A Simulation of Plasma Turbulence from Dust Gradients

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Introduction

Dust in Earth's ionosphere can quickly become charged by electrons in the surrounding plasma. The attachment of electrons to massive dust grains effectively creates a density gradient in the surrounding plasma. Such gradients create instabilities that ground-based radars measure, providing a diagnostic for dust density, dynamics, and lifetime. Previous studies laid the theoretical foundation for studying static, ionized dust layers at 80 – 100 km in Earth's atmosphere, and observations have attributed radar echoes associated with ice grains in the polar mesosphere to charged dust. A recently developed hybrid particle/fluid numerical model of the weakly ionized plasma found in Earth's lower ionosphere is well suited for simulations of dust – plasma interactions. Preliminary simulations with a simple 2 – D dust model exhibit plasma turbulence perpendicular to the ambient magnetic field that can be understood as a modified form of the gradient-drift. This work presents two simulation runs, both of which model the dust layer as a negatively charged Gaussian. The first run uses a flat initial ion distribution and the second run uses an initial ion distribution derived from assuming kinetic equilibrium between ions and electrons. In both runs, the electron distribution adjusts to conserve quasineutrality.

Simulation

Plasma parameters

$(dx,\ dz) = (0.25,\ 0.25)$ m
$(nx,\ nz) = (1024,\ 2048)$ cells
$dt = 1 \times 10^{-5}$ s
$nt = 32768$ steps
$\mathbf{E}_0 = 0.01\,\hat{z}$ V/m
$\mathbf{B}_0 = -2.5 \times 10^{-5}\,\hat{y}$ T
$m_e = 9.1 \times 10^{-31}$ kg
$m_i = 5.0 \times 10^{-26}$ kg
$m_n = 4.6 \times 10^{-26}$ kg
$n_0 = 10^{10}$ m^{-3}
$\nu_e = 3.0 \times 10^{4}$ s^{-1}
$\nu_i = 3.0 \times 10^{3}$ s^{-1}
$T_e = T_i = T_n = 220$ K

- **Ions (NO^+)**: Particle-in-cell method.
- **Electrons**: Inertialess, quasineutral, isothermal fluid.
- Physical parameters model the ***E* region**, where ions are unmagnetized and electrons are magnetized.
- **Dust**: Static, negatively charged Gaussian in vertical direction.
- The hybrid version of our code solves for the quasineutral **electrostatic potential** at each time step, given the electron density, ion flux, and relevant physical parameters (e.g. temperatures and collision frequencies).
- **Electron density** adjusts to preserve quasineutrality.

$$n_e = n_i - Z_d n_d$$

Dust parameters

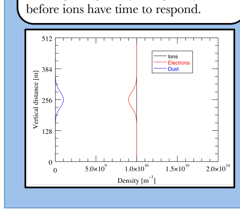
$$n_{d0} = 0.1 n_0$$

$$Z_d = 1 \qquad n_d = n_{d0} e^{-\frac{1}{2}\left(\frac{z-z_0}{\Delta}\right)^2}$$

Initial distributions

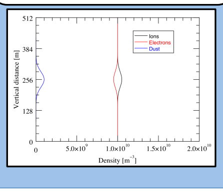
Flat ions

The highly mobile electrons readily collide with and attach to dust grains, creating a negatively charged layer before ions have time to respond.



Gaussian ions

Setting equilibrium ion and electron momenta equal (1) and solving for the ion density yields a quadratic (2). The solution is approximately Gaussian (3).



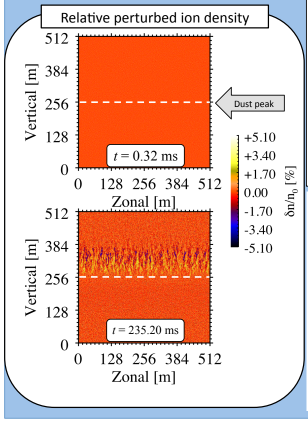
$$\begin{cases} 0 = +e\mathbf{E} - \dfrac{k_B T_i \nabla n_i}{n_i} \\ 0 = -e\mathbf{E} - \dfrac{k_B T_e \nabla n_e}{n_e} \\ n_e = n_i - Z_d n_d \end{cases} \tag{1}$$

$$n_i^2 - n_i Z_d n_d - n_0^2 = 0 \tag{2}$$

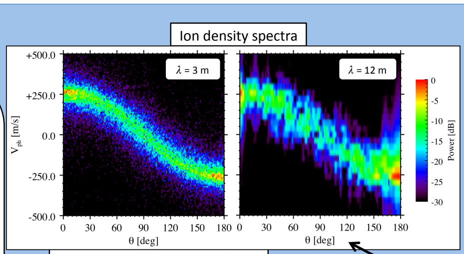
$$n_i = \frac{Z_d n_d}{2}\left[1 + \sqrt{1 + \left(\frac{2n_0}{Z_d n_d}\right)^2}\right] \tag{3}$$

Flat ions

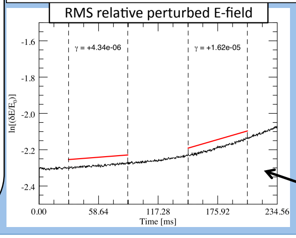
Relative perturbed ion density



Ion density spectra



RMS relative perturbed E-field

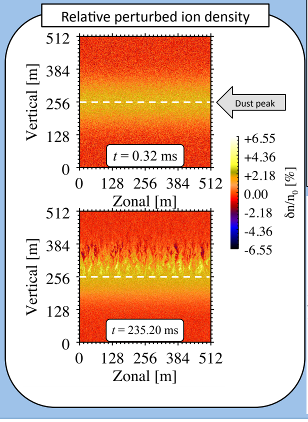


3-m waves: Peak near 0°/180°. Spread ≈ 20°. **12-m waves**: Peak near 175°. Spread ≈ 10°.

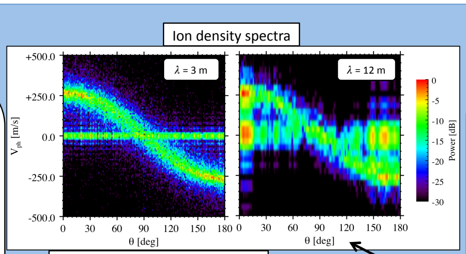
Monotonic increase in amplitude. γ increases by factor of 4. Run does not reach saturation.

Gaussian ions

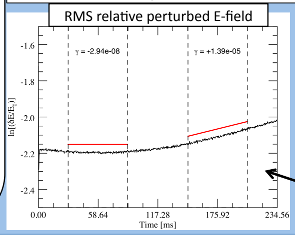
Relative perturbed ion density



Ion density spectra



RMS relative perturbed E-field



3-m waves: Peak near 0°/180°. Spread ≈ 40°. **12-m waves**: Peak near 5°. Spread ≈ 10°.

Non-monotonic amplitude increase. $\gamma \leq$ value for flat ions. Run doesn't reach saturation.

Results

- Turbulent density irregularities evolve along the top edge of the dust layer. Peak amplitudes are 5-7 % of the background plasma density.
- Phase velocity of 3-m and 12-m waves varies as $\cos\theta$ with amplitude roughly 260 m/s in both runs.
- Waves propagate predominantly westward in both runs. 3-m waves show greater spread around due west for Gaussian ions. 12-m waves flow at 5° below due west for flat ions and 5° above due west for Gaussian ions.
- Gaussian ions have a stationary component.
- RMS relative perturbed electric-field amplitude increases for both runs. Final growth rate for the two runs is nearly equal. Increasing amplitude indicates that neither system has reached saturation by the end of the run.

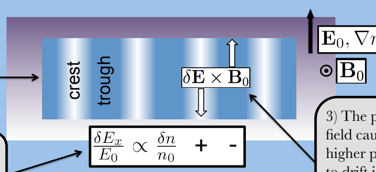
Theory

The linear theory of the gradient drift instability (GDI) can explain the location and phase velocity of simulated density irregularities. The GDI arises in a plasma with magnetized electrons and unmagnetized ions when a density gradient is aligned with the ambient electric field:

$$\mathbf{E}_0 \cdot \nabla n > 0$$

Gradient drift instability

1) Electrons Hall drift ahead of ions, creating small density perturbations.



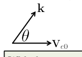
$$\frac{\delta E_x}{E_0} \propto \frac{\delta n}{n_0}$$

2) The density perturbations give rise to a perturbed electrostatic field.

3) The perturbed electric field causes regions of higher perturbed density to drift into regions of lower background density, leading to instability.

GDI phase speed: $V_{ph} = \dfrac{|\mathbf{V}_{e0}|\cos\theta}{1+\Psi_0}$

where $\mathbf{V}_{e0} = \underbrace{\frac{\mathbf{E}_0\times\mathbf{B}_0}{B_0^2}}_{\text{Hall drift}} + \underbrace{\frac{k_B T_e}{e}\frac{\nabla n\times\mathbf{B}_0}{nB_0^2}}_{\text{Diamag. drift}}$



and $\Psi_0 \equiv \dfrac{\nu_i \nu_e}{\Omega_i \Omega_e}$

With the parameters used in these runs,

$$V_{ph} = 270\cos\theta \text{ m/s}$$

Electron attachment to dust grains creates electron “bite-outs”, which have been observed in-situ [*Havnes et al.*, 1996].

Theory predicts that the GDI should occur on the top side of a negatively charged dust layer, where the electron density increases away from the dust density peak [*Rosenberg and Shukla*, 2003].

Conclusions

Simulations of particle ions and inertialess electrons in the presence of a static, negatively charged dust layer produce turbulence that gradient-drift instability theory can explain reasonably well. Wave power indicates westward propagation with greater spread in 3-m waves than in 12-m waves. RMS electric field shows that turbulent growth increases at time progresses, even when the initial distributions are set to be in kinetic equilibrium.

Next steps

- Vary parameters related to the neutral atmosphere, to probe the instability at different altitudes.
- Run the simulations for more time, to explore the turbulent saturation mechanism.
- Run with additional initial distributions, to explore system stability.
- Analyze nonlinear evolution.

References

Havnes et al. (1996), Meter-scale variations of the charge carried by mesospheric dust, *Planet. Space Sci., 44, 1191-1194.*
Rosenberg and Shukla (2003), Gradient-drift instability in space dusty plasmas, *Planet. Space Sci., 51, 1-7.*