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The Effect of a Monatomic Layer on a Surface on the Transition Radiation

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Abstract

The transition radiation of a charged particle crossing the interface of two media having a monatomic impurity layer is investigated. It is shown that at sliding angles of incidence of a particle on the boundary of the media, the transition radiation is mainly determined by the properties of the surface layer. The possibility of using transition radiation to study the surface of substances is discussed. In addition, due to the hard radiation present in space, this research may be important for the use of light monoatomic layers as a material for satellite antennas, "*solar sails*" and cover layers in a future space (interstellar) mission.

Keywords

Relativistic Charged Particle, Transition Radiation, Monatomic Layer, Spectral Angular Distribution of Radiation, Sliding Angle, Investigation of Thin Films, Interstellar Mission

1. Introduction

Transient radiation has been actively investigated by many scientific groups. A significant contribution to the study of transient and quasi-transient radiation was made by Ginzburg, see [1] [2] [3], by Ter-Mikaelyan and Baghiyan [4] [5] [6] [7], and by Prof. Ryazanov and his colleagues [8]-[15]. After some decline in recent years, there has been a revival in the study of various aspects of transient radiation. Among these works it is possible to note following works [16]-[21]. It should be noted that in the works of Ryazanov and Tishchenko [14] and Sukharev *et al.* [20], some aspects of the generation of transient radiation from a monomolecular film and a graphene monolayer have already been considered. In contrast, this work is devoted to the development of a phenomenological theory of the influence of an atomic layer on the surface of two mediums on transient radiation.

The influence of the intermediate layer between two dielectric mediums on the transition radiation is studied in [4] [5] [22] [23] [24]. In these studies, the interface of the media was assumed not to be sharp, but to have a transition layer. The description of the transition layer was reduced to a smooth change in the permittivity in the blur zone, and various models of the intermediate layer were also selected. As noted in [4] [5] [22] [23] [24], in the case when the thickness of the intermediate transition layer is less than the length of radiation formation, the formulas of the transition radiation do not undergo significant changes. In the other extreme case, when the thickness of the intermediate layer is much greater than the length of the radiation formation and the properties of the transition layer change smoothly, the transition radiation is small. Thus, the main parameter characterizing transition radiation in [4] [5] [22] [23] [24] was the length of the radiation formation l_f:

$$l_f = \frac{2\pi V}{\omega\left(1-\beta\sqrt{\varepsilon}\cos\theta\right)} \tag{1}$$

where V is the speed of particle, ε—dielectric penetration, ω—frequency, θ—angle between $\boldsymbol{k}$ and $\boldsymbol{V}$, $\beta = V/c$, and c—speed of light.

The length of the transition radiation formation determines the distance at which the radiation field and the proper field of the particle in the medium are separated. However, the process of generating transition radiation is determined not only by the spatial separation of the radiation field and the particle's own field, but also by the reflection and refraction of waves that appear when the particle's own field crosses the interface of media.

As it is known, the process of reflection and refraction occurs at distances of the order of interatomic distance, *i.e.* at distance much smaller than the length of the radiation formation. In this way The reflection is influenced by the surface roughness, the presence of adsorbed atoms, oxides, as well as the difference in the molecular structure of the substance on the surface from the structure of the substance in its thickness. Qualitative estimates of the effect of surface roughness on transition radiation are given in [6].

Thus, when a particle is falling obliquely, the thickness of the transition layer should not be compared with the length of radiation formation measured along the trajectory of the particle, but with the component of this length normal to the surface of the substance. In the case when, during the sliding fall of a particle, a section of the trajectory with a length equal to the length of the radiation formation lies entirely in the surface monoatomic layer, so the micro-properties of this particular surface atomic layer will determine the spectral characteristics of the transition radiation.

Therefore, if ζ is the sliding angle (the angle between the velocity direction V and the surface), then it is microscopically justified to consider the surface layer under the condition:

$$l_f \zeta \le a \text{ and } l_f \gg a$$

In the case of large sliding angles $\zeta > a/l_f$ including with the normal incidence of a particle on the surface of a substance, the theoretical restriction will be stricter. It is necessary because it is possible to analyze the bulk media by phenomenological methods and the intermediate surface layer of atoms by microscopic methods only if the average distance between the species atoms of the think surface layer l_b is much greater than the interatomic distances between atoms in deep bulk layers:

$$l_b \gg n_0^{-1/3}$$

Below we will consider the effect on the transition radiation of macro-properties of an ideally smooth surface having a monolayer of atoms whose properties differ from those of atoms in the thickness of a bulk substance. An example of such simulation is the air-water interface in the presence of a monolayer of fatty acid molecules on the water surface. It is of interest, based on experimental data on light reflection [25] [26], to estimate corrections to the transition radiation at the boundary, which has a monolayer of adsorbed atoms.

The contribution to the transition radiation from the surface monatomic impurity layer will be noticeable against the background of ordinary "*bulk*" transition radiation when the latter is small. This is possible, in particular, in the case of equality of the dielectric permittivity of the media $\varepsilon_1(\omega) = \varepsilon_2(\omega)$ at a certain frequency or with a sliding particle falling on the interface of the media. In this case, the bulk transition radiation turns to zero, while the monatomic transition radiation from adsorbed atoms on the surface, as will be shown below, is different from zero. Therefore, it is of interest to use transition radiation to obtain information about the near-surface layer. In this case, it is advisable to choose a sliding drop of a particle on the boundary between two dielectric media to study the surface.

In this case, the bulk transition radiation turns to zero, and the transition radiation from the adsorbed atoms on the surface, as will be shown below, differs from zero. Therefore, it is of interest to use transition radiation to obtain information about the near-surface layer. At the same time, to study the surface, it is advisable to choose a sliding drop of a particle on the interface of media.

2. Transition Radiation from a Monolayer of Atoms

In this section we will show the difference between transition radiation in the presence of a monatomic layer between two media and the "*bulk*" transition radiation in the absence of this monatomic layer. Let a particle with charge e, moving uniformly and rectilinearly, intersects a layer of atoms located in the plane $z = 0$ in vacuum. The field of a moving charge creates forced oscillations of bound electrons, which are the source of the radiation field. Oscillations of bound electrons occur both in the plane of the monolayer of atoms and in the direction perpendicular to this monatomic layer. In this case, the components of the polarization currents appear both in the plane of the monolayer j_τ and in the direction perpendicular to the monolayer of atoms j_z.

As it is known, the own field of a moving charge has a large field component transverse to the direction of motion of the particle and a small longitudinal component. Therefore, when a particle slides along the surface of the monolayer at a small angle, the component of the polarization current J_z, normal to the surface of the monolayer, will be greater than the component j_τ. The transition radiation from a monolayer of atoms in a sliding fall is determined by the polarization current j_z and will differ from zero. On the other hand, the "*bulk*" transition radiation at the boundary of the two media is small when the particle slides along the interface of two media. Below we will consider the reason for this difference and determine the spectral-angular distribution of the radiation intensity from the monolayer of atoms.

If the proper field of the particle $\boldsymbol{E}_0$ and the radiation field $\boldsymbol{E}_s$ are smaller than the intraatomic fields, then the displacement of electrons in atoms is small: $\boldsymbol{r}_0 = \boldsymbol{R}_a + \boldsymbol{r}_e$ ($|\boldsymbol{r}_e| \ll |\boldsymbol{R}_a|$). Neglecting the oscillations of the $\boldsymbol{R}_a$ atoms and considering that the wavelengths of the fields $\boldsymbol{E}_0$ and $\boldsymbol{E}_s$ are large compared to the displacement of the electron $\boldsymbol{r}_e$, we write down the equation of motion of bound electrons

$$\frac{\mathrm{d}^2\boldsymbol{r}_0}{\mathrm{d}t^2} + \Gamma\frac{\mathrm{d}\boldsymbol{r}_0}{\mathrm{d}t} + \omega_e^2\boldsymbol{r}_0 = \frac{e}{m}\left(\boldsymbol{E}_0\left(\boldsymbol{R}_a,t\right) + \boldsymbol{E}_s\left(\boldsymbol{R}_a,t\right)\right) \tag{2}$$

where Γ is a damping factor.

In the dipole approximation, the density of micro currents j_μ, induced by the field of a moving charge, has a Fourier component:

$$\begin{gathered}\boldsymbol{j}_\mu\left(\boldsymbol{q},\omega\right) = \frac{-i\omega}{\left(2\pi\right)^3}\sum_{a,e} e\boldsymbol{r}_0\left(\omega\right)\exp\left(-i\boldsymbol{q}\boldsymbol{R}_a\right) \\ \boldsymbol{r}_0\left(\omega\right) = \frac{e}{m}\frac{\boldsymbol{E}_0\left(\boldsymbol{R}_a,\omega\right) + \boldsymbol{E}_s\left(\boldsymbol{R}_a,\omega\right)}{\omega_e^2 - \omega^2 - i\Gamma\omega}\end{gathered} \tag{3}$$

We introduce the density of atoms $N\left(\boldsymbol{r}\right)$ and the polarizability of atoms $\alpha\left(\omega\right)$

$$\begin{gathered}N\left(\boldsymbol{r}\right) = \sum_a \delta\left(\boldsymbol{r} - \boldsymbol{r}_a\right) \\ \alpha\left(\omega\right) = \sum_e \frac{\alpha^2/m}{\omega_e^2 - \omega^2 - i\Gamma\omega}\end{gathered} \tag{4}$$

we get the following:

$$\boldsymbol{j}_\mu\left(\boldsymbol{q},\omega\right) = \frac{-i\omega\alpha\left(\omega\right)}{\left(2\pi\right)^3}\int \mathrm{d}^3\boldsymbol{q}'\boldsymbol{E}\left(\boldsymbol{q}',\omega\right)\int \mathrm{d}^3\boldsymbol{r}\,N\left(\boldsymbol{r}\right)\exp i\left(\boldsymbol{q}'\boldsymbol{r} - \boldsymbol{q}\boldsymbol{r}\right) \tag{5}$$

where $\boldsymbol{E} = \boldsymbol{E}_0 + \boldsymbol{E}_s$.

In the case when the influence of radiation on the motion of bounded electrons can be neglected (for example, in the case of high frequencies $\omega \gg \omega_e$), the spectral-angular distribution of radiation is given by the relation:

$$\frac{\mathrm{d}^2\mathcal{E}}{\mathrm{d}\omega\mathrm{d}\Omega} = \left(2\pi\right)^6\frac{\omega^2}{c^3}\left[\left|\boldsymbol{n}\times\boldsymbol{j}_\mu\left(\boldsymbol{q},\omega\right)\right|^2\right]_{\boldsymbol{q}=\boldsymbol{n}\omega/c} \tag{6}$$

where $\boldsymbol{n}$ is the unit vector to the observation point. Equation (7) can be obtained from Equation (5) and Equation (6):

$$\frac{\mathrm{d}^2\mathcal{E}}{\mathrm{d}\omega\mathrm{d}\Omega}=\frac{\omega^4\alpha^2}{c^3}\iint \mathrm{d}\boldsymbol{q}'_z\,\mathrm{d}\boldsymbol{q}''_z\iint \mathrm{d}^2\boldsymbol{q}'_\perp\,\mathrm{d}^2\boldsymbol{q}''_\perp\cdot\left[\boldsymbol{n}\times E_0\left(\boldsymbol{q}'_\perp,\boldsymbol{q}'_z,\omega\right)\right]\left[\boldsymbol{n}\times\boldsymbol{E}_0^*\left(\boldsymbol{q}''_\perp,\boldsymbol{q}''_z,\omega\right)\right]$$
$$\cdot\iint \mathrm{d}^3\boldsymbol{r}'\mathrm{d}^3\boldsymbol{r}''N\left(\boldsymbol{r}'\right)N\left(\boldsymbol{r}''\right)\exp\left(i\boldsymbol{q}'\boldsymbol{r}'-i\boldsymbol{q}''\boldsymbol{r}''\right)\exp\left(i\frac{\omega}{c}\left(n\boldsymbol{r}''-n\boldsymbol{r}'\right)\right) \tag{7}$$

Since the monatomic layer is allocated in the plane $z_a=0$, it is convenient to additionally introduce the surface density of the distribution of impurity atoms:

$$\nu\left(\boldsymbol{R}\right)=\sum_a\delta\left(x-x_a\right)\delta\left(y-y_a\right) \tag{8}$$

where $\boldsymbol{R}$ is the radius vector in the plane $z=0$. Then

$$N\left(\boldsymbol{r}\right)=\nu\left(\boldsymbol{R}\right)\delta\left(z\right) \tag{9}$$

Substituting Equation (9) into Equation (7) and integrating, we obtain the following equation:

$$\frac{\mathrm{d}^2\mathcal{E}}{\mathrm{d}\omega\mathrm{d}\Omega}=\frac{\omega^4\alpha^2}{c^3}\left|\int \mathrm{d}^2\boldsymbol{q}_\perp\left[\boldsymbol{n}\times\boldsymbol{E}_0\left(\boldsymbol{q}_\perp,z=0,\omega\right)\right]\int \mathrm{d}^2\boldsymbol{R}\nu\left(\boldsymbol{R}\right)\exp\left(i\boldsymbol{q}_\perp\boldsymbol{R}-i\frac{\omega}{c}\boldsymbol{n}_\perp\boldsymbol{R}\right)\right|^2 \tag{10}$$

After averaging Equation (10) over the distribution of atoms in the plane $z=0$, the following could be obtained:

$$\left\langle\nu\left(\boldsymbol{R}'\right),\nu\left(\boldsymbol{R}''\right)\right\rangle=\nu_0^2 w_s\left(\boldsymbol{R}'-\boldsymbol{R}''\right) \tag{11}$$

where $\nu_0=\langle\nu\rangle$ is the average value of the surface density, $w_s\left(\boldsymbol{R}'-\boldsymbol{R}''\right)$ is the probability of finding one atom at point $\boldsymbol{R}'$ and the other at point $\boldsymbol{R}''$. Next, we transform the Equation (10) in the following form:

$$\frac{\mathrm{d}^2\mathcal{E}}{\mathrm{d}\omega\mathrm{d}\Omega}=\left(2\pi\right)^4\frac{\omega^4\alpha^2\nu_0^2}{c^3}\int \mathrm{d}^2\boldsymbol{S}_\perp w_s\left(\boldsymbol{S}_\perp\right)\left|\left[\boldsymbol{n}\times\boldsymbol{E}_0\left(\boldsymbol{q}_\perp,z=0,\omega\right)\right]\right|^2_{\boldsymbol{q}_\perp=\boldsymbol{n}_\perp\frac{\omega}{c}-\boldsymbol{S}_\perp} \tag{12}$$

where $w_s\left(\boldsymbol{S}_\perp\right)$ is the Fourier component of the probability of the distribution. Solving Maxwell's equation for the self-field of the charge, it is not difficult to find the Fourier component for the self electric-field of a moving charge:

$$\boldsymbol{E}_0\left(\boldsymbol{q}_\perp,z=0,\omega\right)=\frac{-ie}{2\pi^2V_z}\frac{\boldsymbol{q}_\perp+\left(\omega-\boldsymbol{q}_\perp\boldsymbol{V}_\perp\right)\left(\boldsymbol{k}_z/V_z\right)-\left(\omega/c\right)\left(\boldsymbol{V}/c\right)}{q_\perp^2-\omega^2/c^2+\left(\left(\omega-\boldsymbol{q}_\perp\boldsymbol{V}_\perp\right)/V_z\right)^2} \tag{13}$$

where $\boldsymbol{k}_z$ is the unit vector of the Oz axis.

As follows from Equation (12) and Equation (13), the energy of the transition radiation in the frequency range of $\mathrm{d}\omega$, and angles $\mathrm{d}\Omega$ is determined by the following relation:

$$\frac{\mathrm{d}^2\mathcal{E}}{\mathrm{d}\omega\mathrm{d}\Omega}=\frac{4e^2\omega^4\alpha^2\nu_0^2}{c^3V_z^2}\int \mathrm{d}^2\boldsymbol{S}_\perp w_s\left(\boldsymbol{S}_\perp\right)$$
$$\cdot\left|\boldsymbol{n}\times\frac{\left(\boldsymbol{n}_\perp\frac{\omega}{c}-\boldsymbol{S}_\perp\right)+\left(\omega-\left(\boldsymbol{n}_\perp\frac{\omega}{c}-\boldsymbol{S}_\perp\right)\boldsymbol{V}_\perp\right)\left(\boldsymbol{k}_z/V_z\right)-\left(\omega/c\right)\left(\boldsymbol{V}/c\right)}{\left(\boldsymbol{n}_\perp\frac{\omega}{c}-\boldsymbol{S}_\perp\right)^2-\omega^2/c^2+\left(\left(\omega-\left(\boldsymbol{n}_\perp\frac{\omega}{c}-\boldsymbol{S}_\perp\right)\boldsymbol{V}_\perp\right)\Big/V_z\right)^2}\right|^2 \tag{14}$$

The formal convertation to the macroscopic electromagnetic theory corresponds to the replacement of $w_s \to \delta_s$. In the macroscopic limit from Equation (14) it is possible to obtain:

$$\frac{\mathrm{d}^2\mathcal{E}}{\mathrm{d}\omega\mathrm{d}\Omega} = \frac{4e^2\omega^4\alpha^2 v_0^2}{c^3}\frac{1}{\left|\left(1-\boldsymbol{n}_\perp\boldsymbol{\beta}_\perp\right)^2-\beta_z^2\cos^2\theta\right|^2} \cdot\left|\beta_z\left[\boldsymbol{n}\times\left(\boldsymbol{n}_\perp-\boldsymbol{\beta}_\perp\right)\right]+\left(1-\boldsymbol{n}_\perp\boldsymbol{\beta}_\perp-\beta_z^2\right)\cdot\left[\boldsymbol{n}\times\boldsymbol{k}_z\right]\right|^2 \tag{15}$$

where $\boldsymbol{n}=\left(\sin\theta\cdot\cos\phi,\sin\theta\cdot\sin\phi,\cos\theta\right)$ is a unit vector to the observation point; $\beta = V/c$.

The first term in Equation (15) describes the radiation caused by the component of the polarization current lying in the plane of the monolayer of atoms (*i.e.* $z=0$). The contribution of the first term to the radiation decreases as the sliding angle of the particle along the monolayer surface decreases; $\zeta = \arctan\left(\beta_z/\beta_x\right)$. At the same time, the second term in Equation (15) does not decrease with an increase in the falling angle of the particle and does not vanish in the limit at $\beta_z \to 0$. This term corresponds to the component of the polarization microcurrent normal to the atomic layer allocated on the plane surface. Thus, the transition radiation from the monolayer of atoms does not tend to zero when the particle is grazing.

3. Reflection of Light and Transition Radiation

As it is already noted above, the transition radiation from one layer of atoms does not tend to zero during a sliding fall, unlike the "*bulk*" standard transition radiation occurred when charge crosses the interface of two mediums. The difference between these two types of transition radiation is explained by the fact that during the usual macroscopic examination of the process of generation of transition radiation at the boundary of two mediums, the component of the surface polarization microcurrent normal to the interface of the medium is not taken into account. Next, we will focus on the description of the surface polarization current based on the Hertz oscillator model.

As it is known, transition radiation can be considered as a process of refraction and reflection of waves generated by the particle's own field. The reflection process is influenced by the state of the surface, which can change over time, *i.e.* the surface can "*deteriorate*". To control the microstate of the surface the ellipsometry method is used in [25] [26], which is based on the study of the reflection of light when it falls on the surface of a substance at a Brewster angle. Obviously, an alternative way to obtain information about the state of the surface is to use transition radiation, during the generation of which the reflection and refraction of the wave, generated when the particle crosses the surface occurs. We will conduct a phenomenological examination of the effect of the reflection process on transition radiation.

To do this, we replace the monatomic layer on the surface with a uniform distribution of Hertz oscillators (just as it is done for light reflection in [27]) and obtain the dependence of the spectral-angular distribution of the intensity of transition radiation on the characteristic parameters of the surface.

First, let the particle cross the interface of the media perpendicular to the interface, then the intensity of the transition radiation can be directly expressed in terms of the Fresnel coefficients for the reflection of plane electromagnetic waves [28]. The energies of the transition radiation in the media ε_1 and ε_2 are respectively equal to:

$$\frac{\mathrm{d}^2\mathcal{E}_1}{\mathrm{d}\omega\mathrm{d}\Omega_1}=\frac{e^2\beta^2\sqrt{\varepsilon_1}}{4\pi^2 c}\left|\frac{\sin\theta_1}{1+\beta\sqrt{\varepsilon_1}\cos\theta_1}+\frac{r_{12}\sin\theta_1}{1-\beta\sqrt{\varepsilon_1}\cos\theta_1}-\frac{\sin\theta_2}{1+\beta\sqrt{\varepsilon_2}\cos\theta_2}\sqrt{\varepsilon_1/\varepsilon_2}\left(1+r_{12}\right)\right|^2 \tag{16}$$

$$\frac{\mathrm{d}^2\mathcal{E}_2}{\mathrm{d}\omega\mathrm{d}\Omega_2}=\frac{e^2\beta^2\sqrt{\varepsilon_2}}{4\pi^2 c}\left|\frac{\sin\theta_2}{1+\beta\sqrt{\varepsilon_2}\cos\theta_2}+\frac{r_{21}\sin\theta_2}{1-\beta\sqrt{\varepsilon_2}\cos\theta_2}-\frac{\sin\theta_1}{1+\beta\sqrt{\varepsilon_1}\cos\theta_1}\sqrt{\varepsilon_2/\varepsilon_1}\left(1+r_{21}\right)\right|^2 \tag{17}$$

where r_{12} and r_{21} are Fresnel coefficients for the light reflection: $\sin\theta_1/\sin\theta_2=\sqrt{\varepsilon_2/\varepsilon_1}$. As it is known [28], the first term in Equation (16) and Equation (17) corresponds to a wave created by the charge itself, the second term to a wave generated in the direction of the boundary and reflected from it, the third term to a wave that came to the observation point after refraction at the boundary of matter. In this case, the transition radiation is polarized so that the electric field vector lies in the plane formed by the normal to the surface of the substance and the radius vector to the observation point. The Fresnel coefficient for this polarization is:

$$r^0_{12(\|)}=\frac{\varepsilon_2\cos\theta_1-\sqrt{\varepsilon_1\left(\varepsilon_2-\varepsilon_1\sin^2\theta_1\right)}}{\varepsilon_2\cos\theta_1+\sqrt{\varepsilon_1\left(\varepsilon_2-\varepsilon_1\sin^2\theta_1\right)}} \tag{18}$$

For the reflection of light, the dependence of the Fresnel coefficient on the state of the surface of matter has been well studied [27]. We generalize the approach described in [27] [29], to describe the effect of a monomolecular layer on the properties of transition radiation. To do this, we represent a monomolecular surface layer by a uniform distribution of Hertz oscillators, then we get the following correction to Fresnel light reflection formulas, which was presented early in [25] [29]:

$$\begin{aligned}
r_{12(\|)}&=\frac{\varepsilon_2\cos\theta_1-\sqrt{\varepsilon_1\left(\varepsilon_2-\varepsilon_1\sin^2\theta_1\right)}+A}{\varepsilon_2\cos\theta_1+\sqrt{\varepsilon_1\left(\varepsilon_2-\varepsilon_1\sin^2\theta_1\right)}+B}\\
A&=-i4\pi\frac{\omega}{c}\left(\sigma_\perp\varepsilon_1\cos\theta_1\sqrt{\varepsilon_2-\varepsilon_1\sin^2\theta_1}-\sigma_z\varepsilon_2\sqrt{\varepsilon_1}\sin^2\theta_1\right)\\
B&=-i4\pi\frac{\omega}{c}\left(\sigma_\perp\varepsilon_1\cos\theta_1\sqrt{\varepsilon_2-\varepsilon_1\sin^2\theta_1}+\sigma_z\varepsilon_2\sqrt{\varepsilon_1}\sin^2\theta_1\right)
\end{aligned} \tag{19}$$

where $\sigma_{\perp}$, σ_z are the characteristic scattering parameters. Substituting Equation (19) into Equation (16) and Equation (17) and taking into account the smallness of $\sigma_{\perp}$, σ_z, it is possible to find transition radiation in the presence of a monomolecular layer on the surface between two dielectric mediums:

$$\begin{aligned}\frac{\mathrm{d}^2\mathcal{E}_1}{\mathrm{d}\omega\mathrm{d}\Omega_1}=\frac{e^2\beta^2\sqrt{\varepsilon_1}}{4\pi^2c}\Bigg|&\frac{\sin\theta_1}{1+\beta\sqrt{\varepsilon_1}\cos\theta_1}+r_{12\|}^0\cdot\frac{\sin\theta_1}{1-\beta\sqrt{\varepsilon_1}\cos\theta_1}\\&-\left(1+r_{12\|}^0\right)\cdot\frac{\sin\theta_2}{1+\beta\sqrt{\varepsilon_2}\cos\theta_2}\sqrt{\varepsilon_1/\varepsilon_2}\\&+\left(\frac{\sin\theta_1}{1-\beta\sqrt{\varepsilon_1}\cos\theta_1}-\frac{\sin\theta_2}{1+\beta\sqrt{\varepsilon_2}\cos\theta_2}\sqrt{\varepsilon_1/\varepsilon_2}\right)\\&\cdot 8\pi i\frac{\omega}{c}\left(\frac{\cos\theta_1}{\sqrt{\varepsilon_1}}\right)\frac{\sigma_{\perp}\varepsilon_1\left(\varepsilon_2-\varepsilon_1\sin^2\theta_1\right)-\sigma_z\varepsilon_2^2\sin^2\theta_1}{\varepsilon_2\cos\theta_1+\sqrt{\varepsilon_1\left(\varepsilon_2-\varepsilon_1\sin^2\theta_1\right)}}\Bigg|^2\end{aligned}\tag{20}$$

The equations for transition radiation in the ε_2 medium are written in a similar way. Thus, corrections to the formulas for light reflection due to the presence of a monatomic layer lead to the corresponding corrections for transition radiation. In addition to the above model of Hertz oscillators, in some special cases, for example, for dielectric molecular crystals, it is possible to carry out a consistent microscopic consideration for light reflection, which leads to corrections [27] other than Equation (19). Substitution in Equation (16) and Equation (17) of the corrections to the light reflection coefficient obtained in [27] gives corrections to the transition radiation in these particular cases. With a normal particle incident on the surface, corrections to the transition radiation due to the presence of a monatomic impurity layer on the surface will dominate over the "*bulk*" transition radiation in the case when the difference between the dielectric permittivities of the mediums is insignificant, that is, both inequalities are fulfilled:

$$\frac{\varepsilon_2-\varepsilon_1}{\varepsilon_0}\ll\frac{\omega}{c}\sigma_{\perp}\sqrt{\varepsilon_0}\cos\theta_1,\quad\frac{\varepsilon_2-\varepsilon_1}{\varepsilon_0}\ll\frac{\omega}{c}\sigma_z\sqrt{\varepsilon_0}\frac{\sin^2\theta_1}{\cos\theta_1}$$

where $\varepsilon_1\sim\varepsilon_2\sim\varepsilon_0$.

4. Effect of Boundary Conditions on Transition Radiation

In the previous section, the normal component of the polarization surface current was described using the Hertz oscillator model and the corrections to the transition radiation were determined by the corresponding corrections to the Fresnel reflection coefficients. However, this can be done quite simply only with a normal falling of charge on the interface between two mediums. In the case of an inclined particle fall, the normal component of the surface microcurrent can be taken into account in the macroscopic description of the generation process by introducing corrections to the usual boundary conditions. The boundary conditions in the presence of Hertz oscillators on the surface of the substance are written, similarly as in [27] [29]:

$$\begin{aligned} & \boldsymbol{E}_{2\perp} - \boldsymbol{E}_{1\perp} = -i4\pi\sigma_z \boldsymbol{q}_\perp E_{2z} \\ & \left[\boldsymbol{k}_z \times \left(\boldsymbol{H}_2 - \boldsymbol{H}_1\right)\right] = -i4\pi\frac{\omega}{c}\sigma_\perp \varepsilon_1 \boldsymbol{E}_{2\perp} \end{aligned} \tag{21}$$

Solving the problem of finding the intensity of transition radiation with boundary conditions Equation (21), it is possible to find the energy of radiation polarized in the plane passing through the normal to the surface and among the direction of radiation in the medium ε_1:

$$\begin{aligned} \frac{\mathrm{d}^2\mathcal{E}_1^\perp}{\mathrm{d}\omega\mathrm{d}\Omega_1} = & \frac{e^2\beta_z^2}{\pi^2 c}\frac{\varepsilon_1\sqrt{\varepsilon_1}\cos^2\theta_1}{\left|(1-b)^2 - \varepsilon_1\beta_z^2\cos^2\theta_1\right|^2}\left(\beta_x\sin\Phi - \beta_y\cos\Phi\right)^2 \\ & \cdot\left|\frac{\dfrac{\beta_z\left(\varepsilon_1-\varepsilon_2\right)}{(1-b)+\beta_z\sqrt{\varepsilon_2-\varepsilon_1\sin^2\theta_1}} + i4\pi\dfrac{\omega}{c}\varepsilon_1\sigma_\perp}{\sqrt{\varepsilon_1}\cos\theta_1 + \sqrt{\varepsilon_2-\varepsilon_1\sin^2\theta_1} + i4\pi\dfrac{\omega}{c}\varepsilon_1\sigma_\perp}\right|^2 \end{aligned} \tag{22}$$

where θ_1 is the angle between the axis Oz and the direction of emission of the radiation quantum; Φ is the polar angle in the XY plane, measured from the Ox axis; $b = \left(\beta_x\cos\Phi + \beta_y\sin\Phi\right)\sqrt{\varepsilon_1}\sin\theta_1$. The energy of the transition radiation polarized in the plane passing through the normal to the interface and the direction of emission of the radiation quantum is equal to:

$$\begin{aligned} \frac{\mathrm{d}^2\mathcal{E}_1^\parallel}{\mathrm{d}\omega\mathrm{d}\Omega_1} = & \frac{e^2}{\pi^2 c}\frac{\sqrt{\varepsilon_1}\cos^2\theta_1}{\sin^2\theta_1\left|(1-b)^2 - \varepsilon_1\beta_z^2\cos^2\theta_1\right|^2} \\ & \cdot\left|\frac{D+C}{\varepsilon_2\cos\theta_1 + \sqrt{\varepsilon_1}K + i4\pi\dfrac{\omega}{c}\varepsilon_1\sigma_\perp\cos\theta_1 K - i4\pi\dfrac{\omega}{c}\varepsilon_1\sigma_z\sin^2\theta_1}\right|^2 \end{aligned} \tag{23}$$

where K, C, and D are equal to:

$$K = \sqrt{\varepsilon_2 - \varepsilon_1\sin^2\theta_1}$$

$$C = \beta_z\left(\varepsilon_2-\varepsilon_1\right)\frac{\sin^2\theta_1\left(1-b-\varepsilon_1\beta_z^2+\beta_z K\right) - b\beta_z K}{1-b+\beta_z K}$$

$$D = i4\pi\frac{\omega}{c}\varepsilon_1\left(\sigma_\perp\beta_z\left(\sin^2\theta_1 - b\right)K - \sigma_z\sin^2\theta_1\left(1-b-\varepsilon_1\beta_z^2\right)\right)$$

The equations for transition radiation in the ε_2 medium for both polarizations are derived similarly. In the non-relativistic limit ($\beta \ll 1$) formulas Equation (22) and Equation (23) are significantly simplified:

$$\begin{aligned} \frac{\mathrm{d}^2\mathcal{E}_1^\perp}{\mathrm{d}\omega\mathrm{d}\Omega_1} = & \frac{e^2\beta_z^2}{\pi^2 c}\varepsilon_1\sqrt{\varepsilon_1}\cos^2\theta_1\left(\beta_x\sin\Phi - \beta_y\cos\Phi\right)^2 \\ & \cdot\left|\frac{\beta_z\left(\varepsilon_1-\varepsilon_2\right) + i4\pi\dfrac{\omega}{c}\varepsilon_1\sigma_\perp}{\sqrt{\varepsilon_1}\cos\theta_1 + \sqrt{\varepsilon_2-\varepsilon_1\sin^2\theta_1} + i4\pi\dfrac{\omega}{c}\varepsilon_1\sigma_\perp}\right|^2 \end{aligned} \tag{24}$$

$$\frac{\mathrm{d}^2 E_1^{\parallel}}{\mathrm{d}\omega \mathrm{d}\Omega_1} = \frac{e^2}{\pi^2 c}\sqrt{\varepsilon_1}\cos^2\theta_1 \sin^2\theta_1 \cdot \left| \frac{\beta_z\left(\varepsilon_2-\varepsilon_1\right)+i4\pi\frac{\omega}{c}\varepsilon_1\sigma_{\perp}\beta_z K - i4\pi\frac{\omega}{c}\varepsilon_1\sigma_z}{\varepsilon_2\cos\theta_1+\sqrt{\varepsilon_1}K+i4\pi\frac{\omega}{c}\varepsilon_1\sigma_{\perp}\cos\theta_1 K - i4\pi\frac{\omega}{c}\varepsilon_1\sigma_z\sin^2\theta_1} \right|^2 \tag{25}$$

where $K=\sqrt{\varepsilon_2-\varepsilon_1\sin^2\theta_1}$. It follows from Equations (22)-(25) that the influence of the monatomic adsorbed layer on the surface of the substance can not be neglected under the conditions:

$$\beta_z\left|\varepsilon_2-\varepsilon_1\right|/\varepsilon_1 \ll \sigma/\lambda$$

$$\left|\varepsilon_2-\varepsilon_1\right|/\sqrt{\varepsilon_1\cos\theta_1} \ll \sigma_{\perp}/\lambda$$

Thus, parallel polarization of transition radiation is most sensitive to the properties of the interface of the mediums at close values of the dielectric permittivity of the mediums, non-relativistic particle velocities and the sliding fall of the particle on the interface. The surface current component normal to the interface, characterized by the σ_z parameter, contributes only to the parallel polarization of the transition radiation, while the tangential component of the surface polarization current affects the radiation of both polarizations. Note that, as follows from Equation (22) and Equation (23), when a particle slides onto the surface the energy of the transition radiation does not vanish and is completely determined by the normal component of the surface polarization current. At $\varepsilon_1=\varepsilon_2$, the equations Equation (22) and Equation (23) convert in the limit of high frequencies into the formula for monatomic layer transition radiation (Equation (15)).

5. Discussion of the Results

It follows from the above that the physical picture of transition radiation in the presence of a monatomic layer on surface between two dielectric mediums is determined by the interference of "*bulk*" and "*surface*" transition radiation. The Equations (22)-(25) make it possible to determine the state of a smooth surface at a sliding falling of a charged particle by the parameters of the transition radiation. Thus, the use of transition radiation in the study of surfaces is an alternative to ellipsometric methods, in which it is used the reflection of a plane electromagnetic wave. In conclusion, based on experimental data on the ellipsometry of light [25] [26], we will evaluate the role of the surface in transition radiation compared to conventional "*bulk*" transition radiation.

To do this, we will compare the energy of transition radiation at the air-water interface in the presence of a monomolecular layer of fatty acids on the surface and in its absence.

Let the electron fall on the air-water interface. For a specially cleaned water surface, the ellipticity coefficient ρ, which is defined as the ratio of the component of the electric field vector, parallel to the plane of light falling, to the component of the electric field vector perpendicular to the this plane, is numerically equal in the reflected wave to [25]:

$$\rho = \left| \frac{E_{ref}^{\parallel}}{E_{ref}^{\perp}} \right| = 45 \times 10^{-5} \tag{26}$$

If the light falls at the Brewster angle $\Phi_B = \operatorname{arctg}\left(\sqrt{\varepsilon}\right)$, in the incident light the components $E_0^{\perp}$ and $E_0^{\parallel}$ are equal. Hence, neglecting the optical anisotropy of molecules on the water surface $\sigma_{\perp} = \sigma_z = \sigma$, we can find the characteristic dispersion parameter:

$$\sigma = \rho \Big/ \left(2\pi \frac{\omega}{c} \sqrt{\varepsilon + 1} \right) \tag{27}$$

Substituting Equation (27) into Equation (23), we find the ratio of the transition radiations from the monomolecular "*surface*" layer on the surface to the original "*bulk*" transition radiation

$$\frac{\mathrm{d}^2 \mathcal{E}_{sufrace}^{\parallel}}{\mathrm{d}^2 \mathcal{E}_{bulk}^{\parallel}} = \frac{4\rho^2}{\beta_z^2 (\varepsilon + 1)} \cdot \left| \frac{\beta_z G \left(\sin^2 \theta_1 - b \right) - \sin^2 \theta_1 \left(1 - b - \beta_z^2 \right)}{(\varepsilon - 1) \sin^2 \theta_1 \left(1 - b - \beta_z^2 + \beta_z G \right) - b \beta_z G} \right|^2 \tag{28}$$

where $G = \sqrt{n^2 - \sin^2 \theta_1}$.

In the case of non-relativistic velocities of the charged particle $\beta \ll 1$, the relation Equation (28) is transformed to the form:

$$\frac{\mathrm{d}^2 \mathcal{E}_{sufrace}^{\parallel}}{\mathrm{d}^2 \mathcal{E}_{bulk}^{\parallel}} \approx \frac{4\rho^2}{\beta_z^2 (\varepsilon + 1)(\varepsilon - 1)^2} \tag{29}$$

It can be seen from Equation (29) that the error in determining the energy of transition radiation, polarized in the radiation plane, which appears as a result of not taking into account the differences in the properties of surface atoms from the properties of atoms allocated in the depth of matter. This difference will be the greater than the smaller the sliding angle $\zeta = \operatorname{arctg}\left(\beta_z / \beta_{\perp}\right)$ and more the ellipticity coefficient. So, for fast electrons with an energy of 30 keV ($\beta = 0.33$), falling at a sliding angle $\zeta = 0.5^0$ on a specially cleaned water surface, in the optical frequency range, where the refractive index of water is equal to $n \sim 1.33$, we get ratio $\mathrm{d}^2 \mathcal{E}_{sufrace}^{\parallel} \big/ \mathrm{d}^2 \mathcal{E}_{bulk}^{\parallel} \sim 2$.

For the surface of a substance covered with a monolayer of impurity adsorbed atoms or molecules, the ratio in the left part in Equation (29) becomes significantly larger. So, for the surface of water covered with a monolayer of fatty acid molecules, the ellipticity coefficient p for which is an order of magnitude higher 563 × 10^{-5} for palmitic acid, 672 × 10^{-5} for stearic acid), we get from Equation (29) rations, which are equal to 3.05 × 10^2 and 4.35 × 10^2, respectively, that is, the transition radiation from the surface monomolecular layer is approximately exceeds the bulk transition radiation by two orders of magnitude.

6. Conclusion and Suggestions

The transition radiation of a charged particle crossing the interface of two media having a monatomic impurity layer is investigated. It is shown that at sliding angles of incidence of a particle on the boundary of the media, the transition radiation is mainly determined by the properties of the surface layer. Therefore, first of all, transient radiation can be used to study the surface of monatomic surface substances. This theoretical path may be of interest to researchers studying the properties of thin monatomic layers and specialists using modern methods of optics and microelectronic lithography.

The second area, which is more interesting for the author, is the use of monoatomic layers in spacecraft technology. Monoatomic layers can have extremely low weight and large surfaces, so such layers can be used as cover materials for protected satellites, space sails or telemetry antennas. Flights to distant planets, as well as interstellar flights, take place outside the Earth's magnetic field, so satellites are exposed to cosmic radiation for a long time. Thus, this research may be of interest to specialists in the field of astrophysics and astronomy. Also pay attention to this study in the author's research series. Note that the question of the basic principles of creating habitable planets for stars in the Milky Way galaxy is discussed in [30]. In [31], it was supposed to create a space rescue base in Tibet, a type of "*Noah's Ark*". The possibility of mining lunar ore is explored by the author in [32]. In [33] [34] [35], the possibility of future interstellar missions was discussed by the author of this study.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

References

[1] Ginzburg, V.L. and Tsytovich, V.N. (1978) Transition Radiation and Transition Scattering Produced in a Vacuum in the Presence of a Strong Electromagnetic Field. *JETP*, **47**, 845-852.

[2] Ginzburg, V.L. (1982) Transition Radiation and Transition Scattering. *Physica Scripta*, **1982**, 182-191. https://doi.org/10.1088/0031-8949/1982/T2A/024

[3] Ginzburg, V.L. (1996) Radiation by Uniformly Moving Sources (Vavilov-Cherenkov Effect, Transition Radiation, and Other Phenomena). *Physics-Uspekhi*, **39**, 973-982. https://doi.org/10.1070/PU1996v039n10ABEH000171

[4] Ter-Mikaelian, M.L. (1972) High-Energy Electromagnetic Processes in Condensed Media. Willey, New York.

[5] Ter-Mikaelian, M.L. (1972) On the Theory of Transition Radiation during the Passage of a Charged Particle through an Arbitrary Interface. *Izd. AN ArmSSR*, **55**, 32-35. (In Russian)

[6] Bagiyan, R.A. and Ter-Mikaelyan, M.L. (1981) Radiation by Uniformly Moving Sources (Vavilov-Cherenkov Effect, Transition Radiation, and Other Phenomena). *JETP*, **54**, 666-672.

[7] Bagiyan, R.A. (2004) Radiation by Uniformly Moving Sources (Vavilov-Cherenkov Effect, Transition Radiation, and Other Phenomena). *Physical Review E*, **69**, Article ID: 026609.

[8] Ryazanov, M.I. and Tilinin, I.S. (1976) Transition Radiation Emitted by an Ultrarelativistic Particle Crossing a Curved Interface between Media. *JETP*, **44**, 1092-1095.

[9] Ryazanov, M.I. (1984) Limits of Applicability of the Macroscopic Theory of Transition Radiation. *JETP Letters*, **39**, 698-700.

[10] Ryazanov, M.I. and Safronov, A.N. (1993) Quasitransition Radiation of a Charged Particle Reflected by a Crystal Surface. *JETP*, **76**, 276-279.

[11] Ryazanov, M.I. and Safronov, A.N. (1993) Quasitransition Surface Wave Radiation. *JETP*, **77**, 672-676.

[12] Ryazanov, M.I. and Safronov, A.N. (1996) Effects of Interference in Transient Radiation. *Laser Physics*, **6**, 708-712.

[13] Ryazanov, M.I. and Safronov, A.N. (1997) Microscopic Theory of High-Frequency Transient Radiation in the Grazing Incidence of a Particle on an Interface. *Laser Physics*, **7**, 1068-1075.

[14] Ryazanov, M.I. and Tishchenko, A.A. (2002) Emission of a Fast Charged Particle Passing through a Monomolecular Film. *Laser Physics*, **12**, 1442-1447.

[15] Koshelev, I.B. and Ryazanov, M.I. (2002) On the Diffraction Emission of a Charged Particle on a Massive Wedge. *Laser Physics*, **12**, 1437-1441.

[16] Serov, A.V. Bolotovskii, B.M. (2008) Transient Radiation of Particles in Dihedral and Trihedral Angles. *Technical Physics*, **53**, 285-290. https://doi.org/10.1134/S1063784208030018

[17] Silva, T.F., Jahnke, C., Lima, R.R., Malafronte, A.A., Vanin, V.R. and Marcos, N. (2011) Transition Radiation and Its Uses in Particle Accelerators. *AIP Conference Proceedings*, **1351**, 183-188. https://doi.org/10.1063/1.3608954

[18] Konkov, A.S., Potylitsyn, A.P. and Polonskaya, M.S. (2014) Transition Radiation of Electrons with Orbital Angular Momentum. *JETP Letter*, **100**, 475-479. https://doi.org/10.1134/S0021364014190084

[19] Nause, A., Dyunin, E., Ianconescu, R. and Gover, A. (2014) Exact Theory of Optical Transition Radiation in the Far and Near Zones. *Journal of the Optical Society of America B*: *Optical Physics*, **31**, 2438-2445. https://doi.org/10.1364/JOSAB.31.002438

[20] Sukharev, V.M., Tishchenko, A.A. and Strikhanov, M.N. (2015) Analytical and Numerical Calculation of Transition Radiation from Graphene Monolayer. *Physics Procedia*, **72**, 504-511. https://doi.org/10.1016/j.phpro.2015.09.033

[21] Gevorkyan, E.A. (2015) The Theory of Transient Radiation of a Charged Particle in a Waveguide with an Anisotropic Magnetodielectric Filling. *Optics and Spectroscopy*, **119**, 286-290. https://doi.org/10.1134/S0030400X15080081

[22] Amatuni, A.Ts. and Korkhmazyan, N.A. (1961) Transition Radiation in the Case of a Diffuse Boundary between Two Media. *JETP*, **12**, 703-708.

[23] Galeev, A.A. (1964) Transition Radiation from a Uniformly Moving Charge Crossing a Diffuse Boundary between Two Media. *JETP*, **19**, 904-909.

[24] Tsytovich, V.N. (1961) Transition Radiation of Currents Passing through a Plasma Boundary. *JETP*, **6**, 554-562.

[25] Kizel, V.A. (1968) Modern Status of the Theory of Light Reflection. *Proceedings—Cambridge Philosophical Society*, **10**, 485-508. https://doi.org/10.1070/PU1968v010n04ABEH003698

[26] Kizel, V.A. (1973) Reflection of Light. Nauka, Moscow. (In Russian)

[27] Sivukhin, D.V. (1984) Theory of Elliptic Polarization of Light Reflected from Iso-

tropic Media. *JETP*, **3**, 269-274.

[28] Frank, I.M. (1966) Transition Radiation and Optical Properties of Matter. *Soviet Physics Uspekhi*, **8**, 729-742. https://doi.org/10.1070/PU1966v008n05ABEH003034

[29] Strachan, C. (1933) The Reflection of Light at a Surface Covered by a Monomolecular Film. *Proceedings—Cambridge Philosophical Society*, **29**, 116-130. https://doi.org/10.1017/S0305004100011373

[30] Safronov, A.N. (2016) The Basic Principles of Creation of Habitable Planets around Stars in the Milky Way Galaxy. *International Journal of Astronomy and Astrophysics*, **6**, 512-554. https://doi.org/10.4236/ijaa.2016.64039

[31] Safronov, A.N. (2020) A New View of the Mass Extinctions and the Worldwide Floods. *International Journal of Geosciences*, **11**, 251-287. https://doi.org/10.4236/ijg.2020.114014

[32] Safronov, A.N. (2023) Theory of the Origin of Terrestrial and Lunar Ores. *International Journal of Geosciences*, **14**, 547-583. https://doi.org/10.4236/ijg.2023.146030

[33] Safronov, A.N. (2024) Life Origin in the Milky Way Galaxy: I. The Stellar Nucleogenesis of Elements Necessary for the Life Origin. *Journal of High Energy Physics, Gravitation and Cosmology*, **10**, 647-680. https://doi.org/10.4236/jhepgc.2024.102040

[34] Safronov, A.N. (2024) Life Origin in the Milky Way Galaxy: II. Scanning for Habitable Stellar Systems on Behalf of Future Space Missions. *Journal of High Energy Physics, Gravitation and Cosmology*, **10**, 681-692. https://doi.org/10.4236/jhepgc.2024.102041

[35] Safronov, A.N. (2024) Life Origin in the Milky Way Galaxy: III. Spatial Distribution of Overheated Stars in the Solar Neighborhood. *Journal of High Energy Physics, Gravitation and Cosmology*, **10**, 693-709. https://doi.org/10.4236/jhepgc.2024.102042