THE ULTRAVIOLET RADIATION AND SOFT X RAYS OF THE SUN

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Usp. Fiz. Nauk **75**, 351-388 (October, 1961)

INTRODUCTION

ABOUT 100 years ago it was discovered that the solar spectrum breaks off abruptly at about 2900 A. Crookes and Cornu attributed this "cut-off" of the solar spectrum to absorption in the earth's atmosphere. Hartley connected this absorption with the presence of ozone in the atmosphere of our planet. This was finally established about a half century ago by Fabry and Bruisson.

Since it was learned long ago that the study of the ultraviolet spectrum of the sun is hindered by the absorption in the earth's atmosphere, the idea naturally arose of lifting apparatus enough to "break through" the absorbing atmospheric layer as much as possible. For example, Lyman organized mountain expeditions for this purpose, and in the 1930's spectrographs were attached to stratospheric balloons which went to a height of 25 km. We now understand why these attempts were doomed to failure. Then, however, little was known about the nature of the upper layers of the atmosphere, and the attempts were quite justified. Figure 1 shows the dependence of the transparency of the earth's atmosphere on wavelength, according to present ideas.

Only after the second world war, thanks to the enormous progress of rocket techniques, was this problem, one of the most important in observational astronomy, solved in principle. In Sec. 2 we shall tell about the outstanding results thus obtained.

Although the direct study of the ultraviolet radiation and x rays of the sun has been possible for only 15 years, certain indirect data permitted fairly long ago a very rough estimate of the intensity of this radiation. The point is that although the hard photon radiation of the sun is only an extremely small fraction of the total flux of solar radiation, it has an enormous effect on the earth's atmosphere. It is the main cause of the formation of ionized layers in the upper atmosphere, which make up the so-called ionosphere. Moreover, this radiation regulates thermal conditions in the upper layers of the atmosphere, and thus determines its extent. On the other hand, the study of the connections between the upper and lower layers of the earth's atmosphere is only beginning, and therefore it cannot be excluded that the hard solar radiation may affect phenomena of such great importance to human activity as the general circulation of the atmosphere, which determines the weather. Consequently, the study of all aspects of the hard radiation of the sun is of great

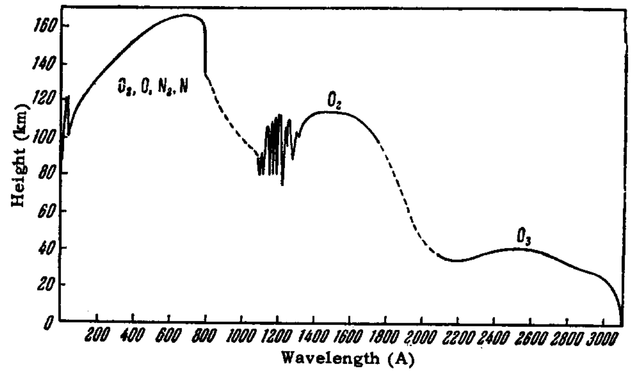

FIG. 1. Transparency of the atmosphere as a function of the wavelength of the radiation. The ordinate is the height at which the intensity of the radiation incident on the earth has been diminished by a factor e.

practical importance, especially for radio communications and astronautics.

The study of the elementary processes in the ionosphere has provided long ago some information about the intensity of the ionizing ultraviolet radiation of the sun. In fact, let us write the fundamental equation for the ionization of one of the ionospheric layers:

$$\frac{dN_e(h)}{dt} = J(h) - \alpha N_e^2(h) + D, \qquad \text{(A)}$$

where N_e is the concentration of electrons, J is the number of ion pairs produced per unit volume and unit time through the photoionization of molecules and atoms of the atmosphere by solar radiation, α is the effective recombination coefficient (this quantity can be obtained empirically, for example during eclipses), h is the height of the part of the atmosphere in question, and D describes the change of the electron concentration owing to diffusion processes.

A relation which is obviously satisfied is

$$Q = \int J(h)\,dh = S_0 \cos z, \qquad \text{(B)}$$

where Q is the number of ion pairs produced in a column of unit cross section passing through the ionospheric layer in question, S_0 is the number of photons from the sun incident on unit area of the earth (outside the atmosphere) per second with energies exceeding the ionization potential of the molecules (atoms) from which ions are formed in the given ionospheric layer, and z is the zenith angle of the sun.

The integral $Q = \int J\,dh$ can be obtained by radio observation (cf., e.g., reference 1). By making some definite hypothesis about the character of the elementary processes in one of the ionospheric layers, one

Table I. The ultraviolet radiation of the sun according to ionospheric observations

Iono-spheric layer	S_0^{theor}	Q^{obs}_{Massey}	Q^{obs}_{Allen}
E (Q$_2$)	$1.0 \cdot 10^{10}$ cm^{-2} sec^{-1}	$6 \cdot 10^{8}$ cm^{-2} sec^{-1}	$5 \cdot 10^{8}$ cm^{-2} sec^{-1}
F_1(OI)	$9.3 \cdot 10^{8}$ cm^{-2} sec^{-1}	$2 \cdot 10^{9}$ cm^{-2} sec^{-1}	$1.9 \cdot 10^{9}$ cm^{-2} sec^{-1}
F_2(N$_2$)	$2.7 \cdot 10^{7}$ cm^{-2} sec^{-1}	$1.5 \cdot 10^{9}$ cm^{-2} sec^{-1}	$2.3 \cdot 10^{9}$ cm^{-2} sec^{-1}

can calculate a value of Q corresponding to this hypothesis. If, for example, as is done in reference 2, we assume that the oxygen molecules (ionization potential $h\nu_0 = 12.2$ ev) are responsible for the formation of ions in the E layer, oxygen atoms ($h\nu_0 = 13.5$ ev) in the E_1 layer, and nitrogen molecules ($h\nu_0 = 15.5$ ev) in the F_2 layer, then we get the values of Q for the various layers that are shown in Table I.

In the second column are the theoretically obtained values of S_0, with the radiation of the sun in the far ultraviolet assumed to be that of an absolutely black body at temperature 6000°. For the F_2 layer Ya. L. Al'pert[1] obtained the much larger value Q^{obs}_{Allen} (sic) $= 4 \times 10^{10}$ cm^{-2} sec^{-1}. This difference in reference 1 was explained by an actual change in the ultraviolet radiation flux of the sun, in accordance with the phase of solar activity. Allen's data[3] correspond to the period of minimum solar activity in 1943-1944, when there were no sunspots at all. We make advance mention here that rocket data indicate a strong dependence of the hard photon radiation of the sun on the 11-year cycle (see Sec. 2).

It must be emphasized that Table I lists only the order of magnitude of Q. These values are of course changed if one makes a different hypothesis about the character of the elementary processes in the ionosphere. We have presented them only as an illustration of the possibilities of indirect methods for determining the flux of hard photon radiation from the sun.

Comparisons of observed values of Q with Planck radiation from the sun at T = 6000° (such as were often made in earlier times by physicists and geophysicists) are without any foundation. In the part of the short-wave spectrum accessible to observation the intensity of the solar radiation is much less than the Planck intensity for T = 6000°. According to theoretical arguments the intensity of the sun's radiation beyond the limit of the Lyman series must correspond to a color temperature close to that at the boundary of the sun, i.e., ~4800°. The depression of the solar radiation can be clearly seen from spectra obtained at high altitudes (cf. Sec. 2).

In the postwar years the entire body of observational data has brought astronomers to the necessary conclusion that an inversion of the kinetic temperature exists in the upper layers of the solar atmosphere (the upper chromosphere and the corona). The temperature of the solar corona is $\sim (1-2) \times 10^6$, and in the transition region between the upper chromosphere and the corona $T \sim 10^5$. The presence of a high kinetic temperature in the corona and the upper chromosphere has posed the problem of the hard photon radiation of the sun in an entirely new form.* Immediately after the war there were several theoretical investigations in this direction. These researches gave the first, rather crude picture of the expected effect. Subsequently the rapid progress of rocket astronomy made it possible to obtain important observational data, on the basis of which one could test the theory and make important new advances in it.

The theory of the ultraviolet radiation of the upper layers of the solar atmosphere, primarily of the corona, will be developed in the next section. The main observational results and a discussion of these results will be presented in Sec. 2.

1. THE ULTRAVIOLET RADIATION OF THE CORONA

The solar corona, regarded as a plasma at very high temperature, must be a source of ultraviolet and soft x rays.

Let us first consider the ultraviolet radiation and soft x rays of the corona with a continuous spectrum. We assume, in accordance with the observations, that the electron temperature T_e of the corona is 10^6 degrees, and in addition regard it as constant for the entire corona. Actually (as follows, for example, from observations of the corona during eclipses) the electron temperature can be different in different regions. It is highest over spots and flares, and lower in the polar regions. As we shall see, however, for not too short wavelengths the continuous-spectrum intensity of the ultraviolet radiation of the corona does not depend very strongly on the assumed value of T_e. It is an important fact that beyond the limit of the Lyman series the corona is optically thin. This follows from the exceptionally high ionization of the matter in the corona. According to our calculations, at $T_e = 10^{-6}$ the ratio of the concentrations of neutral and ionized hydrogen atoms (the most abundant element in the corona) is of the order of 10^{-7} (cf. reference 8). From this it is easy to show that beyond the limit of the Lyman series the optical thickness of the entire corona is of the order of 10^{-6}.

Let us write the transport equation of the ultraviolet radiation of the corona itself:

$$\frac{dI_\nu}{dS} = -k_\nu I_\nu + F_\nu, \qquad (1)$$

where k_ν is the absorption coefficient per unit volume, and $F_\nu d\nu$ is the emission from unit volume of the corona per unit time into unit solid angle in the frequency interval ν, $\nu + d\nu$†:

*The necessity of studying the corona with hard photon radiation was shown theoretically as early as 1945.[4] More detailed calculations were made in 1948[4] and 1949.[6] The detailed calculations of Elwert were made in 1952 and 1954.[7]

†For the derivation of the expression for F_ν see reference 9.

$$F_\nu \, d\nu = \frac{N_i N_e K \, gI e^{-\frac{h(\nu-\nu_0)}{kT_e}} h \, d\nu}{4\pi T e^{3/2}} + \frac{N_i N_e K e^{-\frac{h\nu}{kT_e}} gII \, d\nu}{8\pi \nu_0 T_e^{1/2}}$$

$$= N_i N_e [\Psi_\nu (T_e) + \Phi_\nu (T_e)], \tag{2}$$

where

$$K = \frac{h^3}{(2\pi m k)^{3/2}} \frac{8\pi^2 e^2 \nu_0^2}{mc^3} \frac{2^4}{3\sqrt{3}\pi} = 3.2 \cdot 10^{-6}.$$

The first term in the right member of Eq. (2) corresponds to the emission from recombinations to the ground state of the hydrogen atom, and the second to emission in hyperbolic transitions; $N_i = N_e$ is the concentration of protons, k is Boltzmann's constant, and gI and gII are Gaunt factors, which we shall hereafter set equal to unity.

The solution of Eq. (1) can be obtained immediately:

$$I_\nu (\varrho) = \int F_\nu \, ds = [\Psi_\nu (T_e) + \Phi_\nu (T_e)] \int N_e^2 (s) \, ds, \tag{3}$$

since the optical thickness of the corona is negligibly small. The total intensity emitted from the corona (at frequencies above ν_1) is given by

$$I_{\nu_1} (\varrho) = \int_{\nu_1}^{\infty} I_\nu \, d\nu = e^{-\frac{h(\nu_1 - \nu_0)}{kT_e}} \left[\frac{kK}{4\pi T_e^{1/2}} + \frac{k^2 K T_e^{1/2} e^{-\frac{h\nu_1}{kT}}}{8\pi h \nu_0} \right] \int N_e^2 \, ds$$

$$= \{\Psi_{\nu_1} (T_e) + \Phi_{\nu_1} (T_e)\} \int N_e^2 \, ds, \tag{4}$$

where ρ is the distance from the center of the solar disk, expressed as a fraction of the radius. We notice that the intensity caused by hyperbolic orbits (at $T_e = 10^6$) is 3.15 times that caused by capture to the ground state.

Assuming that for a spherically symmetrical model of the corona N_e can be represented by the formula

$$N_e = 10^8 \left(\frac{A}{r^{n_1}} + \frac{B}{r^{n_2}} \right), \tag{5}$$

we get

$$I_\nu (\varrho) = \{\Psi_\nu (T) + \Phi_\nu (T)\} \Bigg[\frac{A^2}{\varrho^{2n_1 - 1}} \frac{\Gamma(1/2) \Gamma\left(\frac{2n_1 - 1}{2}\right)}{\Gamma(n_1)}$$

$$+ \frac{2AB\Gamma\left(\frac{1}{2}\right) \Gamma\left(\frac{n_1 + n_2 - 1}{2}\right)}{\Gamma\left(\frac{n_1 + n_2}{2}\right)} \frac{1}{\varrho^{n_1 + n_2 - 1}}$$

$$+ \frac{B^2 \Gamma\left(\frac{1}{2}\right) \Gamma(2n_2 - 1)}{\Gamma(n_2)} \frac{1}{\varrho^{2n_2 - 1}} \Bigg]. \tag{6}$$

If, for example, we use for N_e the formula of Allen[10]

$$N_e = 10^8 \left(\frac{1 \cdot 55}{r^6} + \frac{2 \cdot 99}{r^{16}} \right),$$

then

$$I_\nu (\varrho) = \{\Psi_\nu (T_e) + \Phi_\nu (T_e)\} 10^{16} R_\odot$$

$$(1{,}87\varrho^{-11} + 4.08\varrho^{-31} + 5.13\varrho^{-21}). \tag{7}$$

In reference 7 the value of the Gaunt factor was taken to be $g = (3^{1/2}/\pi) \ln (4kT_e/nc\xi)$, where ξ is the Euler constant, but this approximation to g is already invalid for $\lambda < 200 - 300$ A. Therefore the calculations made by Elwert for the soft x-ray region are incorrect.

In reference 11 the more general approximation

$$g = \frac{\sqrt{3}}{\pi} \varrho \ln \left(\frac{\varrho + 1}{\varrho - 1} \right) \frac{e^{2\pi\eta_i} - 1}{e^{2\pi\eta_F} - 1}$$

is used (ρ, η_i, η_F are certain parameters that depend on the speed of the electron). It turns out that in the ultraviolet and soft x-ray regions g = 1, which justifies the assumption we made above.

Up to $\rho = 0.95$ we can get sufficiently good accuracy by using the simple law which holds for plane-parallel layers,

$$I(\theta) = I(0) \sec \theta, \tag{8}$$

where

$$I(0) = \{\Psi(T_e) + \Phi(T_e)\} R_\odot \int_1^\infty N_e^2 (r) \, dr,$$

$\int_1^\infty N_e^2 (r) \, dr = 9.5 \times 10^{15}$ if (5) is used for $N_e(r)$. We further note that for $\rho \to 1$ (from values $\rho > 1$) $\int_{-\infty}^{\infty} N_e^2 (s) \, ds$ is twice the value of $\int_0^\infty N_e^2 (s) \, ds$ calculated for $\rho \to 1$ from values $\rho < 1$. Thus the brightness of the corona in the ultraviolet must be discontinuous at the edges of the solar disk, since the corona is transparent to its own ultraviolet radiation, much of which is screened off by the sun.

In the range $0.9 < \rho < 1.0$ the integral $\int N^2 (s) \, ds$ can be calculated by numerical methods.

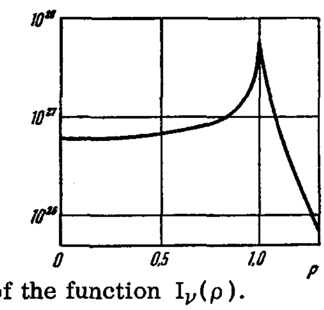

FIG. 2. Brightness distribution of the continuous-spectrum ultraviolet radiation across the solar disk.

Figure 2 shows a graph of the function $I_\nu(\rho)$.

The total flux of ultraviolet radiation of the corona is obviously

$$F = \frac{R_\odot^3}{R^2} \int_1^\infty F_\nu r^2 \, dr = \frac{R_\odot^3}{R^2} \{\Psi_\nu (T_e) + \Phi_\nu (T_e)\} \int_1^\infty N_e^2 (r) \, r^2 \, dr$$

$$= \{\Psi_\nu (T_e) + \Phi_\nu (T_e)\} R_\odot^3 \, 13{,}4 \cdot 10^{16}, \tag{9}$$

where the formula (5) is assumed for N_e.

It is interesting to find the flux of ultraviolet radiation of the corona during the total phase of an eclipse for various possible values of the angular radius of the moon. The results of the calculations are listed in Table II.

Table II

ϱ	1.00	1.02	1.03	1.04
F_{ϱ}/F	0.29	0.20	0.11	0.03

It was assumed above that the hard corona radiation in hyperbolic transitions is due to hydrogen alone. We can take into account the analogous radiation caused by the presence of other elements in the corona. The one to be considered first is helium. We take the relative abundance of helium and hydrogen to be 1 : 5, and we can assume that this ratio is constant for the entire corona (good mixing). Then we must first decrease the intensity of the hard "hydrogen" radiation by $^2/_7$ of its value (because the ratio of the concentrations of protons and free electrons will not be unity, as we had assumed, but $^5/_7$, owing to the double ionization of the helium).

In analogy with Eq. (2) we get the following expression for the intensity of the hard radiation contributed by helium per unit volume of the corona in the frequency interval ν, $\nu + d\nu$ and in unit solid angle:

$$\bar{F}_{\nu}\, d\nu = \frac{[\mathrm{He}^{++}]\, N_e Z^4 K g \mathrm{I} e^{\frac{h(\nu-\nu_1)}{kT_e}}\, h\, d\nu}{4\pi T_e^{3/2}} + \frac{N_{\mathrm{He}^{++}}\, N_e Z^2 k K e^{-\frac{h\nu}{kT_e}}\, g \mathrm{II}\, d\nu}{8\pi \nu_1 T_e^{1/2}}, \tag{10}$$

where $[\mathrm{He}^{++}] = N_e/7$ is the concentration of doubly ionized helium and ν_1 is the limiting ionization frequency of He^+ (for a derivation of (10) cf. reference 9). Just as in the case of hydrogen, we can calculate

$$I_{\nu}^{\mathrm{He}} = \{\overline{\Psi}_{\nu}(T_e) + \overline{\Phi}_{\nu}(T_e)\}\frac{1}{7}\int N_e^2\, ds, \tag{11}$$

$$I^{\mathrm{He}} = \int I_{\nu}^{\mathrm{He}}\, d\nu = \{\overline{\Psi}(T_e) + \overline{\Phi}(T_e)\}\frac{1}{7}\int N_e^2\, ds. \tag{12}$$

The expression for the flux of continuous-spectrum hard "helium" radiation is completely analogous to Eq. (9). The calculations show that the ultraviolet radiation of the corona due to helium is about 1.5 times that due to hydrogen.

According to Eq. (9) the flux of hard radiation from the corona must be proportional to the characteristic expression $i = N_e^2(r)\, r^2 dr$. It is an important fact that the flux of thermal radiofrequency emission from the sun in the decimeter range is also proportional to this same quantity i (cf., e.g., reference 8). This is quite understandable, since in both cases the emitting power of unit volume of the corona is proportional to N_e^2 and for these types of radiation the corona is optically thin. It follows that (in the case of an isothermal corona) the flux of hard continuous-spectrum radiation from the corona must be proportional to the flux of radiofrequency emission from the sun in the decimeter range.

Let us consider the flux from the corona of hard continuous-spectrum radiation with $\nu > \nu_a$. We shall take into account only the emission from hyperbolic transitions. According to Eq. (9) and reference 8, the magnitude of this flux is proportional to F_{rad}, the flux of radio-frequency radiation at a frequency ν:

$$F_{\mathrm{uv}}^{\nu_a} = \frac{N_e^2\{\Psi_{\nu_a}^2(T_e) + \overline{\Phi}_{\nu_a}(T_e) + \Psi_{\nu_a}(T_e) + \Phi_{\nu_a}(T_e)}{\frac{2\nu^2 kT_e}{c^2}\varkappa_{\nu}} F_{\mathrm{rad}}, \tag{13}$$

where $\kappa_{\nu} = \alpha \cdot N_e^2$ is the absorption coefficient of the radio-frequency radiation.[8] It is convenient to use instead of F_{rad} the "effective temperature" of the radio emission of the sun, given by the expression $T_{\mathrm{eff}} = (\lambda^2/2k\Omega_{\odot})\, F_{\mathrm{rad}}$. Then we have the expression

$$F_{\mathrm{uv}}^{\nu_a} = \frac{N_e^2}{\varkappa_{\nu}}\{\Psi_{\nu_a}(T_e) + \overline{\Psi}_{\nu_a}(T_e) + \Phi_{\nu_a}(T_e) + \overline{\Phi}_{\nu_a}(T_e)\}\frac{T_{\mathrm{eff}}}{T_e}. \tag{14}$$

which will be useful in our further discussion.

Both types of hard radiation from the corona—that from hyperbolic transitions and that from recombinations—are due to the presence of ionized hydrogen and helium in the corona. But besides the hydrogen and helium (in which the corona is particularly rich) there must also be present in the corona many ionized atoms of iron, nickel, etc. The recombination of these ions with free electrons will produce radiation with a continuous spectrum of extremely small wavelengths, of the order of tens of Angstroms. It can be shown that the flux of this radiation at the boundary of the earth's atmosphere is of the order of 10^{-3} erg cm^{-2} sec^{-1}, that is, much smaller than the flux of the hydrogen and helium radiations.

Up to now we have considered only the hard radiation of the corona in the continuous spectrum. The corona must also have an extremely rich line spectrum in the short-wave region.

In fact, all iron ions that emit corona lines have resonance potentials of the order of 30 – 40 v, and the nickel ions isoelectronic with the iron ions have somewhat higher resonance potentials.[11] For some of these ions (Fe X, Fe XI, Fe XV) the ultraviolet spectra, very rich in (allowed) lines, have been obtained under laboratory conditions and studied by Edlén.[12] Under the conditions of the solar corona, where collisions of the second kind do not play any appreciable role (even for metastable levels) because of the extreme rarefaction of the matter, the intensity of any emission line is determined by the number of excitations of the initial level. Since excitation by radiation from the photosphere cannot be of any importance in the inner corona (the lines located in the part of the spectrum accessible to observation arise in transitions from metastable levels, and for the extremely short-wavelength "allowed" lines, of which we shall be speaking here, the exciting radiation from the photosphere is very weak), the main mechanism of excitation of the initial levels must be electron impact.

Since the electron temperature in the corona is of the order of millions of degrees, the mean kinetic energy of the electrons is about 150 ev. This means that practically every collision of an electron with any multiply ionized atom can lead to the excitation of a resonance level of the latter. If the effective cross section for excitation of levels with potentials $\sim 30 - 300$ v by electron impact is comparable with that for excitation of sublevels of the ground configuration (with transitions from which the observed emission lines of the corona arise), then the number of "hard" quanta emitted will be comparable with the number of quanta emitted in the observed part of the spectrum. Since, however, the energy of each hard quantum is tens of times that of an "optical" quantum, it can be expected that the absolute value of the intensity of the hard corona radiation will be tens of times the intensity of the observed monochromatic radiation.

The flux of continuous-spectrum radiation from the corona (caused by the scattering of the sun's light by the free electrons of the corona) is ~ 1 erg cm^{-2} sec^{-1}. The line radiation is about 1 percent of the total radiation of the corona. It follows that the expected flux of hard line radiation of the corona is ~ 0.1 erg cm^{-2} sec^{-1}.

For quantitative calculations of the hard monochromatic radiation of the corona it is necessary to know the effective cross sections for the excitation by electron impact of the allowed levels of the ions in the corona. The calculation of exact cross sections of complex atomic systems for comparatively slow electrons is a very hard problem, and it has not yet been solved for the ions in the corona. As a crude approximation to the actual situation we can approach the solution of this problem in the following way.

According to Mott and Massey,[13] the effective cross section for excitation is

$$Q = \frac{16\pi^3 e^4}{v^2 h^2} |x_{0n}|^2 \ln \frac{2mv^2}{\chi}, \tag{15}$$

where instead of the wave vector **k** of the incident electron we have introduced its momentum, and x_{0n} is the coordinate matrix element corresponding to the optical transition in question:

$$|x_{0n}|^2 = \left| \int \Psi_0 x \Psi_n d\tau \right|^2. \tag{16}$$

It is convenient to introduce instead of $|x_{0n}|^2$ another quantity proportional to it, the oscillator strength of the line in question,

$$f_{0n} = \frac{8\pi^2 m}{3h} \nu \, |Z_{0n}|^2 = \frac{8\pi^2 m\nu}{h} |x_{0n}|^2, \tag{17}$$

where ν is the frequency of the line; we have set $|r_{0n}|^2 = 3|x_{0n}|^2$, which is of course at least approximately correct.

Substituting Eq. (17) in Eq. (15) and denoting the excitation energy by χ, we get

$$Q = \frac{2\pi e^4}{mv^2\chi} f_{0n} \ln\left(\frac{2mv^2}{\chi}\right). \tag{18}$$

The amount of energy emitted in a line in the short-wavelength part of the spectrum per unit volume of the corona and unit time is given by

$$4\pi \bar{F}_\nu = N_0 N_e \chi \int_{V_0}^{\infty} \varphi(v)\, v Q(v)\, dv$$
$$= N_0 N_e \frac{4\pi e^4}{(2\pi m k T_e)^{1/2}} f_{0n} \left[e^{-\frac{\chi}{kT}} \ln 4 + \frac{\chi}{kT_e} \left\{ - E_i\left(-\frac{\chi}{kT} \right) \right\} \right], \tag{19}$$

where $\varphi(v)$ is the velocity distribution function of the electrons.

In calculating the hard monochromatic radiation of the corona we must give particular attention to the elements that are most abundant in the universe. There are serious grounds for supposing that the elements that are most abundant in the reversing layer of the sun must also be the most abundant in the corona.

For this purpose let us examine the spectra of ions isoelectronic with hydrogen. A distinguishing feature of this series must be the presence of the extremely intense resonance doublets

$$2^2P_{1^1/_2,\, ^1/_2} - 2^2S_{^1/_2}.$$

We consider those elements of this isoelectronic series that have ionization potentials comparable with those of the corona ions Fe and Ni. For example, the ion O VI, which has ionization potential 137.48 v, is almost entirely absent under the conditions in the corona, where the oxygen is in higher states of ionization.* On the other hand Mg X has an ionization potential 376 v and is quite capable of "existing" in the corona. The ionization potentials of Ne VIII and Na IX are 243 v and 305 v, respectively; consequently these ions also can "live" under coronal conditions.[14]

The spectrum of Mg X has been studied under laboratory conditions.[14] The resonance transition $^2P_{3/2}$—$^2S_{1/2}$ gives a line λ625, and the transition $^2P_{1/2}$—$^2S_{1/2}$ a line λ610. The spectrum of Na IX has also been studied, but because of the relatively low cosmic abundance of sodium we shall not take into account the resonance radiation of coronal Na IX ions (see below). The wavelengths of the corresponding transitions in Ne VIII can be found by linear interpolation. They are λ770 and λ760.

A fact worthy of attention is that the ionization potential of Ne VIII is close to that of Fe X (261 v), and that of Mg X is close to that of Fe XIV (390 v).†

Consequently, on the basis of the existing theory of the ionization of the corona[8] we can draw the conclusion that the abundance of Ne VIII will appear enhanced in those regions of the corona where light of the line Fe X λ6374 predominates, and that of Mg X will appear high in regions of the corona where the line Fe XIV λ5303 is particularly intense.

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*This state of ionization of O is encountered only in the region of the solar atmosphere transitional between the chromosphere and the corona (cf. reference 8).

†That the corona must emit an intense hard monochromatic radiation was shown in 1945.[4] In 1948 Allen and Wooley[5] came to this same conclusion, stating that a line of Mg X is the most intense.

The cosmic abundance of magnesium (relative to hydrogen) is $[\mathrm{Mg}]/[\mathrm{H}] = 3 \times 10^{-5}$. Up to now there have been no data on the abundance of neon in the reversing layer of the sun, since neon lines are not observed in the Fraunhofer spectrum of the sun. Therefore we shall take the relative abundance of neon in the solar atmosphere to be the same as in planetary nebulae, i.e., $[\mathrm{Ne}]/[\mathrm{H}] = 10^{-4}$.

Let us now find the total amount of hard monochromatic radiation (in the resonance lines of Ne VIII and Mg X) that is produced per unit time in the entire corona. We assume here that radiation is produced in each volume element, and we shall regard the corona as a spherically symmetrical formation with the density given by Eq. (5). To simplify the calculation we shall assume that only one resonance line is emitted, and that the relative abundance of the element emitting it is somewhat above the average of the relative abundances of magnesium and neon.

In accordance with the formulas (18) and (5) we have

$$4\pi \int \bar{F}_\lambda \, d\tau = R_\odot^3 \delta 4\pi \int_{1,04}^{\infty} \widetilde{\Phi}(\mathrm{Te}) N_e^2(r) r^2 dr$$

$$= \delta f_{0n} \cdot 4\pi \widetilde{\Phi}(\mathrm{Te}) \cdot 10^{16} \cdot 0{,}66$$

$$= \frac{16\pi^2 e^4 R_\odot^3}{(2\pi m k T_e)^{1/2}} \delta f_{0n} \cdot 10^{16} \cdot 0{,}66 \left[e^{-\frac{\chi}{kT_e}} \ln 4 + \frac{\chi}{4kT_e} \left\{ -E_i\left(-\frac{\chi}{kT_e}\right)\right\}\right], \tag{19a}$$

where τ is a volume element in the corona; the integration is taken over the entire volume of the corona, with its inner boundary taken at the provisional value r = 1.04.

Carrying out the calculation, we get

$$4\pi \int \widetilde{F}_\lambda d\tau = 0{,}6 \cdot \bar{\delta} \cdot 10^{31}, \tag{20}$$

if we assume that $f \sim 0.3$.

Setting $\bar{\delta} = 3 \times 10^{-5}$, which corresponds to the relative abundance of magnesium (whose presence in the solar atmosphere is reliably established), we get as the value of the flux of hard monochromatic radiation of the corona at the boundary of the earth's atmosphere (supposing that half of the radiation that has been calculated falls back on the sun):

$$S_{\mathrm{Mg\,X,\,Ne\,VIII}} = \frac{1}{2} \frac{4\pi \int \bar{F}_\lambda \, d\tau}{4\pi R^2} \approx 0{,}05 \text{ erg/sec}, \tag{21}$$

where R is the distance from the earth to the sun.

There is, however, some uncertainty in these calculations, since the ionization of the magnesium and neon has not been calculated exactly. Also the approximate equality of the ionization potentials of Ne VIII and Mg X to those of Fe X and Fe XIV may not have the result that Ne VIII and Mg X are the most commonly occurring states of ionization of these elements in the various regions of the corona. It is quite possible that the value of $\bar{\delta}$ should be changed to a value smaller by as much as a factor 10.

It can be expected that owing to the existence of hard monochromatic radiation from the corona the integral spectrum of the sun in the region $\lambda < 1000$ A is of the line type.

In fact, if we assume that in this region of the spectrum the photosphere emits like an absolutely black body at a temperature $\sim 4800°$ (the boundary temperature of the sun), then the ratio of the energy it emits in a wavelength interval ~ 1 A in the range $\lambda < 1000$ A to that emitted in one of the corona lines in this region of the spectrum will be smaller than unity. Consequently, in the far ultraviolet region of the spectrum the radiation from the sun must be determined almost exclusively by the corona. As we shall see in Sec. 2, this prediction of the theory has been confirmed by the most recent observations.

A few years after our work, a much more detailed study of the hard monochromatic radiation from the corona was made by Elwert.[7] In his work particular attention was given to the spectral region intermediate between the far ultraviolet and soft x rays ($\lambda < 300$ A). Specifically, Table III shows the wavelengths of transitions of the cosmically most abundant elements in suitably high states of ionization.

Table III

Ion	Transition	λ	$Y_{zi} \cdot 10^6$		
			$T_e = 6 \cdot 10^5$	$7 \cdot 10^5$	10^6
He II	$1s-2p$	304	3	2	2
C IV	$1s^2 2s\,^2S_{1/2} - 1s^2 3p\,^2P_{1/2}$	312	0,08	0,02	—
C V	$1s^2\,^1S_0 - 1s2p\,^1P_1$	40	0.4	0,6	1,5
C VI		33	0,01	0,05	0,7
N V	$1s^2 2s\,^2S_{1/2} - 1s^2 3p\,^2P_{1/2}$	210	0,0	0,3	0,2
N VI	$1s^2\,^1S_0 - 1s2p\,^1P_1$	29	0,07	0,3	2
N VII		19	—	—	0,1
O VI	$1s^2 2s\,^2S_{1/2} - 1s^2 3p\,^2P_{1/2}$	150	4	2	1
O VII	$1s^2\,^1S_0 - 1s2p\,^1P_1$	22	—	0,03	0.5
Ne VII		95	4	2	—
Ne VIII		85	9	7	7
Mg VIII	$2s^2 2p\,^2P_{1/2} - 2s^2 3d\,^2D_{3/2}$	75	1	0,5	—
Mg IX	$2s^2\,^1S_0 - 2s3p\,^1P_1$	63	0.3	0,6	0.5
Mg X	$2s\,^2S_{1/2} - 3p\,^2P_{1/2}$	58	0.02	0,15	0,6
Si VIII	$2s^2 2p^3\,^4S_{3/2} - 2s^2 3p^2 3s\,^4P_{5/2}$	67	1.2	1,2	0,1
Si IX	$2s^2 2p^2\,^1S_0 - 2s^2 2p3d\,^1P_1$	55	0.4	0,8	0,5
Si X	$2s^2 2p\,^2P_{3/2} - 2s^2 3d\,^2D_{5/2}$	51	0.01	0,2	1
Si XI		42	—	—	0,4
S VII		70	0.3	0,2	—
S VIII		60	0.3	0.7	0,1
S IX		52	0.05	0.3	0,4
S X		43	—	—	0,5
Fe IX	$3s^2 3p^6\,^1S_0 - 3s^2 3p^5 4s\,^3P_1$	105	1	0,3	—
Fe X	$3s^2 3p^5\,^2P_{3/2} - 3s^2 3p^4 4s\,^2P_{1/2}$	97	4	1.5	—
Fe XI	$3s^2 3p^4\,^3P_1 - 3s^2 3p^3 4s\,^3S_1$	88	4	5	0,7
Fe XII		73	1,3	4	3
Fe XIII		65	0.04	0,7	4
Fe XIV		62		0.1	2
Fe XV		55			0,4

Elwert calculated the effective cross sections for excitation by electron impact for various ions in the corona, by treating them as hydrogenlike systems. We shall not go into the details of these calculations.

We remark, however, that extra refinement of the theory (as in reference 7) seems to us unnecessary, because in any case the use of the Born approximation in the calculation of the cross sections brings in very large errors. On the other hand calculations not based on the Born approximation are very complicated, and at present it is hard to make them for the large number of collision processes that occur in the corona.

Rather lengthy calculations made in reference 7 give for the monochromatic volume luminosity for a line belonging to a definite ion the result

$$J_{zi} = N_e^2 4\sqrt{\pi} f_3 \propto a_0^2 c\chi_H \left(\frac{\chi_H}{kT}\right)^{1/2} Y_{zi}, \qquad (22)$$

where f_3 is a dimensionless factor to allow for possible errors in the method used to calculate the cross sections, α is the fine-structure constant, and $Y_{zi} \propto n_i$, where n_i is the concentration of the particular ion in the corona and Y_{zi} is a function of the temperature which also depends on the parameters of the line in question. It obviously involves the calculated effective cross section for the transition considered. Table III contain values of Y_{zi} for various lines and various temperatures of the corona.

Although the calculated effective cross sections contain large errors and the actual values of the monochromatic volume luminosity may be very different from the theoretical values, Table III is very interesting. First of all we note that the quantity n_i included as a factor in Y_{zi} is obtained on the basis of the theory of the ionization of the corona (cf. e.g., reference 8). Thus the changes of Y_{zi} with change of temperature reflect the changes of the state of ionization of the corona.

Table III is essentially the analog of the classical ionization theory of the change of intensity of spectral lines with changing temperature, which was developed for conditions of thermodynamic equilibrium in papers by Saha, Milne, and Fowler. The intensity of a line in the ultraviolet or x-ray region of the spectrum reaches a maximum at a certain temperature. For example, the line Mg IX λ 63 A has its maximum intensity at $T_e = 7 \times 10^5$. Many lines in Table III show monotonic variation of intensity with temperature. This, however, is due simply to the fact that the values of Y_{zi} have been calculated over a comparatively narrow range of temperatures.

Knowing Y_{zi}, we can find the flux of radiation in the individual corona lines that falls on the boundary of the earth's atmosphere. The values of these fluxes are shown in Fig. 3 for various temperatures. The abscissa is the wavelength, and ordinates are values of the fluxes divided by the quantity $Q' = f_3 Q$; f_3 is the previously mentioned "uncertainty factor" in Elwert's calculations, and Q is the parameter for the inhomogeneity of the corona (see above). In this diagram circles denote values of the radiation flux beyond the series limit of ionized helium (228 A) and for a group of corona ions concentrated around 50 A. As can

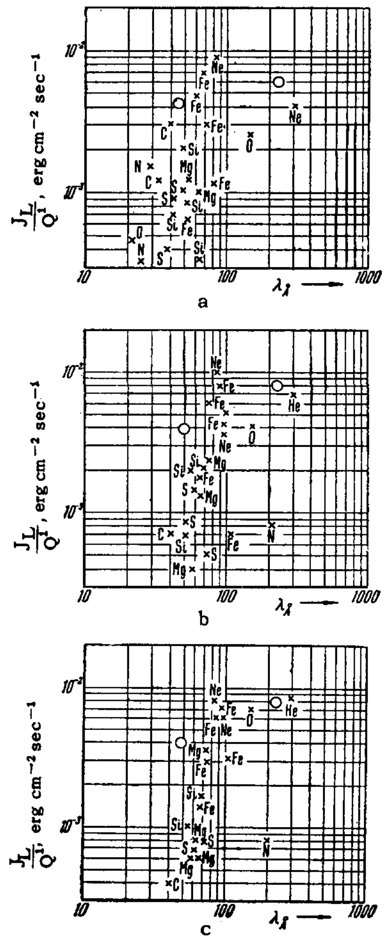

FIG. 3. Fluxes of radiation for individual lines (Elwert[7]): a) 6×10^5 °K; b) 7×10^5 °K; c) 10^6 °K.

be seen from Fig. 3, the "line" radiation of the corona at $T_e = 10^6$ is appreciably displaced toward shorter wavelengths as compared with the radiation at $T_e = (6-7) \times 10^5$. In the former case the "center of gravity" of the emission lines is near 60 A, and in the latter near 80 – 90 A.

The total flux of radiation at the boundary of the earth's atmosphere is $0.06\,Q$ erg cm^{-2} sec^{-1}, of which, at $T_e = 10^6$, at least $0.04\,Q$ erg cm^{-2} sec^{-1} is in the region around 60 A.

It would be interesting to extend these calculations to the region of higher temperatures, for example $(1.5-2.0) \times 10^6$ and above.

It can already be seen from Table III that at lower electron temperatures the lines of He II, O VI, and other lines belonging to ions with relatively low ionization potentials, can reach considerable intensities. The corresponding temperature, of the order of 10^5, can be reached in the region of the solar atmosphere located between the upper chromosphere and the inner corona.

From observations made only in the optical region of the spectrum it is very difficult, if not impossible, to find the physical characteristics of this very interesting "transitional" region. On the other hand, observations in the ultraviolet part of the spectrum can give (and, as we shall see in the next section, do give) extremely important information about the "transition" region.

We may assume that in the "transition" region $N_e \approx 10^9$ cm^{-3}, that the height of the layer is about 3×10^9 cm, and that $T_e \sim 3 \times 10^5$. Evidently this region, like the upper chromosphere and the corona, has an extremely inhomogeneous "ragged" structure. The temperature and density must be largest above the flare fields. The "emission figure" is $\int N_e^2\, dh = 10^{28}$ cm^{-5}, whereas for the corona $\int N_e^2\, dr = 5 \times 10^{26}$ cm^{-5}. Of course inclusion of the inhomogeneity of the distribution in height of the ionized gas can change these estimates, but it is far from clear where the "uncertainty factor" is larger—in the corona or in the "transition" region.

Since the emission figure of the "transition" region is much larger than that of the corona, and the temperatures there can be such that, for example, O VI and N V are the most frequent stages of ionization of these elements, the ultraviolet lines of O VI, N V, and so on can be very intense. A particularly intense line must be that of He II, $\lambda = 304$ A, because of the extremely large cosmic abundance of helium.

Since the lines in question are allowed and the initial level is the ground state for the corresponding ion, the optical thickness must be considerable in the region of the line. The development of a theory of the production of such strong lines under the conditions of the "transition" region is only beginning.

The optical thickness must also be appreciable for the allowed ultraviolet corona lines, and this must obviously lead to a change of the brightness distribution as compared with that found above. This question is discussed by Elwert,[15] and we shall now give the results of his calculations.

In the neighborhood of a spectral line the absorption coefficient is given by

$$K_\nu = \frac{2\pi^{3/2}e^2}{mc}\frac{f}{\Delta\nu_D}e^{-(\Delta\nu/\Delta\nu_D)^2}. \qquad (23)$$

Let us set

$$v = \frac{\Delta\nu}{\Delta\nu_D}, \quad r_0 = \frac{e^2}{mc^2}, \quad K_0 = 2\pi^{3/2} c r_0 \frac{1}{\Delta\nu_D}.$$

Then the total intensity of the line after passage through the scattering layer is given by

$$J = J_0 \frac{2}{\sqrt{\pi}} \int_0^\infty \exp\{-v^2 - \tau_0 e^{-v^2}\}\, dv, \qquad (24)$$

where $\tau_0 = NK_0 f$ is the optical thickness at the center of the line (N is the number of scattering atoms on the line of sight). Expanding Eq. (24) we have

$$J = J_0\left(1 - \frac{\tau_0}{1!\sqrt{2}} + \frac{\tau_0^2}{2!\sqrt{3}} + \cdots\right). \qquad (25)$$

In the case of the resonance lines of Mg X, $K_0 \approx 10^{14}$ (if $f = 0.3$ and the temperature, which determines the Doppler half-width, is $T = 10^6$). Taking for the relative abundance of magnesium the value 3×10^{-5}, we find that the number of magnesium ions in a radial column of unit cross section is $N \sim 3 \times 10^{18} \times 3 \times 10^{-5} \sim 10^{14}$ cm^{-2}. Consequently, $\tau_0 \sim 1$.

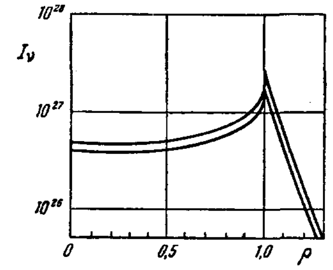

FIG. 4. Brightness distributions across the sun's disk for monochromatic ultraviolet radiation in the cases $\tau = 0.5$ and $\tau = 1.0$.

This calculation shows that the corona cannot be regarded as transparent for allowed ultraviolet and x-ray lines produced in it. According to Elwert's estimates, the optical thicknesses for many strong coronal lines in the soft x-ray region of the spectrum are $\sim 0.3 - 1.0$.

Inclusion of the effect of finite optical thickness on the brightness distribution in a corona line across the sun's disk leads to the calculation of integrals of the type

$$I^*(\varrho) = I_0 \int N_e^2 J[\tau_0(N_e)]\, dx. \qquad (26)$$

The integration has been carried out by a numerical method. The brightness distribution of monochromatic corona radiation across the sun's disk is shown in Fig. 4 for $\tau_0 = 0.5$ and $\tau_0 = 1.0$. Figure 5 shows Elwert's calculated brightness distribution for a nonspherical minimal corona. As compared with the brightness distribution for an optically thin layer (see Fig. 2), the curves obtained when self absorption is taken into account differ in some features. An important difference is that in the latter case the increase of brightness at the edge is not so pronounced.

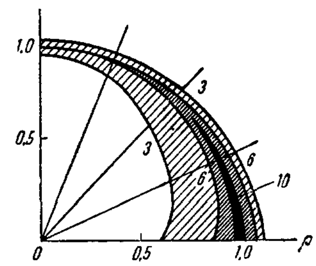

FIG. 5. Brightness distribution of ultraviolet monochromatic radiation for the minimal corona ($\rho = r/r_\odot$).

Up to now we have been regarding the corona as a spherically symmetrical formation. Actually it has a rich structure. Above active regions the corona is especially dense, and also has a higher temperature. Inclusion of effects of the structure of the corona and the presence in it of large-scale inhomogeneities must surely bring considerable changes in the theoretical brightness distribution of ultraviolet radiation across the disk. The true brightness distribution must be extremely irregular. Above active regions we must expect that there will be more or less extended and very

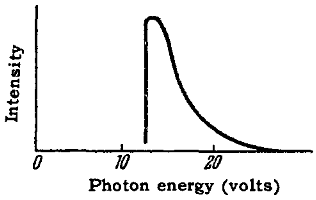

FIG. 6. Spectral distribution of the ultraviolet recombination radiation of the chromosphere.

bright "spots" of ultraviolet and soft x rays. We shall see later that observations have indeed revealed the existence of such spots.

Another source of ultraviolet radiation beyond the limit of the Lyman series must be the upper chromosphere and the transition region of the solar atmosphere between the upper chromosphere and the corona. The temperature in this region must be some tens of thousands of degrees, and $N_e \sim 10^{10} - 10^{9}\ \mathrm{cm}^{-3}$. Because of the large density the flux of radiation from the upper chromosphere and the transition region with $\lambda < 1200$ A can be an order of magnitude larger than that from the corona. Because of the relatively small T_e, however, the intensity must fall rapidly at 700 – 800 A. In 1949 we made a rough estimate of the magnitude of this flux for $T = 20{,}000°$.[4] The results of the calculations (the intensity as a function of the photon energy $h\nu$) are shown in Fig. 6. Figure 7 shows schematically the spectral distribution of the total coronal and photospheric radiation in the continuous spectrum with $h\nu > 13.5$ ev.[4] Just as in the case of the hard coronal radiation, the hard radiation from the upper chromosphere and the transition region must have a "spotty" structure, with sharply greater intensity over active regions. Although T is smaller in the intermediate region between the upper chromosphere and the corona than it is in the corona, N_e is much larger. Therefore the emission $\int N_e^2\,dr$, which determines the intensity, is much larger than in the corona. Consequently, we can expect that the intensities of lines belonging to the "intermediate" (higher than in the chromosphere and lower than in the corona) stages of ionization of abundant elements (for example, O VI, N V) will be large.[17] In the next section a preliminary model of the intermediate region will be discussed on the basis of an analysis of the observed ultraviolet radiation of the sun.

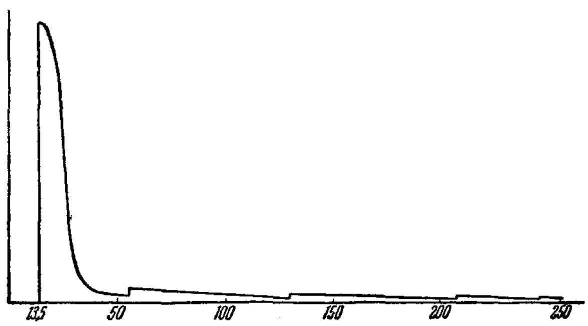

FIG. 7. Scheme of spectral distribution of "continuous" radiation of the chromosphere and corona.

It will be shown in that section to what extent the observations which it has been possible to make in recent years confirm the theoretical ideas we have developed here.

2. SURVEY OF THE MAIN RESULTS OF ROCKET AND ARTIFICIAL SATELLITE OBSERVATIONS OF THE ULTRAVIOLET RADIATION AND SOFT X RAYS OF THE SUN

As has already been remarked in Sec. 1, the development of rocket technology during the second world war opened up the possibility of carrying detectors of hard photon radiation to heights at which the absorption of the atmosphere becomes unimportant. In the period after the war we have witnessed the very successful and rapid development of this new and important branch of astronomy, which has received the name of "rocket astronomy." At present rocket astronomy, along with rocket geophysics, is a science which, though it has the closest connections with astrophysics (or geophysics), differs decidedly from the older science in its methods of investigation. We cannot pretend to give here an exhaustive exposition of the main results, to say nothing of the methods, of rocket astronomy. Our task is to show how the results of the observations agree with the theoretical ideas developed in the preceding section.

First let us enter very briefly into the history of these researches. While the war was still going on the German scientists Kippenhauer and Regener planned studies of the ultraviolet radiation of the sun by means of rockets.[18] By 1943 they had prepared a special spectrograph with fluorite optics. Moreover, an automatic aiming apparatus was being developed to point at the sun. But the fascist regime cared very little for scientific research without direct military importance. The Kippenhauer-Regener project was never brought to realization.

After the war the Americans seized a number of type V-2 rockets as military trophies. American scientists at the Naval Research Laboratory used these rockets to study the ultraviolet radiation of the sun. For this purpose they constructed a special spectrograph, by means of which, on October 10, 1946, from a height of 55 km, the spectrum of the sun down to 2200 A was obtained for the first time.*

In subsequent years the techniques of rocket astronomy were steadily perfected. An extremely important development was that of a reliable tracking device (in two coordinates), with which, in spite of the lack of stabilization of the rocket, the radiation detector can be aimed at the sun with adequate accuracy.

*In the Soviet Union a good spectrum of the sun down to 2470 A was obtained in 1958 by A. V. Yakovleva and others.[19]

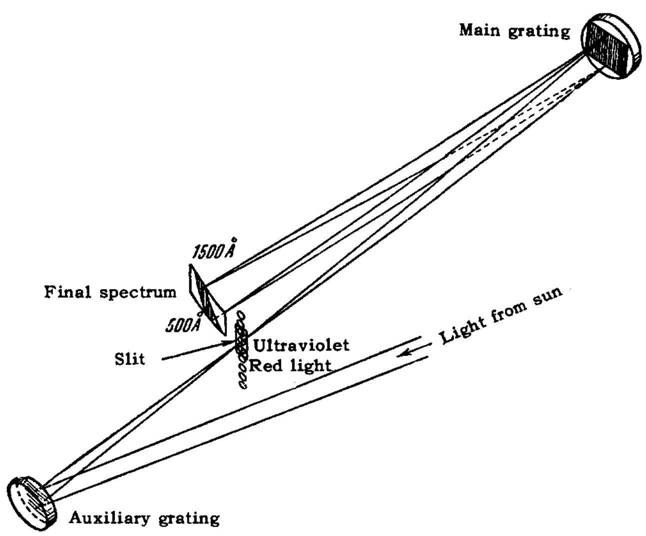

FIG. 8. General arrangement of the spectrograph.

Studies of the hard photon radiation of the sun have followed three trends. The first was to obtain high-quality slit spectrograms of the ultraviolet radiation of the sun. Particular attention was paid to the study of the line L_α.

The second research trend is characterized by the use of various sensitive detectors of the hard photon radiation of the sun in combination with filters of various spectral widths. The readings of a detector carried in a rocket are telemetered to the earth. These researches were begun in 1948 in the Naval Research Laboratory, with the use of a thermoluminescent phosphor as the detector. A result of this work was the detection of the emission line L_α in the spectrum of the sun. Subsequently much better and more sensitive detectors came into use—photon counters and ionization chambers; outstanding successes were achieved in the development and perfecting of these devices.

An important advantage of indicators of this type is the possibility of absolute measurements of fluxes of hard radiation. Because they have practically no lag, such detectors are indispensable in the study of rapidly varying fluxes of hard photon radiation observed at the time of bursts. They are also extremely useful in the study of the transparency of the earth's atmosphere in various spectral regions; such studies provide an experimental determination of the stratification of various atoms and molecules in the atmosphere.

The third trend in rocket research is to obtain images of the sun in various parts of the ultraviolet and x-ray spectra. Although this work began only very recently, highly interesting results have already been obtained.

Let us now go on to the description of the solar spectrum in the short-wave region. The results of the observations have been published in references 20 — 23, and also in a review article.[24] We shall base our remarks on the latest and best observations of the period 1959-1960.[25]

The schematic arrangement of the spectrograph with which these spectra were obtained is shown in Fig. 8. This is the usual scheme of a spectrograph with normal incidence of the light rays, with a curved auxiliary grating introduced. Like the main grating, it has a 40-cm radius of curvature and 600 lines per millimeter. The gratings are used in the first order. The first grating resolves the image of the sun up into a "vertical" spectrum along the slit. The astigmatism that it introduces is exactly compensated by the second (main) grating. The latter disperses the light incident on the slit in the horizontal plane. The slit width corresponded to 1 A. With this choice of slit width it is possible to register both the individual spectrum lines and the continuum.

Figure 9 shows spectra of the sun obtained with this spectrograph, extending from λ 2100 to 500 A. We do not show the spectrum of the sun in the region 2900 — 2100 A, which cannot be observed from the earth's surface but was obtained as early as 1946, since it is quite like the ordinary solar spectrum and holds no particular interest for us. The first thing the spectrograms show is that at λ 2085 the continuous spectrum of the sun falls off sharply in intensity to a value corresponding to the residual intensities of the Fraunhofer lines. We remark that in the range 2900 — 2100 A the continuous spectrum of the sun corresponds to $T = 4500$. Beginning at λ 2085 A the visibility of the Fraunhofer lines is poor. At about 1550 A the character of the continuous spectrum shows a qualitative change and the Fraunhofer lines disappear completely. This strictly continuous spectrum can be followed down to 1000 A. Already at 2000 A the solar spectrum begins to show emission lines superimposed on the continuum. Beginning at 1500 A the spectrum of the sun is basically a bright-line spectrum, as predicted by the theory (see preceding section). At about 1648 A the line of He II analogous to H_α is clearly seen. The bright resonance line L_α of hydrogen is seen at 1216 A. In all, 11 lines of the Lyman series can be seen in the spectra of Fig. 9. Besides L_α, there are bright resonance lines of O I, C II, C III, Si IV, S III, O VI, and N II in the region 1400 — 1000 A. They are, however, less intense than L_α by at least an order of magnitude. We note in passing that according to many measurements with ionization chambers the radiation flux of L_α is about 6 erg cm^{-2} sec^{-1}. The flux of L_β is smaller by a factor 60.

The bright Lyman continuum is seen at 912 A, and can be followed down to 800 A. Undoubtedly it arises in the upper chromosphere, in the region of the flocculae. This follows from its uneven structure in the direction perpendicular to the dispersion. If this Lyman continuum were produced in the corona, its intensity would not fall off so rapidly and it would extend with almost constant brightness through the entire spectrum (see Fig. 7). This is also to be expected theoretically (see preceding section, Fig. 6).

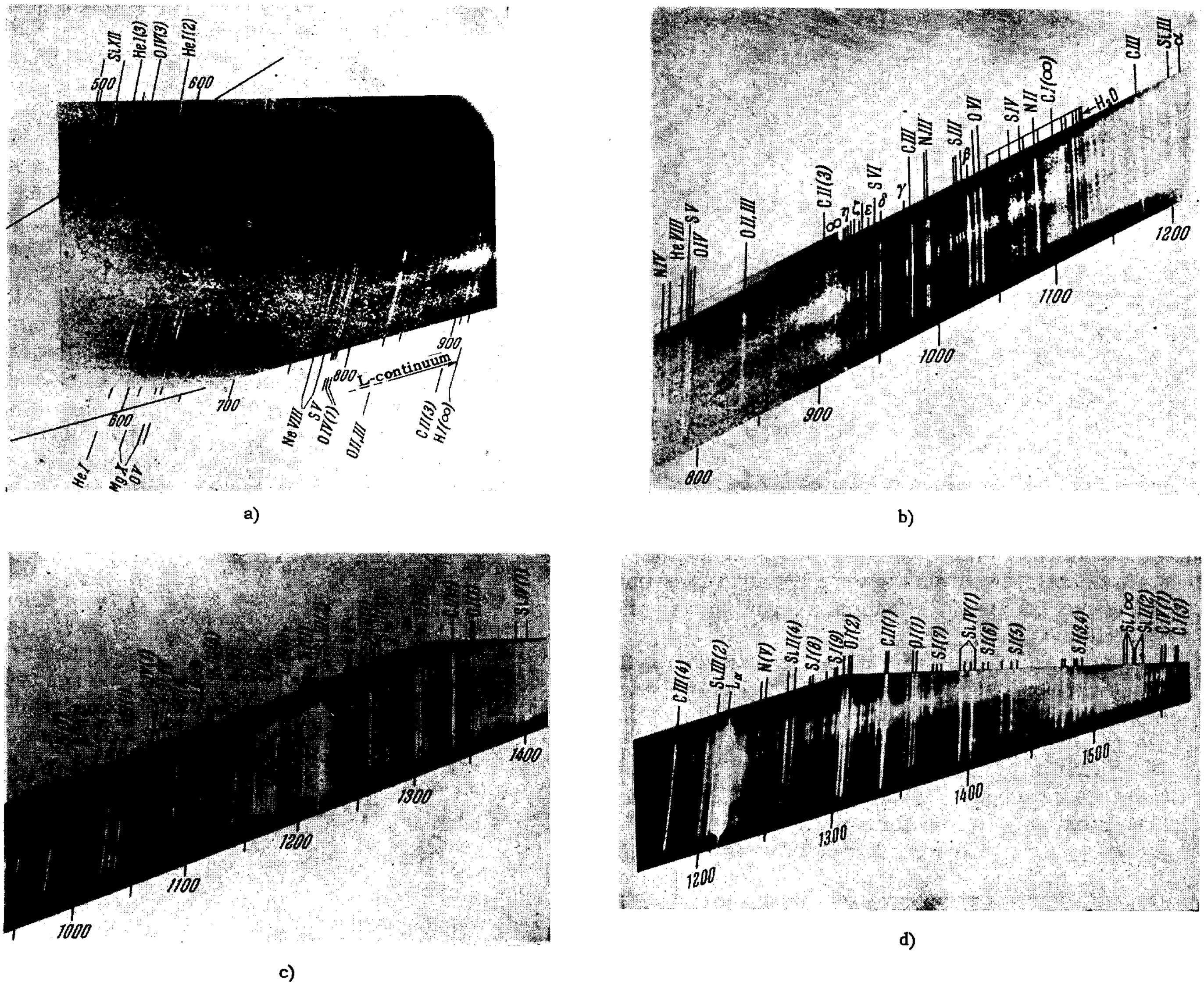

FIG. 9a, b, c, d. Spectrum of the sun in the region 2100 > λ > 500, April 19, 1960.

The coronal hydrogen and helium continua begin to predominate over the chromospheric continua only at λ = 700 — 600 A (see Fig. 7), but they are too weak to be visible in these spectrograms. Although there is as yet no exact photometry of these spectra, we can judge from the gradient of the brightness of the Lyman continuum that the "equivalent" electron temperature of the active regions of the upper chromosphere (at the level where the Lyman continuum is emitted) is ~ 10,000 — 15,000°.

Beyond λ < 800 A the spectrum becomes weaker; there is much scattered light, and possibly the sensitivity of the emulsion falls. Here one can see the following emission lines: unresolved line of O II – O III, lines of O IV, O V, N IV, and also the resonance corona lines of Ne VIII and Mg X, which have been described in detail in Sec. 1. The line of Na IX is absent; this is due to the relatively small abundance of sodium. At the edge of the spectrogram one can see the resonance line λ 584.3 of neutral helium.

At the very end of the spectrum shown in Fig. 9 it has been possible to identify two weak corona lines of Si XII, λ 499.7 — 521.2. They cannot be made out in this reproduction. Altogether about 200 emission lines have been registered in the region 1500 — 500 A of the solar spectrum. Since there is still no photometry of these spectra, it is hard to speak about the relative intensities of the spectral lines, especially in the region beyond the limit of the Lyman series, which is of most interest to us.

It is noteworthy that there are a great many lines belonging to the "intermediate" stages of ionization of the cosmically abundant light elements. We have in mind the bright lines of C IV, N V, O V, O VI, and so on. Undoubtedly they are produced in the "transition" layer between the chromosphere and the corona.

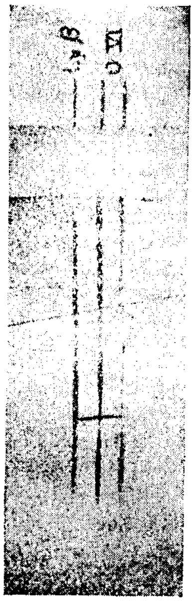

FIG. 10. Highly enlarged part of the solar spectrum near L_β.

From the spectrograms that have been obtained one can also get some idea about the character of the intensity distribution of the lines across the disk of the sun. It turns out that different lines behave differently in this respect. Figure 10 shows a highly magnified part of the spectrum near L_β. Beside this line is the resonance line of O VI. It can be clearly seen that the latter line is brighter at the edge, while L_β does not show this effect. The line of O VI is emitted in the region of the solar atmosphere intermediate between the chromosphere and the corona. Therefore its becoming brighter toward the edge is completely explained by the theory developed in the preceding section.

FIG. 11. Highly enlarged part of the solar spectrum near λ 1240.

On the disk both lines, L_β and the O VI line, show brightening in two places. This is explained by the fact that the slit of the spectrograph intersected two active regions. This effect is particularly well visible in the Lyman continuum.

Figure 11 shows an enlargement of part of the solar spectrum near λ 1240. It can be seen that near the bright line N V λ 1242 there is a weak line, which goes out beyond the edge of the sun by at least 3′. This is a new corona line which has not yet been identified.

In 1958-59 Rense and Violett used an oblique-incidence grating spectrograph to get solar spectra in the wavelength region from L_α to 80 A.[26] They found about 100 emission lines on their spectrograms. The brightest lines besides L_α are He II 303.78 and He I 584.3. The He II line is considerably more intense than the He I line. Most of the other lines belong to intermediate stages of ionization of the most abundant light elements. According to reference 26, the line λ 303.78 is especially intense. After correction for absorption in the earth's atmosphere its intensity, according to reference 26, is even larger than that of L_α. It seems to us, however, that the procedure used for the correction is not correct and that the result of Rense and Violett is extremely doubtful. According to preliminary estimates made in reference 26, the total intensity of the lines in the region $\lambda < 912$ A, which mainly belong to the chromosphere and the intermediate region, is about the same as the intensity of L_α. This result also needs confirmation. The agreement of the spectrogram of Rense and Violett with that of Purcell and Tousey is very poor in the parts of the spectrum where they overlap. The large amount of scattered light which is unavoidable in an oblique-incidence spectrograph makes the results of Rense and Violett unreliable.

In 1960 Hinteregger, using monochromators with photoelectric registration, obtained a number of traces of the solar spectrum in the range 1300 — 60 A with a resolution of several Angstroms.[27] The most prominent details in the spectrum obtained by him are: the lines He I λ 584.3, He II λ 303.78, He II λ 256.32, the hydrogen continuum at 912 A, and the ionized-helium continuum at 228 A. Absolute measurements of fluxes by this method are quite reliable. They have been made by relating the radiation flux in a narrow spectral interval to that in the line L_α. This last flux was simultaneously measured with an ionization chamber.

Figure 12 shows a trace of the solar spectrum in the range $1300 > \lambda > 250$ A. The observations were made at a height of 235 km on August 23, 1960. On the same diagram curves are drawn corresponding to flux values of 10^{10}, 10^9, and 10^8 photons-cm^{-2} sec^{-1} $(\Delta\lambda)^{-1}$, where $\Delta\lambda$ is the spectral resolution, $\sim 3 - 5$ A. Some bright lines are registered in the second and third orders. For the majority of the emission lines the absorption by still higher layers of the atmosphere is

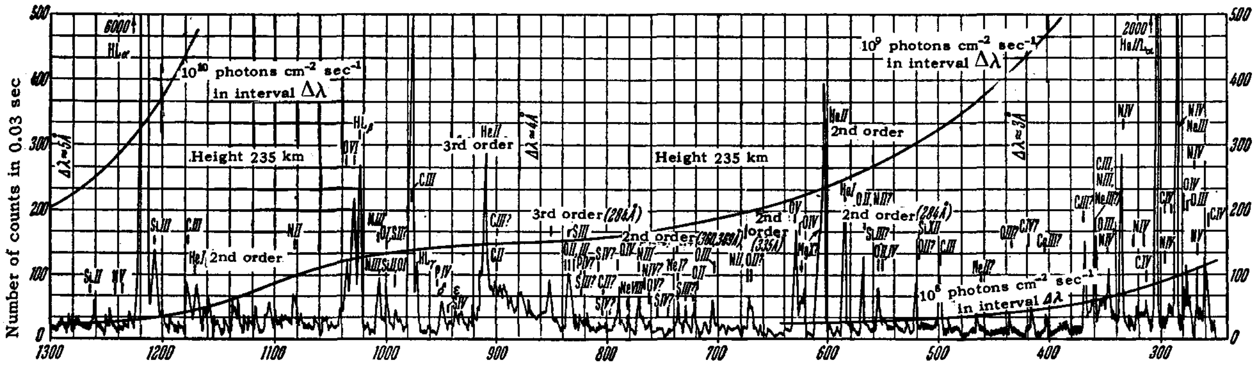

FIG. 12. Trace of the solar spectrum in the region 1300 > λ > 250 A (Hinteregger[27]).

already negligible. In other cases the correction for atmospheric absorption can be made.

According to Hinteregger the radiation fluxes from the brightest lines of the sun in this spectral region are $F_{L_\alpha} = 3.3$ erg cm^{-2} sec^{-1} (which is less than the value from Friedman's observations by almost a factor two; possibly this is due to a decrease of solar activity in the period of Hinteregger's observations), $F_{L_\beta} = 0.03$ erg cm^{-2} sec^{-1}, and for the Lyman continuum, 0.07 erg cm^{-2} sec^{-1} in the region 912 – 900 A and 0.11 erg cm^{-2} sec^{-1} in the region 900 – 840 A. The flux from the corona lines of Ne VIII (770 – 780) is 0.015 erg cm^{-2} sec^{-1}, and that from the MgX line at 610 A is 0.05 erg cm^{-2} sec^{-1} (the other Mg X line merges with a line of N V). It is curious that the flux from the Mg X lines is more than three times that from the Ne VIII lines. This can easily be understood, since the ionization potential of Mg X is close to that of Fe XIV, which is responsible for the emission of the brightest coronal line in the optical range of wavelengths. The radiation flux from the continuum of He II in the range $166 < \lambda < 228$ is about 0.1 erg cm^{-2} sec^{-1}. The radiation flux from the resonance line of He II, λ 304, is 0.25 erg cm^{-2} sec^{-1}, and that from the He I line λ 584 is 0.10 erg cm^{-2} sec^{-1}. An outstandingly intense line among those of the "intermediate" region is λ 976, which belongs to C III; its radiation flux is 0.08 erg cm^{-2} sec^{-1}. The line λ 335 (N IV) gives a flux of 0.047 erg cm^{-2} sec^{-1}. According to Hinteregger's observations the total flux of radiation from the sun in the spectral region $912 > \lambda > 500$ A is 0.53 erg cm^{-2} sec^{-1}, and that in the region $500 > \lambda > 260$ A is 0.54 erg cm^{-2} sec^{-1}. Finally, for the spectral region $260 > \lambda > 44$ A Hinteregger gives a flux value ~ 1.2 erg cm^{-2} sec^{-1}, which is based on other observations.

The work of Hinteregger is a major achievement of rocket astronomy. It has great significance for the physics of the sun and for the problem of the formation of ionospheric layers.

Summarizing all of the observational data existing at the present time, we must say that the main contribution to the radiation in the ultraviolet part of the sun's spectrum in the range $912 > \lambda > 100$ A is that from the upper chromosphere and the transitional region between the corona and the chromosphere. Unfortunately, little is known as yet about the physical conditions in this interesting region. Obviously the main method for studying this region, which in many respects is still mysterious, is the analysis of the ultraviolet spectrum of the sun, and also of the data of radioastronomy.

A recently published paper by G. S. Ivanov-Kholodnyi and G. M. Nikol'skii contains a first attempt at an interpretation of the observations on the ultraviolet spectrum of the sun.[28] Since, as has already been emphasized, the most intense lines of this spectrum belong to the intermediate region, a primary problem is to extend the existing theory of the ionization in the corona to a lower temperature range. The calculations which are made in reference 28 show, for example, that the maximum intensity of the line of C VI is reached at $T = 8.7 \times 10^4$, and that of the line of O VI, at $T = 2.5 \times 10^5$.

There must be a large temperature gradient between the upper chromosphere and the inner corona. Over a distance of some tens of thousands of kilometers the temperature changes from ~ 10^4 to 10^6. Therefore in the transition region there is always a layer where the temperature corresponds to the maximum intensity of the lines of any given ion. The calculations made in reference 28 show that the "width" of the layer where the lines of any particular ion are emitted is given by the expression

$$T_2 - T_1 = \frac{T_0}{2}, \tag{27}$$

where T_2 and T_1 are the temperatures at the upper and lower limits of the region where the line is emitted, and T_0 is the "most favorable" temperature, which corresponds to the middle of the layer.

The intensity of any line in the transition region is related to the characteristics of the medium through the expression

$$\int_{h(T_1)}^{h(T_2)} N_e^2 T^{-3/2} dh = \bar{N}_e^2 T_0^{-3/2} [h_2 - h_1] \equiv \Delta\varphi(T_0) = \frac{2{,}3\cdot 10^{12}\cdot I}{K\left[\frac{n_i}{\Sigma n_i} W^1\right]}, \tag{28}$$

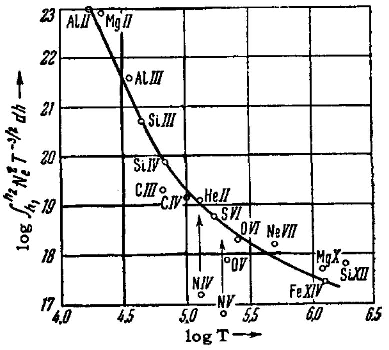

FIG. 13

where I is the intensity of the line; $n_i/\Sigma n_i$ is the ratio of the ions in the given state of ionization to all the ions of the element in question; W^1 is the probability of excitation by electron impact; and K is the relative abundance of the element in question. The Born approximation is used in the calculation of W^1.

The quantity $\Delta\varphi(T_0)$ is a generalization of the important concept of "emission figure" $ME = \int N_e^2\,dh$, which determines the intensities of lines of gas nebulae.

The main observational material used in reference 28 is the results of Rense and Violett,[26] and the intensities given in reference 26 are subjected to a decided and rather arbitrary correction. This is of course the weak point of this methodologically very interesting work. The intensities so obtained are used with the formula (28) to construct the curve shown in Fig. 13. Although, as already mentioned, the estimates of absolute intensities made in reference 26 are debatable, the actual existence of a relationship is evidently real. This gives us reason to think that the foundations of the theory of the intermediate region developed in reference 28 are correct. The analysis of the observations of the ultraviolet radiation of the sun, and also of radioastronomical data, is used in reference 28 to construct a model of the transition region. Figure 14a shows curves of $T_e(h)$ according to various models. The solid curves correspond to the models derived in reference 28 for the active and quiescent regions of the sun. Figure 14b shows curves of $N_e(h)$ for the active and quiescent regions. In the future it will be necessary to make analogous calculations on the basis of more reliable determinations of line intensities and improved values of the effective cross sections. In the ultraviolet region of the solar spectrum the coronal emission plays a relatively small role relative to the emission of the intermediate region. In this part of the spectrum the monochromatic radiation of the corona is evidently weaker than its "hydrogen" and "helium" continua. This continuum has so far not been obtained in spectrograms, evidently because of the presence of scattered light in the spectrographs. The obtaining of this continuum is an important problem of rocket astronomy.

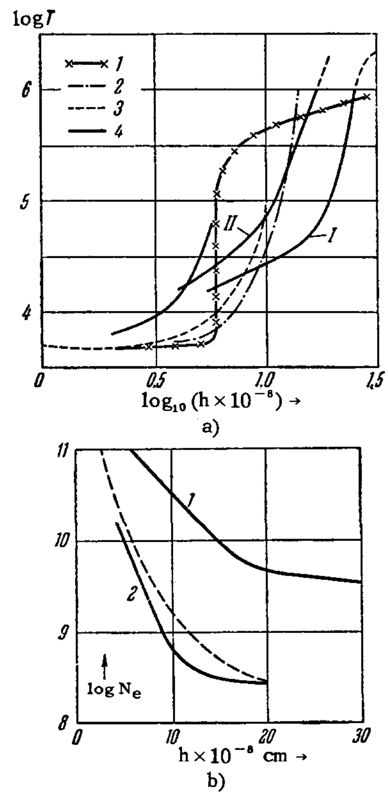

FIG. 14. a) Curves of $T_e(h)$ according to various models; b) curves of $N_e(h)$ for active and quiescent regions.[28]

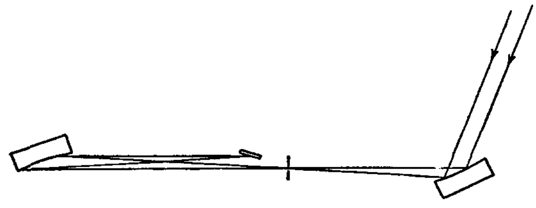

FIG. 15. Scheme of spectrograph for measuring profile of solar L_α.

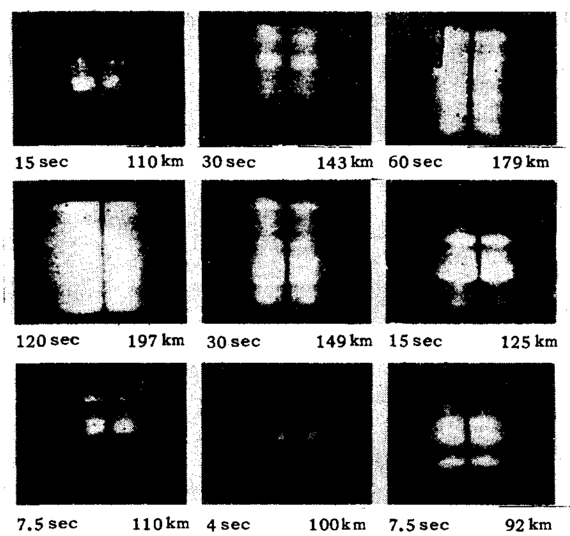

FIG. 16. Photographs of L_α in the solar spectrum.

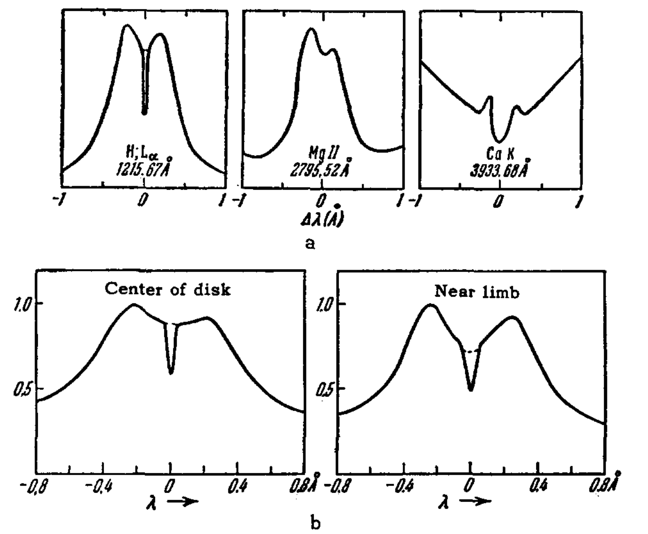

FIG. 17. a) Profiles of L_α, K Ca II, and Mg II lines in spectrum of sun; b) profiles of L_α for center and edge of solar disk.

Studies of the shape of the emission line L_α in the solar spectrum by means of a spectrograph of high resolving power are of great importance for the physics of the sun. The schematic arrangement of the spectrograph is shown in Fig. 15. The thirteenth order of the diffraction spectrum is used. The instrumental width was 0.03 A.[29] Figure 16 shows photographs of the spectrum line L_α. Figure 17 shows profiles of this line corresponding to the center and edge of the solar disk. For comparison, profiles of the well known K line of Ca II and of the resonance line λ 2795.52 of Mg II are also shown. The main difference between the profile of L_α and those of the other lines is the presence of a narrow absorption line in the center of the line (in the photographs shown in Fig. 16 it is seen as a narrow black band). The absorption in the center of the line is due to the presence of atomic hydrogen in the upper layers of the earth's atmosphere. This rarefied blanket of hydrogen surrounding our planet (the so-called "geocorona") is of outstanding interest in geophysics and is at present the object of intense research. It follows from the profile of L_α that the number of neutral hydrogen atoms in a column of unit cross section passing through the geocorona is about $(3-5) \times 10^{12}$ cm^{-2}, and their kinetic temperature is in the range 800 — 2000°. The hydrogen atoms in the geocorona cause intense scattering of the L_α quanta. This

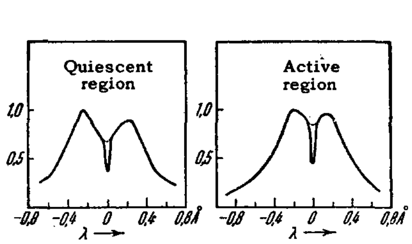

FIG. 18. Profile of L_α for active and quiescent regions of the sun.

phenomenon is observed in night rocket flights at great altitudes.[30,31]

From Fig. 17a one can perceive a considerable similarity of the profiles of L_α and of the resonance lines of Mg II and Ca II (if, of course, we allow for the fact that the Ca II emission is observed in the center of a strong absorption line). In all cases there is a flat minimum of the intensity in the neighborhood of the middle of the line. The distance between the maxima of the profile is about 0.4 A out of a total line width ~ 2 A. In all three lines the "shorter-wave" maximum is the more intense. There are definite indications that the profile of L_α is somewhat different in active and quiescent regions of the sun (Fig. 18). In quiescent regions the flat minimum in the middle of the line is wider and deeper. As is well known, a similar effect is also observed for the profile of the line of Ca II. It is also true that the characteristic differences between the profiles of L_α in the center and at the edge of the solar disk (see Fig. 17b) are like those observed long ago for the line of Ca II.

By the use of the modern theory of the production of the chromosphere lines developed by Thomas and Jefferies[32] we can conclude that the electron temperature in the region where the middle of the line L_α is produced is in the range 55,000 — 90,000 for the quiescent regions and in the range 70,000 — 115,000 for the active regions above flocculae. Knowing the total flux from the entire line (~ 6 erg cm^{-2} sec^{-1}, according to observations with ionization chambers), on the basis of the Thomas-Jefferies theory we can estimate the concentration of electrons at the level where the middle of L_α is produced. This concentration turns out to be in the range from 2×10^9 (quiescent regions) to 3×10^{10} cm^{-3} (active regions).

Thus we can draw the conclusion that the middle of the line L_α is produced in the transitional region of the solar atmosphere between the chromosphere and the corona. Therefore the detailed study of the profile of L_α with very high dispersion is in particular a valuable method for investigating the transitional region.

It can be supposed that within the next few years it will be possible to get the profile of the line He^+ λ 304 A. This would be very useful for the study of the nature of the intermediate region. Besides this, the presence (or absence) of a narrow absorption line in the center of this profile would give valuable information about the presence of gas in interplanetary space. It is of course not to be expected that there would be ionized helium in the geocorona.

The corona itself, generally speaking, should also emit the line L_α. It is, however, difficult in the highest degree to observe this weak emission, because of the presence of the comparatively very strong line L_α produced in the lower layers of the solar atmosphere. It is not excluded, however, that individual relatively cold parts of the corona (for example, places where the process of condensation of coronal material into protuberances is going on) can be rather strong sources of the emission of L_α. In future (evidently rather soon) it will be possible to study this effect by the method of high-quality direct photographs of the sun in the light of the line L_α (see below).

An important direction of research in rocket astronomy has been the effective application of photon counters and ionization chambers in combination with filters. This method has been used, for example, to study the possible variations of the flux of solar radiation in the line L_α, especially at the time of solar flares. The result was a rather unexpected one: the radiation flux in this line is surprisingly constant, and does not increase during solar flares.[33]

The most interesting and important results of this type of research concerns the soft x rays from the sun.[33-35] At the present time there is a large amount of data, including an entire cycle of solar activity (1948-1960). The studies were made by the use of filters, which for the most part covered the following sections of the spectrum: 2 — 8 A, 8 — 18 A, and 44 — 60 A. It was found that at the time of a minimum of solar activity the solar x-ray spectrum of measurable intensity extends only to 10 — 20 A. At the time of maximum activity, however, it can be measured down to 5 — 6 A. All of these statements apply to the "unperturbed" sun. The ratio of maximum to minimum total flux of solar x radiation is about 7.

According to the most reliable data, obtained in the summer of 1959 by means of ionization chambers and Geiger counters in combination with suitable filters, the average (over four rocket flights) flux of the soft x radiation in the spectral band 44 — 60 A is 0.14 erg cm^{-2} sec^{-1}. These observations are for a maximum of the solar activity.

The x radiation of the quiescent sun can be explained partly by the thermal emission of the corona, caused by free-free and free-bound transitions in hydrogen and ionized helium. The theory of this effect has been developed in Sec. 1. The various emission lines of coronal ions can be another component of this radiation. The fact that in a period of maximum solar activity the x-ray spectrum of the quiescent sun extends considerably farther into the short-wavelength region can be explained by the fact that the mean temperature of the corona at the time of a maximum is somewhat higher than at the time of a minimum. This brings with it a change of the state of ionization of the corona and, in consequence, a change of its hard monochromatic radiation. According to radioastronomical observations at a wavelength of 10.7 cm, the effective temperature of the sun at a maximum is $\sim 73{,}000°$, and at a minimum $\sim 37{,}000°$.[36] Then by the formula (14) the values of the flux of "continuous" radiation from the corona with $\lambda < 60$ A for $T = 1.5 \times 10^6$ will be 0.023 and 0.012 erg cm^{-2} sec^{-1}, respectively. The observations give for the maximum a flux larger by a factor 6. Consequently we can draw the conclusion that most of the x radiation of the sun is concentrated in discrete lines.

The large increase of the total flux of x radiation of the quiescent sun at the maximum as compared with the minimum is explained both by the increase of the density of the corona and by the increase of its mean kinetic temperature. At a constant temperature the continuous-spectrum thermal x radiation in a given spectral interval must be proportional to the flux of thermal r-f radiation of the sun in the decimeter range. The latter, however, does not vary from maximum to minimum by more than a factor 2 — 2.5.[36] If the measured variations of the sun's x radiation are actually so large, they are again to be explained by the change of the mean temperature of the corona combined with the change of the mean density from maximum to minimum. This important question calls for further study.

A problem of great importance is that of the intensity distribution of the x radiation of the corona across the disk of the sun. From the theory developed in the preceding section, we have three important conclusions: a) the intensity distribution across the disk must be extremely inhomogeneous. Where the corona is comparatively hot and dense, i.e., in active regions located above chromospheric flocculae, the intensity of the x radiation must be many times as large as in quiescent regions; b) a certain part of the x radiation (10 to 20 percent, see Fig. 2) must come from regions in the corona beyond the visible disk of the sun; c) there must be a brightening toward the edge of the disk (see Fig. 2).

It is interesting to note that the sources of decimeter radio radiation must also be distributed across the sun in just the same way, because the intensity of the decimeter radiation, like that of the soft x radiation, must be proportional to the emission figure.

To what extent do the observations confirm these predictions of the theory?

The problem of obtaining the intensity distribution of the x radiation across the disk of the sun has much in common with the analogous problem for the decimeter range in radioastronomy. In radioastronomy this problem has been solved either by studying the variation of the radiation flux during an eclipse of the sun or by obtaining "images" of the sun in the wavelength range in question by means of large radiotelescopes with high resolving power. The problem in rocket astronomy has been solved in similar ways.

During the eclipse of the sun on October 12, 1958 in the South Pacific five small rockets were sent up from the deck of a ship (Fig. 19). These rockets carried detectors of x radiation in the wavelength ranges 8 — 18 A and 44 — 60 A. The measured flux values were recorded by telemetry. The times of firing of the rockets were calculated in such a way that, allowing for the relatively short flight times, one could get in-

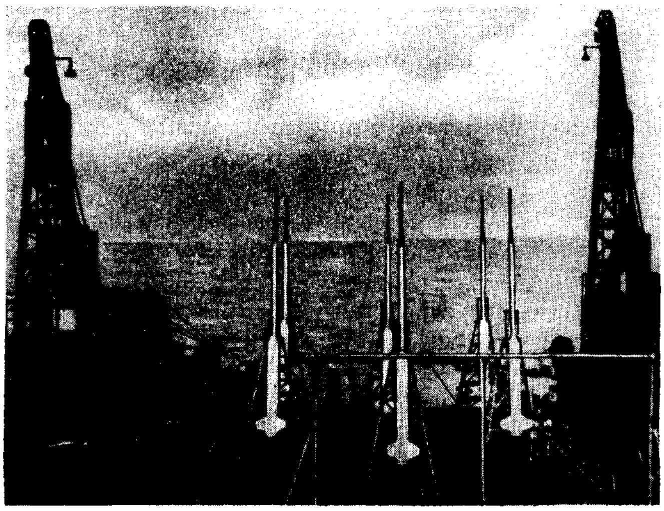

FIG. 19. American rockets mounted on the deck of a ship, used to study the behavior of the x radiation of the sun during an eclipse.

formation at different stages of the eclipse, including totality. The height reached by the rockets was 250 km.

It was found that at the time of the total phase of the eclipse the flux of x radiation does not fall to zero (as it would if the sources of the radiation were located on the surface of the sun or in the chromosphere), but drops to a certain value that amounts to 10 to 13 percent of the value without the eclipse. Simultaneous observations showed that during the total phase the flux of L_α radiation fell by a factor 2000.[37]

The "eclipse curve" for the flux of x radiation showed good correlation with the covering by the moon of the active regions on the sun. In particular, when the moon covered the east edge of the solar disk there was a very strong drop of the flux of x radiation. Just at that time there was a strong flare field at that edge of the solar disk.

These observations fully confirmed two of the main predictions of the theory (the coronal origin of the x radiation of the sun and the large inhomogeneities in the brightness distribution). The third prediction (brightening toward the edge) has been confirmed in the course of another observation of great importance in principle, which we now proceed to describe.

On April 19, 1960 a photograph of the sun in x rays (spectral range 60 – 20 A) was obtained for the first time.[37,38] Although this photograph is of course not to be compared in quality with "ordinary" photographs, it has sufficient resolving power to reveal the most characteristic details in the intensity distribution of x radiation across the disk of the sun. This photograph was obtained by means of a camera obscura from a height of 195 km. The aperture of the camera was 0.013 cm in diameter and 16 cm long. It was covered with a special film which absorbed the visible and ultraviolet radiation of the sun. An automatic guiding device kept the axis of the camera directed toward the center of the solar disk to an accuracy of 1′. Because of the precession and motion of the rocket, however, the camera rotated around its axis. On account of this rotation the

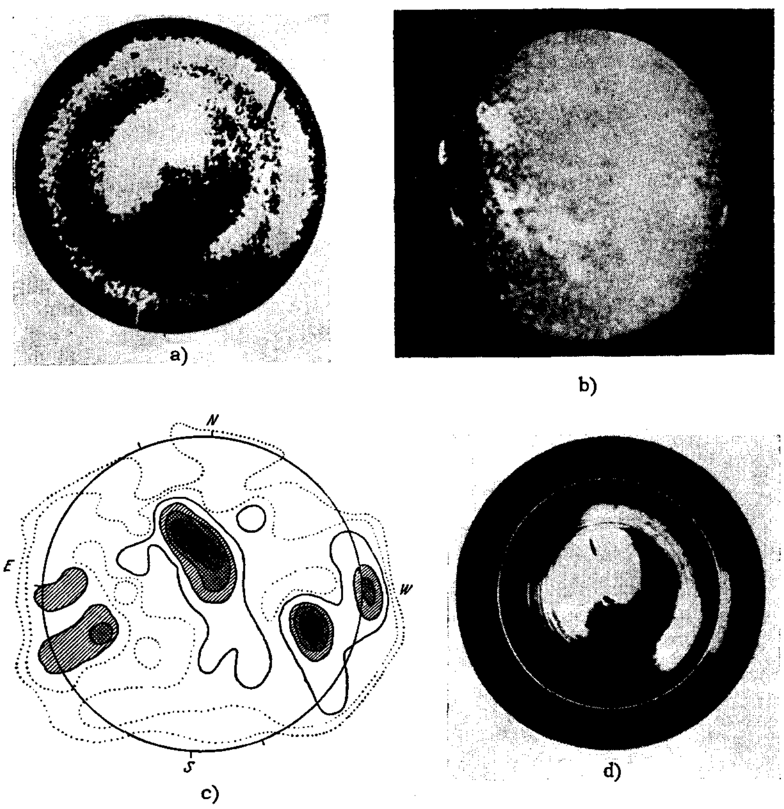

FIG. 20. Photographs of the sun in x rays (a), and in the K line of Ca II (b), radio image of the sun in wavelength 10 cm (c), and photograph of rotating radio image of the sun (d).

image of the sun shows each "point" of detail spread out over an arc $\sim 170°$, with a radius of curvature proportional to the distance of the given feature from the center of the sun's disk. The exposure was of the order of a few minutes.

The photograph of the sun in soft x rays so obtained is shown in Fig. 20a. For comparison Fig. 20b shows a spectroheliogram of the sun in light of the K line of Ca II, taken on the same day. A comparison of these two photographs shows that obviously the regions of increased brightness of the x radiation coincide with the fields of flocculae. The brightness of these spots in the case of x rays is about an order of magnitude above that of the "unperturbed" background. If we now take into account the effect of rotation of the camera obscura around its axis, the contrast in brightness is ~ 70! Figure 20c shows a radio image of the sun in wavelength 10 cm, obtained on the same day as the x-ray image.

It is interesting to note that at a wavelength of 10 cm the contrast of the brightnesses of individual features does not exceed $10-20$.[37] This again indicates that the x radiation is affected by the higher electron temperature in the active regions of the corona, which lie above the flare fields (see foregoing discussion). On the other hand the decimeter radiation of the sun depends essentially only on the density distribution of the plasma of the corona. It seems to us that this is one more proof that the x radiation of the corona is due to discrete spectral lines.*

Figure 20d shows a photograph of the radio image of the sun when it was rotating at a suitable angular velocity, and this displays the similarity of the radio and x-ray images.

Although the "smearing out" of the image caused by the rotation of the camera has a large effect, especially near the edge of the image of the sun, on a certain small part of the limb one can see a clearly marked brightening, as predicted by the theory (see Sec. 1). The brightness contrast of limb and center is found to be ~ 2. This also agrees well with the idea that most of the x radiation is concentrated in discrete lines, and that for these the optical thickness is ~ 1 (see Sec. 1). We must, however, take into account the low resolving power of the camera (practically $\sim 3'$). Therefore it would be premature to make a more detailed comparison of the observed brightening at the edge with that predicted theoretically.

Decreasing the exposure time will greatly improve the quality of x-ray images of the sun. There is every reason to believe that this will be accomplished in the near future.

Besides the photograph of the sun in x rays there have been obtained up to the present several rather

*It was predicted theoretically in reference 28 that in the soft x-ray region the brightness contrast of the "spots" and the unperturbed regions of the sum must be ~ 100, and that the radiation is a line spectrum.

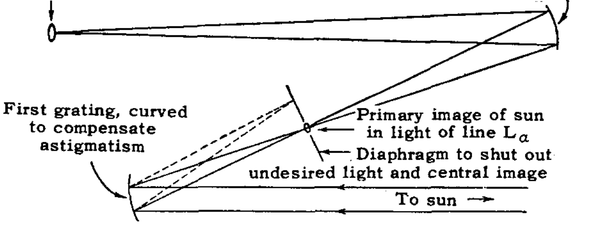

FIG. 21. Scheme of double monochromator for obtaining image of sun in light of line L_α.

good photographs in light of the line L_α. Such photographs have been obtained by Purcell and Tousey by means of a double monochromator[39] (shown schematically in Fig. 21). Two curved diffraction gratings (600 lines per millimeter, radius of curvature 40 cm) are used in the first order. The first grating forms an image of the sun in L_α light, and this is singled out by a diaphragm. The second grating then forms the "working" stigmatic image of the sun with double dispersion. This gives great sharpness in the photograph, i.e., is decreases the disturbing background of other lines close to L_α. The main advantage of this system is the elimination of astigmatism, which has led to considerable distortion of the image in other systems. Since the brightness of the sun in L_α is rather large, the exposures used were very short, ~ 0.02 sec, and this made the problem of guidance easier. In particular, the rotation of the image around

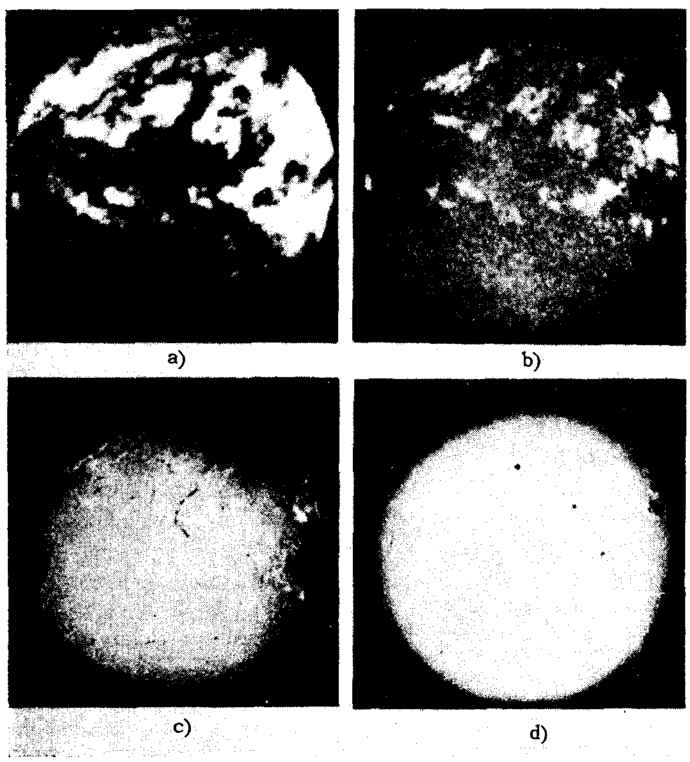

FIG. 22. Photograph of the sun in L_α light, and also photographs of the sun in K and H_α light.

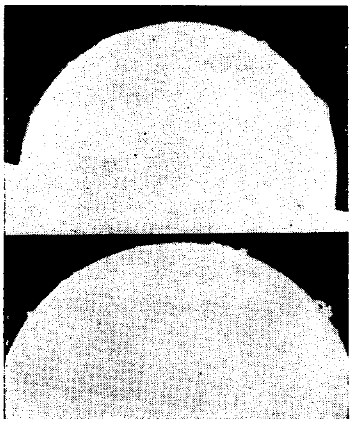

FIG. 23. Photographs of protuberances in L_α and H_α light.

the axis of the optical system, which caused so much distortion of the x-ray photograph of the sun, is here quite unimportant.

Figure 22a shows a photograph of the sun in the line L_α; the figure also shows spectroheliograms of the sun in light of H_α and K Ca II taken simultaneously at the Meudon observatory (Fig. 22b, c). There is an obvious general resemblance of the three photographs; the photograph in L_α light is more like that in K Ca II than it is like that in H_α light. This has a natural explanation in the fact that the effective level for emission of L_α is much higher than that for H_α, while the level for the K line is intermediate between them. The intensity contrast of the bright and weak details in the L_α photograph is about twice that in the K photograph. The intensity above the active regions is about 5 times that above quiescent regions. From this and a consideration of the areas on the disk covered by these regions we can draw the conclusion that the flux of L_α at the time of a maximum must be 1.5 — 2 times that at the time of a minimum. In Fig. 23 one can see the first images that have been obtained of protuberances in L_α and H_α light.

The monochromatic images of the sun which have been obtained in the short-wavelength region are of extraordinary importance for solar physics. One of the very next tasks contemplated is that of obtaining images of the sun by a method analogous to that described above in the light of He^+ λ 304, and also in that of O VI λ 1031.9 — 1037.6 (see the spectrogram of the sun in Fig. 9). The latter line originates in the intermediate region between the corona and the chromosphere. It can be expected that it will show a marked brightening toward the edge. Of especial interest for the physics of the solar corona are plans to obtain images of the sun in the light of the lines Ne VIII λ 770.4 — 780.3 and Mg X λ 609.7 — 624.9. Ultraviolet monochromatic images of the corona will have a great advantage over the images of the corona in lines of the visible part of the spectrum, which are obtained by means of narrowband filters. In the latter case one cannot observe the corona on the disk. For this reason the construction of maps of the corona is a rather long and complicated and, what is most important, not altogether reliable procedure, since during the time in which the sun rotates about its axis there can be rather large changes in the corona. Meanwhile, in the construction of such maps one always of necessity makes the assumption that during the entire time of observation, extending over a half period of the sun's rotation, the monochromatic corona remains unchanged.

It is a matter of great interest to study the character of the changes in the L_α and x-ray emission at the time of appearance of solar flares. The existing data are for flares of strength 2^+. In all cases x radiation has been registered only after some minutes had elapsed after the maximum of the optically observed flare.[35]

The recorded maximum flux of soft x radiation in the band 44 — 60 A was 1.8 erg cm^{-2} sec^{-1}, which is about 10 times the level of emission of the quiescent sun. Another characteristic feature of the x-ray emission is its greater hardness in comparison with the emission from the quiescent sun. The ratio of counting rates with filters passing the ranges 8 — 20 and 2 — 8 A is 23 for the quiescent sun and goes down to 6 — 7 at the time of a flare, and also when active protuberances associated with flares are present.

A new interesting feature of the flares observed in rocket researches is the appearance of streams of extremely hard x-ray quanta with energies of tens and even hundreds of kilovolts. These streams of quanta have been detected by means of proportional and scintillation counters with the use of beryllium and beryllium-aluminum windows. This phenomenon has been observed for all the flares of class 2^+ that have been studied. As the authors of these researches indicate, the spectral composition of this hard radiation corresponds to the bremsstrahlung of a hydrogen plasma heated to a temperature of 120×10^8 °K. In our opinion, however, this radiation is most likely of a nonequilibrium character. It is evidently due to the acceleration to extremely high energies of a comparatively small fraction of the particles that are in the region of the flare. The presence of such corpuscles in the region of a flare follows from the observations of radio bursts of types IV and V (cf. reference 41). It is also shown directly by the presence of a solar component in the primary cosmic rays, which is observed at the time of a flare.

According to the observations, the duration of the phenomenon of the emission of ultrahard photons at the time of a flare is of the order of several minutes. The flux of energy in the photons harder than 20 kev has been found to be about 5×10^{-6} erg cm^{-2} sec^{-1}, and they penetrate into the earth's atmosphere to a level ~45 km.

3. THE EFFECT OF THE HARD RADIATION OF THE SUN ON THE IONIZATION OF THE EARTH'S ATMOSPHERE

As has been brought out in the preceding sections, the hard photon radiation of the sun is generated in the corona and in the layer intermediate between the corona and the chromosphere. In general the present theoretical ideas satisfactorily explain the results of the observations. To a large extent, however, this is true for the corona proper rather than for the intermediate region. The physical conditions in the latter region of the solar atmosphere are as yet not completely clear.

The importance of studies of the ultraviolet and x-ray emissions from the sun is due primarily to the decisive influence they have on the state of ionization of the upper layers of the earth's atmosphere. The theory of this effect depends on the values of two main factors: a) the quantitative and qualitative characteristics of the ionizing hard radiation from the sun, and also all the sorts of variations this radiation undergoes; b) the physical conditions in the upper atmosphere, its chemical, molecular, and ionic composition, and the changes of its characteristics with time. We note that these properties of the upper layers of the earth's atmosphere in turn depend to a considerable extent on the action on it of the hard radiations of the sun, both photon and corpuscular. Thus the problem of constructing a theory of the ionosphere which can satisfy the increased requirements of practical work is a very difficult one.

Rocket geophysics, which has been developed in recent years in parallel with rocket astronomy, has opened up possibilities for studying the properties of the upper layers of the atmosphere by direct methods. Launchings of artificial satellites have made it possible to get extremely valuable data on the density of the atmosphere at great heights and about its variations, its molecular and ionic composition, and so on. This very rich material, which is rapidly increasing in amount as direct methods for the research are developed, is a basis for the construction of more modern theories of the ionosphere. At present, however, the assimilation of this material is only beginning.

In this section we confine ourselves to only the most general considerations on the causes of the formation of the various ionospheric layers. The outermost of these layers is evidently formed on account of the absorption of solar photons by atoms and molecules of oxygen and nitrogen. We note that it was previously supposed that at heights corresponding to the F layer there is practically no molecular oxygen. Rocket studies have shown, however, that in this region there is a rather large amount of O_2, which is carried up by convection currents from lower layers of the atmosphere. Values of the absorption coefficients as functions of the wavelength are known experimentally for O_2 and N_2, and can be calculated theoretically for O I and N I (cf., e.g., reference 42). It is from these data, together with the data on the density and chemical and molecular composition of the atmosphere at various heights that Fig. 1 has been constructed.

Thus it has been possible to establish that in the region of the F layer there is absorption of the photon radiation of the sun beyond the limit of the Lyman series. The maximum of the ionization must be associated with the level in the atmosphere at which the optical thickness for the hard radiation being absorbed is approximately unity. It follows from this that the very hard radiation of the sun must be responsible for the ionization of the deeper layers of the atmosphere (see below).

An analysis of the solar spectrum shows that the most powerful emissions beyond the limit of the Lyman series are concentrated: a) Right at the series limit, in the region $912 > \lambda > 850$ A; this radiation is due to the upper layers of the chromospheric flocculae, and its flux is about $0.1 - 0.2$ erg cm^{-2} sec^{-1}. b) In radiation beyond the series limit of ionized helium. This radiation originates in the intermediate region of the solar atmosphere. According to the observations of Hinteregger,[27] the flux at the earth is close to 0.1 erg cm^{-2} sec^{-1}. c) In a large number of other bright lines, the brightest of which belong to He I, O II, O III, O IV, O I, N IV, and C III. These lines originate in the intermediate region. The coronal lines of Ne VIII and Mg X are also to be included here. The total flux of radiation in these lines is ~ 0.5 erg cm^{-2} sec^{-1}. d) In the resonance line of He II at 303.7 A, which is evidently the brightest line in this part of the solar spectrum. The probable value of the flux of radiation in this line is close to 0.3 erg cm^{-2} sec^{-1}.

Along with the ionization, the hard radiation from the sun must cause heating of the upper atmosphere. The data on the density of the upper atmosphere obtained by means of rockets and artificial satellites oblige us to conclude that the temperature at heights exceeding 300 km is $\sim 1500 - 1700°$ K. Besides this, large fluctuations of the density are observed in the upper layers of the earth's atmosphere, which are associated with solar activity. Undoubtedly the solar photon radiation plays an important, if not decisive, role in the heating of the upper layers of the atmosphere (the so called "thermosphere"). At the same time, under certain conditions the corpuscular radiation of the sun can also be rather important, especially at times of active occurrences on the sun.[43] For a complete understanding of the causes of heating in the upper layers of the earth's atmosphere it is necessary to know the intensities of the ultraviolet emission lines in the solar spectrum and the character of the variations of these intensities.

We note that in the photoionization of atoms and molecules of the upper atmosphere by the "monochromatic" hard radiation of the sun (for example, by quanta of the resonance line of He II with energy 40.7 ev) the energies of the photoelectrons are rather large (~ 27 ev). Such electrons will in turn ionize surrounding atoms and molecules of the atmosphere and excite luminescence in them. This last fact is of great interest, but we cannot discuss this purely geophysical problem here.

To summarize, we can conclude that the hard radiation of the corona is evidently of secondary importance in the formation of the ionospheric F layer. Matters are quite different in the case of the lower lying E layer of the ionosphere.

Analysis of the coefficient for absorption of ultraviolet radiation by the earth's atmosphere shows that only photons with energies exceeding 165 ev (which corresponds to $\lambda < 75$ A) can penetrate to the E layer.[5] It was once believed that in the E layer oxygen atoms are ionized by photons with $h\nu > 12.2$ ev (cf., e.g., Table I). The continuous absorption coefficient of O_2 is, however, anomalously small. Still it is known that in the absorption spectrum of O_2 there are intense bands superposed on the weak continuum, and in these bands the absorption coefficient is thousands of times the value in the continuum. On this basis Nicolet suggested that in the E layer there may occur processes of "preionization" in which molecules of O_2 in "overexcited" states can become ionized spontaneously.

There is, however, little real basis for the mechanism of "preionization." It is most probable that an excited molecule will spontaneously go back to the initial state, since at such heights collisions are extremely rare. There are other serious difficulties with the hypothesis, which there is no space to discuss here.

The production of the E layer is easily explained by photoionization of atoms and molecules of oxygen and nitrogen by hard coronal radiation with $\lambda < 75$ A. It follows from Eqs. (4) and (10) that at a temperature of 1,500,000° the fraction of the hard "hydrogen" and "helium" emission from the corona with $\lambda < 75$ A is 30 percent of the total flux. We must add to this the hard coronal radiation concentrated in discrete lines, which evidently makes the main contribution to the x-ray emission of the sun (see Sec. 1). There is quite enough of this radiation for the formation of the E layer.

The x radiation of the corona will ionize both atoms and molecules of oxygen, and also molecules of nitrogen. The absence of a sufficient number of N_2^+ ions in the E layer (which follows from an analysis of the twilight band λ 3914, and also from direct measurements with rockets) is explained by the rapid "destruction" of N_2^+ ions owing to reactions with other components of the earth's atmosphere (this also applies to the F layer).

Observations made during total eclipses of the sun give the decisive proof of the coronal origin of the hard photon radiation that ionizes the E layer. Ionospheric observations during eclipses have been made repeatedly. In the analysis of such observations it was previously assumed that the sources of the ionizing radiation are uniformly distributed over the sun's disk. It long since became clear, however, that this hypothesis about the distribution of the sources of ionizing radiation cannot satisfactorily explain the results of ionospheric observations made during eclipses. In a number of cases the minimum of the electron concentration in the layer was not delayed relative to the total phase of the eclipse (as it should have been if the ionizing radiation of the sun were "shut off"), but occurred simultaneously with the total phase and sometimes even preceded it.

Therefore long ago some students of the ionosphere came to the conclusion that the sources of ionizing radiation are not distributed uniformly over the sun's disk, but are concentrated in separate active regions (cf., e.g., reference 45). Analyzing the ionospheric observations made at the eclipse of 1945, Waldmeier concluded in 1947 that these active regions on the sun coincide with the regions of the corona where the green line λ 5303 is enhanced.[46] In another case (the eclipse of 1952) the results of the ionospheric observations could be explained by the assumption that 64 percent of the ionizing radiation of the sun is uniformly distributed over the disk, and 25 percent is concentrated in a narrow ring at the limb.[47] Analogous observations of the minimal corona in 1954 could be satisfied by the same model, but altered so that the bright ring of ionizing radiation was absent in the polar regions of the sun.[48]

In 1955 Ratcliffe showed from an analysis of a large quantity of eclipse ionospheric data that from 10 to 15 percent of the ionizing radiation is concentrated beyond the limits of the optical disk of the sun.[49] Other authors also came to similar conclusions.

These results are in good agreement with theoretical expectations if we assume that the ionizing agent is the soft x radiation of the corona. The calculations made in Sec. 1 show that for an angular radius of the moon equal to 1.02 — 1.04 from 15 to 20 percent of the ionizing radiation comes to us from regions of the corona that are beyond the visible disk of the sun. Direct observations of the sun's soft x radiation made during the eclipse of October 12, 1958 fully confirm these calculations. According to the direct observations described in the preceding section the flux of hard radiation quanta in the spectral interval 60 — 44 A is about 5×10^8 cm^{-2} sec^{-1}. All of these quanta will be absorbed in the E layer and produce ionization there. On the other hand, the explanation of the observed degree of ionization in this layer on purely "ionospheric" considerations calls for 5×10^8 ionizing quanta per square centimeter per second (see Table I).

Thus we can regard it as established that the cause of the ionization in the E layer of the ionosphere is the soft x radiation of the corona.

Let us briefly consider the question of the mechanism of ionization of the D layer. The L_α quanta can penetrate to these low altitudes and produce in this region ionization of nitric oxide molecules NO (ionization potential 9.5 ev). On the other hand, the extremely hard radiation of the sun ($\lambda \sim 1-3$ A) can also penetrate to such altitudes. It has recently been shown by direct measurements made with rockets that the concentration of NO in the upper atmosphere is entirely insufficient for the formation of the D layer by the photoionization of nitric oxide by L_α quanta.[50] From these experiments it follows directly that the hard x-radiation of the sun is responsible for the formation of the D layer.

During large solar flares, as is well known, there is a sharp increase of the ionization in the D layer, which often leads to catastrophic disruption of short-wave radio communications. According to the old theory of Martyn[51] the cause of the ionization is the increased emission of L_α quanta at the time of the flare. As early as 1949, however, we criticized the Martyn theory and advanced arguments in favor of the idea that the cause of the ionization of the D layer during a flare is the x radiation with $\lambda \sim 1-2$ A[52] generated in the region of the flare. Later a similar hypothesis was suggested by some other authors.

The latest observations made with rockets sent up at the time of flares settle the question definitely in favor of x radiation as the cause of the "bursts" of ionization in the D layer. The results of these observations have already been discussed in the preceding section. It has been shown that at the time of flares the x-ray spectrum of the sun becomes much "harder" than that of the quiescent sun. The number of hard x-ray quanta emitted at the time of a flare is more than enough for the production of the observed ionization in the D layer. Simultaneous observations have shown that the integrated flux of line L_α radiation from the sun does not show great changes at the time of a flare. This proves that the L_α quanta cannot in any way be the cause of the ionospheric disturbances in the D layer associated with flares on the sun.

Very recently these results have been completely confirmed by a large amount of statistical material. The artificial satellite Explorer VII carried detectors for x rays and L_α quanta. The observations extended over the entire life of the satellite. A large number of flares were registered during this time. In all cases they were accompanied by sharp increases in the flux of x rays from the sun, while the flux of L_α emission was almost unchanged.

Thus the data of rocket astronomy and the theory of the solar corona and chromosphere completely explain the entire observed pattern of ionization of the earth's atmosphere.

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Translated by W. H. Furry