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THOMSON SCATTERING OF ELECTROMAGNETIC WAVES IN POLAR MESOSPHERE CONTAINING THE CHARGED DUST

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Abstract. On the basis of the kinetic theory, simple formulas for differential and total cross-sections of incoherent radio scattering in the polar mesosphere, containing charged dust, are received. As the model of medium the six-component plasma, consisting from electrons, positive and negative ions and clusters, and one sort of neutral particles has been used.

Introduction

At present for research of the polar mesosphere the Thomson (or incoherent) radio scattering on random fluctuations are widely used. For definition of medium parameters by this method it is necessary to know the character of influence of various species of the charged particles of the mesosphere on a frequency spectrum (or an autocorrelation function), polarization and total power of scattered radiation [Sheffield, 1975; Suni et al., 1989].
Researches of the mesosphere by the Thomson scattering method are carried out from the end of the 70th years of the last century [Fukuyama and Kofman, 1980; Ivanov and Tereshchenko, 1983]. As the model of the mesosphere it was used poorly ionized five-component plasma consisting from electrons, positive and negative ions, charged particles of dust and neutral particles. However, formulas of the scattering spectrum received for the model of medium are bulky enough and do not allow to determine quickly and precisely parameters of mesospheric plasma.
Below, using the kinetic theory of the Thomson scattering, which was developed earlier [Suni et al., 1989], we shall receive simple analytical expressions for differential and total cross-sections of radiowaves, scattering in the mesospheric plasma containing charged dust.

Total cross-section of scattering

For solution of the task we shall make use of the expression for the differential cross-section of incoherent scattering of radiowaves $d\sigma$ from the work [Suni et al., 1989]:

$$d\sigma = \frac{r_e^2 N_e}{\pi\,\omega}\,\mathrm{Re}\left\{A_e\left(1 - A_e/A\right)\right\}, \tag{1}$$

where

$$A = -i\,q^2\,D_e^2 + \sum_\alpha n_\alpha\,z_\alpha^2\,A_\alpha\;; \tag{2}$$

$$A_\alpha = \left[-i + \left(y + i\,\psi\right)I\right]/\left(1 + \psi\,I\;\right); \qquad I_\alpha = \int_0^\infty \exp\left[i\left(y + i\,\psi\right)t - t^2/4\right]\mathrm{d}t\;;$$

$$y_\alpha = \frac{\omega}{q}\sqrt{\frac{m}{2T}}\;; \qquad \psi_\alpha = \frac{\nu}{q}\sqrt{\frac{m}{2T}}\;; \qquad n_\alpha = \frac{N_\alpha}{N_e}\;;$$

$r_e = e^2 / m_e c^2 = 2.8\cdot10^{-15}$ m is the classical radius of electron; e, m_e and N_e are the charge, mass and electron concentration; ω is the frequency shift of scattered radiation due to chaotic thermal movements of scatterers; $q = 4\pi/\lambda$ is the module of scattering vector; λ is the transmitter wavelength; $D_e = \sqrt{T/4\pi N e^2}$ is the electron Debye length; $z_\alpha, m_\alpha, \nu_\alpha, N_\alpha, T_\alpha$ are the total charge, mass, collision frequency with neutrals; concentration and temperature of the charged particles of different kinds α (positive and negative simple ions and clusters and dust particles).
All values, concerning to electrons of plasma, we shall symbolize by the index e, to ions - by the index i, to clusters - by the index cl, and to neutral particles - by the index n.

For simplicity of record we believe that, except for negative charged clusters, all other charged particles of plasma are single-charged ones. In this case the condition of the general neutrality of the mesospheric plasma will become:

$$N_e\left(1+\lambda^- + f^-\right) = N_i\left(1+f^+\right), \tag{3}$$

where

$\lambda^- = N_i^- / N_e$; $f^- = z\,N_{cl}^- / N_e$; $f^+ = N_{cl}^+ / N_i^+$; z is the charge number; parameters of negative charged particles are marked by the sign "minus", and parameters of positive charged particles are marked by the sign "plus".

Let's note, that the differential cross-section of scattering $d\sigma$ is the power, scattered by unit scattering volume in a unit solid angle per unit interval of frequency and per unit of energy-flux density of the incident wave. The total cross-section of scattering σ is the integral of the expression (1) over all frequency Doppler shifts ω.
Taking into account the condition (3), the contour integration of the expression (1) over all frequency shifts ω can be presented so:

$$\sigma = \frac{r_e^2\,N_e}{\left(1+q^2\,D_e^2\right)}\left\{q^2\,D_e^2 + \frac{1+\lambda^-}{2\left(1+\lambda^-\right)+f^-\left(1+z\right)+q^2\,D_e^2}\left[1+\frac{\lambda^- + f^-\left(1+z\right)}{1+\lambda^-}\right]\right\}. \tag{4}$$

It follows from this that the total cross-section of scattering does not depend on the parameter f^+, i.e. from the ratio between quantity of positive clusters N_{cl}^+ and quantity of usual ions N_i^+. It means that under screening of probe particles single-charged positive ions behave just as simple positive ions.
The first term in (4) describes scattering on screened electrons, the second one describes scattering on the screened positive ions and clusters, the third one describes scattering on the screened negative ions, and the fourth one describes scattering on negative clusters when the charged particles of plasma are considered as probe charges [Rosenbluth and Rostoker, 1962]. The appearance of negative ions may lead to a change in the functional relation between the total scattered power and electron concentration in the mesosphere. The increase in total scattered power is caused by damping of the Coulomb interaction between electrons and positive ions due to partial screening of the latter by negative ions.
From the equation (4) it is evident that if we could measure the reflected power then, basically, it is possible to determine the high-altitude structure N_e, or N_i^-, or N_{cl}^-. At the same time, the total cross-section of scattering will be approximately twice more than in absence of negative particles of plasma. In the absence of dust particles ($f^- = 0$) the expression for the total cross-section of scattering (4) passes on the result from the works [Fukuyama and Kofman, 1980; Ivanov and Tereshchenko, 1983].

Differential cross-section or spectrum of scattering

Under the conditions of the experiment, where the radar wavelength was significantly greater than double the Debye circumference of the electrons ($q\,D_e << 1$) and the collision frequency of ions with neutrals significantly exceeds the Doppler shift of the ions ($\psi_\alpha >> 1$), the expression for the spectrum (1) will become:

$$d\sigma = \frac{r_e^2}{\pi\,\omega}\,\mathrm{Re}\left\{\frac{\sum\limits_\alpha n_\alpha\,z_\alpha^2\,A_\alpha}{1+i\sum\limits_\alpha n_\alpha\,z_\alpha^2\,A_\alpha}\right\}, \tag{5}$$

where

$$A_\alpha = \frac{1}{2\,y\,\psi + i}. \tag{6}$$

Substituting (6) in to (5), after bulky, but not difficult, calculations, it is possible to present the differential cross-section of scattering $d\sigma$ in such a way:

$$d\sigma = \frac{r_e^2\, N_e}{\pi\, q}\sqrt{\frac{2m_i}{T}}\;\frac{\psi_i\left[1+2\lambda^- + f^-\left(1+z\right)\right]a}{4\, y_i^2\, \psi_i^2 + \left[2\left(1+\lambda^-\right)+f^-\left(1+z\right)\right]^2 a^2}\,, \tag{7}$$

where

$$a = \frac{\left(1+f^+\right)\left[1+2\lambda^- + \left(1+z\right)f^-\right]}{\left(1+\gamma\, f^+\right)\left(1+\lambda^- + f^-\right)+\left(1+f^+\right)\left(\beta\,\lambda + \eta\, z\, f^-\right)}\,; \tag{8}$$

$$\beta = \frac{m_i^-\, \nu_i^-}{m_i\, \nu_i}\,; \qquad \gamma = \frac{m_{cl}^+\, \nu_{cl}^+}{m_i\, \nu_i}\,; \qquad \eta = \frac{m_{cl}^-\, \nu_{cl}^-}{m_i\, \nu_i}\,.$$

This implies that the width of a spectrum at the level of half intensity is defined by expression:

$$\Delta\omega = \frac{2\, q^2\, T}{m_i\, \nu_i}\left[2\left(1+\lambda^-\right)+\left(1+z\right)\, f^-\right]a\,. \tag{9}$$

As apposed to the effect of collisions, which constrict the scattering spectrum, negative ions and clusters expand it. Here the amplitude of the center of the spectrum decreases. The change in the particle screening condition leads to expansion of scattering spectrum.

In absence of positive and negative clusters ($f^+ = f^- = 0$) and at $\beta = 1$ the factor $a = 1$ and the received formulas for the cross-sections of scattering (4) and (7) pass on the result from the works [Fukuyama and Kofman, 1980; Ivanov and Tereshchenko, 1983]:

$$\sigma = \frac{r_e^2\, N_e}{\left(1+q^2\, D_e^2\right)}\left\{q^2\, D_e^2 + \frac{1+2\lambda^-}{2\left(1+\lambda^-\right)+q^2\, D_e^2}\right\}, \tag{10}$$

$$d\sigma = \frac{r_e^2\, N_e}{\pi\, q}\sqrt{\frac{m_i}{8T}}\;\frac{\psi_i\left(1+2\lambda^-\right)}{y_i^2\, \psi_i^2 + \left(1+\lambda^-\right)^2}\,, \tag{11}$$

$$\Delta\omega = \frac{4\, q^2\, T}{m_i\, \nu_i}\left(1+\lambda^-\right). \tag{12}$$

Let's estimate the value of the factor a for the plasma containing usual positive and negative ions. In this case

$$a = \frac{1+2\,\lambda^-}{1+\left(1+\beta\right)\lambda^-}\,. \tag{13}$$

For calculation of the factor a it is possible to make use of the formula for the collision frequency of ions with neutral particles from the work [Sheffield, 1975].

$$\nu_{\alpha n} = \frac{8}{3}\left(2\,\pi\, T\,\frac{m_n}{m_\alpha\left(m_\alpha + m_n\right)}\right)^{1/2} r_{\alpha n}^2\, N_n\,. \tag{14}$$

where

$r_{\alpha n}$ is the sum of the effective radii of the interactive particles (typically $r_{\alpha n} \cong 10^{-10}\,\text{m}$).

Using (14), the expression for parameter β can be represented in following form:

$$\beta \cong \left(\frac{m_i^- \left(m_i + m_n \right)}{m_i \left(m_i^- + m_n \right)} \right)^{1/2} . \tag{15}$$

Substituting this expression in (13) and using the altitude distribution the negative ion to electron density ratio λ^-, it is possible to find the coefficient a on the heights of the polar mesosphere.

Estimations show that for the conditions, which are typical for the polar mesosphere [Fukuyama and Kofman, 1980], the value a can very from changes from ~1 down to certainly 0.88. Therefore under calculations of parameters of medium using a zero approximation the value a can be equated with 1.

Conclusion

Thus formulas for radiowaves scattering cross-sections in the plasma containing charged dust are received. The obtained expressions are the most general ones and are submitted in the form which is convenient for the analysis and diagnostics of the polar mesosphere by the method of incoherent scattering. It is shown that presence of dust in the ionosphere leads to broadening the spectrum of scattering. For negative dust particles the broadening is more strongly. The presence of dust plasma leads to amplification of intensity of scattering radiation, but the amplification is no more than twice in comparison with the case of absence of dust.

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