Scattering of electromagnetic waves in dusty plasmas with variable charges on dust particles

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(Received 24 March 1994)

The scattering of electromagnetic radiation in multicomponent unmagnetized plasmas with dust particulates is considered. It is demonstrated that the effect of capture of electrons and ions by the dust particles can affect the scattering of the electromagnetic waves. In particular, dependence of the scattering cross section on new parameters characterizing the charging process is found. The expressions for static longitudinal dielectric permittivity taking into account perturbations of the capture process are first obtained.

PACS number(s): 52.25.Dg, 52.35.Ra, 52.35.Fp, 52.75.Di

Study of dusty plasmas is important for a number of applications in laboratory plasmas and modern plasma technologies (e.g., plasma etching), as well as in space plasmas and a plasma of the earth's environment [1–12]. The dust particles (grains) are highly charged as a rule, and are of size a much less than the Debye length r_{De}. The grains are charged by plasma currents, photoemission, secondary emission, etc. Previously, mostly plasmas with constant (on characteristic time scales of considered processes) charges on dust particles have been considered. However, recently [8–12] effects of variable charges on dust particles have been investigated. In this case, the collective waves pertubate the process of dust charging which in turn effects the dielectric properties of dusty plasmas.

Scattering of electromagnetic waves in plasmas [13–15] is a powerful diagnostic method which has been successfully used in laboratory and active geophysical experiments (see, e.g., Refs. [16–24]). For dusty plasmas, this technique is useful for many applications, e.g., in estimation of pollution in the earth's atmosphere. If heavy dust particles are embedded, they obviously contribute to the scattering process. In consideration of a dust particle, the usual Thomson scattering is small and mostly effective is the so-called transition scattering [25] which is connected with scattering by screening cloud surrounding the massive charged particle. Recently, scattering of longitudinal [2,3] and electromagnetic [4,5] waves in dusty plasmas has been investigated for the cases of linear and nonlinear screening of the dust grains. However, effects of dust charging have not been considered in Refs. [2–5].

Here, on the basis of a recent kinetic theory [10,11] of dusty unmagnetized plasmas, the process of scattering of electromagnetic waves is considered taking into account effects of variable charges on dust particles. The model considers spherical immobile dust grains with the same radius a, which are linearly screened by plasma particles. We demonstrate that the scattering cross-section is now dependent on auxiliary parameters characterizing the dust plasma component.

To find the (transition) scattering of electromagnetic waves on a dust particle, we use the procedure elaborated in Refs. [4,5]. In particular, the scattering cross-section is given by

$$\sigma^{\mathrm{em}} = \sigma^T \frac{3c^3}{16\pi} \int d\mathbf{k} \left(1+\cos^2\Theta\right) \frac{|Z^{\mathrm{eff}}_{\mathbf{k}-\mathbf{k}_0}|^2}{\omega_0^2} \times\delta(\omega_0 - \sqrt{\omega_{pe}^2 + k^2c^2}), \tag{1}$$

where σ^T is the cross-section of the Thomson scattering,

$$\sigma^T = \frac{8\pi}{3}\frac{e^4}{m_e^2c^3}, \tag{2}$$

c is the light speed, Θ is the angle between incident and scattered waves, subscript 0 corresponds to the incident wave with frequency $\omega_0 = (\omega_{pe}^2 + k_0^2c^2)^{1/2}$, m_e and $-e$ are the electron mass and charge, respectively, $\omega_{pe} = (4\pi n_e e^2/m_e)^{1/2}$ is the electron plasma frequency, and $-Z^{\mathrm{eff}}_{\mathbf{k}}e$ is the "effective charge" of the dust particle. In the linear approximation, the effective charge is given by

$$Z^{\mathrm{eff}}_{\mathbf{k}} = Z_d \frac{\varepsilon^{(e)}_{\mathbf{k}} - 1}{\varepsilon_{\mathbf{k}}}, \tag{3}$$

where $-Z_d e$ is the equlibrium charge of the dust particle, and

$$\varepsilon_{\mathbf{k}} = \varepsilon^{(e)}_{\mathbf{k}} + \varepsilon^{(i)}_{\mathbf{k}} - 1 \tag{4}$$

is the complete static dielectric permittivity (i.e., $\varepsilon^{(\alpha)}_{\mathbf{k}}$ corresponds to the dielectric function of α plasma component) taking into account perturbations of the charging process. Thus, to find the scattering cross-section for the problem considered, it is necessary to obtain expressions

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1063-651X/94/50(2)/1422(5)/$06.00

for the dielectric functions.

The current on a dust particle is given by [26]

$$I(q) = \sum_\alpha \int_{V_d} d\mathbf{v}\, e_\alpha \sigma_\alpha v f_\alpha, \tag{5}$$

where the subscript $\alpha = e, i$ describes electrons or ions, $v \equiv |\mathbf{v}|$ is the particle speed, f_α is the distribution function of the corresponding particle velocities, e_α is the electron (ion) charge ($e_e = -e$ and $e_i = e$), q is the charge of the dust particle, and $\sigma_\alpha = \sigma_\alpha(q, v)$ is the charging cross section,

$$\sigma_\alpha = \begin{cases} \pi a^2 \left(1 - \frac{2e_\alpha q}{a m_\alpha v^2}\right) & \text{if } \frac{2e_\alpha q}{a m_\alpha v^2} < 1 \\ 0 & \text{if } \frac{2e_\alpha q}{a m_\alpha v^2} \geq 1, \end{cases} \tag{6}$$

m_α is the electron or ion mass. The phase volume V_d of integration in $\mathbf{v}$ space is defined by step function σ_e, see (6). The last inequality in (6) gives restriction on particle charging speeds only for electrons (we remind that the dust particles are negatively charged, i.e., $q < 0$). Therefore, only sufficiently fast electrons can charge the dust particles.

For equilibrium distribution functions, we have

$$I^{\rm eq}(-Z_d e) = 0. \tag{7}$$

Equation (7) defines the charge of the dust particle in the state of equilibrium. If the equilibrium distributions are thermal, then the equilibrium charge is given by

$$\frac{\omega_{pe}^2}{v_{T_e}} \exp\left(-\frac{Z_d e^2}{a T_e}\right) = \frac{\omega_{pi}^2}{v_{T_i}} \left(\frac{T_i}{T_e} + \frac{Z_d e^2}{a T_e}\right), \tag{8}$$

where $\omega_{pi} = (4\pi n_i e^2/m_i)^{1/2}$ is the ion plasma frequency, $v_{T_\alpha} = (T_\alpha/m_\alpha)^{1/2}$ is the thermal velocity, and T_α is the corresponding temperature.

Furthermore, it is convenient to introduce the dimensionless variables (see [10])

$$\tau \equiv \frac{T_i}{T_e}, \qquad z \equiv \frac{Z_d e^2}{a T_e}, \tag{9}$$

where $T_{e(i)}$ is the electron (ion) temperature. Also, we introduce the following dimensionless parameter [6,7]

$$P \equiv \frac{n_d}{n_e} \frac{a T_e}{e^2}, \tag{10}$$

where n_d is the dust density. Note that the value of P can vary largely depending on the plasma parameters.

The charging dissipative process is described by the charging frequency $\nu_d^{\rm eq}$ which for Maxwellian particle distributions is given by

$$\nu_d^{\rm eq} \equiv -\left.\frac{\partial I(q)}{\partial q}\right|_{q=-Z_d e} = \frac{1}{\sqrt{2\pi}} \frac{\omega_{pi}^2 a}{v_{Ti}} (1 + \tau + z). \tag{11}$$

To obtain this equation, we used (8). Note that expression (11) takes place for any P and for $n_e \neq n_i$. Comparison of this rate with the ion-ion collision frequency [10] demonstrates that this process can be the most important dissipative process for dusty plasmas. Furthermore, the frequency $\nu_{ed}^{\rm eq}$ characterizing the rate of capture of electrons by dust particles in the equilibrium state can be introduced by

$$\begin{aligned} \nu_{ed}^{\rm eq} = \frac{n_d}{n_e} \int d\mathbf{v} \sigma_e v f_e &= 2\sqrt{2\pi} a^2 v_{Te} n_d e^{-z} \\ &= \nu_d^{\rm eq} P \frac{\tau + z}{1 + \tau + z}, \end{aligned} \tag{12}$$

where we have assumed Maxwellian distribution of electrons. The rate (12) determines specific damping of Langmuir and electromagnetic waves due to charging effects in dusty plasmas.

In kinetic description of the charging processes (see for details Ref. [11]), the distribution function of dust particles can be defined as

$$f_d = f_d(q, \mathbf{r}, t), \tag{13}$$

where the charge q is the additional independent variable. In the case of spherical grains with the same radius a and the same equilibrium charge $-Z_d e$, we have

$$f_d^{\rm eq} = n_d \delta(q + Z_d e). \tag{14}$$

For the first moments we then find

$$n_d = \int f_d dq = \text{const} \tag{15}$$

and

$$Q = \frac{1}{n_d} \int q f_d dq, \tag{16}$$

where Q is the averaged charge of a dusty particle. The corresponding kinetic equation is given by (we suppose that the dust particles have infinite masses and, consequently, $v_d = 0$)

$$\frac{\partial f_d}{\partial t} + \frac{\partial}{\partial q} I(q) f_d = 0. \tag{17}$$

The kinetics of electrons and ions are described by the usual distribution functions f_α. The corresponding kinetic equations for the electrons or ions taking into account charging collisions is given by

$$\frac{\partial f_\alpha}{\partial t} + \mathbf{v} \cdot \frac{\partial f_\alpha}{\partial \mathbf{r}} + \frac{e_\alpha}{m_\alpha} \mathbf{E} \cdot \frac{\partial f_\alpha}{\partial \mathbf{v}} = -\int \sigma_\alpha v f_d f_\alpha dq. \tag{18}$$

In the equlibrium state, we have the isotropic equilibrium electron (ion) distribution $f_\alpha^{\rm eq}$; the term with magnetic field in the expression for the Lorentz force has been neglected in the left hand side of (18).

We introduce (small) perturbations of the above distribution functions

$$f_d = f_d^{\rm eq} + \delta f_d, \qquad f_\alpha = f_\alpha^{\rm eq} + \delta f_\alpha, \tag{19}$$

$|\delta f_d| \ll |f_d|$, $|\delta f_\alpha| \ll |f_\alpha|$, and linearize kinetic equations (17) and (18) with respect to these perturbations. Furthermore, we suppose that external sources compensate the electron and ion capture by the dust in the zero approximation. Here we note that, in principle, the ionization process can either be perturbed by δf_e (e.g., if the ionization is due to electron impact) or can affect dust (e.g., if the ionization is by radiation). For simplicity, we exclude such possibilities in the present investigation.

Thus we obtain for the dust particle distribution function

$$\frac{\partial \delta f_d}{\partial t} + \frac{\partial}{\partial q}[I^{\rm eq}(q)\delta f_d] + \frac{\partial}{\partial q}[\delta I(q) f_d^{\rm eq}] = 0, \qquad (20)$$

where

$$I(q) = I^{\rm eq}(q) + \delta I(q), \qquad \int I^{\rm eq}(q) f_d^{\rm eq} dq = 0,$$

$$\delta I(q) = \sum_\alpha \int d\mathbf{v} e_\alpha \sigma_\alpha v \delta f_\alpha. \qquad (21)$$

For the electron (ion) distributions we have

$$\frac{\partial \delta f_\alpha}{\partial t} + \mathbf{v}\cdot\frac{\partial \delta f_\alpha}{\partial \mathbf{r}} + \frac{e_\alpha}{m_\alpha}\mathbf{E}\cdot\frac{\partial f_\alpha^{\rm eq}}{\partial \mathbf{v}} = -\nu_{\alpha d}^{\rm eq}(v)\delta f_\alpha - \delta\nu_{\alpha d}(v) f_\alpha^{\rm eq}, \qquad (22)$$

where $\nu_{\alpha d}(v)$ is the rate of electron (ion) capture which depends on v [such that $\nu_{\alpha d}^{\rm eq} = \int d\mathbf{v}\nu_{\alpha d}^{\rm eq}(v) f_\alpha^{\rm eq}/n_\alpha$], and

$$\nu_{\alpha d}^{\rm eq}(v) = \int \sigma_\alpha v f_d^{\rm eq} dq, \qquad \delta\nu_{\alpha d}(v) = \int \sigma_\alpha v \delta f_d dq. \qquad (23)$$

Note that the equilibrium rate (12) is connected with (23) by

$$\nu_{ed}^{\rm eq} = \frac{1}{n_e}\int d\mathbf{v}\nu_{ed}^{\rm eq}(v) f_e^{eq}. \qquad (24)$$

Therefore, we finally find that Fourier component of the linear perturbation of averaged charge on dust particles is

$$\delta Q_{\mathbf{k}\omega} = \frac{i}{\omega + i\nu_d^{\rm eq}}\frac{1}{1+G_{\mathbf{k}\omega}}\frac{1}{n_d}\int I_{\mathbf{k}\omega}^{(1)}(q) f_d^{\rm eq} dq, \qquad (25)$$

and that of the linear perturbation of the electron (ion) distribution function is given by

$$\delta f_{\alpha,\mathbf{k}\omega} = -\frac{ie_\alpha/m_\alpha}{\omega - \mathbf{k}\cdot\mathbf{v} + i\nu_{\alpha d}^{\rm eq}(v)}\mathbf{E}_{\mathbf{k}\omega}\cdot\frac{\partial f_\alpha^{\rm eq}}{\partial \mathbf{v}} + \frac{1}{\omega + i\nu_d^{\rm eq}}\frac{1}{1+G_{\mathbf{k}\omega}}\frac{\sigma'_\alpha v f_\alpha^{\rm eq}}{\omega - \mathbf{k}\cdot\mathbf{v} + i\nu_{\alpha d}^{\rm eq}(v)} \times \int I_{\mathbf{k}\omega}^{(1)}(q) f_d^{\rm eq} dq. \qquad (26)$$

In Eqs. (25) and (26), the following notations have been used:

$$I_{\mathbf{k}\omega}^{(1)}(q) = \sum_\alpha \int_{V_d} d\mathbf{v}\frac{-ie_\alpha\sigma_\alpha v}{\omega - \mathbf{k}\cdot\mathbf{v} + i\nu_{\alpha d}^{\rm eq}(v)} \times \left(\frac{e_\alpha}{m_\alpha}\mathbf{E}_{\mathbf{k}\omega}\cdot\frac{\partial f_\alpha^{\rm eq}}{\partial \mathbf{v}}\right) \qquad (27)$$

and

$$G_{\mathbf{k}\omega} = \frac{-n_d}{\omega + i\nu_d^{\rm eq}}\sum_\alpha \int_{V_d} d\mathbf{v}\frac{e_\alpha\sigma_\alpha^{\rm eq}\sigma'_\alpha v^2 f_\alpha^{\rm eq}}{\omega - \mathbf{k}\cdot\mathbf{v} + i\nu_{\alpha d}^{\rm eq}(v)} = \frac{-1}{\omega + i\nu_d^{\rm eq}}\sum_\alpha \int_{V_d} d\mathbf{v}\frac{\nu_{\alpha d}^{\rm eq}(v) e_\alpha\sigma'_\alpha v f_\alpha^{\rm eq}}{\omega - \mathbf{k}\cdot\mathbf{v} + i\nu_{\alpha d}^{\rm eq}(v)}, \qquad (28)$$

where

$$\sigma_\alpha^{\rm eq} = \frac{1}{n_d}\int \sigma_\alpha(q) f_d^{\rm eq} dq = \sigma_\alpha(-Z_d e) \qquad (29)$$

and

$$\sigma'_\alpha \equiv \frac{\partial\sigma_\alpha(q)}{\partial q}. \qquad (30)$$

Note that σ'_α is also the step function on v, which should be taken into account by the same phase-space volume V_d of integration over $\mathbf{v}$ as in integration of expressions containing the charging cross section (6).

To calculate the longitudinal dielectric permittivity, we use a Poisson equation in which the Fourier component of the linear charge density perturbation is given by

$$\rho_{\mathbf{k}\omega} = n_d \delta Q_{\mathbf{k}\omega} + \sum_\alpha \int d\mathbf{v} e_\alpha \delta f_{\alpha,\mathbf{k}\omega}. \qquad (31)$$

Therefore, for the longitudinal dielectric permittivity we find

$$\varepsilon_{\mathbf{k}\omega} = 1 + \frac{4\pi}{k^2}\sum_\alpha \frac{e_\alpha^2}{m_\alpha}\int d\mathbf{v}\frac{1}{\omega - \mathbf{k}\cdot\mathbf{v} + i\nu_{\alpha d}^{\rm eq}(v)} \times \left(1 + \frac{i\nu_{\alpha d}^{\rm eq}(v)}{\omega + i\nu_d^{\rm eq}}\frac{1+\Gamma_{\mathbf{k}\omega}}{1+G_{\mathbf{k}\omega}}\right)\left(\mathbf{k}\cdot\frac{\partial f_\alpha^{\rm eq}}{\partial \mathbf{v}}\right), \qquad (32)$$

where $k = |\mathbf{k}|$, and

$$\Gamma_{\mathbf{k}\omega} = \sum_\alpha \int_{V_d} d\mathbf{v}\frac{-ie_\alpha\sigma'_\alpha v f_\alpha^{\rm eq}}{\omega - \mathbf{k}\cdot\mathbf{v} + i\nu_{\alpha d}^{\rm eq}(v)}. \qquad (33)$$

In the case of Maxwellian particle distributions and static [$\omega \ll \max(kv_{T_\alpha}, \nu_d^{\rm eq}, \nu_{\alpha d}^{\rm eq})$] longitudinal perturbations, we have the following expressions:

$$\Gamma_{\mathbf{k},\omega=0} = \frac{\pi n_d a^2 e^{-z}}{Pk}\left[\frac{v_{T_e}}{v_{T_i}}\frac{1}{\tau + z} + \sqrt{\frac{4z}{\pi}}\int_1^{+\infty} dx e^{-x^2(z-1)}\right], \qquad (34)$$

and

$$G_{\mathbf{k},\omega=0} = -\frac{\pi}{2}\frac{\tau + z}{1+\tau+z}\frac{\pi n_d a^2}{k}\left\{\int_0^{+\infty} dx\frac{xe^{-x}}{x+z} + \frac{1}{1+\tau}\left[1 + \frac{2z}{\pi\tau}\int_0^{+\infty} dx\frac{e^{-x}}{x} \times \arctan\left(\frac{k}{\pi n_d a^2}\frac{\tau x}{\tau x + z}\right)\right]\right\}. \qquad (35)$$

Thus, in the considered static approximation we have

$$\begin{aligned}\varepsilon_{\mathbf{k},\omega=0} &= 1+\frac{1}{k^2r_{De}^2}+\frac{1}{k^2r_{Di}^2}\\ &+\frac{4\pi n_d a}{k^2}\frac{1+\tau}{\tau}\frac{\tau+z}{1+\tau+z}\frac{1+\Gamma_{\mathbf{k},\omega=0}}{1+G_{\mathbf{k},\omega=0}}\\ &= 1+\frac{1}{k^2r_{De}^2}\frac{1+\tau}{\tau}\left(1+P\frac{\tau+z}{1+\tau+z}F_{\mathbf{k}}\right), \quad (36)\end{aligned}$$

where $r_{Di}=r_{De}\sqrt{\tau}$ is the ion Debye length and the form factor $F_{\mathbf{k}\omega}$ is defined by

$$F_{\mathbf{k}}=\frac{1+\Gamma_{\mathbf{k},\omega=0}}{1+G_{\mathbf{k},\omega=0}}. \quad (37)$$

We see that the charging process leads to the appearance of an additional real part in the static longitudinal dielectric permittivity. In particular, this additional term depends on parameter P. Note also that factor before the function $F_{\mathbf{k}}$ in the right hand side of (36) is exactly equal to $\nu_{ed}^{\rm eq}/\nu_d^{\rm eq}$, see (12).

For the electron part of the longitudinal dielectric permittivity, which is present in Eq. (3), we can easily obtain from (32)

$$\begin{aligned}\varepsilon^{(e)}_{\mathbf{k},\omega=0} &= 1+\frac{1}{k^2r_{De}^2}+\frac{4\pi n_d a}{k^2}\frac{\tau+z}{1+\tau+z}\frac{1+\Gamma_{\mathbf{k},\omega=0}}{1+G_{\mathbf{k},\omega=0}}\\ &= 1+\frac{1}{k^2r_{De}^2}\left(1+P\frac{\tau+z}{1+\tau+z}F_{\mathbf{k}}\right). \quad (38)\end{aligned}$$

Thus, for the effective charge (3) we finally find

$$Z_{\mathbf{k}}^{\rm eff}=Z_d\left(1+\frac{1}{\tau}+\frac{k^2r_{De}^2}{1+PF_{\mathbf{k}}(\tau+z)/(1+\tau+z)}\right)^{-1}. \quad (39)$$

We have found that the effective cross-section of scattering of electromagnetic waves on a dust particle depends not only on the scattering parameter $1/kr_{De}$ but also on parameters characterizing charging process, in particular P.

To conclude, we have studied the scattering of incident electromagnetic on a dust particle taking into account the charging effects. The recent kinetic theory [10,11] which allows us to consider self-consistently the process of charging and its perturbations due to collective oscillations has been used to calculate the scattering cross-section. It is found that the effect of capture of plasma electrons by dust particles leads to the dependence of the effective cross-section on parameters characterizing the charging process. Also, the expression for static dielectric permittivity in dusty plasmas taking into account the capture process is presented.

The considered situation corresponds to the case of small surface grain potential φ_0: $|e\varphi_0|/T_e \ll 1$, when we take into account only linear terms in the Poisson equation. In the case of high surface potential, $|e\varphi_0|/T_e > 1$, another approach is needed (if the charging process does not pertubate by plasma fields, the problem has been investigated in Ref. [4]). We also note that the elastic scattering effect can be important [3]. The latter is similar to nonlinear Landau damping: the dust grains play the role of the second wave, and plasma electrons interact with the low-phase-velocity beat wave from the incident wave and zero–frequency wave due to plasma inhomogeneities around the grains. This effect has been investigated in Ref. [3], and its contribution to high-frequency ($\omega \sim \omega_{pe}$) longitudinal dielectric permittivity is proportional to $Z_d^2n_d^2/n_e^2 = z^2P^2$. This indicates that (at least for $P \gg 1$) the above effect could be significant for scattering of electromagnetic waves. However, even for the simplest case of constant charges on dust particles, no corresponding investigation has been done yet.

The obtained results should be useful for diagnostics in various multicomponent dusty plasmas such as those technological devices, earth's ionosphere, etc. Finally, we note that the developed kinetic theory can be used to study non-static scattering effects in dusty plasmas with variable charges on dust particles (i.e., when frequency of scattered wave is not equal to that of incident wave, $\omega_{\rm sc} \neq \omega_0$). In the latter case, the effective scattering charge depends on $\delta\omega = \omega_{\rm sc} - \omega_0$, and we have the same expression (3) where the corresponding dielectric permittivities are functions on $\delta\omega$ also. Expressions for the low-frequency dielectric permittivities in the case $kv_{Te} \gg \delta\omega \gg kv_{Ti}$ have been found in Ref. [10].

I would like to thank L. Besley, J. Lowke, and A. Murphy for stimulating discussion, and D. Melrose for hospitality.

[1] Phys. Scr., special issue on physics of dusty plasmas, **45**, 454 (1992).
[2] V. Tsytovich, U. de Angelis, and R. Bingham, J. Plasma Phys. **42**, 429 (1989).
[3] U. de Angelis, R. Bingham, and V.N. Tsytovich, J. Plasma Phys. **42**, 445 (1989).
[4] R. Bingham, U. de Angelis, V.N. Tsytovich, and O. Havnes, Phys. Fluids B **3**, 811 (1991); **4**, 283(E) (1992).
[5] V.N. Tsytovich, Phys. Scr. **45**, 521 (1992).
[6] O. Havnes, T.K. Aslaksen, and F. Melandsø, J. Geophys. Res. Lett. **95**, 6581 (1990).
[7] F. Melandsø and O. Havnes, J. Geophys. Res. **96**, 5837 (1991).
[8] F. Melandsø, Phys. Scr. **45**, 515 (1992).
[9] F. Melandsø, T. Aslaksen, and O. Havnes, Planet. Space Sci. **41**, 321 (1993).
[10] V.N. Tsytovich and O. Havnes, Comments Plasma Phys. Controlled Fusion **15**, 267 (1993).
[11] S.V. Vladimirov, Phys. Plasmas **1**, 2762 (1994).
[12] S.V. Vladimirov, Phys. Rev. E **49**, 997 (1994).
[13] M.N. Rosenbluth and N. Rostoker, Phys. Fluids **5**, 776 (1962).
[14] D.E. Evans and J. Katzenstein, Rep. Prog. Phys. **32**, 207 (1969).
[15] J. Sheffield, *Plasma Scattering of Electromagnetic Radiation* (Academic, New York, 1975).

[16] A.Y. Wong and R.J. Taylor, Phys. Rev. Lett **27**, 644 (1971).
[17] H.C. Carlson, W.E. Gordon, and R.L. Showen, J. Geophys. Res. **77**, 1242 (1972).
[18] A.Y. Wong, J. Santoru, and G.C. Siojee, J. Geophys. Res. **86**, 7718 (1981).
[19] W. Scales and P. Kinter, J. Geophys. Res. **95**, 10 623 (1990).
[20] J.A. Fejer, M.P. Sulzer, and J.H. Eddler, J. Geophys. Res. **96**, 15 985 (1991).
[21] P. Stubbe, H. Kohl, and M.T. Rietveld, J. Geophys. Res. **97**, 6285 (1992).
[22] A.J. Stocker, *et al.*, J. Atmos. Terr. Phys. **54**, 1555 (1992).
[23] A.B. Murphy and A.J.D. Farmer, J. Phys. D **25**, 634 (1992).
[24] A.B. Murphy and P. Kovitya, J. Appl. Phys. **73**, 4759 (1993).
[25] V.L. Ginzburg and V.N. Tsytovich, *Transition Radiation and Transition Scattering* (Hilger, London, 1990).
[26] L.J. Spitzer, *Physical Processes in the Interstellar Medium* (Wiley, New York, 1978).