Plasma Turbulence of Non-Specular Trail Plasmas as Measured by a High Power Large Aperture Radar

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Outline

• Meteoroid Diffusion
  - Introduction to Meteor Trails
    ▪ Motivation
    ▪ Formation
    ▪ Detection
  - Turbulence Onset Times
  - Ambipolar Diffusion Coefficient
  - Trail Diffusion Shape
  - Parallel and Perpendicular Variations to the Magnetic Field

Image Courtesy of Universe Today, 2010
Motivation

- Understand plasma expansion in a collisional environment
- Better understanding of the ionosphere through small perturbations to the background plasma
- Extend to the expansion of plasma in space created from a meteoroid strike on a satellite
- Verify trail diffusion simulations with radar data results

Courtesy of Dyrud et al., 2001
Formation of Meteoroid Trails

- Meteoroids heat up and ablate in Earth’s atmosphere
- Collisions ionize neutral air molecules
- Produces plasma regions
  - Head – region directly surrounding meteoroid
  - Trails – region left behind meteoroid
Formation of Meteoroid Trails

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Ionized Particles

Hot Meteoroid
Formation of Meteoroid Trails

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ALTAIR System

- Dual Frequency
  - VHF (160 MHz)
  - UHF (422 MHz)
- High Resolution
- Dual Circular Polarization
- Monopulse Angles
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- Data Set
  - 2007 year long collect
  - 100,000+ head echoes
  - TBD nonspecular trails
Polarization and Frequency

• Transmit in RC and expect return to be LC, but both LC and RC returns are detected

• Three possible explanations
  ▪ Modification of the RF wave due to wave frequency, plasma layer width, collision frequency, or electron density
  ▪ Geometric changes, such as multiple scatters from meteoroid fragmentation or asymmetry in the trail shape
  ▪ Striations in the trails

• UHF and VHF SNR depend on wavelength raised to ~6
Meteor Trail Case Studies

Left Circular Return
Nov. 18, 2007 – 6 AM

Right Circular Return
Nov. 18, 2007 – 6 AM
VHF Detection
Jan. 6, 2007 – 5 AM

UHF Detection
Jan. 6, 2007 – 5 AM

Non-Specular Trail
Head Echo
Turbulence Onset: Results

Average over 152 nonspecular trails

Average Time Delay vs. Altitude

Average Time Delay For Signal Return Type
Turbulence Onset: Results

Average over 108 VHF and 43 UHF nonspecular trails

Average Time Delay for VHF Trails

Average Time Delay for UHF Trails

- Average Time Delay (LC)
- Average Time Delay (RC)
- Average Time Delay (LC + RC)
- 25 ms Delay
- 40 ms Delay
Ambipolar Diffusion Coefficient

**Assumptions**
- Weakly ionized
- Collisional frequency is large

**Accounts for the diffusion of both ions and electrons in a plasma via an electric field**

**In the presence of a magnetic field, the electrons would simply move along the field lines**

Ambipolar Diffusion Coefficient:

\[ D_a = \frac{\mu_e D_i + \mu_i D_e}{\mu_i + \mu_e} \]

\[ D = \frac{KT}{mv} \quad \mu = \frac{|q|}{mv} \]

From a radar signal:

\[ \tau = \frac{\lambda^2}{16 \pi^2 D_a} \]

(Greenhow et al., 1955)
- Fit a line to SNR vs. time for a given altitude
- Calculated for each altitude when SNR is $1/e$ of initial value
Diffusion Coefficient: Results

Model: \( h = 4.43 \times \log(D_a) + 87.9 \)

Courtesy of Galligan et al., 2002

Shaded areas around data signify error bars
Diffusion Coefficient: Results

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Courtesy of Galligan et al., 2002

Shaded areas around data signify error bars
Diffusion Shape: Results
Diffusion Shape: Results

- \( t = 0.0348 \) sec
- \( t = 0.1043 \) sec
- \( t = 0.2087 \) sec
- \( t = 0.3391 \) sec
- \( t = 1.0348 \) sec

Legend: LC (dB)
Diffusion Shape: New Axis

- Centered at the middle point of the head echo
- Rotated such that x-axis is parallel with the magnetic field
Parallel & Perpendicular Variation

Jan. 5, 2007 – 5 AM
Parallel Variation

Jan. 5, 2007 – 5 AM
Perpendicular Variation

Jan. 6, 2007 – 5 AM
Parallel Variation

Jan. 6, 2007 – 5 AM
Perpendicular Variation
Parallel & Perpendicular Variation

Weighted Slopes

- Weighted Slopes for Parallel to Magnetic Field Line
- Weighted Slopes for Perpendicular to Magnetic Field Line

<table>
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<th>Trail Numbers</th>
<th>Fitted Slopes (km/sec)</th>
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Parallel & Perpendicular Variation

Weighted Slopes for Parallel to Magnetic Field Line

Weighted Slopes for Perpendicular to Magnetic Field Line
Cite: Stanford Aeronautics & Astronautics

Parallel & Perpendicular Variation

Weighted Change in Standard Deviation

![Graph showing weighted change in standard deviation for parallel and perpendicular trails. The x-axis represents trails, and the y-axis represents change in standard deviation. The graph includes markers for parallel and perpendicular trails, with parallel trails shown in blue and perpendicular trails in red.]
Conclusion

• From the turbulence onset times:
  - There is large agreement with previous simulations with the large increase in onset times at lower altitudes possibly indicating ambient conditions

• From the ambipolar diffusion coefficient:
  - There is agreement in the upward trend with previous studies, but the order of magnitude is not in agreement

• From the diffusion structure:
  - There is evidence that the plasma is expanding in several directions (meteoroid direction and perpendicular/parallel to magnetic field) and is not in agreement with some of the assumptions made for ambipolar diffusion.

• Ambipolar Diffusion Coefficient is not sufficient to explain the diffusion process that occurs when meteoroids ablate in the ionosphere
Future Work

• Develop method for including both directions in calculations of the diffusion process for nonspecular trails

• Examine changing diffusion shape of nonspecular trails

• Explore the effects of polarization on plasma scattering
QUESTIONS?