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Using Plasma Turbulence to understand the Global Impact of Billions of Daily Meteors

Every day billions of meteoroids impact and disintegrate in the Earth's atmosphere. Current estimates for this global meteor flux vary from 2000–200,000 tons per year, and estimates for the average velocity range between 10 km/s to 70 km/s [*Cziczo et al.*, 2001; *Janches et al.*, 2000; *Taylor*, 1995; *Ceplecha et al.*, 1998; *Mathews et al.*, 2001]. Understanding this meteor flux is important for several fields of study from solar system evolution, upper atmospheric physics to manned and unmanned space flight. Yet, the basic properties of this global meteor flux, such as the average mass, velocity, and chemical composition remain poorly understood [*Mathews et al.*, 2001]. The research outlined in this report aims to improve our understanding of these meteors, by improving our capabilities to observe and interpret observations of these small (sand grain and dust size) meteor impacts. We begin with a brief description of the physical processes of interest to provide a context for the reader.

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For decades, meteor observations were typically made with photographic and TV cameras and small meteor radars, and much was learned about the continuous impact of meteors ranging in size from sand grains to large boulder sized meteoroids. Yet, over the past decade, large radars such as the European Incoherent Scatter (EISCAT) Radar and the Arecibo Observatory in Puerto Rico have been pointed towards the sky to measure meteor impacts. These radars have observed two types of radar meteor reflections that have become known and now widely studied. These reflections are known as meteor head echoes and non-specular trails. An example of these types of observations is shown in Figure 1. This figure shows a meteor head echo followed by trail reflections, called non–specular trails. While the head echo is believed to be a cloud of electrons moving at the speed of the meteoroid, the non-specular trail echoes result from radio scatter from plasma turbulence. Both of these reflections occur to plasma phenomena and turbulence, and to understand them and what they are telling us, we need to understand the plasma turbulence occurring during reflection. Additionally, because these observations produce such detailed signatures, they show great promise as tools for deriving more complex parameters about meteoroids and the atmosphere they interact with. Already, it has become clear that these reflections largely result from the very frequent impact of small dust sized meteors, that were to small for conventional observation. For example the Arecibo radar observes a region of sky approximately 300 meters in diameter, and in the morning counts over 2000 meteors per hour [*Dyrud et al.*, 2005; *Janches et al.*, 2000].

Our current understanding of the physical processes occurring during the early stages of a small meteor atmospheric entry remains somewhat anecdotal and can be summarized as follows. As a meteor enters the Earth's atmosphere near 100 km altitude, the particle heats up and atoms begin boiling off the surface in a process known as ablation. Depending on energy, the ablated meteor atoms are ionized (freeing an an electron from the atom, producing a positively charged ion and negatively charged electron) upon collision with an air molecule. These newly produced meteor ions cool after approximately 10 collisions, which takes between a fraction of a millisecond at 80 km and as long as one millisecond at 110 km [*Jones*, 1995]. During this thermalization process, the plasma density near the meteoroid could be very high, allowing for the scattering radar reflections. In order to understand the large radar observations of this stage the researchers at CAS have developed a computer simulation, the results of which are shown in Figure 2. This figure plots the density of plasma (gas composed of ions and electrons) as a function of distance from the mete-

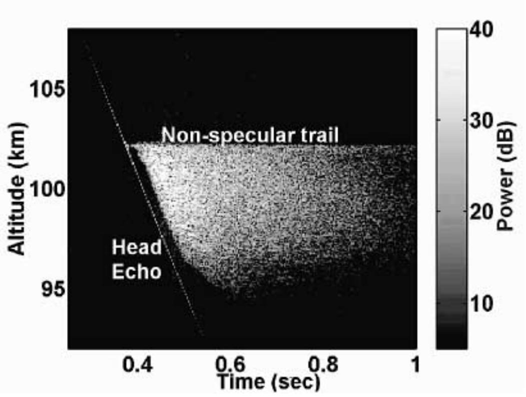
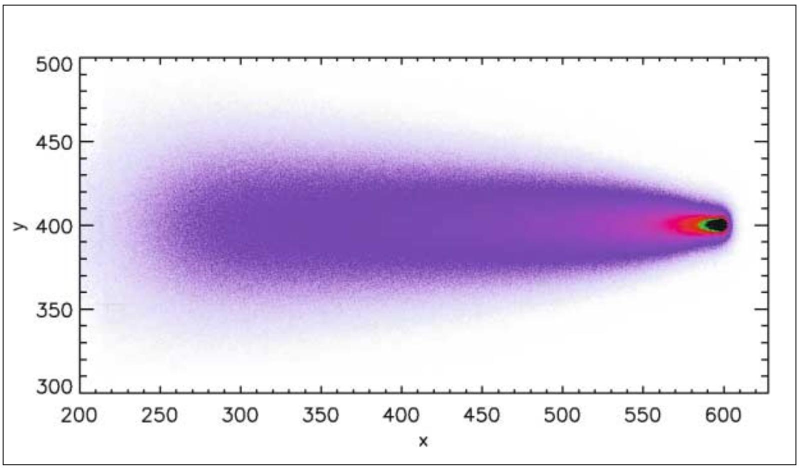


Figure 1. Altitude-time-intensity image of a head and subsequent non-specular echoes over extended range from ALTAIR VHF Radar. The diagonal line to the left is called a head echo, while the echoes spread in range and time to the right are the non-specular trail. Figure reproduced from *Close et al.* [2002].

Figure 2. Results from a meteor plasma simulation. This figure shows the color representation of the plasma density surrounding a meteor. The meteor simulated here was producing 10^{12} ions per meter traveled, and was moving against the surrounding atmosphere at a rate of 40 km/s.



oroid body. The meteoroid in this simulation was traversing to the right at a velocity 40 km/s. This work shows that the meteor generated plasma should be observable with a large radar, but that care must be taken when interpreting the results. We expect simulations such as these to greatly enhance our capabilities to interpret the radar reflections from meteors, and assess their speed and size with improved accuracy.

The evolution of a meteor trail continues in the following manner, and the effects of plasma turbulence become all the more obvious. Once the meteor plasma has cooled, the result is a large trail or column of enhanced ionization near 100 km altitude, which may extend between 10 and 20 km in length. Our understanding of next stages of evolution result directly from super computer simulations of plasma instability and turbulence within meteor trails published in [*Dyrud et al.*, 2005; *Dyrud et al.*, 2002, 2001]. These stages can be described by best with reference to these simulations, and example of which is shown in Figure 3. This figure shows

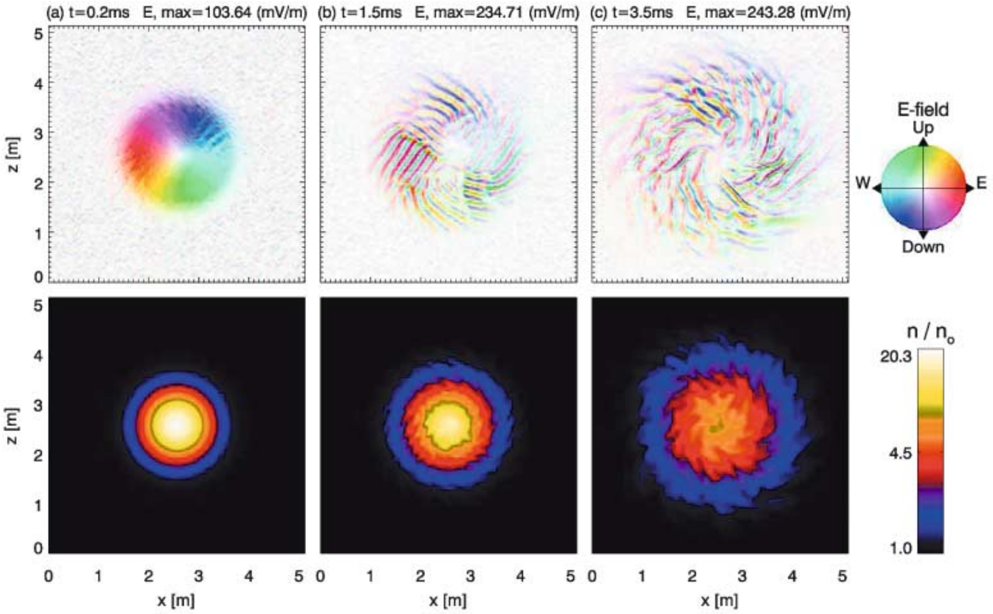


Figure 3. Simulation of a meteor trail electric field, E(top panels) and density ratio of the trail plasma to the background ionospheric density, (bottom panels) at three different times.

a cross-section of meteor trail plasma and the electric fields that develop within the trail. The simulation shows that the meteor plasma is highly unstable to the development of waves shown in the second column of panels. These waves are a cousin of naturally occurring waves in the ionosphere near the aurora [*Farley and Balsley*, 1973]. The third column shows that these waves become turbulent, generating a flower-like pattern in the density. It is this turbulent structuring that is highly reflective to radars, and accounts for the observations shown Figure 1.

Further modeling, the details of which are beyond the scope of this report, has shown that the development of turbulence upon meteor trails is highly dependent on the specific conditions of the meteor trail. This is allowing researchers to use these large radar observations of meteors to derive a tremendous amount of information about the meteor that generated the trail and the atmosphere where the trail resides. Work continues, but we are already using plasma turbulence theory combined with observations to calculate meteor velocities, masses and estimates of composition. As these data become refined, new estimates for the source size and speed of the this global meteor flux should be dramatically improved.

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