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On the Ultra-violet Radiation from the Solar Corona. I

By

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Abstract

Weak ultraviolet radiation emitted by the corona has been calculated. The main factor of the emission is the free-free transition of hydrogen.

Anomalous excitation of He in the flash spectrum has been investigated in terms of the radiation from the corona. It corresponds to the temperature radiation of 8000 and 16500 for the ionization potential of HeI and HeII respectively. Theoretical intensities of HeI lines show a maximum at certain height as is known observationary.

Coronal radiation is ineffective to the ionization of hydrogen. Hydrogen anomaly observed in the flash may be sought for in any other sources.

§ **1.** *Introduction.* Anomalous behaviour of helium in the flash spectra is well known. It cannot be accounted for by the thermal excitation of the photospheric temperature. The anomalous excitation has often been attributed to the excess ultraviolet radiation from the photosphere or to the excitation by the high speed corpuscules.

Anomalies in the solar atmosphere is not limited to the helium in the chromosphere. In the coronal region, super-excitation discloses itself in a more definite form; according to B. Edlén's identification[1] of the coronal emissions, Fe and other metallic elements are in a state of strong ionization. Naturally, some intimate connection may be expected between them. In fact, as early as 1935, G. G. Cillié and D. H. Menzel[2] has pointed out observationally in the eclipse plate of 31 August 1932 that the region of abnormal chromospheric excitation is connected with the great intensification of the coronal spectrum above it.'

It seems now generally believed that the corona is possessed

1. B. Edlén: *Ark. för Mat. Astr. och Fys.*, B, 28, No. 1; (1941).
2. G. G. Cillié and D. H. Menzel: *Harv. Circ.*, **410**, (1935).

of extremely high electron temperature. Assuming such a high temperature of order some million degrees, it follows that the corona must emit a weak ultraviolet radiation. In the present paper, we have estimated the amount of it and tried to seek the source of excitation of the chromospheric He anomaly in it.

§ **2.** *Radiation from the corona.* We assume that the chemical composition of the corona is the same as that of the reversing layer. In the coronal region, hydrogen is ionized strongly. Let N_e be the particle density of the electron. This is also equal to the density of proton. Then the energy emitted by the free-free transition per sec. per c. c. in the frequency range $(\nu, \nu+d\nu)$ is given by

$$N_e^2\phi_\nu d\nu = N_e^2 Z^2 \frac{2^7\pi^3}{(6\pi)^{3/2}}\left(\frac{m}{kT_\varepsilon}\right)^{1/2}\frac{\varepsilon^6}{c^3m^2}e^{-h\nu/kT_\varepsilon}\,d\nu, \qquad (2\cdot1)$$

where $Z\varepsilon$ means the nuclear charge. For hydrogen, we take $Z=1$. T_ε is the electron temperature, m the electron mass, c the light velocity, and k the Boltzmann constant.

Integrating it with respect to ν from zero to infinity, we find for the total energy emitted per sec. per c.c. as

$$N_e^2\Phi = N_e^2Z^2\frac{2^7\pi^3}{(6\pi)^{3/2}}\left(\frac{kT_\varepsilon}{m}\right)^{1/2}\frac{\varepsilon^6}{hc^3m}\,. \qquad (2\cdot2)$$

Inserting numerical values in the expression (2•1), we get

$$N_e^2\phi_\nu d\nu = N_e^2\; 6.67\times10^{-38}T_\varepsilon^{-1/2}e^{-h\nu/kT_\varepsilon}\,d\nu, \qquad (2\cdot1)'$$

and for (2•2),

$$N_e^2\Phi = N_e^2\; 1.40\times10^{-27}T_\varepsilon^{1/2}.$$

Compared to the free-free transition, the emission due to the bound-free transition is weaker for the electron temperature of the order of million degrees; emission per sec. per c.c. by the capture of electron to the j-th level is

$$N_e^2Z^4\frac{2^9\pi^5}{(6\pi)^{3/2}}\frac{\varepsilon^{10}}{m^2c^3h^3}\left(\frac{m}{kT_\varepsilon}\right)^{3/2}\frac{1}{j^3}e^{\chi_j/kT}\,e^{-h\nu/kT_\varepsilon}\,d\nu$$

$$= N_e^2Z^4\frac{2.10\times10^{-32}}{T_\varepsilon^{3/2}j^3}e^{\chi_j/kT_\varepsilon}\,e^{-h\nu/kT_\varepsilon}\,d\nu, \qquad (2\cdot3)$$

where χ_j means the ionization potential from the j-th level. Integrating (2. 3) with respect to ν from χ_j to infinity, we find

$$N_e^2 Z^4 \frac{2^9\pi^5}{(6\pi)^{3/2}} \frac{\varepsilon^{10}}{m^{1/2}c^3h^3} \frac{1}{(kT_\varepsilon)^{1/2}} \frac{1}{j^3} = N_e^2 Z^4 \frac{4.39\times 10^{-22}}{T_\varepsilon^{1/2} j^3}. \qquad (2\cdot 4)$$

From the dependence of these formulae on Z, we can infer that the emissions from the metallic ions are small compared with that of hydrogen owing to their small abundance.

§ 3. Consider the concentric shell of the corona of thickness dr, whose distance from the center of the sun is r. According to (2∘1), the $(\nu, \nu+d\nu)$ radiation emitted per sec. by the $(r, r+dr)$ shell is $N_e^2\,\phi_\nu\, 4\pi r^2\, dr$.

A fraction W of this, flows into the chromosphere, where W is the dilution factor of a point at distance r:

$$W=\frac{1}{2}\left\{1-\sqrt{1-\left(\frac{R}{r}\right)^2}\right\}, \qquad (3\cdot 1)$$

in which R means the radius of the upper boundary of the chromosphere. Assuming the chromosphere as a layer of thickness 10,000 km, we tentatively take R=705,000 km. Thus the incident flux from the coronal region, per sec. per square cm. is given by

$$\pi F_\nu=\int_R^\infty W\left(\frac{r}{R}\right)^2 N_e^2\,\phi_\nu\, dr. \qquad (3\cdot 2)$$

Density distribution N_e has been derived from observations by S. Baumbach[1]. ϕ_ν is indepedent, or r, if we assume a constant electron temperature. After the numerical integration we get

$$\int_R^\infty W\left(\frac{r}{R}\right)^2 N_e^2 dr=2.6\times 10^{26}. \qquad (3\cdot 3)$$

Therefore, we have

$$\pi F_\nu=1.75\times 10^{-11} T_\varepsilon^{-1/2} e^{-h\nu/kT_\varepsilon}. \qquad (3\cdot 2)'$$

By the way, we shall calculate the flux at a distant point r_1. It is given by

$$\pi F_\nu(r_1)=\left(\frac{R}{r_1}\right)^2 \int_R^\infty (1-W)\left(\frac{r}{R}\right)^2 N_e^2\,\phi_\nu\, dr, \qquad (3\cdot 4)$$

or numerically,

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1. S. Baumbach: *A. N.*, **263**, 121, (1937).

$$\pi F_\nu(r_1) = \left(\frac{R}{r_1}\right)^2 2.2 \times 10^{-11} T_\varepsilon^{-1/2} e^{-h\nu/kT_\varepsilon}. \qquad (3\cdot4)'$$

Coronal ultraviolet radiation will be responsible for the anomalous spectra of comets and the upper atmosphere of the earth. The above formula may be used for the consideration of them.

§ 4. *Contact temperature.* Spectral energy distribution of the free-free emission is seen from (2•1)′ or (3•2)′. It, of course, differs from the Planck's distribution. But it may be convenient to express the intensity at any given frequency ν in terms of the tempersture radiation. From (3•2)′ we know that the mean intensity of ν-radiation is

$$J_\nu = \frac{1}{4\pi} C \frac{1}{T_\varepsilon^{1/2}} e^{-h\nu/kT_\varepsilon}, \quad C = 1.75 \times 10^{-11}. \qquad (4\cdot1)$$

Equating it to the Planck formula $\frac{2h\nu^3}{c^2} e^{-h\nu/kT}$, and solving for T, we find

$$\frac{1}{T} = \frac{1}{T_\varepsilon} + \frac{k}{h\nu} \ln\left(\frac{8\pi h\nu^3}{c^2} T_\varepsilon^{1/2} C^{-1}\right). \qquad (4\cdot2)$$

Let χ be the energy $h\nu$ expressed in eV. Inserting numerical values we get

$$\frac{1}{T} = \frac{1}{T_\varepsilon} + \frac{1.97 \times 10^{-4}}{\chi}\left(8.18 + \frac{1}{2} \log T_\varepsilon + 3 \log \chi\right). \qquad (4\cdot2)'$$

In the following, we shall call T the contact temperature.

At the Lyman limit, $\chi = 13.53\ eV$. Assuming $T_\varepsilon = 10^6$, we get for the contact temperature $T = 4710$. This is lower than the effective temperature of the sun. In fact, at the Lyman limit, radiation from the corona is less than one hundredth that of the Planck radiation of temperature 5700. Therefore, coronal radiation has no influence on the ionization of hydrogen. The former becomes equal to the Planck of 5700 first at $\chi = 16.4\ eV$.

The above consideration shows also that the first ionizations of metallic elements are not affected by the coronal radiation, since their ionization potential lies in the range from 5 to 8 eV. The effect on the second ionization is also small. It will not change their order. For the third ionization, the coronal radiation is effective. But their concentrations are small and will be difficult to detect observationally. Thus we conclude that the coronal radiation has no influence on the ionization of metallic elements. These results conserve the current interpretation on the metallic ionization and at the same time show that the high temperature hypothesis of the corona does not contradict to the observations.

He is an exception. Its ionization potential is high. The contact temperature amounts to 8000 and 16500 for the first and the second ionization potential respectively, so that the source of ionization is mainly due to the coronal radiation and a small fraction of it is in a state of ionization. But owing to its great abundance, it can amply be detected by the observation.

It is well known that the He and H is greatly enhanced in the flash spectra. In the remaining part of this paper, we shall investigate the anomaly in terms of the coronal radiation. As has been shown above, coronal ultraviolet radiation is indifferent to the hydrogen excitation. The anomalous behaviour of it may be sought for in any other sources. It may be due to the large opacity of the chromosphere to the Lyman radiation.