27. — SOLAR ULTRA-VIOLET AND X-RAY LINE EMISSION

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Some time ago an attempt was made by Woolley and Allen (1948, 1950) to calculate the ultra-violet emission spectrum of the corona and chromosphere. Since that time the spectrum has been observed from rockets and the emission lines that actually appear are mainly those predicted for the upper chromosphere. In the present paper the original calculations have been extended and refined with the view to interpreting the observations.

SOLAR ATMOSPHERE DATA

The amount of radiation emitted by a particular ion in the corona or chromosphere will depend on the number of atoms within the range of temperature that produces this ion. For the purpose of calculation it is convenient to divide the solar atmosphere into temperature layers. The emission for each layer then depends on the chemical composition, various atomic cross-sections, and the quantity $\int N_e^2 \, dV$ where N_e is the electron density and the volume integration extends through that part of the temperature layer that is visible from the earth. A model of the corona and chromosphere is required only to the extent of providing the value of $\int N_e^2 \, dV$ for each temperature layer. In this paper we use the Oster (1956) model II, and the data adopted are given in Table I. The coronal value of $\int N_e^2 \, dV$ is from Elwert (1954) and van de Hulst (1950) (sunspot maximum). No correction has been made for density inhomogeneity.

The corona is regarded as an isothermal region at electron temperature T of 800000 °K in approximate agreement with the interpretation of ionization (e. g. Waldmeier, 1952) and radio

emission in the metre band (e. g. Newkirk 1959). The higher temperatures suggested by Schwartz and Zirin (1959) are well established for atomic but not for electronic velocities. There are, in fact, some reasons for expecting a distinct difference between the kinetic temperatures of the atoms (which probably receive the coronal energy) and the electrons (which give the energy out).

TABLE I

Layer	Temperature	Height range	$\int N_e^2 \, dV$
	°K	km	10^{50} cm^{-3}
A	800000	whole corona	0.32
B	400000	8600 — 9900	0.028
C	200000	7500 — 8600	0.10
D	100000	6700 — 7500	0.35
E	50000	5900 — 6700	1.20
F	25000	5200 — 5900	4.0
G	12500	4600 — 5200	12.6

The adopted abundance of various elements relative to hydrogen is as follows.

Element	H	He	C	N	O	Ne	Mg	Si	S	Fe
$\log(N_E/N_H)$	0.0	−0.9	−3.7	−3.8	−3.2	−3.6	−4.6	−4.5	−4.9	−4.8

RATE COEFFICIENTS

The calculations require the ionization rate, the recombination rate, and the collision excitation rate.

The ionization formula (Woolley and Allen 1948) is

$$N_i/N_a = S/\alpha \tag{1}$$

where N_i is the number density of upper ions, N_a the number density of atoms or lower ions, S the collision ionization rate, and α the recombination rate.

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A recent general formula for S by Burgess, van Regemorter and Seaton (1960) may be written

$$S = 1.15 \times 10^{-8} \left(3.1 - \frac{1.2}{Z} - \frac{0.9}{Z^2}\right) \frac{\zeta \, T^{1/2}}{I^2} \, 10^{-5040 \, I/T} \text{ cm}^3 \text{ s}^{-1} \quad (2)$$

where I = ionization potential in volts,

         T = electron temperature in °K,

         ζ = number of electrons in the outer shell

         Z = ionic change after ionization.

Using 2.5 as a representative value for the term in brackets the numerical constant becomes 2.9×10^{-8}. This has been used throughout. For comparison Elwert's (1952) formula (using $c_2 = 2.0$, $f_2 = 0.8$, $G_2 = 0.8$, and $h_2 = 1.0$) leads to a numerical constant of 1.3×10^{-8}. The Schwartz and Zirin (1959) values are much less and do not appear to follow the same form. There is some ambiguity in selecting the appropriate value for ζ in Fe ; the maximum value adopted for any ion was 8.

The Elwert (1952) value used for the recombination coefficient (using $G_1 = 0.8$, $f_1 = 0.8$) becomes

$$\alpha = 0.97 \times 10^{-12} \, I \, n_o \, g \, T^{-1/2} \quad \text{cm}^3 \text{ s}^{-1} \quad (3)$$

where n_o = ground level total quantum number of the atom or lower ion

     $g \simeq 4$ for Fe and 3 for other listed atoms.

This is in reasonable agreement with Unsöld's (1955) statement of the formula.

The ionization ratio becomes

$$N_i/N_a = S/\alpha = 1.0 \times 10^4 \, T \, I^{-3} \, 10^{-5040 \, I/T} \, \zeta/n_o \quad (4)$$

for all listed atoms except Fe for which the constant is 0.75×10^{-4}. From this formula the ratio (N_a/N_E), where N_E is the total number density for the element, may readily be calculated.

The collision excitation rate is taken from a formula for per-

mitted ionic lines by Burgess, van Regemorter and Seaton (1960). It may be written

$$L = 5.1 \times 10^{-4} \ T^{-1/2} \ W^{-1} \ f \ 10^{-5040 \ W/T} \ cm^3 \ s^{-1} \qquad (5)$$

where $\quad W =$ excitation energy in electron volts

$\qquad f =$ oscillator strength.

It should be remarked that if the rate coefficients of Elwert (1952) or Woolley and Allen (1948) had been used throughout there would have been no important change in the general results or conclusions.

The number of photons emitted per cm^3 as a result of collision excitations is

$$L \ N_e \ N_a = L \ (N_E/N_H) \ (N_a/N_E) \ N_e^2$$

where $\quad N_E/N_H =$ number abundance of element relative to H

$\qquad N_a/N_E =$ fractional abundance of element in the ground state of the atom or lower ion.

$\qquad N_e \ (\simeq N_H) =$ electron density.

The flux $\mathscr{F}$ in erg $cm^{-2} \ sec^{-1}$ outside the earth's atmosphere becomes

$$\mathscr{F} = 2.9 \times 10^{-43} \ T^{-1/2} \ f \ (N_E/N_H) \ (N_a, N_E) \ 10^{-5040 \ W/T} \int N_e^2 \ dV \qquad (6)$$

in which all factors may be estimated.

SPECTROSCOPIC CONSIDERATIONS

A decision is required on which arrays are important and what f-values are to be adopted for (6).

In his discussion on coronal line emission Elwert (1954) considered only one array in each ion and chose the strongest for which $\Delta n = 1$, where Δn is the change in total quantum number. However in many atoms and ions the strongest transitions and highest f-values are for $\Delta n = 0$. These have smaller W and from (6) will have larger $\mathscr{F}$. It is important that calculations should be made for both $\Delta n = 1$ and $\Delta n = 0$ and that the strongest and most representative arrays should be considered. The arrays represented

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in the successive columns of Table 2 and the adopted f-values for the most intense multiplets are as follows

$$\Delta n = 1 \qquad \Delta l = + 1 \qquad f = 0.5$$
$$\Delta n = 1 \qquad \Delta l = - 1 \qquad f = 0.1$$
$$\Delta n = 0 \qquad \Delta l = + 1 \qquad f = 0.2$$
$$\Delta n = 0 \qquad s^2 p^{\zeta-2} - s p^{\zeta-1} \quad f = 0.05$$

where $\Delta l = + 1$ means that the orbital quantum number increases when moving from ground to upper configuration. The adopted f-values are fairly realistic for the high ions but for low ions and neutral atoms one might expect the $\Delta n = 1$ values to be lower and the $\Delta n = 0$ values to be higher. The low f-values adopted for the equivalent moving electron represented by $s^2 p^{\zeta-2} - s p^{\zeta-1}$ is suggested by experience with neutral atoms (Allen and Asaad, 1957).

Only excitations from ground terms are included in the present analysis.

Results

The collected results are given in Table 2. The list of atoms and their ions includes only those that should be detectable in the sun's ultra-violet spectrum (using threshold $\log \mathscr{F} = - 2.2$).

The wavelengths tabulated represent the main multiplet of each array. Usually all lines of the multiplet are within a few Å of this tabulated value but for Fe the arrays are too complex to represent by a single wavelength. Wavelengths in *italics* are for multiplets that can be detected in existing spectra.

There are only two columns of calculated values, one for $\Delta n = 1$ and one for $\Delta n = 0$. Whenever there are two entries in the λ columns it is the calculation for the $\Delta l = + 1$ case that has been tabulated and this is regarded as applicable for both. Actually the $\Delta l = + 1$ case would usually give the greater $\mathscr{F}$ but the difference does not justify further tabulation. Emissions that come mainly from the corona are labelled c.

Table 2

Atom	λ Δn = 1 Δl = +1	Δl = −1	λ Δn = 0 Δl = +1	sp	Log ℱ Calculated Δn = 1	Δn = 0	Observed Δn = 1	Δn = 0
	Å				in erg cm⁻²s⁻¹ at earth			
H I	1216				+2.0		+0.8	
He I	584				+0.3		−0.8	
He II	304				+0.2		−0.3	
C I	1277	1657		1561	−2.2	−2.5	−0.6	−1.0
C II	687	858		1335	−1.8	−0.8	−1.4	−0.2
C III	386		977		−2.0	−0.3		0.0
C IV	312		1549		−1.7	−0.5		−0.4
N I	953	1200		1134	−2.9	−2.9	−1.9	−1.7
N II	533	671		1085	−2.5	−1.4		−0.3
N III	374	452		990	−2.3	−1.2	−1.7	−1.5
N IV	247		765		−2.3	−0.8		−1.7
N V	209		1240		−2.4	−1.0		−1.1
O I	1027	1304			−2.1		−0.9	
O II	430	539		833	−0.7	−1.3	−1.0	−1.2
O III	305	374		833	−2.0	−0.6	−0.9	−1.2
O IV	238	279		789	−1.9	−0.9	−1.3	−1.1
O V	172		629		−1.8	−0.6	−1.3	−0.8
O VI	150		1035		−1.9	−0.7	−1.0	+0.2
Ne IV	172	208		543	−2.8	−1.7		
Ne V	143	168		570	−2.7	−1.8		−1.3
Ne VI	123	139		560	−2.7	−2.1		
Ne VII	104		480		−2.7	−1.8		
Ne VIII	88		776		−1.8 c	−1.3 c	−0.5	−1.1
Mg IX	62		360		−2.8 c	−2.1 c		
Mg X	58		620		−2.5 c	−1.7 c		−1.2
Si I	1848	2520	2210	2060	−3.2	−3.2		
Si II	992	1530	1262	1814	−2.7	−2.4	−1.0	0.0
Si III	566		1206		−2.3	−1.2		−0.3
Si IV	458		1400		−2.3	−1.1		−0.7
Si XI	44		300		−3.2	−2.1 c		
S I	1320	1480	1430	1390	−3.6	−3.7	−2.0	−2.2
S II	650	910	900	1255	−3.4	−2.6		−1.4
S III	480	682	680	1195	−3.4	−2.8		−1.6
S IV	390	551	659	1068	−3.2	−2.5		−1.9
S V	300		786		−3.0	−1.9		−1.7
S VI	249		940		−3.3	−2.2		−1.9
Fe I			4000			−2.0		
Fe II	2500	2000	2500		−0.6	−1.0		

For observations I have used the list of emission lines by Violett and Rense (1959), the reproduced spectrum of the Naval Research Laboratory (1959), and the data from Johnson, Malitson, Purcell and Tousey (1958). I have made eye estimates of the line intensities on the N. R. L. photograph and converted them into intensity flux in absolute units by comparison with the measures of Aboud, Behring and Rense (1959). Lines on the short wave side of about 1000 Å were multiplied by 3 to allow for supposed light loss and sensitivity factors. The emissions published by Violett and Rense (1959) do not agree very well with the N. R. L.photograph. Any line given in this list but not found on the photograph was allotted an intensity that would make it just detectable. Line intensities were added to give $\mathscr{F}$ for the multiplet. Obviously the estimates are very rough. They are given in the last two columns of the table and refer to the italic entries of the λ columns. For O IV and Si II, where two wavelengths are italicised in one double column, both have the observed intensity.

Discussion

A direct comparison of calculated and observed fluxes is shown in Fig .1. Because the neutral atoms and Si II are influenced by the low chromosphere the calculations will not be satisfactory and they are not considered any further.

There are many reasons that could be invoked to explain the small absolute difference (about 0.3 in the logarithm) between calculations and observations. For example (a) the f-values for $\Delta n = 0$ could be greater, (b) the thickness of the upper chromosphere (often called the transition layer) could be greater, or (c) the transition could occur at a lower level. For the present state of calculations and observations the absolute agreement is very good.

In my view the scatter in Fig. 1. is not entirely due to observational data but indicates some inaccuracies in the assumed atomic

data S, α, L, or f. More accurate observations should give some interesting atomic information.

Fig 1
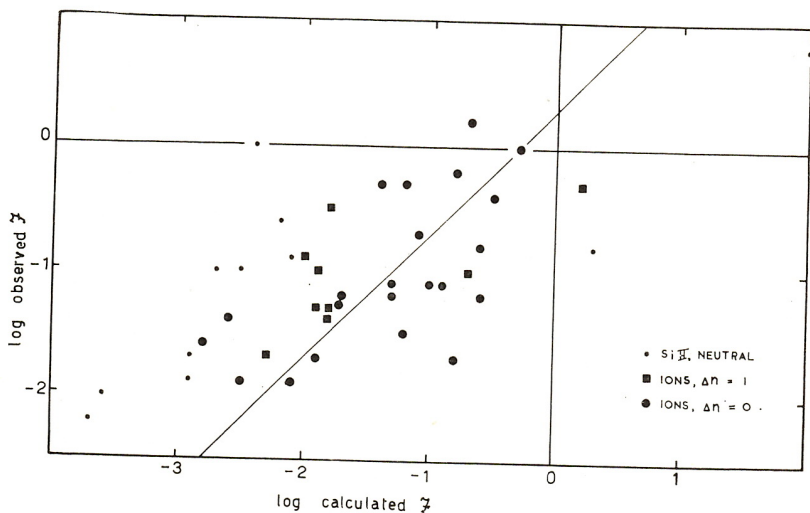
The distribution of spectrum lines in the X-ray region emitted by the corona (much of the data omitted from Table 2) is very similar to that calculated by Elwert (1954). In addition there are a number of strong coronal lines due to $\Delta n = 0$ transitions in the 200 — 800 Å region. These lines, omitted by Elwert, give most of the coronal line energy. However the upper chromospheric lines in the region $\lambda > 200$ Å give still more energy and dominate the total emission.

TABLE 3

Total emission in erg cm^{-2} sec^{-1} *at earth for three spectral regions*

Region		0 — 100 Å	100—800 Å	800—1200 Å
Corona	(calc)	0.05	0.09	0
Corona	(obs.)	0.3??	0.14	0
Upper chromosphere	(calc.)	0	4	1
Upper chromosphere	(obs.)	0	1.4	4

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Estimates of the total emission in a spectral region are inclined to be dependent on one or two strong multiplets which might be of doubtful accuracy. Adding the results as they stand we obtain Table 3. Both observations and calculations are well above the requirement of the ionosphere which is about 0.1 erg cm^{-2} s^{-1} (Allen 1958).

One of the main intentions of the analysis has been to obtain some information on the upper chromosphere. In particular we would like to discriminate between the chosen Oster model II and the sharp transition model of Woolley and Allen (1950). For the latter model the division between high and low temperature is so sharp that there would be a vanishingly small number of low ion (II and III) emissions. To investigate the question we plot in Fig. 2 the values of log. (observed $\mathscr{F}$ /calculated $\mathscr{F}$) against the degree of ionization. There is no very systematic change of log (obs./calc.) with ionization. This speaks strongly in favour of the Oster model and against the sharp transition.

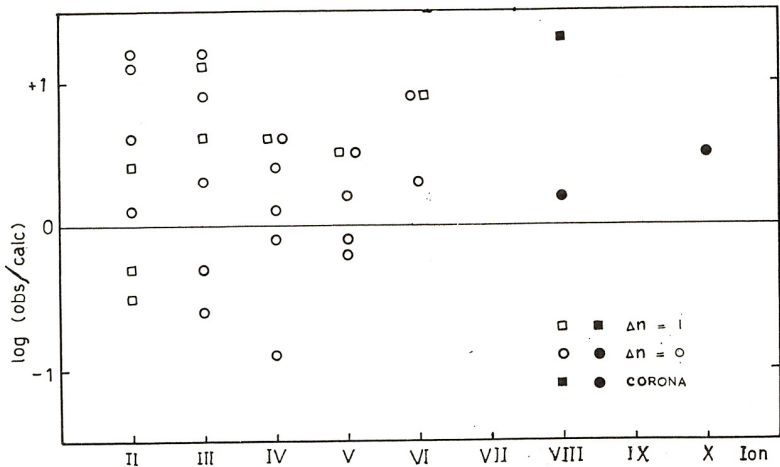Fig.2 _ Relation between log (Observed/Calculated) flux and degree of ionization

Fig. 2 does not reveal any important discrepancy between the $\Delta n = 1$ and $\Delta n = 0$ calculations. Both types of transition are of comparable importance in the spectra.

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