as will be shown below. First, it should be noticed that the [*Fe* VII] lines which have been observed in several novae and peculiar stars do not appear in the corona. Besides, the ground configuration of *Fe* IX gives only one single level and *Fe* IX has no metastable state. As for *Fe* VIII, the splitting of the ground term ^2D is too small to give any astronomically observable transition. Hence, as far as iron is concerned, the investigation should be concerned with *Fe* X and higher stages of ionization. Similar considerations apply to other atoms, especially nickel. A survey of possible level separations shows that coronal transitions should be searched for mainly within the configurations $3s^23p$, $3s^23p^2$, $3s^23p^4$, and $3s^23p^5$ of the elements in the iron group.[7] Because of the relative cosmical abundances, iron should be expected first; nickel next.

II. TERM INTERVALS IN THE CONFIGURATIONS $3s^23p$, $3s^23p^2$, $3s^23p^4$, AND $3s^23p^5$ OF *Fe* AND *Ni*

The configurations $3s^23p$ and $3s^23p^5$ give rise to a ^2P term only, whose splitting can be easily and accurately extrapolated according to the regular doublet law. Hence, this splitting varies with the atomic number Z as $(Z - \sigma)^4$, the screening constant σ being nearly constant. The data for the $3s^23p$ and $3s^23p^5$ sequences are collected in Table 2. The linear variation of $\sqrt[4]{\zeta}$, ζ being two-thirds of the term separation, appears clearly.

In the $3s^23p$ sequence, the splitting could be determined up to *Sc* IX by lines of the $3s^23p^k-3s3p^{k+1}$ type of transition, and correspondingly up to *V* VII for $3s^23p^5$. These transitions have considerably longer wave lengths than other combinations with the ground term, particularly for the higher stages of ionization. Hence, they will provide the most accurate values for the level separations. The separations for *Cr* VIII, *Mn* IX, *Fe* X, and *Co* XI, directly derived from the transitions $3s^23p^5-3s^23p^44s$ observed in the laboratory by Edlén,[6] are not of comparable accuracy and therefore are not included in Table 2.

From Table 2 it appears clearly now that the forbidden transitions between the two sublevels of the ^2P term of *Fe* XIV, *Ni* XVI, *Fe* X, and *Ni* XII agree in wave numbers with four of the coronal lines—the [*Fe* XIV] transition giving the strong green line. It will be shown later that the intensity ratios of homologous lines of iron and nickel are in accordance with the relative cosmical abundance of these elements, simultaneously indicating the degree of ionization of the coronal matter.

The extrapolation problem is more complex for the configurations $3s^23p^2$ and $3s^23p^4$, which, in order of increasing energy, furnish respectively the following levels: $^3P_0$, $^3P_1$, $^3P_2$, $^1D_2$, $^1S_0$ and $^3P_2$, $^3P_1$, $^3P_0$, $^1D_2$, $^1S_0$. The $^1S_0$ level lies too high above $^1D_2$ to give observable lines. But, besides the transitions between the ^3P components which are analogous to those of the $3s^23p$ or $3s^23p^5$ configurations, we have also to consider the transitions from $^1D_2$ to ^3P. It will be apparent from what follows that coronal lines might be expected especially for the following transitions: $^1D_2-{}^3P_2$, $^3P_2-{}^3P_1$, $^3P_1-{}^3P_0$ of $3s^23p^2$, and $^1D_2-{}^3P_1$, $^3P_1-{}^3P_2$ of $3s^23p^4$.

[7] The $3s^23p^3$ configuration (*Fe* XII and *Ni* XIV) cannot produce forbidden lines of appreciable intensity, as will be shown later.

For a provisional extrapolation of these differences, one might assume the ^{3}P splittings proportional to $(Z - \sigma)^4$, and the ^{1}D $-$ ^{3}P intervals proportional to Z. However, deviations from these simple relations become increasingly large because of the successive change from *LS* to *JJ* coupling when *Z* increases along an isoelectronic sequence. Hence, use had to be made of the more complicated theoretical formulae for intermediate coupling. The reviewer will not go into the details of the practical procedure followed by Edlén in applying these theoretical formulae to his extrapolation problem, but it

TABLE 2

COMPARISON OF THE GROUND-TERM SPLITTINGS IN THE ISOELECTRONIC SEQUENCES $3s^23p$ (*Al* I, *Si* II, ...) AND $3s^23p^5$ (*Cl* I, *A* II, ...). $\zeta = \frac{2}{3}\Delta\nu$

Z	Ion	$(^2P_{1\frac{1}{2}} - {}^2P_{\frac{1}{2}})$ Cm^{-1}	$\sqrt[4]{\zeta}$	Diff.	Ion	$(^2P_{\frac{1}{2}} - {}^2P_{1\frac{1}{2}})$ 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	1492	5.616	.579	*Cl* I	881	4.923	0.636
18	*A* VI	2210	6.195	.564	*A* II	1432	5.559	.603
19	*K* VII	3131	6.759	.560	*K* III	2162	6.162	.589
20	*Ca* VIII	4305	7.319	.552	*Ca* IV	3115	6.751	.576
21	*Sc* IX	5759	7.871		*Sc* V	4325	7.327	.567
22	*Ti* X	....	....		*Ti* VI	5825	7.894	.558
23	*V* XI	....	....	.543	*V* VII	7657	8.452	
24	*Cr* XII	....	....		*Cr* VIII	....	......	.553
25	*Mn* XIII	....	....		*Mn* IX	....	......	
26	*Fe* XIV	18,852.5*	10.588		*Fe* X	15,683.2*	10.112	
27	*Co* XV	....	....	0.538	*Co* XI	....	......	0.545
28	*Ni* XVI	27,762*	11.664		*Ni* XII	23,626*	11.203	

* Coronal lines.

should be stressed that the results of the extrapolation are of an accuracy similar to that for $3s^23p$ and $3s^23p^5$. The only difficulty concerns *Fe* XIII, in which case it is impossible to decide, from the extrapolated wave numbers only, how to allot the two very close infrared coronal lines to $^3P_1 - {}^3P_0$ or to $^3P_2 - {}^3P_1$. However, a definite identification will be possible on the basis of intensity considerations. The $^3P_1 - {}^3P_0$ and $^3P_2 - {}^3P_1$ transitions of *Ni* XV correspond respectively to the coronal lines λ 6702 and λ 8024. The interval $^1D_2 - {}^3P_2$ of *Fe* XIII corresponds to the strong ultraviolet coronal line λ 3388. The same transition of *Ni* XV falls outside the observable spectral range.

Figure 1 illustrates the relative level positions for the various isoelectronic sequences considered; the transitions actually observed in the corona are indicated by arrows and

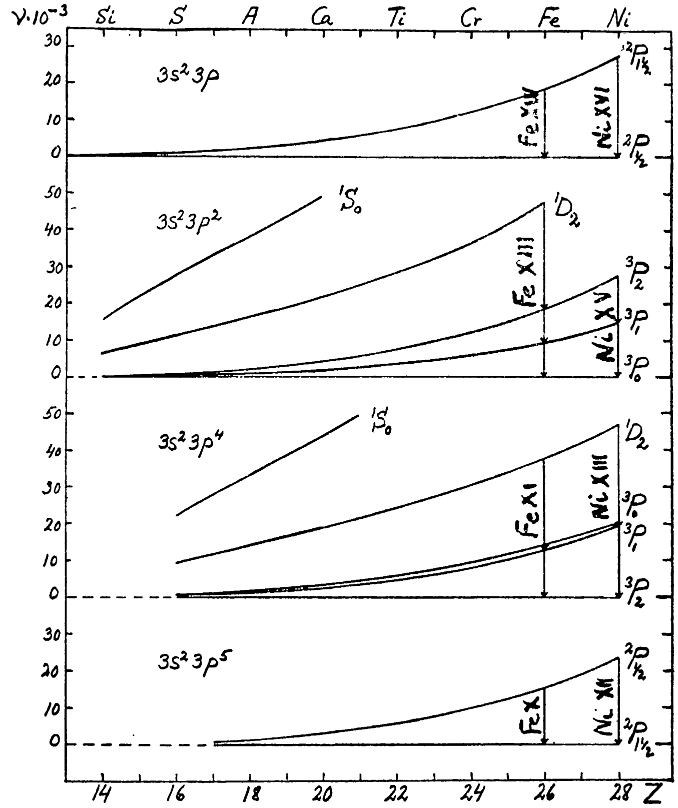
ν·10⁻³
Si
S
A
Ca
Ti
Cr
Fe
Ni
3s²3p
3s²3p²
3s²3p⁴
3s²3p⁵
Fe XIII
Ni XV
Fe XI
Ni XIII
Fe X
Ni XII
Ni XVI
Z

FIG. 1

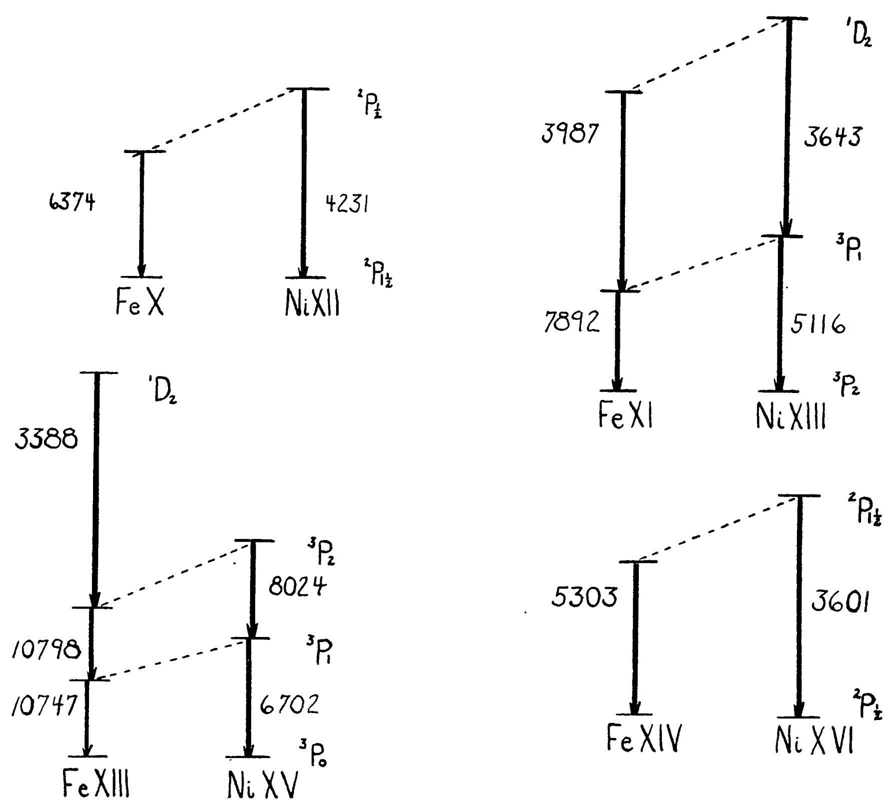
6374
4231
Fe X
Ni XII
3987
3643
7892
5116
Fe XI
Ni XIII
3388
8024
10798
10747
6702
Fe XIII
Ni XV
5303
3601
Fe XIV
Ni XVI

FIG. 2

are also shown in Figure 2. All in all, at the present stage, 13 coincidences have been observed between the wave numbers of coronal lines and those of transitions in the ground configurations $3s^23p$, $3s^23p^2$, $3s^23p^4$, and $3s^23p^5$ of *Fe* and *Ni*. These 13 coronal lines account for more than nine-tenths of the total intensity of the coronal line emission.

The next step is a discussion of the observed intensities in order to ascertain whether these are compatible with the theoretical transition probabilities, with the cosmical abundances of the elements, and with definable ionization and excitation conditions in the corona.

III. LINE INTENSITIES

There is no initial state of the ions considered for which more than one transition has been identified in the corona. Hence, the intensity ratios of the various forbidden lines depend upon the physical conditions. In this connection it should be remembered that

TABLE 3

TRANSITION PROBABILITIES A

Transition	Iron			Nickel		
	Ion	$\nu\times10^{-3}$	A (in Sec^{-1})	Ion	$\nu\times10^{-3}$	A
$3s^23p^5\ ^2P_{1/2}-{}^2P_{1\frac{1}{2}}$	*Fe* X	15.68*	69	*Ni* XII	23.63*	237
$3s^23p^4\ ^1D_2-{}^3P_1$	*Fe* XI	25.08*	9.5	*Ni* XIII	27.44*	18
$^1D_2-{}^3P_2$		37.74	92		46.98	257
$^3P_0-{}^3P_1$		(1.71)	0.25		(0.65)	0.01
$^3P_0-{}^3P_2$		(14.38)	0.02†		(20.19)	0.06†
$^3P_1-{}^3P_2$		12.67*	44		19.54*	157
$3s^23p^2\ ^1D_2-{}^3P_2$	*Fe* XIII	29.51*	87	*Ni* XV	(35.47)	229
$^1D_2-{}^3P_1$		38.77	72		(47.93)	221
$^3P_2-{}^3P_1$		9.26*	9.7		12.46*	22
$^3P_2-{}^3P_0$		18.56	0.01†		27.38	0.05†
$^3P_1-{}^3P_0$		9.30*	14		14.92*	57
$3s^23p\ ^2P_{1\frac{1}{2}}-{}^2P_{1/2}$	*Fe* XIV	18.85*	60	*Ni* XVI	27.76*	193

* Coronal lines.

† These are electric quadrupole probabilities; all other values of A are magnetic dipole probabilities.

considerable variations in the intensity ratios of the coronal lines have been repeatedly observed, as already mentioned in the beginning.

The intensity of a forbidden transition of probability A_1 and wave number ν may be expressed in arbitrary units by the classical formula

$$I=\frac{\eta\nu A_1}{A_1+A_2+A_3+\dots+B+C}, \tag{1}$$

where η is the number of ions arriving in the initial metastable state per second; A_1, A_2, A_3, are the probabilities of the various spontaneous transitions from the initial state; and B and C are the probabilities of de-excitation by collision and radiative absorption.

It is possible to determine fairly accurately the probabilities of the transitions considered here. For all lines observed in the corona the probabilities of the electric quadrupole are extremely small, compared with the probabilities of the magnetic dipole. Edlén bases his determinations on recent investigations by S. Pasternack[8] and by Shortley, Aller, Baker, and Menzel.[9] The values adopted are listed in Table 3. The fol-

[8] *Ap. J.*, **92**, 129, 1940.

[9] *Ap. J.*, **93**, 178, 1941.

lowing additional remarks should be made. For *Fe* XI the total probabilities of transitions from $^1S_0$ are:

	A
$^1S_0 - {}^1D_2$	14
$^1S_0 - {}^3P_0$	0
$^1S_0 - {}^3P_1$	910
$^1S_0 - {}^3P_2$	3

Similar values are obtained for *Fe* XIII, *Ni* XIII, and *Ni* XV. Hence, we may assume that practically all ions arriving in $^1S_0$ will be transferred to $^3P_1$. For *Fe* XI the probability of $^1D_2 - {}^3P_0$ is only 0.002, i.e., vanishingly small compared with the other $^1D - {}^3P$ transitions; this is also true for the other ions *Fe* XIII, *Ni* XIII, and *Ni* XV.

De-excitation by absorption of radiation is probably unimportant, since the next higher configuration, $3s3p^{k+1}$, combining with the ground configuration, $3s^23p^k$, corresponds to an excitation potential of about 35 volts in all the *Fe* ions and somewhat more in the *Ni* ions. In any case, the de-exciting radiation must be of wave length shorter than λ 400, and the intensity of the solar radiation in this spectral region is probably extremely small.

It is further assumed by Edlén that de-excitation of the metastable levels by electron collisions ($^3P_0$ excluded) can be neglected in comparison with the spontaneous transitions. Such an assumption is extremely probable. If de-excitations by electron collisions were much in excess relative to the de-excitations by radiative emission, a Boltzmann distribution would result; and, because of the high electron temperature ($T_e \simeq 250{,}000^\circ$; motivated below), the number of ions in the various levels of the ground configuration would be approximately proportional to their statistical weights. Consequently, the line intensities in a given ion would be proportional to $(2J + 1)\, A\nu$. In *Fe* XIII, for example, the intensity ratios of the transitions $^1D_2 - {}^3P_2$, $^3P_2 - {}^3P_1$, $^3P_1 - {}^3P_0$ would be given approximately as 128:4.6:3.9, while the observed intensity ratios for the corresponding coronal lines $\lambda\lambda$ 3388, 10,798, and 10,747 are 16:35:55, according to B. Lyot.[2] Such a discrepancy is too large to be attributed to observational uncertainties.

Other evidence is provided by estimating the probability of collisional de-excitation of a metastable level, following a method similar to the treatment of the [*O* III] problem in the nebulae by Hebb and Menzel[10] and by Menzel, Aller, and Hebb.[11] Hebb and Menzel derived by wave mechanics certain parameters $\Omega\,(A, B)$ with which to express the collisional cross-sections for transitions, upward as well as downward, between two levels A and B. In the case of the $2s^22p^2$ configuration of *O* III, numerical values of Ω were given for all level combinations. Edlén noticed that the parameter Ω' defined by

$$\Omega'(A, B) \times (2J_A + 1)\,(2J_B + 1) = \Omega\,(A, B) \qquad (2)$$

is approximately equal for all the [*O* III] transitions, and he made the simplifying plausible assumption that Ω' may be considered as a constant characteristic for a certain ion and configuration.

Assuming an electron density N_e and a Maxwellian velocity distribution of the electrons corresponding to a temperature T_e, the formula of Hebb and Menzel gives the following probability for a collisional de-excitation of a metastable level:

$$B = 8.54 \times 10^{-6} N_e T_e^{-1/2} \Omega' \Sigma\,(2J + 1)\,, \qquad (3)$$

the Σ being taken over all the lower levels.

In comparing the probabilities A and B, the fact that the electron density in the corona ($N_e^{\rm cor} \simeq 10^8\ {\rm cm}^{-3}$, according to Baumbach[12]) is higher than in most nebulae

[10] *Ap. J.*, **92**, 408, 1940. [11] *Ap. J.*, **93**, 230, 1941. [12] *A.N.*, **263**, 121, 1937.

($N_e^{\text{neb}} \simeq 10^4$ cm^{-3}) is compensated by the much greater transition probabilities of the coronal transitions and also, to a lesser extent, by the higher electron temperature of the corona. The values of the ratio of the number of collisional de-excitations to the number of spontaneous transitions were estimated, assuming $\Omega' = 0.5$; they indicate that, except in the case of $^3P_0$, the spontaneous transitions have a decided predominance over the collisional de-excitations.

Next we have to estimate the numbers of excitations per cubic centimeter and per second into certain levels. Edlén computes these numbers in the case of an excitation by collisions of electrons having a Maxwellian velocity distribution corresponding to the temperature T_e. But he mentions the fact that the conditions for an excitation by radiation are considerably more favorable in the corona than they are in nebulae. In the first place, the ratio between exciting and excited intensity is of a much higher order of magnitude; and, in the second place, the corresponding transition probabilities are roughly 10^4 times greater. No attempt is being made to estimate the amount of an eventual radiative excitation.

The number of excitations per cubic centimeter and per second in a certain level with inner quantum number J and excitation energy ν may be approximately given as

$$n = W N_{\text{ion}} , \tag{4}$$

where N_{ion} is the total number per cubic centimeter of the ions in question and where (from the results of Hebb and Menzel)

$$W = 8.54 \times 10^{-6} N_e T_e^{-1/2} \Omega' (2J + 1)\, e^{-1.45\nu/T_e} , \tag{5}$$

Ω' being the same quantity as considered before. For $T_e = 250{,}000°$ and $N_e = 10^8$ cm^{-3}, we get

$$n = 1.71\,(2J + 1)\, e^{-1.45\nu/250{,}000} \Omega' N_{\text{ion}} . \tag{6}$$

The factor $e^{-1.45\nu/250{,}000}$ for all the considered levels lies between 0.5 and 0.9 and thus plays only a minor role. If we adopt, as before, $\Omega' \simeq 0.5$, n turns out to be of the same order of magnitude as N_{ion}, which means that, on the average, each metastable level is being excited about once per second in every ion. All the values of the factor

$$n' = 1.71\,(2J + 1)\, e^{-1.45\nu/250{,}000} \tag{7}$$

are between 1.0 and 7.5. For ions with several metastable levels an addition to the population of the lower levels is caused by "cascading" from the upper levels. The corresponding enrichment factors α are easily determined from the transition probabilities.

The values of n' and of $\eta' = \alpha n'$ are given in Table 4. Assuming $B = C = 0$, formula (1), giving the intensity of a line in arbitrary units, now becomes

$$I = \eta' \nu \frac{A}{\Sigma A} \Omega' N_{\text{ion}} , \tag{8}$$

where ν and A refer to the transition considered, and η' and ΣA refer to its initial level.

In case several transitions are observed in the same ion, the quantities $\eta' \nu (A/\Sigma A)$ should represent their relative intensities. This can be tested in the case of *Fe* XI, *Fe* XIII, and *Ni* XIV and is satisfactorily confirmed by the observed intensities when considering the observational uncertainties. From the extrapolated term separations alone, it was impossible to decide how each one of the two close infrared lines λ 10,747 and λ 10,798 is to be identified with the separate transitions $^3P_1 - {}^3P_0$ and $^3P_2 - {}^3P_1$. The assignment was primarily made to correspond with the intensity ratio of the analogous *Ni* XV lines. This is now confirmed by the intensity estimates based on formula (8).

Next comes the comparison of intensities of lines belonging to different kinds of ions. Let N_A be the number of atoms of the element A per cubic centimeter, n_A be the relative number referred to 100 atoms of *Fe*, and X be the relative abundance of a certain ionization stage. Then N_{ion} is equal to XN_A and proportional to Xn_A. The intensity may thus be expressed:

$$I = \eta' \nu \frac{A}{\Sigma A} n_A \Omega' X \,. \tag{9}$$

We provisionally assume $n_{Fe} = 100$ and $n_{Ni} = 5.2$, as has been found in meteorites.[13]

TABLE 4

VALUES OF n' AND $\eta' = an'$ FOR THE METASTABLE LEVELS OF THE *Fe* AND *Ni* IONS

LEVEL	IRON			NICKEL		
	Ion	n'	η'	Ion	n'	η'
$^2P_{1/2}$	*Fe* X	3.1	3.1	*Ni* XII	2.9	2.9
$^1S_0$	*Fe* XI	1.0	1.0	*Ni* XIII	0.9	0.9
$^1D_2$		6.5	6.5		6.1	6.1
$^3P_0$		1.5	1.5		1.5	1.5
$^3P_1$		4.7	8.0		4.5	5.7
$^1S_0$	*Fe* XIII	1.0	1.0	*Ni* XV	0.8	0.8
$^1D_2$		6.0	6.0		5.4	5.4
$^3P_2$		7.5	10.8		7.0	9.8
$^3P_1$		4.8	19.2		4.6	17.9
$^2P_{1 1/2}$	*Fe* XIV	5.9	5.9	*Ni* XVI	5.6	5.6

TABLE 5

CALCULATED AND OBSERVED INTENSITIES*

CONFIGURATION	TRANSITION	IRON					NICKEL				
		Ion	$A/\Sigma A$	I'	I (Obs.)	$R=I$ Obs./I'	Ion	$A/\Sigma A$	I'	I (Obs.)	$R=I$ Obs./I'
$3s^23p^5$	$^2P_{1/2}-{}^2P_{1 1/2}$	*Fe* X	1	43	8.1 (18)	0.19 (0.42)	*Ni* XII	1	3.1	2.6 ...	0.84 ....
$3s^23p^4$	$^1D_2-{}^3P_1$	*Fe* XI	0.09	14	0.7 ...	0.05	*Ni* XIII	0.06	0.5	faint ...	....
	$^3P_0-{}^3P_2$		0.07	1.4	... ...	....		0.9	1.2	... ...	....
	$^3P_1-{}^3P_2$		1	70	... (13)	.... (0.19)		1	5.2	4.3 (2.2)	0.83 (0.42)
$3s^23p^2$	$^1D_2-{}^3P_2$	*Fe* XIII	0.55	87	16 ...	0.18	*Ni* XV	0.51	4.5	uv ...	....
	$^3P_2-{}^3P_1$		1.00	89	... (35)	.... (0.39)		1.00	5.6	... (0.5)	.... (0.09)
	$^3P_1-{}^3P_0$		1	160	... (55)	.... (0.34)		1	12	5.4 (2.0)	0.45 (0.17)
$3s^23p$	$^2P_{1 1/2}-{}^2P_{1/2}$	*Fe* XIV	1	100	100 (100)	1 (1)	*Ni* XVI	1	7.2	2.1 ...	0.29 ....

* The observed intensities quoted first in the sixth and eleventh columns are from W. Grotrian (*Zs. f. Ap.*, **2**, 106, 1931; **7**, 26, 1933); the second are intensities by Lyot, reduced on a scale similar to Grotrian's.

Let us introduce I' proportional to $\eta'\nu(A/\Sigma A)n_A$ and normalized to 100 for λ 5303. All the other values of I' are immediately obtained as

$$I' = 0.89 \times 10^{-5} \eta' \nu \frac{A}{\Sigma A} n_A \,. \tag{10}$$

The values of I' are given in Table 5. The ratio $R = (I_{\text{obs}}/I')$ is proportional to $\Omega' x$.

[13] V. M. Goldschmidt, *Norske Videnskaps Akademie Skrifter. I. Mat. Naturv.-Klasse*, No. 4, 1938.

We may assume equal values of Ω' for isoelectronic ions of *Fe* and *Ni*. In comparing isoelectronic ions the ratio of the R-values will thus be equal to the ratio of the values of X. It is clear at once from Table 5 that an ionization maximum appears at about the stages XIII or XIV. Probably over 95 per cent of the atoms are found in the stages from X to XVI; about half of them in the stages XIII and XIV.

Table 5 shows that for both *Fe* XI and *Ni* XIII the intensity of the $^3P_0-{}^3P_2$ transition is not zero. The extrapolated wave numbers are accurate enough to exclude any identification with hitherto observed coronal lines. Their absence may be due to observational difficulties; yet it may also be caused by collisional de-excitation of $^3P_0$, as the previously estimated probability of collisional de-excitation indicates.

The transitions $3s^23p^4\,{}^1D_2-{}^3P_0$ and $3s^23p^2\,{}^3P_2-{}^3P_0$ fall within the observable range; but their estimated intensities are too small, and no trace of line is found at their predicted wave lengths.

On the whole, the conclusion of this discussion is that the proposed identifications are compatible with the observed intensity ratios of the coronal lines.

IV. OTHER IONIZATION STAGES OF *Fe* AND *Ni*

From the foregoing considerations it is clear that transitions between levels of the ground configurations of *Fe* X, XI, XIII, XIV, and of *Ni* XII, XIII, XV, XVI, provide most of the coronal identifications. Although *Fe* XII and *Ni* XIV must be quite abundant in the corona, we should not expect any coronal lines to be attributed to them because of the relative positions of the levels of their $3s^23p^3$ configuration. The term ^2D is too high, relative to the ground level ^4S; and the splittings of ^2D and ^2P are too small to produce observable lines. Only $^2P_{1/2}-{}^2D_{2 1/2}$ could fall within the observable range, but this transition has a vanishingly low probability. The lower stages of ionization have already been considered previously. Their absence is in accordance with the degree of ionization already estimated for the corona. As for *Fe* XV, XVI, and XVII and the corresponding *Ni* ions, their ground configurations give only one single level $^1S_0$ or $^2S_{1/2}$. Stages higher than *Fe* XVII are improbable, since the ionization increases quite abruptly when passing from *Fe* XVII to *Fe* XVIII when the L shell is broken up.

While no further transition within the ground configuration of *Fe* and *Ni* ions can thus be expected, we may still consider the second lowest configuration of *Fe* XV and *Ni* XVII in which two metastable levels occur, viz., $3s3p\,{}^3P_0$ and $^3P_2$. These levels cannot combine with the ground level $3s^2\,{}^1S_0$ under any circumstances, but the transition between $^3P_2$ and $^3P_1$ is possible through magnetic dipole radiation. From Edlén's study of the ultraviolet spectrum of *Fe* XV the wave number of the $3s3p\,{}^3P_2-{}^3P_1$ transition may be estimated as 14,120 cm^{-1}, which is close enough to the only remaining infrared line (ν = 14,161 cm^{-1}; λ 7059). This identification is very probable. The excitation energy, 31.9 volts, is considerably higher than for the previously identified transitions; but this does not constitute any objection if the electron temperature is of the order of from 200,000° to 400,000°.

Nine metastable states with excitation energies of the order of 50 volts also occur in *Fe* IX and *Ni* XI. They belong to the $3s^23p^53d$ configuration; and a number of combinations may arise between them, some of them falling in the observable region. Their wave lengths cannot be predicted at present. Yet it seems not excluded that some faint coronal lines might be explained as such transitions in *Fe* IX and *Ni* XI.

V. FORBIDDEN LINES OF OTHER HIGHLY IONIZED ATOMS

Considering the great intensity of certain transitions of *Fe* and *Ni*, it appears reasonable to search for the corresponding transitions of the neighboring metals. But, although the wave numbers can be accurately predicted with the aid of the *Fe* and *Ni* identifications, no coincidence appears. This, however, may be explained readily if the chemical composition of the corona is similar to that of the solar atmosphere or, for that matter, of the meteorites.

Assuming relative abundances of the metals similar to those found by V. M. Goldschmidt[13] in the meteorites, and taking into account the ionization conditions, a few

TABLE 6

ESTIMATED WAVE LENGTHS AND INTENSITIES OF SOME TRANSITIONS NOT YET OBSERVED

Transition	λ_{air}	Intensity	Transition	λ_{air}	Intensity
Co XV $^2P_{1½}-^2P_{½}$	4349.4	0.4	*Cr* XII $^2P_{1½}-^2P_{½}$	8159	0.6
Mn XIII $^2P_{1½}-^2P_{½}$	6539	0.7	*Co* XIV $^3P_1-^3P_0$	8448	0.3
S XII $^2P_{1½}-^2P_{½}$	7536	2			

TABLE 7

COMPARISON OF THE GROUND-TERM SPLITTINGS IN THE ISOELECTRONIC SEQUENCES $2s^22p$ (*B* I, *C* II, ...) AND $2s^22p^5$ (*F* I, *Ne* II, ...). $\zeta = \frac{2}{3}\Delta\nu$

Z	Ion	$(^2P_{1½}-^2P_{½})$ Cm^{-1}	$\sqrt[4]{\zeta}$	Diff.	Ion	$(^2P_{½}-^2P_{1½})$ Cm^{-1}	$\sqrt[4]{\zeta}$	Diff.
5	*B* I	15.1	1.787	0.768	....	....	....	
6	*C* II	64.0	2.555	.730	....	....	....	
7	*N* III	174.5	3.285	.722	....	....	....	
8	*O* IV	386.5	4.007	.715	....	....	....	
9	*F* V	746	4.722	.720	*F* I	404.0	4.051	0.727
10	*Ne* VI	1316	5.442	.703	*Ne* II	782	4.778	.713
11	*Na* VII	2139	6.145	.706	*Na* III	1364	5.491	.716
12	*Mg* VIII	3304	6.851	.709	*Mg* IV	2226	6.207	.713
13	*Al* IX	4900	7.560		*Al* V	3440	6.920	.715
14	*Si* X	....	......		*Si* VI	5097	7.635	.708
15	*P* XI	....	......	0.712	*P* VII	7268	8.343	.711
16	*S* XII	(13,266)	......		*S* VIII	10,081	9.054	.711
17	*Cl* XIII	....	......		*Cl* IX	13,641	9.765	
18	*A* XIV	22,935?	11.120		*A* X	(18,063)	......	.710
19	....	....	....		*K* XI	23,475	11.185	0.710
20	....	....	....		*Ca* XII	30,028	11.895	

additional weak lines might possibly be expected. They are listed in Table 6, the intensities being estimated on the basis of $I = 100$ for the green line.

Considering that two coronal lines have been satisfactorily attributed to forbidden transitions in *Ca* XIII ($2s^22p^4$) and *Ca* XII ($2s^22p^5$), we should examine the other possible transitions within configurations $2s^2 2p^k$. The laboratory data for the splitting of ^2P of $2s^2 2p$ and $2s^2 2p^5$ are collected in Table 7.

In the $2s^2 2p^5$ sequence, *K* XI does not provide any identification; this is due to the low abundance of *K* (about one-tenth of *Ca*). But the splitting for *A* X, which is accurately determined, coincides with the wave number of the occasionally observed coronal line λ 5536. Although the cosmic abundance of argon is not known, the identification of λ 5536 is quite plausible. Neon has been shown by Unsöld[14] to be a very abundant element; hence we may also expect argon to be fairly abundant.

The extrapolation to *A* XIV in the sequence $2s^2 2p$ gives a wave number quite close to that of the faint coronal line λ 4359, but this coincidence may not be significant. The same transition in *S* XII (approximately λ 7536) is more likely expected than *A* XIV but is not observed.

In the $2s^2 2p^4$ configuration, only $^3P_1 - {}^3P_2$ of *Ca* XIII can be found in the corona; the corresponding transition of *A* XI is estimated at λ 6919.

In the $2s^2 2p^2$ sequence, the extrapolated value of $^3P_1 - {}^3P_0$ or $^3P_2 - {}^3P_1$ for *Ca* XV is approximately 17,700 cm^{-1}. This is close to the line λ 5694 observed by Lyot. But this identification is also questionable, since the ionization potential of *Ca* XIV is considerably higher than for any other coronal ion. On the other hand, Lyot[2] found the line to have an exceptional character.

No forbidden or permitted line of *Si*, *Mg*, *C*, *N*, *O*, or *Ne* is possible in the corona under the actual ionization conditions.

Finally, the lines of *H* and *He* II might be present in the corona. The hitherto observed intensity of these lines has been ascribed to the chromosphere or to prominences.

VI. CONCLUSION

The main results are collected in Table 8. The wave lengths of the coronal lines are from Mitchell's compilation[15] and from Lyot's later measurements. The intensities are from Grotrian (col. 3) and Lyot (reduced values, col. 4). The sixth column gives the transition probability: all the identified lines are due to magnetic dipole radiation. The seventh and eighth columns give the excitation potential and the ionization potential of the next preceding ionization stages. Only four coronal lines (λλ 3454, 4567, 3801, and 4311) remain unidentified, the latter two being very faint.

In the light of the present identifications a physical significance may be attributed to the determinations of width of the coronal lines. As shown by Lyot and by Waldmeier, the line profiles are symmetrical and entirely explainable by the Doppler effect of a Maxwellian velocity distribution. The kinetic temperature derived from the observed widths agrees as to the order of magnitude with the temperature estimated from the established degree of ionization. The identifications agree perfectly with the classification of coronal lines in groups which, according to Lyot, appear strengthened or weakened in certain coronal regions.

Edlén's identification of the coronal lines has opened an immense new field in solar and stellar physics. A first theoretical attempt at explaining the origin of the high-energy coronal particles has recently been published by H. Alfvén.[16] In normal times Edlén's discovery would have already inspired many other theoretical investigations. There is not the slightest doubt that it will affect the whole orientation of solar research for years to come. In the inner corona Grotrian[17] found the mean velocity of the scattering electrons to be 4.10^8 cm sec^{-1}; in thermal equilibrium this corresponds to 350,000°.

[14] *Zs. f. Ap.*, **21**, 22, 1941.

[15] *Handb. d. Ap.*, Vols. **4** and **7**.

[16] *Arkiv f. Matem., Astr. och Fys.*, **27**, A, No. 25, 1941.

[17] *Zs. f. Ap.*, **8**, 155, 1934.

The intensity of the *He* II lines in the flash spectrum is much too great to be acceptable at a temperature $T \simeq 6000°$.[18] There is no doubt that the superexcitation observed in the corona results from the same physical factors as the small density gradient and the large turbulence.

Waldmeier's[19] numerous investigations with the coronagraph of Arosa (Switzerland) take an additional significance on the basis of their relation with Edlén's work.

TABLE 8

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.*
3328	30039	1.0	....	*Ca* XII $2s^22p^5\,{}^2P_{\frac{1}{2}}-{}^2P_{1\frac{1}{2}}$	488	3.72	589
3388.1	29507	16	....	*Fe* XIII $3s^23p^2\,{}^1D_2-{}^3P_2$	87	5.96	325
3454.1	28943	2.3	....	....	....	....	....
3601.0	27762	2.1	....	*Ni* XVI $3s^23p\,{}^2P_{1\frac{1}{2}}-{}^2P_{\frac{1}{2}}$	193	3.44	455
3642.9	27443	....	....	*Ni* XIII $3s^23p^4\,{}^1D_2-{}^3P_1$	18	5.82	350
3800.8	26303	....	....	....	....	....	....
3986.9	25075	0.7	....	*Fe* XI $3s^23p^4\,{}^1D_2-{}^3P_1$	9.5	4.68	261
4086.3	24465	1.0	....	*Ca* XIII $2s^22p^4\,{}^3P_1-{}^3P_2$	319	3.03	655
4231.4	23626	2.6	....	*Ni* XII $3s^23p^5\,{}^2P_{\frac{1}{2}}-{}^2P_{1\frac{1}{2}}$	237	2.93	318
4311	23190	....	....	....	....	....	....
4359	22935	....	....	?*A* XIV $2s^22p\,{}^2P_{1\frac{1}{2}}-{}^2P_{\frac{1}{2}}$	108	2.84	682
4567	21890	1.1	....	....	....	....	....
5116.03	19541.0	4.3	2.2	*Ni* XIII $3s^23p^4\,{}^3P_1-{}^3P_2$	157	2.42	350
5302.86	18852.5	100	100	*Fe* XIV $3s^23p\,{}^2P_{1\frac{1}{2}}-{}^2P_{\frac{1}{2}}$	60	2.34	355
5536	18059	....	....	*A* X $2s^22p^5\,{}^2P_{\frac{1}{2}}-{}^2P_{1\frac{1}{2}}$	106	2.24	421
5694.42	17556.2	....	1.2	?*Ca* XV $2s^22p^2\,{}^3P_1-{}^3P_0$	95	2.18	814
6374.51	15683.2	8.1	18	*Fe* X $3s^23p^5\,{}^2P_{\frac{1}{2}}-{}^2P_{1\frac{1}{2}}$	69	1.94	233
6701.83	14917.2	5.4	2.0	*Ni* XV $3s^23p^2\,{}^3P_1-{}^3P_0$	57	1.85	422
7059.62	14161.2	....	2.2	*Fe* XV $3s3p\,{}^3P_2-{}^3P_1$	....	31.7	390
7891.94	12667.7	....	13	*Fe* XI $3s^23p^4\,{}^3P_1-{}^3P_2$	44	1.57	261
8024.21	12458.9	....	0.5	*Ni* XV $3s^23p^2\,{}^3P_2-{}^3P_1$	22	3.39	422
10746.80	9302.5	....	55	*Fe* XIII $3s^23p^2\,{}^3P_1-{}^3P_0$	14	1.15	325
10797.95	9258.5	....	35	*Fe* XIII $3s^23p^2\,{}^3P_2-{}^3P_1$	9.7	2.30	325

* The ionization potential refers to the next lower ionization stage.

This applies also to other solar research carried on by Kiepenheuer in Germany, by Lyot in France, by the Harvard, Mount Wilson, and Michigan groups in this country, and by others. A discussion of all these other solar investigations related in some way to the corona problem lies beyond the scope of the present review.

P. SWINGS

MCDONALD OBSERVATORY
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[18] A. Unsöld, *Physik der Sternatmosphären*, p. 420, Berlin, 1938.

[19] *Zs.f. Ap.*, **19**, 21, 1939; **20**, 172, 1940; **20**, 317, 1941; **20**, 323, 1941; **21**, 120, 1942.