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ON INTERPRETATION OF THE RADIATION OF CORONAL SUPRATHERMAL STREAMS. II

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This is the second part of the series of two articles which consider the effect of Compton scattering of the photospheric radiation on fast electrons of the coronal suprathermal streams. As compared to the previous part, a more realistic height-dependent model problem is treated. The results of numerical calculations for the mean frequency change and the proper cross-section for both the sunward and antisunward directed beams of electrons are given as a function of height and the slope angle. It is concluded that, depending on the angle between directions of the initial outburst and magnetic field, the scattering on the beams moving away the Sun may produce measurable drifts in frequency to shortwave as well as to longwave domains of the spectrum. At the same time, the sunward directed beams result only in an increase in the photon energy.

Key words: *Sun:corona:coronal suprathermal streams*

1. *Introduction.* We continue discussing the role of the Compton effect in scattering of the solar photospheric radiation on coronal suprathermal streams. The previous paper of this series [1] (hereafter Paper I) dealt with the relatively simple model problem in which the incident radiation was supposed to be monodirectional beam. Such assumption is evidently valid for great distances over the Sun, while it is usually assumed that the propagation of streams occurs in the region of the intermediate corona (from a fraction of the solar radius to several radii from the surface of the Sun). In an early extended paper, Eddy [2] analysed a very well recorded long linear structure of typically 10" width seen in the 1922 corona photographed on large plates. A good reproduction of one of the plates is presented in the famous book "A New Sun" [3]. This linear thread called by Eddy a coronal ray, extended from $h \approx 1,2$ to $h \approx 3$ solar radii and kept its transverse width almost constant. Thus, the more accurate formulation of the problem must allow for the fact that the photospheric radiation falls within a certain solid angle subtended by the solar disc, as seen from a given height.

Another reason that makes the problem dependent on height concerns overlapping of several streamers. A good argument in favor of this effect is that, typically at heights $h \geq 1$ solar radius, the streamers are often showing some evidence of a small twist, although they extend very much along the line of sight. In case of a fine thread, the twist would be seen even better but this is not observed. Therefore, the necessity appears to treat the effect of the Compton scattering on an ensemble of streamers intersected by the line of sight. It is obvious that, on account of curvature of the solar surface, the contribution of each projected beam into observed radiation will be different due to difference in the heights of radiating volumes along the line of sight. Moreover, the number of streams seen at great heights will be also varied. The fact is that the physical properties of the electrons beam (density, velocity and parameter α specifying the direction of motion) in the model problem we consider are assumed to be identical along its length. Such assumption is understood to be valid up to a certain height H over the Sun, or stating differently, there must exist a maximum length for the beam with predefined values of the mentioned parameters. This, in turn, implies that the number of the fan-streamers projected onto line of sight will vary with height.

The outline of the paper is as follows. We begin by describing the geometrical model at hand and presenting the needed formulas. The next section is devoted to the results of calculations which reveal the dependence of the mean frequency change on inclination with respect to the line of sight. Further, we discuss the effect produced by an ensemble of fan-streamers projected onto line of sight. For expository reasons, the case of Planck's function as a frequency distribution of incident radiation is considered. The results obtained are discussed in the final section.

2. *The geometrical model.* Fig.1 shows schematically the geometry of the scattering process for a single beam of electrons. Here we avail ourselves of the notations adopted in Paper I. We recall only that the angles ψ_i and ψ_f specify the directions of incident and scattered photons, while the angle Φ defines the inclination of the symmetry axis of the electron beam. The latter is referenced from perpendicular to the line of sight and takes positive values for inclinations towards the observer, and negative ones for opposite direction. A rectangular Cartesian coordinate system is introduced with the axis Oz directed along the symmetry axis of the beam and with the plane xOz involving the line of sight. The line of sight with the impact parameter h (referenced from the solar surface) intersects the electron beam at a point O chosen as the origin of the coordinate system. From this point the solar disc is seen within a solid angle

$$\Omega = 2\pi \int_0^{\delta_0} \sin\delta \, d\delta , \tag{1}$$

where $\delta_0 = \arcsin \dfrac{\cos\Phi}{1 + (h/R)}$, and R is the radius of the Sun.

The components of the unit vectors along directions of the electron motion, incident and scattered photons are respectively

$$\begin{aligned} &\mathbf{v}_0(\cos\alpha\cos\varphi, \cos\alpha\sin\varphi, \sin\alpha), \\ &\mathbf{n}(\sin\delta\cos\phi, \sin\delta\sin\phi, \cos\delta), \\ &\mathbf{n}'(\cos\Phi, 0, \sin\Phi), \end{aligned} \tag{2}$$

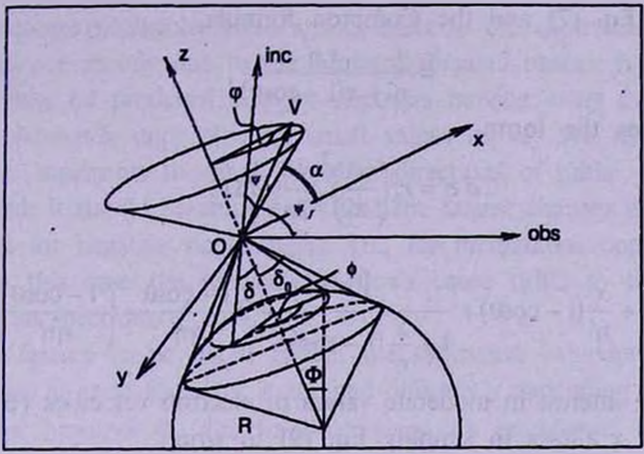

Fig.1. The geometry of the Compton scattering of photospheric radiation on a single beam of electrons with allowance for the solid angle.

so that

$$\begin{aligned}\cos\theta &= (\mathbf{n}, \mathbf{n}') = \sin\delta\cos\phi\cos\Phi + \cos\delta\sin\Phi,\\ \cos\psi_i &= (\mathbf{n}, \mathbf{v}_0) = \sin\delta\cos\alpha\cos(\varphi - \phi) + \cos\delta\sin\alpha,\\ \cos\psi_f &= (\mathbf{n}', \mathbf{v}_0) = \cos\alpha\cos\Phi\cos\varphi + \sin\alpha\sin\Phi.\end{aligned} \tag{3}$$

In the particular case of $\delta_0 = 0$, Eqs. (3) lead to the results given in Paper I (see Eqs. (14) there).

As before, the quantity of interest for us is the mean value of the frequency change resulting from interaction of a photon with the electron beam

$$\frac{\langle x' \rangle}{x} = \frac{\int x' d\sigma}{x \int d\sigma}, \tag{4}$$

where $d\sigma$ is the differential cross-section of interaction, the explicit expression of which was presented in Paper I (cf. Eq. (8)), and has the form

$$d\sigma = \pi r_e^2 \frac{dt}{2(mcx\eta)^2}\left\{\frac{x\eta}{x'\eta'} + \frac{x'\eta'}{x\eta} - 2\frac{1-\cos\theta}{\eta\eta'} + \left(\frac{1-\cos\theta}{\eta\eta'}\right)^2\right\}, \tag{5}$$

where the following notations are used

$$\eta = \gamma(1 - \beta\cos\psi_i), \quad \eta' = \gamma(1 - \beta\cos\psi_f), \quad t = -2kk', \tag{6}$$

$r_0 = \left(e^2/mc^2\right)^2$ is the classical radius of electron, and $\beta = |\mathbf{p}|/c$, $\gamma = \left(1 - \beta^2\right)^{-1/2}$ is the relativistic factor. We recall also that the incident and scattered photons are described by the 4-momenta k, k' and the dimensionless energies, x, x' measured in units of mc^2.

The relativistic invariant t may be expressed in terms of the invariant $x'^2 d\Omega = x'^2 \sin\theta\, d\theta\, d\varphi$ (see, [4]) as follows

$$dt = m^2c^2x'^2 d\Omega. \tag{7}$$

In view of Eq. (7) and the Compton formula,

$$x' = \frac{x\eta}{\eta' + x(1-\cos\theta)}, \tag{8}$$

Eq. (5) takes the form

$$d\sigma = r_e^2 \left(\frac{x'}{x}\right)^2 \frac{U_0}{2\eta^2} d\Omega, \tag{9}$$

where

$$U_0 = 1 + \frac{x}{\eta'}(1-\cos\theta) + \frac{1}{1+\frac{x}{\eta'}(1-\cos\theta)} - 2\frac{1-\cos\theta}{\eta\eta'} + \left(\frac{1-\cos\theta}{\eta\eta'}\right)^2. \tag{10}$$

As far as we interest in moderate values of electron velocities ($\beta \le 0.4$), the smallness of x allows to simplify Eq. (9) to write

$$d\sigma = r_e^2 \frac{U_0}{2\eta'^2} d\Omega, \tag{11}$$

where now

$$U_0 = 1 + \left(1 - \frac{1-\cos\theta}{\eta\eta'}\right)^2. \tag{12}$$

Integration in Eq. (4) extends over the entire domain of variation of δ and the azimutal angles φ and ϕ. For fixed δ, the first of Eqs. (3) yields $d\cos\theta = \sin\delta\cos\Phi\, d\cos\phi$. With this in mind, we substitute Eq. (11) into Eq. (4) to obtain

$$\frac{\langle x'\rangle}{x} = \frac{\int_0^{\delta_0}\sin\delta\, d\delta \int_{-1}^{1} d\zeta \int_{-1}^{1} U_0 \frac{\eta\, d\xi}{\eta'^3\sqrt{1-\xi^2}}}{\int_0^{\delta_0}\sin\delta\, d\delta \int_{-1}^{1} d\zeta \int_{-1}^{1} U_0 \frac{d\xi}{\eta'^2\sqrt{1-\xi^2}}}, \tag{13}$$

where $\xi = \cos\varphi$, $\zeta = \cos\phi$. In writing Eq. (7) we neglect the limb darkening effect, so that it differs from its counterpart in Paper I (cf. Eq. (16)) by two additional integrations over δ and ϕ [1].

3. *Numerical results.* Fig.2 presents the graphs of the relative mean frequency change resulted from scattering on a single beam of moving electrons. Calculations made for two different heights ($h/R = 0.25; 4$) illustrate the height dependence of the effect. We see that the observing pattern for both heights is qualitatively reminiscent of that described previously in Paper I, in which the incident radiation was supposed to be monodirectional. This especially concerns, as might be expected, great distances from the Sun (the case $h/R = 4$ in Fig.2), for which the role of the solid angle of incident

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[1] *The term $\sqrt{1-\xi^2}$ in denominators of the proper integrals in Eq. (16) of Paper I was omitted, which does not introduce, however, any essential changes in numerical results obtained and in final conclusions.*

radiation becomes negligible. Here again, drifts to the shortwave domain of the spectrum are mainly due to the sunward directed beams. It is seen that such drifts may be produced also by electrons moving away the Sun. This occurs for $\Phi \geq -\pi/6$ and relatively small values of α. We recall that the parameter α represents the angle between directions of initial outburst and magnetic field. It should be emphasized that the largest changes in frequencies are observed for negative slope angles, i.e., for inclinations opposite to the observer. In this case the antisunward flows cause drifts to the longwave domain of the spectrum.

Another feature to be noted is that the saturation behavior of the frequency change at great distances is attained differently depending on the slope angle Φ: for negative Φ, the limiting values are established much faster, than in the opposite case. It is seen that, for $\Phi = -\pi/3$, only minor

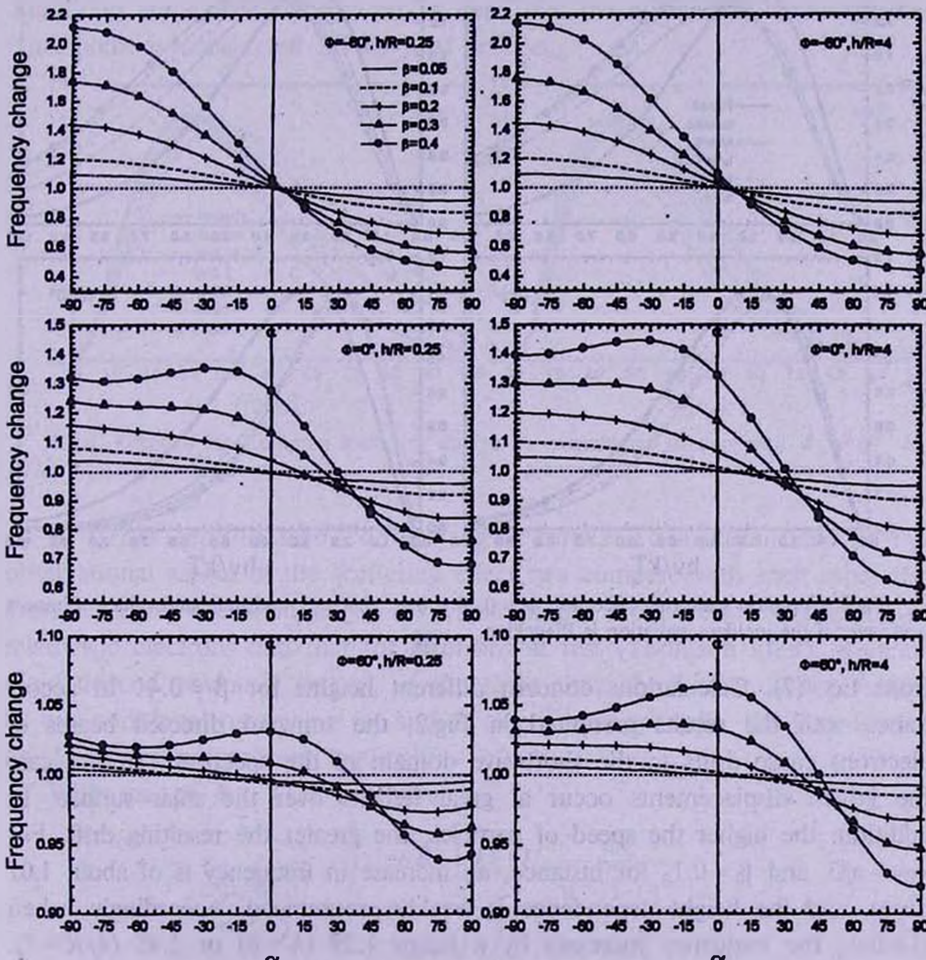

Fig.2. Dependence of the relative frequency change on α for fixed values of β and inclination angles Φ. The dotted line corresponds to $\langle x' \rangle / x = 1$.

differences are observed between the results corresponding to the two values of impact parameter, while the difference in heights over the solar surface is significant: $1.5R$ $(h/R=0.25)$ and $9R$ $(h/R=4)$.

For expository reasons, we demonstrate in Fig.3 the effect of Compton scattering on a single beam of electrons perpendicular to the line of sight, if the intensity of incident radiation is assumed to be Planckian. The dimensionless intensity evaluated for scattered radiation is

$$I(x)=I_0\,x^3\Big/\left[\exp\left(\frac{x}{r}\right)-1\right], \tag{14}$$

where $x=h\nu/kT$, $I_0=2(kT)^3/(ch)^2$, k is Boltsmann's constant, T is the effective temperature, and h is Planck's constant. The ratio $r=\langle x'\rangle/x$ is found

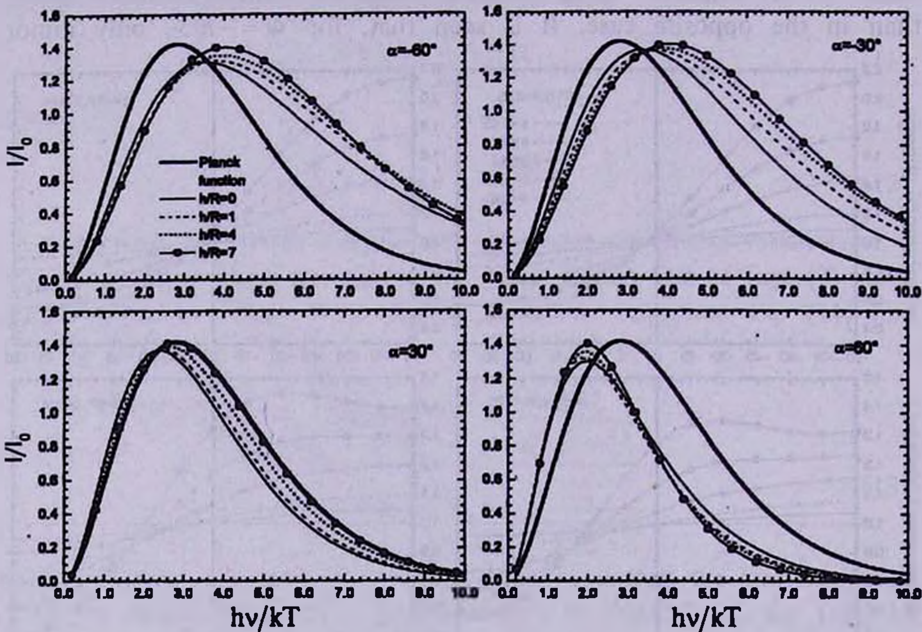

Fig.3. Compton scattering effect for $\Phi=0$, $\beta=0.4$, $H/R=8$ and indicated values of impact parameter if the incident radiation is Planckian.

from Eq. (7). Calculations concern different heights for $\beta=0.4$. In accordance with the results presented in Fig.2, the sunward directed beams of electrons cause drifts to the shortwave domain of the spectrum. In this case the largest displacements occur at great heights over the solar surface. In addition, the higher the speed of particles, the greater the resulting drift. For $\alpha=-\pi/3$ and $\beta=0.1$, for instance, an increase in frequency is of about 1.07 times, and the height dependence is weakly pronounced. Accordingly, when $\beta=0.4$, the frequency increases by a factor 1.29 $(h=0)$ or 1.43 $(h/R=7)$. It is also of interest the changes in the intensity of the scattered radiation in the optical domain of the spectrum. For instance, at $\lambda=5000$ Å (i.e.,

$h\nu/kT \approx 5$, for $T = 5700$ K) it grows by a factor 1.2, if $\beta = 0.1$, and, correspondingly, by a factor $1.56 \div 1.80$ (depending on height), if $\beta = 0.4$.

Turning now to the case of antisunward directed beams, we see that, depending on the value of α, the drifts may occur to both the shortwave and longwave regions of the spectrum. For $\alpha \geq \pi/6$, the scattering at all heights leads to reddening of incident radiation. The greater the height and the value of α, the more significant is the observed effect. For $\alpha = \pi/3$, the photons' energy decreases by a factor of 1.07 ($\beta = 0.1$) and $1.4 \div 1.6$ ($\beta = 0.4$). This reduces the intensity observed at $\lambda = 5000$ Å by a factor of 1.28 ($\beta = 0.1$) and $2.6 \div 4$ ($\beta = 0.4$).

The effect of an ensemble of radially directed streams for $H/R = 4$ and with the mean slope angle $\Phi_0 = \pi/3$ is shown in Fig.4. The spread of inclination angles around Φ_0 is $\pi/12$. Again, as in Fig.3, the shifts of Planckian are remarkable and let us hope that the effect may be observable. This point is considered in the next section.

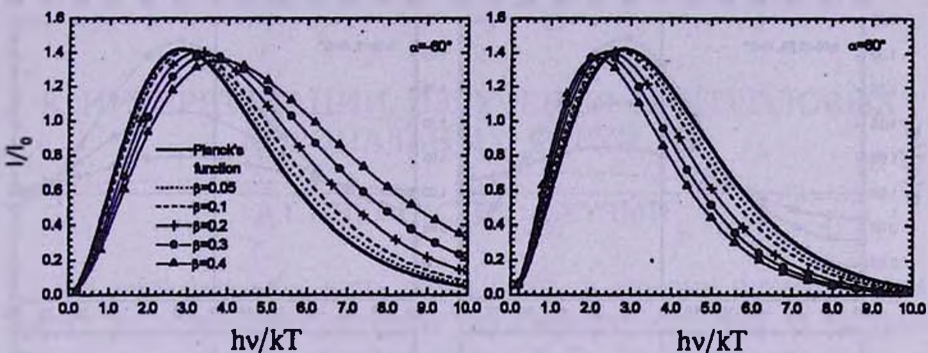

Fig.4. Effect of the Compton scattering due to an ensemble of streams with $\Phi_0 = 60°$ for $H/R = 4$ and $h/R = 0.25$.

4. *Cross-section and concluding remarks.* To make an idea on the observational aspect of the scattering effect, we compare with each other the averaged (over the solid angle Ω) value of the cross-section evaluated for relativistic electrons and that for electrons at rest (Thomson limit). Both of them depend obviously on Φ, at the same time the former is determined by two additional parameters α and β (for simplicity's sake, the dependence on δ_0 is not pointed out explicitly).

With use of Eq. (11) we have

$$\frac{\sigma(\alpha,\Phi,\beta)}{\sigma_T(\Phi)} = \frac{\int_0^{\delta_0} \sin\delta\, d\delta \int_{-1}^{1} d\zeta \int_{-1}^{1} U_0 \frac{d\xi}{\eta'^2\sqrt{1-\xi^2}}}{\pi \int_0^{\delta_0} \sin\delta\, d\delta \int_{-1}^{1} \left(1+\cos^2\theta\right) d\zeta}. \tag{15}$$

Integrations in the denominator are performed analytically to yield an explicit expression for σ_T

$$\sigma_T = 2\pi\left[\left(1+\frac{1}{3}\cos^2\Phi\right)(1-\cos\delta_0)+\frac{1}{3}\left(1-\frac{4}{3}\cos^2\Phi\right)\left(1-\cos^3\delta_0\right)\right]. \qquad (16)$$

The results of calculations obtained from Eq. (15) for several slope angles and two values of impact parameters ($h/R=0.25$; 4) are given in Fig.5. We see that the dependence on height is insignificant: only minor differences are

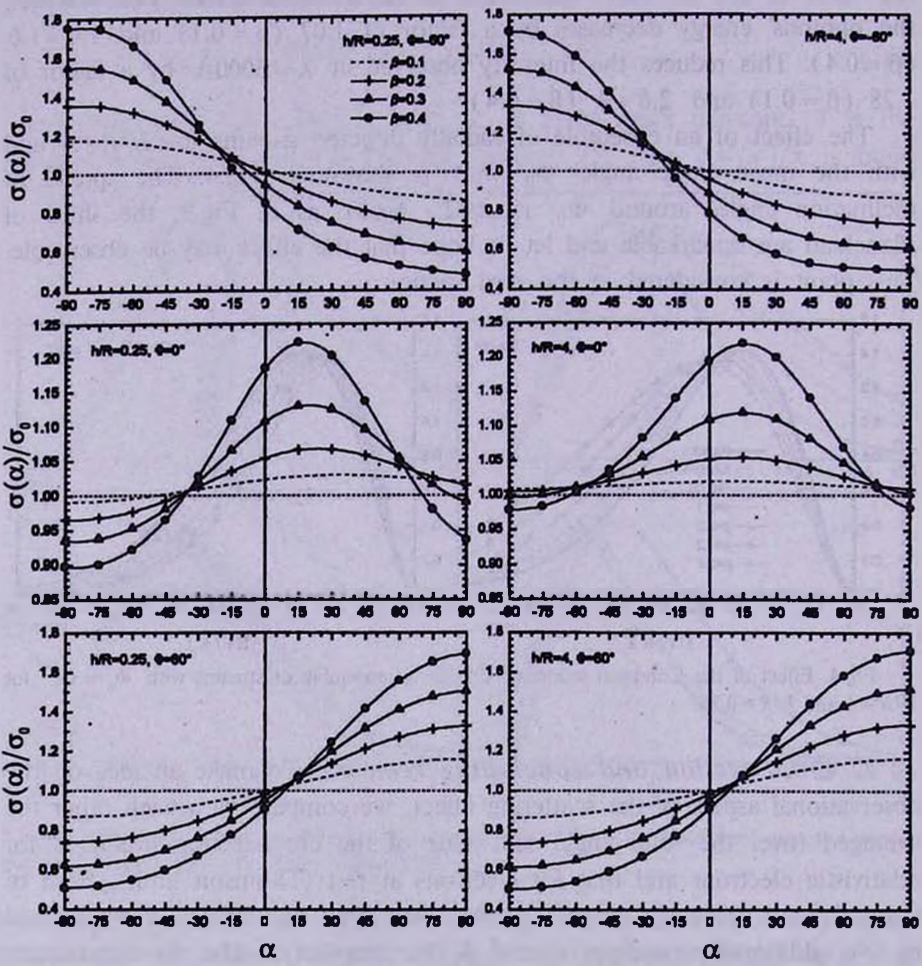

Fig.5. The ratio of the averaged cross-sections for Compton scattering to that of Thomson scattering for two heights and indicated values of Φ.

exhibited in case of $\Phi=0$. We conclude further that the cross-section of interest to us may exceed that for Thomson scattering up to 1:8 (for $\beta=0.4$) times, as it is the case of $\Phi<0$ ($\Phi>0$) and sunward (antisunward) directed beams.

Combining these results with those given in Fig.2, we see that the role of the Compton scattering is most efficient for negative slope angles. In this case the scattering on the sunward directed beams shortens the wavelengths, while the beams of electrons moving away the Sun (which are of primary importance from the point of view of suprathermal streams) produce drifts to the longwave domain of the spectrum. The shortening of wavelengths for antisunward directed beams may be observed merely for $\Phi > 0$ and small values of α ($\le \pi/6 \div \pi/4$, depending on height) but the resulting effect is obviously smaller.

The above analysis shows that in some cases the effect of the discussed mechanism of the radiation redistribution may be measurable even for relatively moderate energies of electrons if only the fractional density of such electrons is not too small.

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К ИНТЕРПРЕТАЦИИ ИЗЛУЧЕНИЯ НАДТЕПЛОВЫХ КОРОНАЛЬНЫХ СТРУЙ. II

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Это заключительная часть серии работ, в которых рассматривается эффект комптоновского рассеяния фотосферного излучения на быстрых электронах надтепловых корональных струй. По сравнению с предыдущей работой обсуждается более реалистичная, зависящая от высоты модельная задача. Приводятся результаты численных расчетов, показывающие зависимость среднего относительного изменения частоты и соответствующего дифференциального сечения от высоты и угла наклона электронного пучка. Рассмотрены как удаляющиеся от Солнца пучки электронов, так и пучки, направленные к нему. Делается заключение, что в зависимости от угла между направлениями начального выброса и магнитного поля рассеяние на электронах, удаляющихся от Солнца, могут вызвать измеряемые смещения падающего излучения как в коротковолновую, так и в длинноволновую области спектра. Рассеяние же на обратно направленных пучках приводит лишь к увеличению энергии фотонов.

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