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 dust grains often gives rise to a dusty plasma in the surrounding plasma. Such plasmas create instabilities that ground-based radar observers, providing a diagnostic for dust density, dynamics, and lifetime. Previous studies laid the theoretical foundation for studying static, isolated dust layers at B – 100 km in Earth’s atmosphere, and observations have attributed radar echoes associated with dust 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 ionosphere can quickly become charged by electrons in the geomagnetic field of the ambient magnetic field that coalesced under-neath the modified form of the GDI. This work presents two simulations, one of which modeled 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.

Plasma parameters

- **Ions (NO)**: Particle-in-cell method.
- **Electrons**: Inertialess, quasineutral, isothermal fluid.
- **Physical parameters models**: Fluid model, where ions are unmagnetized and drifting at the phase velocity of simulated local gravity.
- **Electrostatic potential**: The electrostatic potential arises in a plasma with unmagnetized ions when a perturbation in the electrostatic potential is applied at times t > 0.
- **Electron drift**: The electron drift causes regions of higher perturbed density to drift into regions of lower perturbed density, leading to instability.

Simulation

**Flat ions**

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

**Gaussian ions**

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

\[ \frac{d}{dt} \left( n_i \right) = -n_e \frac{E_i}{m_i} \]

**Density peak**

Electron “bite-outs”, electron drift ahead of ions, creating small density perturbations

Initial distributions

**Flat ions**

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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 θ with amplitude roughly 200 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 show less spread due west for flat ions and 5° above due west for Gaussian ions.
- Gaussian ions have a stationary component.
- RMS relative perturbed electric-field magnitude 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.

Dust parameters

- **Electron density**: \( \rho_e = \rho_d \) or \( \rho_d \approx \rho_e \)
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Theory

The linear theory of the gradient drift instability (GDI) can explain the locations 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: \( E_0 \parallel \nabla n_d \).

1) Electrostatic field
2) The density perturbations give rise to an electrostatic field.
3) The perturbed electric field causes regions of higher perturbed density to drift into regions of lower perturbed density, leading to instability.
4) The perturbed electric field is given by \( E_d = E_0 + \nabla \phi_d \).
5) The electron density increases away from the dust density peak (Robinson 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

Hemes et al. (1996), Gradient-drift instability in space dusty plasmas, Planet. Space Sci., 44, 1191-1194.