Current driven instability in Earth′s dusty mesospheric layer

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Measurements during the Polar Mesospheric Summer Echoes (PMSE) conditions suggest the presence of large amount of dust particles in the Earths lower ($\sim 80-90\,$km) atmosphere with average sizes $\sim 0.1\,\mu$, and number densities $\sim 10^3\,\mathrm{cm}^{-3}$. The visible manifestations of these phenomena are clouds of icy particles called Polar Mesospheric Clouds (PMC), when viewed from space, and Noctilucent Clouds (NLC), when viewed by observers on Earth [Vladimirov & Klumov, 2010]. The ratio of charged to neutral dust particles is about 5 to 10 percent of the total dust number density implying that the most of the dust particle in the layer is neutral.

The presence of $10-30\,$nm dust particles in the upper and lower mesosphere is a regular phenomenon and these particles are either neutral or carry one electronic charge. Further, since dust is much heavier than the plasma particles (dust mass $\sim 10^{-18}\,\mathrm{g} - 10^{-17}\,\mathrm{g}$) it will lead to relative drift between the plasma and dust. Thus presence of charged dust changes the plasma diffusivity at $85-90\,$km and causes a vertical current due to the accumulation of positively charged dust at the top and negatively charged dust at the bottom of the layer. Such an electric field has been observed in the past [Zadorozhny et al., 1993].

The cause of the ionospheric irregularities is often attributed to the current driven, electrostatic instability and it is believed that the electrojet is unstable due to the relative streaming of the plasma particles across the magnetic field. Note that Farley–Buneman instability treats the magnetic field as passive dynamical quantity, notwithstanding the observed daily variation of the magnetic fields in the narrow belt of the geomagnetic equator at $90-120\,$km. In the present work we shall investigate the current driven electromagnetic instability where the ambient current is aligned to the background magnetic field and is caused by the relative drift between plasma particles.

The $80-120\,$km region of Earths ionosphere is weakly ionised with neutral number density ($n_n = 10^{12} - 10^{14}\,\mathrm{cm}^{-3}$) far exceeding the ion number density ($n_i = 10^3\,\mathrm{cm}^{-3}$). The charged dust number density is similar to the ion number density, i.e. $Z\,n_d = 10^3\,\mathrm{cm}^{-3}$ and neutral dust density is an order of magnitude larger than the charged dust number density [Havnes et al. 1996]. In a weakly ionized medium, often plasma inertia is neglected and a linear relationship between the electric field $\mathbf{E}$ and plasma current $\mathbf{J}$, $\mathbf{E} = \sigma\cdot\mathbf{J}$ is derived, where σ is the conductivity tensor. The neglect of plasma inertia implies that the plasma dynamical response frequency is much smaller than respective gyro–frequencies, implying that only low frequency wave can be considered in such a framework. The weakly ionized, collisional plasma dynamics can be investigated either in the multi–fluid or the single fluid framework. Whereas multi–fluid framework is well suited to describe the high frequency fluctuations, the multi–fluid set of equation can be reduced to single fluid, MHD like equations to investigate the low frequency behaviour of the medium. The collision not only leads to the damping of the high frequency waves, but in the low frequency limit it can also *gel* the medium together. Clearly, when the dynamical response time is much smaller than the collisional time, the multi–component set of equations can be reduced to a single fluid description. We model the $85-100\,\mathrm{km}$ layer of the Earth as a multi–component, weakly ionized plasma consisting of plasma particles, charged and neutral dust and neutral particles. The multi–fluid equation can be easily reduced to the single fluid equation.

We shall define the mass density of the bulk fluid as $\rho \approx \rho_n$. Then the bulk velocity is $\mathbf{u} \approx \mathbf{v}_n$. The continuity equation for the bulk fluid becomes

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho\, \mathbf{u}) = 0\,. \tag{1}$$

The momentum equation can be derived by adding plasma equations

$$\rho\, \frac{d\mathbf{u}}{dt} = -\nabla P + \frac{\mathbf{J} \times \mathbf{B}}{c}\,. \tag{2}$$

We shall define the plasma Hall parameter

$$\beta_j = \frac{\omega_{cj}}{\nu_{jn}}\,, \tag{3}$$

as the ratio of the cyclotron $\omega_{cj} = q_j\, B/m_j\, c$ to the collision ν_{jn} frequency. The relative drift of the magnetic field through the plasma can be quantified in terms of Hall parameter. Inverting the generalized Ohms law $\mathbf{J} = \sigma_{\parallel}\, \mathbf{E}_{\parallel} + \sigma_P\, \mathbf{E}_{\perp} + \sigma_H\, \mathbf{E} \times \mathbf{B}/B$ in terms of electric field, $\mathbf{E}$ gives

$$\frac{c^2}{4\pi}\mathbf{E}' = \eta\, \mathbf{J}_{\parallel} + \eta_H\, \mathbf{J} \times \mathbf{b} + \eta_{\mathbf{P}}\, \mathbf{J}_{\perp}\,. \tag{4}$$

Here η_H is Hall diffusivity, η is the Ohm diffusivity and Pedersen diffusivity $\eta_P = \eta + \eta_A$ where η_A is the ambipolar diffusivity. The symbol $\mathbf{b} = \mathbf{B}/|\mathbf{B}|$, the electric field is written in the neutral frame and parallel and perpendicular components of the current $\mathbf{J}$ refers to the orientation with respect to the ambient magnetic field. Taking curl of above equation, with the help of Maxwell equation $c\,\nabla \times \mathbf{E} = -\partial_t \mathbf{B}$, we arrive at the following induction equation

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \left[(\mathbf{u} \times \mathbf{B}) + \beta_i^2\, \frac{(\mathbf{J} \times \mathbf{B}) \times \mathbf{B}}{c\, \rho_i\, \nu_{in}} - \beta_i^2\, \frac{\mathbf{J} \times \mathbf{B}}{e\, n_i} - \frac{4\pi\eta}{c}\, \mathbf{J} \right]. \tag{5}$$

Note that at a height of $80-100\,\mathrm{km}$, since $\omega_{ci} \sim 10^2\,\mathrm{s}^{-1}$, for collision frequency $\nu_{in} = 5.8 \times 10^4\, n_{n+14} A_{20}^{-1/2}$ where A is the mean neutral molecular mass in atomic mass units and $A_{20} = A/20$, $n_{n+14} = n_n/10^{14}\,\mathrm{cm}^{-3}$, one gets $\beta_i \ll 1$. In this limit, we shall neglect all the diffusive term and assume that the magnetic flux is frozen in the weakly ionised plasma.

We assume that the plasma is immersed in a uniform background magnetic field $\mathbf{B} = (0,0,B)$. Often, plasma inhomogeneities coupled with the field aligned current are thought to be responsible for the wide range of waves and fluctuations in the Earths ionosphere. An electric field in the lower mesosphere and in the vicinity of NLC has been observed in the past [Zadorozhney et al., 1993]. The typical value of such an field aligned electric field is of the order of $\sim 1V/m$ [Klumov et al., 2000]. The presence of field aligned current may cause the lowering of the threshold for lower hybrid waves . Thus, we shall assume an equilibrium current $\mathbf{J} = (0,0,J)$ aligned to the ambient magnetic field.

Following standard procedure, we can arrive at following dispersion relation

$$\left(\frac{\omega}{\omega_A}\right)^4 - 2\left(\frac{\omega}{\omega_A}\right)^2 + 1 - \left(\frac{4\pi J}{ckB}\right)^2 = 0\,, \tag{6}$$

Here ω_A is the Alfvén frequency. In the absence of current, preceding equation describes Alfvén wave in the neutral medium where the inertia of the bulk fluid balances the magnetic fluctuations. When $J \neq 0$ the necessary condition for the instability $C_0 < 0$ becomes

$$J > \frac{cB}{4\pi} k\,, \tag{7}$$

which implies that no matter how weak the strength of the ambient current density, this condition can be always satisfied for sufficiently long wavelength fluctuations. Therefore, we may conclude that low frequency, long wavelength fluctuations in the medium will be suspect to the current driven instability. Writing $\omega = \omega_r + i\,\omega_i$, the growth rate of the instability becomes

$$\omega_i = \left(\frac{4\pi J/c}{kB} - 1\right)^{1/2} \omega_A\,. \tag{8}$$

Note that the expression in the bracket on the right hand side is always positive for the instability to exist. The growth rate, Eq. (8) can be also be written as

$$\omega_i = \left(\frac{J/e n_e v_A}{k\,\delta_i} - 1\right)^{1/2} \omega_A\,. \tag{9}$$

where ion skin depth $\delta_i = v_A/\omega_{ci}$.

It is known that the presence of charged dust just below the electrojet region may affect the electrojet currents. We shall assume that the charge number density $\sim 10^3\,\mathrm{cm}^{-3}$ and calculate

$\sigma \approx cen_e \beta_e/B$ for $\beta_e = 10^4$ and $B = 0.3\,\mathrm{G}$. Thus for a $1\,\mathrm{V/m}$ electric field in the dusty mesosphere, one gets from $J = \sigma E$, $4\pi J/cB = 2.2 \times 10^{-5}$ in cgs unit. Thus wavelength of the order of km can destabilise the dusty layer. Therefore, a small dust layer at the bottom of the E region can excite the low frequency, long wavelength instability.

As has been noted above Farley–Buneman instability (FBI) is known to create plasma irregularities in the E-region, at heights where the electrons are strongly magnetized. The interplay of the Earths electric and geomagnetic field produces currents which give rise to the FBI. In dusty mesospheric layer where the electrons are strongly magnetized, it would appear that the collisional drag of the ions by neutral flows may cause the development of a similar instability. However the necessary condition of the FBI, i.e. the relative drift between the plasma particles must exceeds the acoustic speed of the bulk fluid would imply a strong current in the mesosphere which is not supported by the observations. Therefore, FBI may not be important in the lower mesosphere.

To summarise, the current driven instability in a collisional, magnetized, dusty medium has been analysed in the present work. The low frequency, long wavelength waves in the magnetic field aligned current medium can become unstable to the low frequency fluctuations if the ratio of the current to the background field is larger than the light speed times the wavenumber. The growth rate of the instability depends on $J/en_e v_A$. The instability could play an important role in the Earths mesosphere.

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