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Effect of dust particles on two-stream instability: A possible explanation for the persistence of ionization trails of Leonid meteor showers

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Assuming a collisional plasma having dust particles and only electrons are magnetized, the two-stream instability is studied for the excitation of low frequency waves. The production and losses of both ions and electrons are included. In the absence of production, it is shown that losses by attachments of both ions and electrons on dust particles, two-stream instability require the drift velocity greater than ion acoustic velocity. The growth rate is reduced and the wave amplitude at saturation is reduced. Therefore the generation and magnitudes of ionization density irregularities is reduced. It is expected that the cross-field diffusion of ionization due to wave turbulence is affected. It is known that during meteor shower periods the E-region of the ionosphere has a significant number of dust particles. Therefore density irregularities in the ionosphere are modified. Also amplitude dependent diffusion rate is reduced. It is suggested that the presence of dust particles may be a reason for persistence of ionization trails seen for longer periods during Leonid meteor showers

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1 Introduction

Ground based instruments, rockets and satellites, observe in the E-region the presence of strong electron density fluctuations during the day-time and weaker density fluctuations in the night time. The radar echoes observed at Jicamarca in Peru has identified two types of density irregularities, i.e. Type-1 irregularities, which have narrow spectral peak and their velocities are very close to the ion-acoustic velocity and Type-2 irregularities, which have a broader spectrum. The Type-1 irregularities are excited by the mechanism of two-stream instability and the Type-2 irregularities by the phenomena of gradient drift instability[1-2]. Both irregularities are stronger in the height region of 105-115 km. Rockets at Thumba, India over the equatorial region[3] measure the characteristics of these irregularities. An excellent summary of ionospheric irregularities is available in the book by Kelley[4].

Dust particles due to meteors populate the ionosphere. A maximum deposition occurs in the 70-90 km height region[5]. The main components seen in the E-region are metallic ions[6-8], Fe^+, Mg^+ and Ca^+. The estimated peak metallic ion densities are of the order ~ 10^4 cm^{-3}. This value is supported by the model calculations assuming that meteors are the main sources. Apart from these, density irregularities, ionization and other features in the low-density region between E- and F-layers, are associated with dust particles introduced by meteors. The extremely low effective conductivity of the mesospheric dusty plasma can explain the existence of vertical electric fields observed in the lower mesosphere, in the vicinity of noctiluscent clouds and polar mesospheric solar summer echoes[10]. One of the significant observation is that the ionization trails left by Leonid meteor on 17 Nov. 1998 lasted for 94-203 s. Some trails lasted[11] more than 20 min. At a given temperature the dust particles in plasma acquire a negative charge due to larger thermal velocity of electrons as compared to ions. This changes the nature of lower-frequency waves and instabilities[12-15]. Dust particles also change the behaviour of currents in the ionosphere[16-17]. It is expected that wave turbulence can give rise to an effective increase of collision frequency and thus modify the diffusion rate[18].

In this paper, the excitation of waves by two-stream instability has been studied. The loss rates of electrons and ions by their attachment onto the dust particles are included. The equations of motion and continuity equations are linearized. The resulting dispersion relation is analyzed and a possible relationship between dust particles and wave excitation is shown. This result is applied to the ionospheric irregularities in the E-region and to explain the cause for the persistence of ionization trails seen during the meteor-showers[11].

2 Dispersion relation

For convenience, it is assumed that the homogeneous plasma having dust particles and consisting of electrons and singly charged ions, in the presence of uniform and homogeneous magnetic field, which is along the *z*-axis of the right hand co-ordinate system. Electrons are magnetized, i.e. their collision frequency with neutrals, ν_e is smaller than the electron gyro-frequency, Ω_e. The ions are cold and unmagnetized as their collision frequency with neutrals, ν_i, is greater than its gyro-frequency, Ω_i.. The number densities of electrons and ions being smaller than neutrals the collision frequency between ions and electrons are neglected. The subscript *i* is used for ions, *e*, for electrons and *d*, for dust particles and subscript, 0, for the equilibrium values. There is a uniform electric field E_0 along the *x*-axis, which gives rise to charge dependent drift velocity V_{e0} of electrons along the *y*-axis.

$$V_{e0} = -\frac{eE_0}{m_e}\frac{\Omega_e}{\Omega_e^2+\nu_e^2} \qquad \ldots(1)$$

The continuity equation

$$\frac{\partial n}{\partial t} + \nabla \cdot n\mathbf{V} = (\Lambda - \Gamma)n \qquad \ldots(2)$$

and the equation of motion

$$m\frac{d\mathbf{V}}{dt} = e\left(\mathbf{E} + \frac{\mathbf{V}\times\mathbf{B}}{c}\right) - \frac{\nabla P}{n} - m\nu\mathbf{V} \qquad \ldots(3)$$

are linearized and solved separately for both the ions and the electrons. The term Γ is the loss rate and Λ is the production rate of the component shown by the subscript. The symbols *e*, *n*, *m*, *P*, **V**, **E**, **B** and *c*, respectively are charge, number density, mass, pressure, velocity, electric field, magnetic field and velocity of light. The pressure *P* is taken to be $= n\,k_B\,T_e$, where k_B is the Boltzmann constant and T_e the electron temperature. Subscripts *x*, *y*, and *z* denote the components in those directions. The other quantities have standard meanings. The CGS electrostatic units are used throughout. An additional assumption made is that the plasma is quasi-neutral, i.e. $n_i = n_e$. This restricts the application of the present analysis to the medium having the total dust charge density, $n_{do}\,z_d\,e$ much less than electron charge density, $n_{0e}\,e$. Here z_d is the number of electron charges on the dust particles.

It is assumed that the production rate is proportional to the number density, *n*. This is a good approximation when the ionization sources are electrons. The perturbed wave propagates along the *y*-direction and is approximated by $\mathbf{E} = -\nabla\varphi$ where φ is its potential. The electron inertia is neglected and then Eq. (3) linearized. In this case perturbed velocities are given by

$$v_{ex} = -\imath k\frac{\Omega_e}{\Omega_e^2+\nu_e^2}\left(\frac{e\varphi}{m_e} - \frac{n_e}{n_0}C_{se}^2\right) \qquad \ldots(4)$$

and

$$v_{ey} = \imath k\frac{\nu_e}{\Omega_e^2+\nu_e^2}\left(\frac{e\varphi}{m_e} - \frac{n_e}{n_0}C_{se}^2\right) \qquad \ldots(5)$$

where C_{se} denotes the electron sound speed $= \sqrt{\frac{2k_BT_e}{m_e}}$. Here and henceforth the subscript 1 is omitted for the perturbed quantities. Similarly the perturbed ion velocity is

$$v_{iy} = \frac{ek\varphi}{m_i}\frac{1}{\omega+\imath\nu_i} \qquad \ldots(6)$$

By linearizing Eq. (2), the perturbed electron density is found to be

$$\frac{n_e}{n_0} = \frac{kv_{ey}}{\omega - kV_{e0} + \imath(\Lambda_e - \Gamma_e)} \qquad \ldots(7)$$

and the perturbed ion density is

$$\frac{n_i}{n_0} = \frac{kv_{iy}}{\omega + \imath(\Lambda_i - \Gamma_i)} \qquad \ldots(8)$$

Eqs (6) and (8) give the ion perturbation

$$\frac{n_i}{n_0} = \frac{\imath k^2 e\varphi}{m_i}\frac{1}{[\omega+\imath\{\Gamma_i - \Lambda_i\}](\omega+\imath\nu_i)} \qquad \ldots(9)$$

Using Eqs (5) and (7), it is found that the perturbed electron density is

$$\frac{n_e}{n_0}=\frac{\imath k^2\nu_e e\varphi}{m_e}\,\frac{1}{([\nu_e^2+\Omega_e^2][\omega-kV_{e0}-\imath\{\Gamma_e-\Lambda_e\}])+\imath k^2\nu_e C_{se}^2} \qquad \dots (10)$$

The quasi-neutrality condition, i.e. $n_i = n_e$, when used on Eqs (9) and (10) give the dispersion relation

$$\begin{aligned}D(\omega,k)&=[\omega-kV_{e0}-\imath\{\Gamma_e-\Lambda_e\}(\nu_e^2+\Omega_e^2)]\\&+\imath\nu_e k^2C_{se}^2-\imath\nu_e\frac{m_i}{m_e}[\omega^2+\imath\omega(\nu_i-\Lambda_i+\Gamma_i)\\&-\nu_i\{\Gamma_i-\Lambda_i\}]=0\end{aligned} \qquad \dots (11)$$

The dispersion relation Eq. (11) is solved by equating it to

$$D(\omega,k)=D_{\mathrm{r}}(\omega,k)+\imath D_{\mathrm{i}}(\omega,k) \qquad \dots (12)$$

where subscripts r and i denote real and imaginary parts. It is assumed that ω is equal to $\omega_r + i\gamma$, such that the ratio γ/ω_r is very much less than 1 and expand $D(\omega,k)$ around $\omega = \omega_r$ by

$$D(\omega,k)=D(\omega_{\mathrm{r}},k)+\imath\gamma\left.\frac{\partial D(\omega,k)}{\partial\omega}\right|_{\omega=\omega_{\mathrm{r}}} \qquad \dots (13)$$

We set $\omega_r = \omega$ and equate the terms in Eqs (11), (12), and (13). In the low frequency and long wave length limit the real part $D(\omega,k)=0$, by neglecting the term $\Gamma_e-\Lambda_e$ and the term $k^2C_{se}^2\nu_e$ gives the relation

$$\omega=\frac{kV_{e0}[\nu_e^2+\Omega_e^2]}{[\nu_e^2+\Omega_e^2]+\dfrac{m_i}{m_e}\nu_e(\nu_i+\Lambda_i-\Gamma_i)} \qquad \dots (14)$$

The growth rate, γ by the relation

$$\gamma=\frac{D_i(\omega,k)}{\left.\dfrac{\partial D(\omega,k)}{\partial\omega}\right|_{\omega_r=\omega}} \qquad \dots (15)$$

is found to be

$$\gamma=-\frac{k^2\nu_eC_{se}^2-\nu_e\dfrac{m_i}{m_e}\omega^2-(\Lambda_e-\Gamma_e)[\nu_e^2+\Omega_e^2]-\nu_e\nu_i\dfrac{m_i}{m_e}(\Lambda_i-\Gamma_i)}{[\nu_e^2+\Omega_e^2]+\dfrac{m_i}{m_e}\nu_e(\nu_i-\Lambda_i+\Gamma_i)} \qquad \dots (16)$$

When the growth and losses of both electrons and ions are absent, Eq. (14) and Eq. (16), respectively reduce to Eqs (4.36a) and (4.36 b) of Kelley[4].

3 Discussions

In the present analysis, the growth rate is positive when

$$\omega^2>k^2C_{si}^2-\frac{\dfrac{m_e}{m_i}(\Lambda_e-\Gamma_e)[\nu_e^2+\Omega_e^2]-\nu_e\nu_i\dfrac{m_i}{m_e}(\Lambda_i-\Gamma_i)}{\nu_e} \qquad \dots (17)$$

where $C_{si}=\sqrt{\dfrac{2k_BT_e}{m_i}}$ is the ion acoustic velocity. When the productions of ions and electrons are absent, the growth rate is positive when

$$\omega^2>k^2C_{si}^2+\frac{\dfrac{m_e}{m_i}\Gamma_e[\nu_e^2+\Omega_e^2]+\nu_e\nu_i\dfrac{m_i}{m_e}\Gamma_i}{\nu_e} \qquad \dots (18)$$

From Eq. (18) it is seen that for a finite electron loss-rate, i.e. $\Lambda_i > 0$ due to the presence of dust particles, because of high ratio of Ω_e to ν_e, the resonant velocity ω/k increases. When $\nu_e < \Omega_e$ and as $\nu_i\Gamma_i$ is smaller than the other two terms, the wave phase velocity needed for the marginal instability is

$$\frac{\omega^2}{k^2}=C_{si}^2+\frac{\Gamma_e\Omega_e\Omega_i}{\nu_e^2k^2} \qquad \dots (19)$$

This value is much larger than that in the absence of dust particles. The drift velocity at the marginal instability is now

$$V_d=(1+\frac{m_i}{m_e}\frac{\nu_e(\nu_i+\Gamma_i)}{[\nu_e^2+\Omega_e^2]})\sqrt{C_{se}^2+\frac{\Gamma_e\Omega_e\Omega_i}{k^2\nu_e}} \qquad \dots (20)$$

Both show that the effect of presence of dust particles is felt stronger at longer wave lengths. Hence the lower frequency is strongly affected. In support of the present analysis the authors would like to remind the reader that the loss of electrons during the dust charging introduces friction like effects in the wave excitation in dusty plasmas[23,24].

It is found from Eq. (9) that at saturation, the electron density fluctuations are related to the electric field fluctuations, $\delta E = k\varphi$ by

$$\frac{\delta E}{E_0}=\frac{m_i}{m_e}\frac{\Omega_e(\nu_i+\Gamma_i)}{[\nu_e^2+\Omega_e^2]+\frac{m_i}{m_e}\nu_e[\nu_i+\Gamma_i]}\frac{n_e}{n_0} \quad \ldots (21)$$

Please note that though the ion loss-rate also affects the wave amplitudes, in the discussion the authors have omitted its contribution, as it has been assumed that the ions are cold.

It is known that electrostatic waves can scatter electrons and can lead to anomalous cross-field diffusion. This diffusion rate is proportional to anomalous electron collision frequency, ν_E, which in turn is proportional to δE^2. The value of anomalous collision frequency can be as large as 18 ν_e electron-neutral collision frequencies, which is $\approx 1.5 \times 10^6$ s^{-1}. This value is also supported by the observation in the ionosphere, that the electron collision frequency is enhanced during the disturbed conditions. If δE is reduced by 0.5 from its original value, then ν_E is reduced by 0.25. There is a 4-fold increase in diffusion time. If the decay of ionization trails is by the cross-field diffusion, then the decay time will be increased. Therefore, ionization trails can persist for the longer periods.

In this connection, the authors would like to quote that observed collision frequencies in the ionosphere are lower than those computed using the standard atmospheric model by a factor[23] of ≈ 1 at 100 km height ≈ 3 at 110 km and ≈ 10 at 130 km. Therefore to explain this difference, the enhanced ν_e is needed. There is a height difference in the observed current maxima and the calculated conductivity maxima. To explain these differences the presence of electrostatic turbulence[18] and dust distribution[16] are invoked.

Meteor ablation and recondensation lead to formation of small particles[8]. Based on stead state theory the dust number density at mesopause is $\geq 10^3$ cm^{-3} for 1 nm size particles and it will be more than 10^4 cm^{-3} if the size is in the range of fraction of nm[8]. The charged dust density at 90 km height in the polar winter mesosphere is observed by multiple sounding rockets to be in the range of 100 cm^{-3}. This is estimated to be 5-10% of the total dust density[19-20].

For the realistic estimation of the total loss rate one needs to know the size and nature of dust particles and their attachment coefficients. As the dust particle distribution is not well known, the authors shall discuss qualitatively the attachment rate in support of the present analysis. Here neither the dust charge nor the dust density is included in the dynamics. This estimate does not affect the conclusion reached here but justify the studies presented in this paper.

We estimate the electron-loss rate, Γ_e, by neglecting the surface properties of dust particles and setting the attachment coefficient to unity. This gives

$$\Gamma_e = \sigma_0 C_{se} \quad \ldots(22)$$

Here σ_0 as the cross section for the attachment which will be equal to the collision cross-section for electrons with the dust particles multiplied by the sticking coefficient S_e, for electrons on the dust particles. If one puts S_e equal to 1 then the total loss rate will be equal to the number density of the dust particles multiplied by the average cross-section for one dust particle.

The model calculations suggest an approximate height distribution of dust particles to be of the form $e^{-x/h}$. Here h is the approximate scale height. If we use the dust number density n_{d0} of micron size at the 90 km height, such that the total attachment cross section to be equal to be that of collision cross-section of ions will be 2.5×10^3 cm^{-3} and h to be approximately 10 km then attachments coefficient at ionospheric heights will be 100 s^{-1}. This value suggests that even a moderate density of dust particles can give rise to significant values of Γ_e as presented in the earlier analysis[16-17].

As presented here, it is seen that the attachment of electrons on to the dust particles increase the drift velocity needed for the wave growth. This drift velocity is more than that can arise due to the electric field, E_0 estimated by the slab geometry. Therefore, a reduction in excitation of waves is expected and the saturated wave-amplitudes are reduced. As hinted earlier, there is a reduction in the cross-field diffusion. Therefore, it is suggested that this can be one of the main reasons for the persistence of the ionization trails seen for longer periods, during the Leonid meteor showers. The authors support the method given by Ossakow *et al.*[21] rather than that given by Huba *et al.*[22] as appropriate to include losses of electrons and ions due to the presence of dust particles in the analysis of wave excitations.

4 Conclusions

The principal result presented here is that the electron density irregularities in the E-region of the ionosphere are affected by the presence of dust particles. Reanalyzing the two-stream instability by considering the electron loss rate shows this. The main observations of the present study are: (i) The electron loss rate increases the value of the drift velocity and this value can be much higher than the ion-acoustic velocity and (ii) the saturation amplitude is reduced in the process.

It is also known that during intense meteor shower periods, a large number of dust particles are introduced and a significant number is in the size range of micron and sub-micron. This will lead to an enhanced loss rate of electrons by attachment onto the dust particles. Therefore, one can safely conclude that the wave activity is greatly reduced. Though the nonlinear limit on the saturation of wave turbulence has not been estimated, one can believe that the strength of turbulence is reduced. Hence the turbulence depended diffusion rate is reduced. This can be a reason for the persistence of the ionization trails for longer periods, seen during the Leonid meteor shower days[11].

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