АСТРОФИЗИКА

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ON INTERPRETATION OF RADIATION OF THE CORONAL SUPRA-THERMAL STREAMS. I.

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This is the first part of the series of two articles aimed at revealing the role of the Compton effect in scattering of the solar photospheric radiation by coronal supra-thermal streams. The simplest situation of a single beam of electrons gyrating around the strength lines of magnetic field is considered. Attention is focused to the height-independent problem, in which the role of the spatial angle of incident radiation is ignored. Analytical expressions for the frequency change of interacted photons and for proper cross-section of the scattering process are derived. The results of numerical calculations show that the effect may become essential even for moderate energies of fast electrons and will be observable if only the fractional density of fast electrons is not too small.

1. *Introduction.* For a long time high resolution eclipse images taken near the time of the solar maximum of activity did show multiple thread-like streams and/or straight and fine rays of unknown origin; this structure was sometimes called "fan-streamer" [1]. They are seen above limb active regions which produced flares before. Coronal streams are one of the intriguing short-lived phenomena of the magnetically dominated part of the outer atmosphere of the Sun. They probably represent fluxes of relativistic electrons (with velocities v up to 10^5 km/s) moving along spiral trajectories determined by forces of magnetic origin. These streams were considered by radio-astronomers to explain plasma emissions which drift very rapidly in frequencies (type III bursts). The beams induce plasma oscillations at the local plasma resonance frequency which depends on the local density of electrons. A self-focusing mechanism is not excluded to keep the particles confined in the beam. It is usually assumed that the propagation of the beams occurred in the region of the intermediate corona (0.2 to several radii from the surface of the Sun but always above flaring regions). The usually observed effect of type III bursts is the longwaveward drift of the emission frequency which is believed to be connected with generation of electron fluxes travelling antisunward in direction of decreasing density. However, some observational data reported during the past few years (see, e.g., [2-4]) indicate the accelerated electrons over short time scales and travelling toward the photosphere thus producing the frequency drift to the shorter wavelengths.

During a decade the most popular dynamical phenomenon which has been considered as a possible source of "non-thermal" solar wind has been coronal holes and the famous CME (Coronal Mass Ejections). However, CME are only episodically related to active region flares; filament eruptions and escaping prominences are more typical phenomena of a CME. They are indeed believed not to be related to flares, although sometimes it has been suggested that a CME can induce a flare.

There is no doubt that at least big flares produce large disturbances of the magnetic field of the surrounding corona as well as large flows of energetic particles in the MeV and up to the GeV range (neutrons and energetic muons arc recorded with Cosmic Rays Monitors at the time of a flare, etc.). The ubiquitous optical fine rays seen above active flaring regions are excellent candidates to consider for modelling the interaction of the beam of relativistic electrons with the photospheric radiation and surrounding coronal plasma.

The question we discuss in this series is whether the Compton scattering effects (CSE) are important in interpreting the radiation of streams observed in optical and shorter wavelengths regions of the spectrum. This point was never considered by theorists although the contribution of this radiation to the solar wind flux is certainly of great interest. Obvious implications will follow for stellar atmosphere physics when flares are important.

The theoretical investigation of the coronal CSE assumes a study of the Compton interaction of tlie solar photospheric radiation with fast electron beams assuming curved trajectories of their motion. Due to complex geometry of the photon-electron interaction, the problem requires a separate treatment different from that in deriving the so-called redistribution function appearing in the transfer equation and considered in [5-8]. The series consist of two papers. The first one deals with the Compton scattering of photospheric photons on a single beam of electrons gyrating in the magnetic field at a given height over the Sun. We start by considering the simplest situation which assumes that the incident radiation represents a parallel beam of photons so that the height-dependence of the CSE is ignored. Obviously, this approximation is the more accurate, the higher the distances from the solar surface. In Sec.2 we derive an analytical expression for differential cross-section describing the photon-electron interaction in the observer's frame (in which the electron is moving). The description of the geometrical model and derivation of an explicit formula for the mean frequency change resulting from the single event of the Compton scattering are given in Sec.3. The cross-section averaged over the single beam of electrons is evaluated. We present the results of numerical calculations which are briefly discussed in the final section. In view of that above said the electron fluxes in both antisunward and sunward directions are considered.

The height-dependent formulation of the problem in question with allowance for the changes in the spatial angles, in which the photospheric radiation falls, as well as the total effect of an ensemble of streams along the line of sight will be considered in the following paper of this series.

2. *Compton scattering.* Compton scattering provides a means by which electrons interact with photons without changing the photons number. The differential cross section valid for any system reads [9]

$$d\sigma = 8\pi r_e^2 \frac{\tilde{m}^2 dt}{\left(s-\tilde{m}^2\right)^2}\times$$
$$\left\{\left(\frac{\tilde{m}^2}{s-\tilde{m}^2}+\frac{\tilde{m}^2}{u-\tilde{m}^2}\right)^2+\left(\frac{\tilde{m}^2}{s-\tilde{m}^2}+\frac{\tilde{m}^2}{u-\tilde{m}^2}\right)-\frac{1}{4}\left(\frac{s-\tilde{m}^2}{u-\tilde{m}^2}+\frac{u-\tilde{m}^2}{s-\tilde{m}^2}\right)\right\}, \tag{1}$$

where r_e is the classical radius of electron, $\tilde{m} = mc$, m is the electron mass, c is the light velocity and s, u, t are the kinematic invariants defined as follows

$$s = \tilde{m}^2 + 2\,pk, \quad u = \tilde{m}^2 - 2\,pk', \quad t = -2\,kk'. \tag{2}$$

In writing Eq. (1) both the photon and electron are assumed unpolarized. Hereafter we avail ourselves of the commonly used notations: k and p are 4-momenta of photon and electron before interaction, while k' and p' are 4-momenta of photon and electron resulting from interaction. In terms of kinematic invariants Compton's formula has the form

$$s + u + t = 2\tilde{m}^2. \tag{3}$$

To proceed we need the explicit expressions for the scalar products appearing in Eq. (2)

$$pk = hm\nu\eta, \quad pk' = hm\nu'\eta', \quad kk' = \frac{h^2}{c^2}\nu\nu'(1-\cos\theta), \tag{4}$$

where h is Planck's constant, ν and ν' arc the initial and final photons frequencies, θ is the scattering angle; besides we have introduced

$$\eta = \gamma(1 - \beta\cos\psi_i), \quad \eta' = \gamma(1 - \beta\cos\psi_f), \tag{5}$$

where $\beta = |\vec{p}|/c$, $\gamma = \left(1-\beta^2\right)^{-1/2}$ is the relativistic factor, ψ_i and ψ_f are the angles composed by directions of incident and scattered photons with direction of the electron momentum.

In view of Eqs. (2) and (4), one may rewrite Eqs. (1) and (3) in the form

$$d\sigma = \pi r_e^2 \frac{dt}{2x^2\tilde{m}^2\eta^2}\left\{\left(\frac{1}{x\eta}-\frac{1}{x'\eta'}\right)^2+2\left(\frac{1}{x\eta}-\frac{1}{x'\eta'}\right)+\left(\frac{x\eta}{x'\eta'}+\frac{x'\eta'}{x\eta}\right)\right\} \tag{6}$$

and

$$x' = \frac{x\eta}{\eta' + x(1-\cos\theta)}, \tag{7}$$

where $x = h\nu/mc^2$, $x' = h\nu'/mc^2$. Finally, incorporating Compton's formula (7) into Eq. (6), we obtain

$$d\sigma = \pi r_e^2 \frac{dt}{2x^2\tilde{m}^2\eta^2}\left\{\frac{x\eta}{x'\eta'}+\frac{x'\eta'}{x\eta}-2\frac{1-\cos\theta}{\eta\eta'}+\frac{(1-\cos\theta)^2}{\eta^2\eta'^2}\right\}. \tag{8}$$

According to Eqs. (2) and (4), $dt = -2h^2\nu(1-\cos\theta)d\nu'/c^2$ so that, for fixed θ, with help of Eq. (7) we have

$$dt = \frac{2h^2 v^2 \eta(1-\cos\theta)}{c^2[\eta' + x(1-\cos\theta)]^2} d\eta' \tag{9}$$

and

$$d\sigma = \frac{\pi r_e^2}{\eta}\left\{\frac{x\eta}{x'\eta'} + \frac{x'\eta'}{x\eta} - 2\frac{1-\cos\theta}{\eta\eta'} + \frac{(1-\cos\theta)^2}{\eta^2\eta'^2}\right\}\frac{(1-\cos\theta)d\eta'}{[\eta' + x(1-\cos\theta)]^2} \tag{10}$$

or

$$d\sigma = \frac{\pi r_e^2}{\eta}\left\{\frac{\eta'}{\eta' + x(1-\cos\theta)} + \frac{x(1-\cos\theta)}{\eta'} + \left(1 - \frac{1-\cos\theta}{\eta\eta'}\right)^2\right\}\frac{(1-\cos\theta)d\eta'}{[\eta' + x(1-\cos\theta)]^2}\cdot \tag{11}$$

This is the requisite formula which will be of use below.

3. ***The geometrical model.*** Let us consider a single beam of electrons moving along spiral trajectories around the strength line of the magnetic field (axis Oz in Fig.1) which makes a certain angle Φ with the direction perpendicular to the line of sight. The angle Φ is assumed to be positive for slopes towards the observer and negative in the opposite case. For convenience, we choose the Cartesian system of coordinates in such a way that the line of sight lies in the plane xOz. If we suppose that all electrons involved in the beam are moving along similar trajectories (i.e. with the same step of the spiral), the velocity vectors υ will then have the same projection on the axis Oz. Hence at a given height, the velocity vectors of tlie moving electronic flux make one and the same angle (referred hereafter to as α) with the plane xOz.

For the begin, we treat the simplest situation and suppose that the incident radiation is a parallel beam of photons thus ignoring the role of the solid angle within which the solar photosphere is seen at a given height over the Sun. It is evident that this approximate case represents a limit to which the solution of the more general problem approaches at high distances from the Sun. We are interested in the mean value of the frequency (or energy) change, $\langle x' \rangle / x$, resulted from the Compton scattering on an ensemble of electrons moving with

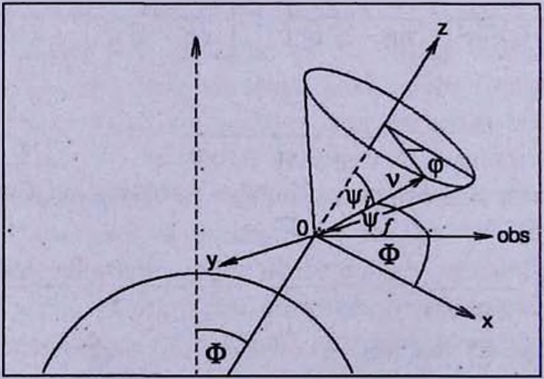

Fig.1. The geometrical model of the Compton scattering of photospheric radiation on the beam of relativistic electrons. The solid angle of incident radiation is assumed to be zero.

different azimuthal angles φ. In view of the assumption just made, the solution of the problem depends only on three parameters α, Φ and β (or γ).

The required quantity is

$$\frac{\langle x' \rangle}{x} = \frac{\int x' d\sigma}{x \int d\sigma}, \tag{12}$$

where the integration extends over the entire domain of variation of the azimuthal angle φ. By virtue of the Compton formula (7) we may write

$$\frac{\langle x' \rangle}{x} = \frac{1}{\sigma_0} \int \frac{\eta}{\eta' + x(1-\cos\theta)} d\sigma, \tag{13}$$

where $\sigma_0 = \int d\sigma$.

It can be seen from Fig.1 that in this special case we simply have $\theta = \frac{\pi}{2} - \Phi$ and $\psi_l = \frac{\pi}{2} - \alpha$, so that

$$\begin{gathered} \cos\theta = \sin\Phi, \quad \eta = \gamma(1 - \beta\sin\alpha), \\ \eta' = \gamma[1 - \beta(\xi\cos\alpha\cos\Phi + \sin\alpha\sin\Phi)], \end{gathered} \tag{14}$$

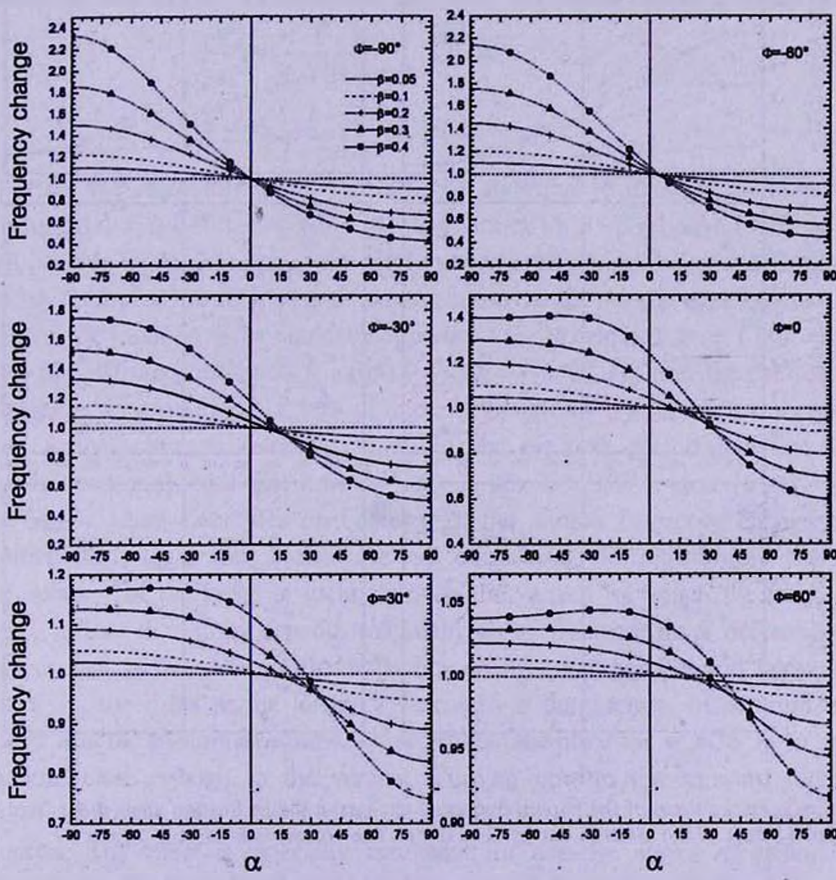

Fig.2. Dependence of the photon frequency change on α for fixed values of β and the inclination angle Φ. The dotted line corresponds to $< x' >/x = 1$.

where $\xi = \cos\varphi$.

Since ξ varies in the interval [-1,1], the values of η' lie between

$$\eta = \gamma[1 - \beta\cos(\alpha - \Phi)] \quad \text{and} \quad \overline{\eta} = \gamma[1 + \beta\cos(\alpha + \Phi)]. \tag{15}$$

On the other hand, for the most part of the incident photospheric radiation, $x(= h\nu/mc^2)$ is of the order of $10^{-4} \div 10^{-6}$ and can be safely neglected in Eqs. (11), (13) as compared to η' if only β is not very close to unity. With this assumption in force, we obtain

$$\frac{\langle x' \rangle}{x} = \eta \frac{\int\limits_{\eta'}^{\overline{\eta}'} \left[1 + \left(1 - \frac{1 - \sin\Phi}{\eta\eta'}\right)^2\right] \frac{d\eta'}{\eta'^3}}{\int\limits_{\eta'}^{\overline{\eta}'} \left[1 + \left(1 - \frac{1 - \sin\Phi}{\eta\eta'}\right)^2\right] \frac{d\eta'}{\eta'^2}}, \tag{16}$$

or which is the same

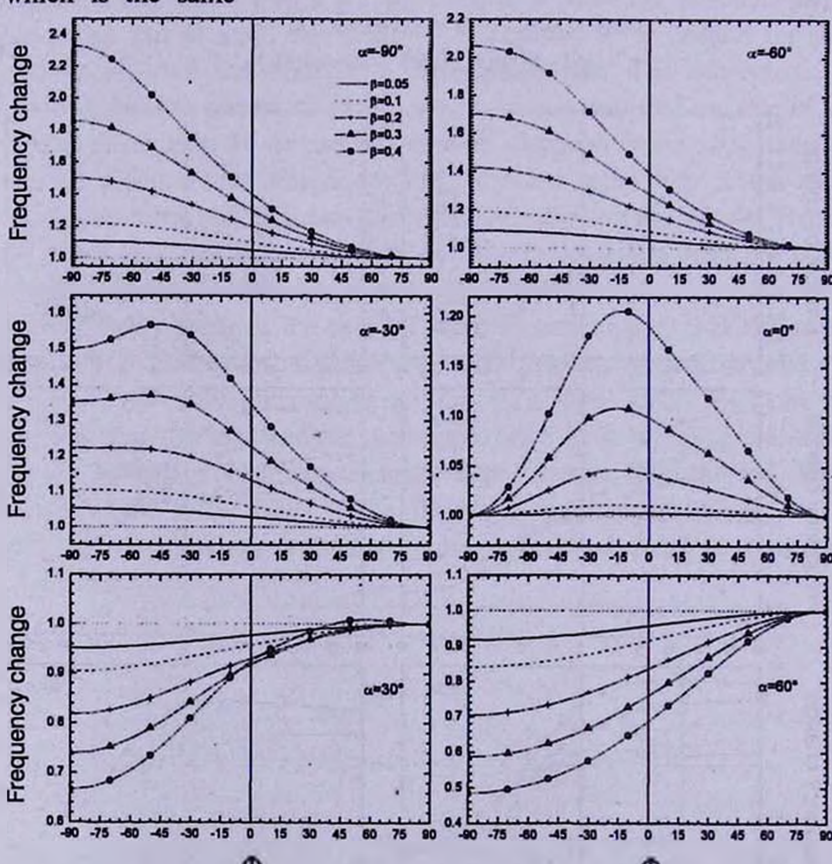

Fig.3. Dependence of the photon frequency change on the inclination angle Φ for fixed α and indicated values of the electron energy. The dotted line corresponds to $< x' >/x = 1$.

$$\frac{\langle x' \rangle}{x} = \eta \frac{\int_{-1}^{1} \left[1 + \left(1 - \frac{1-\sin\Phi}{\eta\eta'} \right)^2 \right] \frac{d\xi}{\eta'^3}}{\int_{-1}^{1} \left[1 + \left(1 - \frac{1-\sin\Phi}{\eta\eta'} \right)^2 \right] \frac{d\xi}{\eta'^2}}. \tag{17}$$

Performing integrations yields

$$\frac{\langle x' \rangle}{x} = \frac{\tilde{\eta}}{\gamma^2} \frac{A\tilde{\eta}^2 - 2s\tilde{\eta}B + s^2 C}{2\tilde{\eta}^2 - s\tilde{\eta}A + s^2 B}, \tag{18}$$

where the following notations are introduced:

$$A = \frac{2a}{a^2 - b^2}, \quad B = \frac{3a^2 + b^2}{3(a^2 - b^2)^2}, \quad C = \frac{a(a^2 + b^2)}{(a^2 - b^2)^3}, \quad \tilde{\eta} = \gamma\eta,$$

and

$$a = 1 - \beta\sin\alpha\sin\Phi, \quad b = \beta\cos\alpha\cos\Phi, \quad s = 1 - \sin\Phi.$$

In the limiting cases $\alpha = \pm\pi/2$, which correspond to antisunward and sunward monodircctional fluxes of electrons, Eq. (18) simplifies and takes the form

$$\frac{\langle x' \rangle}{x} = \frac{1-\beta}{1-\beta\sin\Phi}, \quad \text{if } \alpha = \pi/2, \tag{19}$$

$$\frac{\langle x' \rangle}{x} = \frac{1+\beta}{1+\beta\sin\Phi}, \quad \text{if } \alpha = -\pi/2. \tag{20}$$

We see that the values of $\langle x' \rangle / x$ for $\alpha = \pi/2$ are equal to or less than unity and vary from 1 ($\Phi = \pi/2$) to $1-\beta$ ($\Phi = 0$), and further to $(1-\beta)/(1+\beta)$ ($\Phi = -\pi/2$). For all possible inclination angles the photon energy decreases so that the Compton scattering results in the drift of incident spectrum to the longer wavelengths. For $\alpha = -\pi/2$, the situation is diametrically opposite: $\langle x' \rangle / x$ increases from 1 ($\Phi = \pi/2$) to $1+\beta$ ($\Phi = 0$), and further to $(1+\beta)/(1-\beta)$ ($\Phi = -\pi/2$), i.e. now the drift occurs to the shorter wavelengths. It is also of interest the case of $\alpha = 0$, when the conical surface, forming by the velocity vectors of the electron gas, degenerates into plane. One can easily find that now $\langle x' \rangle / x = 1$, for $\Phi = \pm\pi/2$, and $\langle x' \rangle / x = \gamma^2$, when $\Phi = 0$. More clear idea on behavior of the photon frequency change may be formed from Fig.2 and 3. Starting with considering the antisunward directed fluxes, we see that the range of inclinations to the vertical for which the frequency change is greater than unity depends essentially on α. Increase in α decreases this interval as well as the value of the frequency change. For positive and fairly large values of α. the drifts to the longer wavelengths is donunating. In addition, one may infer that the maximum shortwaveward drifts take place for $\alpha \leq 30^\circ \div 40^\circ$ and inclinations close enough to the vertical. Turning now to the sunward directed fluxes of electrons, we observe that the drift occur preferably to the higher frequencies. The effect is especially significant for negative angles of inclination.

For these effects to be observable the value of the proper cross-section for the photon-electron interaction must be sufficiently large. In the problem at hand, the quantity of importance from this viewpoint is the cross-section averaged over the single beam of electrons. This quantity referred to as $<\sigma_0>$ is obtained from Eq. (11) by integrating over the all azimutal angles φ or over all possible values of η':

$$\langle\sigma_0\rangle = \pi r_e^2 \frac{1-\sin\Phi}{\eta(\overline{\eta}-\underline{\eta})}\int_{\underline{\eta}}^{\overline{\eta}}\left[1+\left(1-\frac{1-\sin\Phi}{\eta\eta'}\right)^2\right]\frac{d\eta'}{\eta'^2}. \tag{21}$$

Then we obtain

$$\langle\sigma_0\rangle = \pi r_e^2 \frac{D}{\gamma}\left[2-2aD+\left(a^2+\frac{b^2}{3}\right)D^2\right], \tag{22}$$

where we have introduced the notation $D = (1-\sin\Phi)/2(a^2-b^2)$. Remind that, in accordance with the comment made at the outset of this section, the equations just derived are valid for all β, excluding those in close vicinity of unity.

Fig.4a, b demonstrate variations of the mean cross-section (expressed in terms of the Thomson scattering cross-section $\sigma_T = (8\pi/3)r_e^2$) with α and Φ for two typical values of β $(= 0.1; 0.4)$, respectively. We infer that, due to the factor $1-\sin\Phi$, tlie interaction is more efficient for negative values of Φ. On the other hand, turning again to Fig.3, we observe that the largest drifts in frequencies occur just for these angles.

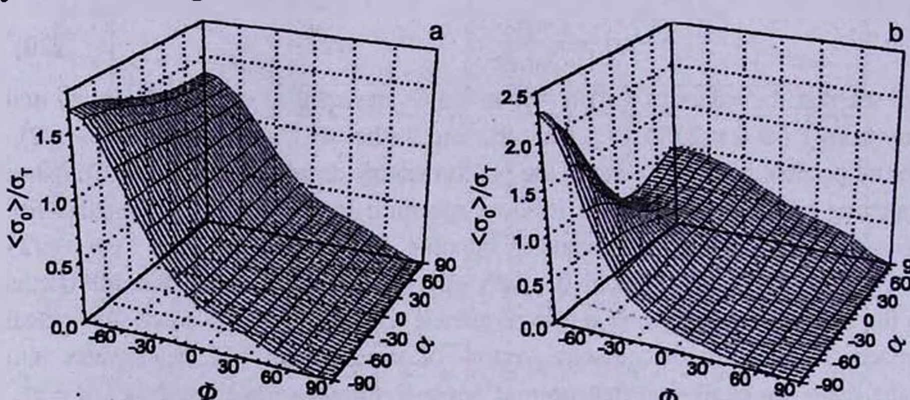

Figure 4: Dependence of the Compton scattering cross-section averaged over the beam, on α and Φ for (a) $\beta = 0.1$, (b) $\beta = 0.4$.

4. *Concluding remarks.* The results obtained at this intermediate stage may be summarized as follows. At least at high distances over the solar limb the frequency change in the supra-thermal streams radiation resulting from the Compton scattering may become essential even for moderate energies of electrons. For electrons moving off the Sun, the longwave-ward drifts of spectrum are more likely, while the opposite ones are due preferably to the opposite directed beams of electrons. The effect is expected to be detectable if only the fractional density of fast electrons is not very small. The more comprehensive discussion of this point will

be presented in the following paper in which a more realistic model with allowance for the contribution of an ensemble of beams along the line of sight is considered.

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К ИНТЕРПРЕТАЦИИ ИЗЛУЧЕНИЯ НАДТЕПЛОВЫХ КОРОНАЛЬНЫХ СТРУЙ. I

А.Г.НИКОГОСЯН, С.КУЧМИ

Это первая часть серии из двух работ, которые ставят целью выявить роль Комптон-эффекта при рассеянии солнечного фотосферного излучения на надтепловых струях короны. Рассматривается простейший случай единичного пучка электронов, движущихся по спиралевидным траекториям вокруг силовых линий магнитного поля. Обсуждается не зависящая от высоты задача, в которой пренебрегается величина телесного угла, внутри которого падает излучение. Получены аналитические выражения для относительного изменения частоты рассеивающихся фотонов и усредненного по пучку электронов сечения комптоновского взаимодействия. Приводятся результаты численных расчетов, которые показывают, что эффект может стать существенным даже при умеренных энергиях электронов и легко наблюдаться при условии, если парциальная плотность таких электронов не является слишком малой.

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