Particle in Cell Simulations of a Meteoroid Head Plasma

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Motivation

Meteoroids are a major source of metals in the atmosphere (Na, K, Li, Ca, Fe, and others). However, meteoroid mass distributions contain large uncertainties up to two orders of magnitude in some regimes. The main reasons for the uncertainties are the assumptions that go into calculating meteoroid masses from data. High power large aperture (HPLA) radars frequently detect meteors from 70-140 km altitude. With a models that relate the radar cross section to meteor plasma density, and the parent meteoroid to the meteor plasma, it is possible to determine the meteoroid's mass. However, current models contain many assumptions that have not been experimentally verified, such as the plasma density profile. While it is not currently possible to perform ground experiments in the mass and velocity regimes of meteors, we can run simulations in order to get an approximate plasma density distribution. Particle in cell (PIC) simulations are a useful tool to investigate meteor plasma and improve meteoroid mass flux estimates.

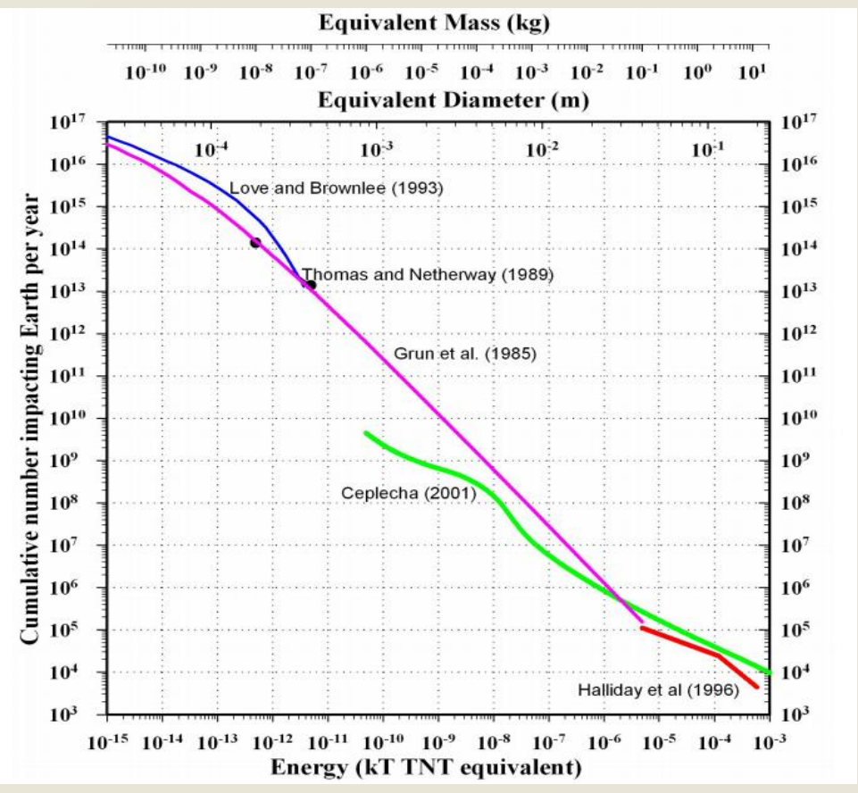


Figure 1: Purposed meteoroid mass distributions [1]

[1] National Research Council. *Limiting Future Collision Risk to Spacecraft: An Assessment of NASA's Meteoroid and Orbital Debris Programs.* Washington DC: The National Academies Press, 2011.

Introduction

When a meteoroid enters the atmosphere, it experiences high energy collisions with atmospheric molecules. A typical meteoroid detected by HPLA radars travels at 60 km/sec. At these speeds, the total energy of a collision with a single N_2 molecule is over 20 times the dissociation energy of N_2 plus the ionization energy of a nitrogen atom. This causes the region close to the meteoroid to fill with a plasma with density orders of magnitude larger than the background ionospheric plasma. Due to their smaller mass, electrons will have a much larger thermal velocity and will diffuse faster than the ions. The electrons will move away from the meteoroid until either the ambipolar electric field pulls them back towards the ions, or they collide with a neutral molecule. In the altitude range that radars detect meteors, the mean free path of the atmosphere ranges from about 0.01-10 m. The Debye length in the region of maximum plasma density is approximately 0.001 m. Therefore, there are two regimes to investigate: a collisionless, dense plasma close to the meteoroid, and a collisional, less dense plasma far from the meteoroid. We present particle in cell simulations of both regimes.

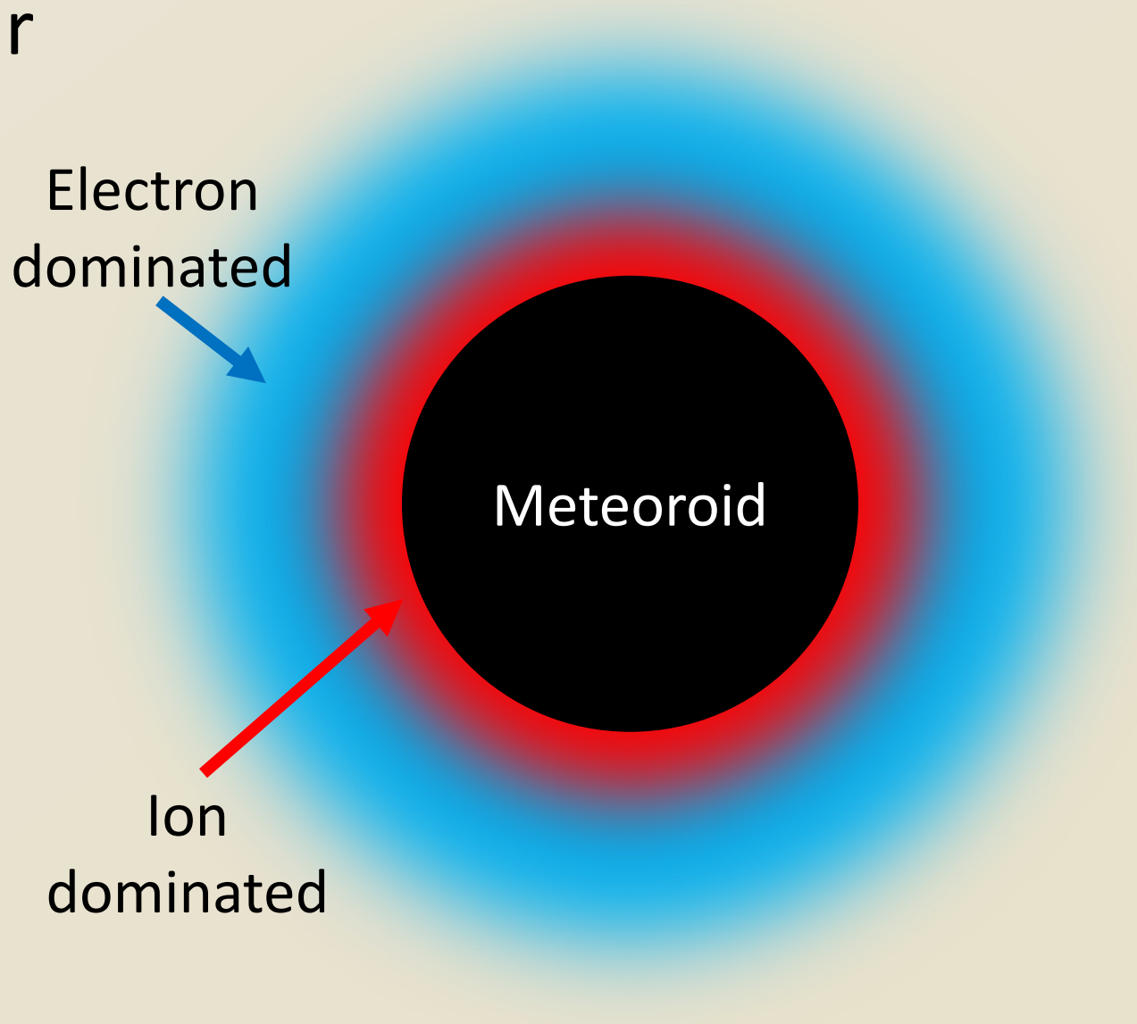


Figure 2: Plasma surrounding meteoroid shortly after collisions with atmospheric molecules.

Purposed Density Distributions

When determining meteoroid mass from radar head echo observations, one must assume a plasma density distribution. The main distributions used in literature are the Herlofson approximation, a parabolic exponential, and a Gaussian. All distributions are assumed to be spherically symmetric

Herlofson
$$n = \begin{cases} n_o & \text{for } r < r_a \\ n_o + \frac{n_b - n_o}{(r_b - r_a)} r & \text{for } r_a \le r < r_b \\ n_b & \text{for } r_b \le r \end{cases}$$

Parabolic Exp.
$$n = n_o \frac{e^{\gamma r}}{(e^{\gamma r}+1)^2} \qquad \gamma = \frac{2\pi}{r_o}$$

Gaussian
$$n = n_o e^{\frac{-r^2}{2{r_o}^2}}$$

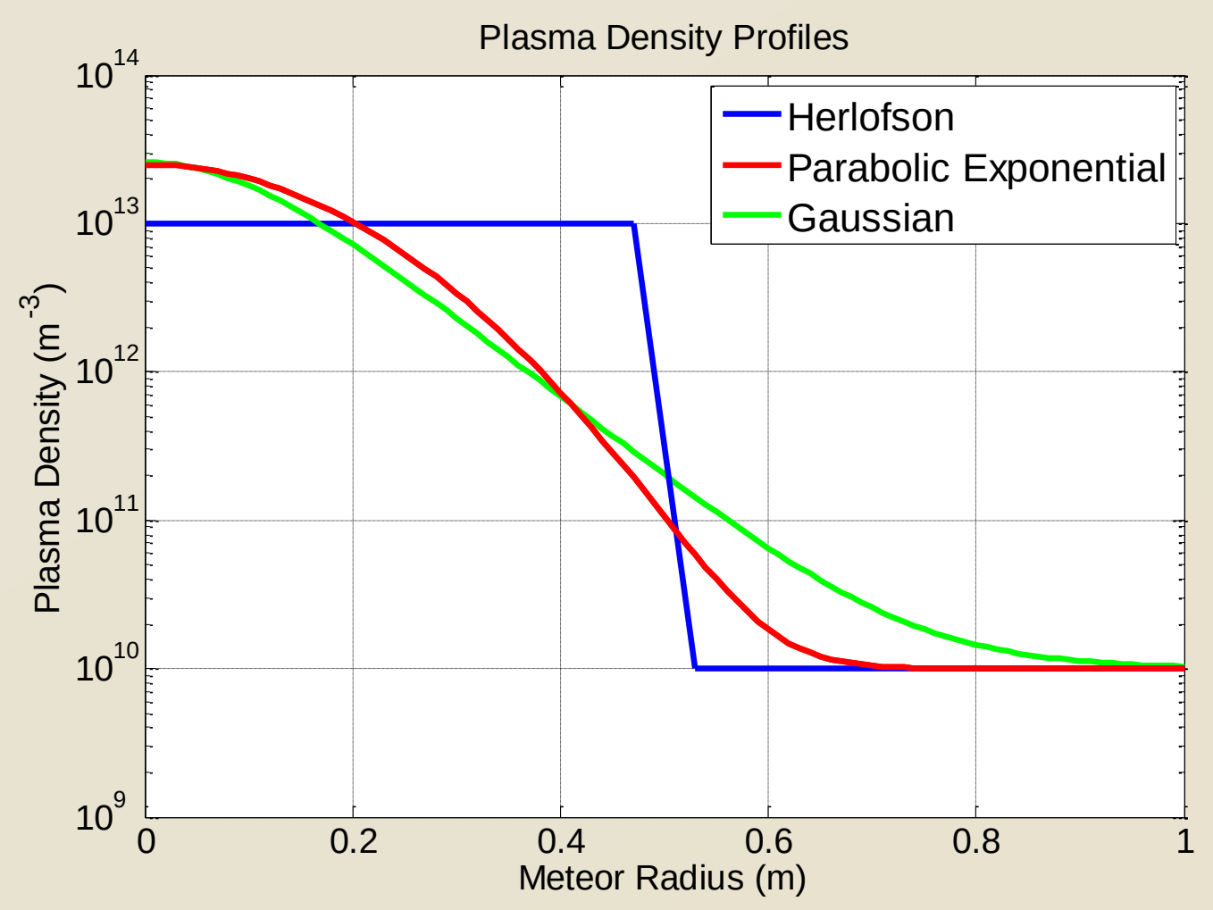


Figure 3: Purposed meteor plasma density distributions. These distributions are chosen based on assumptions and simplifications to allow for analytical solutions for electromagnetic wave scattering.

Simulation Parameters

Small Scale Simulation:

A collisionless plasma emitting from a spherical source will be spherically symmetric. Therefore, we restrict ourselves to a 1D simulation to obtain maximal spatial resolution. We model the meteoroid as a point source emitting ions and electrons with

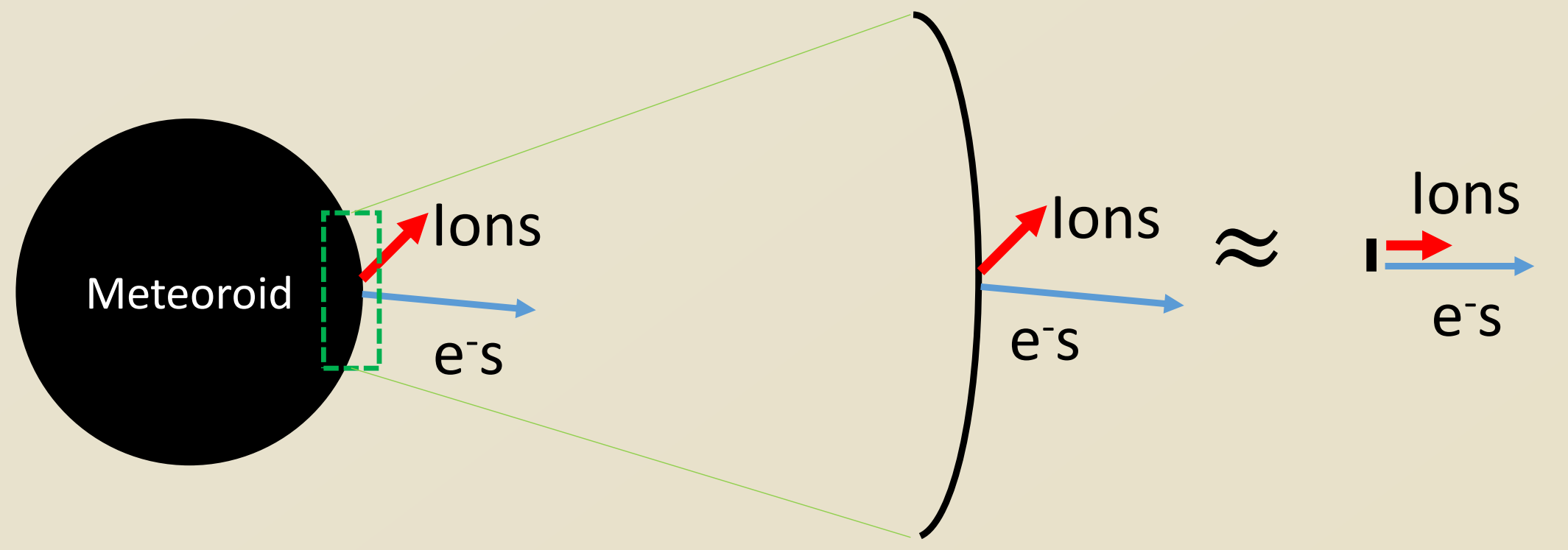


Figure 4: The small scale simulation of a collisionless plasma emanating from a point source

Large Scale Simulation:

To examine the spherical asymmetry of the plasma density due to collisions with a fast moving neutral background, a 2D simulation is required. We apply Monte Carlo collisions based on the collisional cross section of diatomic Nitrogen with electrons and monatomic Nitrogen ions to determine if a collision occurs.

Parameter	Small Scale (1D)	Large Scale (2D)
Δx (m)	1 x 10^{-5}	5 x 10^{-3}
Δt (sec)	1 x 10^{-12}	1 x 10^{-9}
Collisions	No	Yes
Total T (sec)	1 x 10^{-8}	1 x 10^{-5}

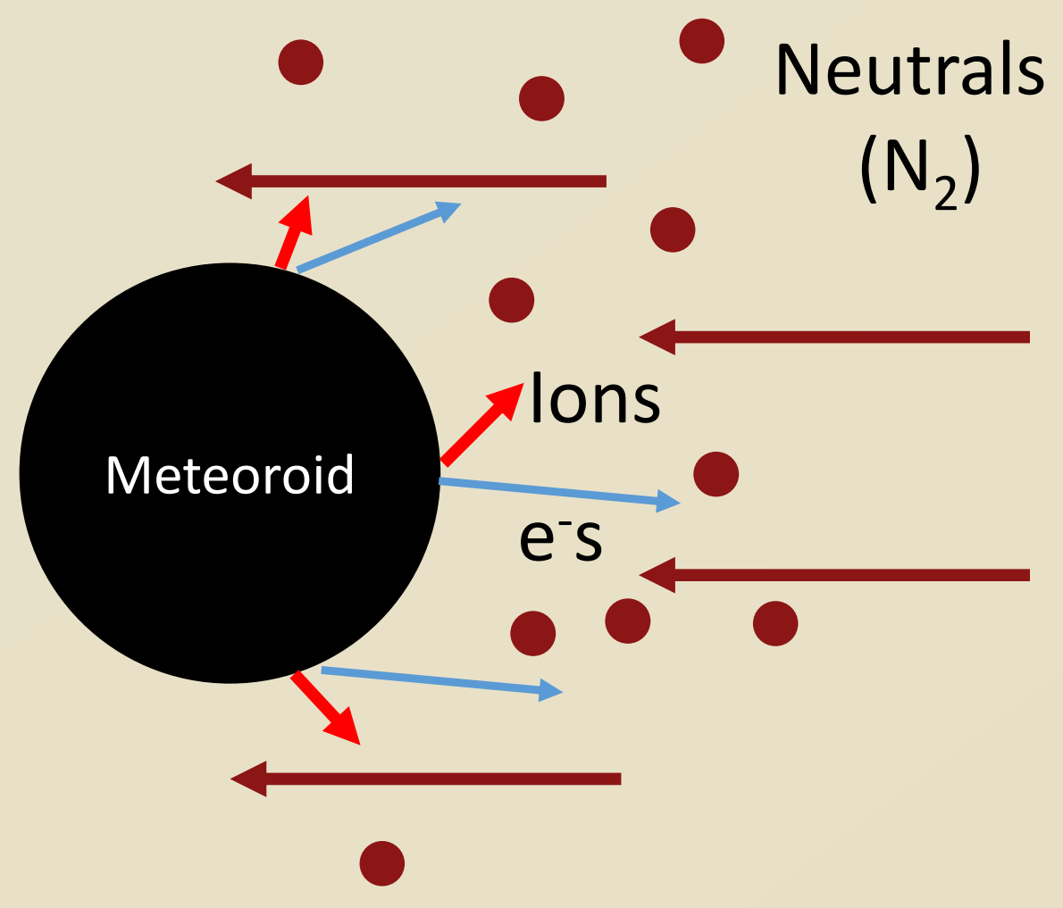


Figure 5: The large scale simulation of a collisional plasma with a spherical source. The background neutrals move at 60 km/s with a thermal velocity of 344 m/s.

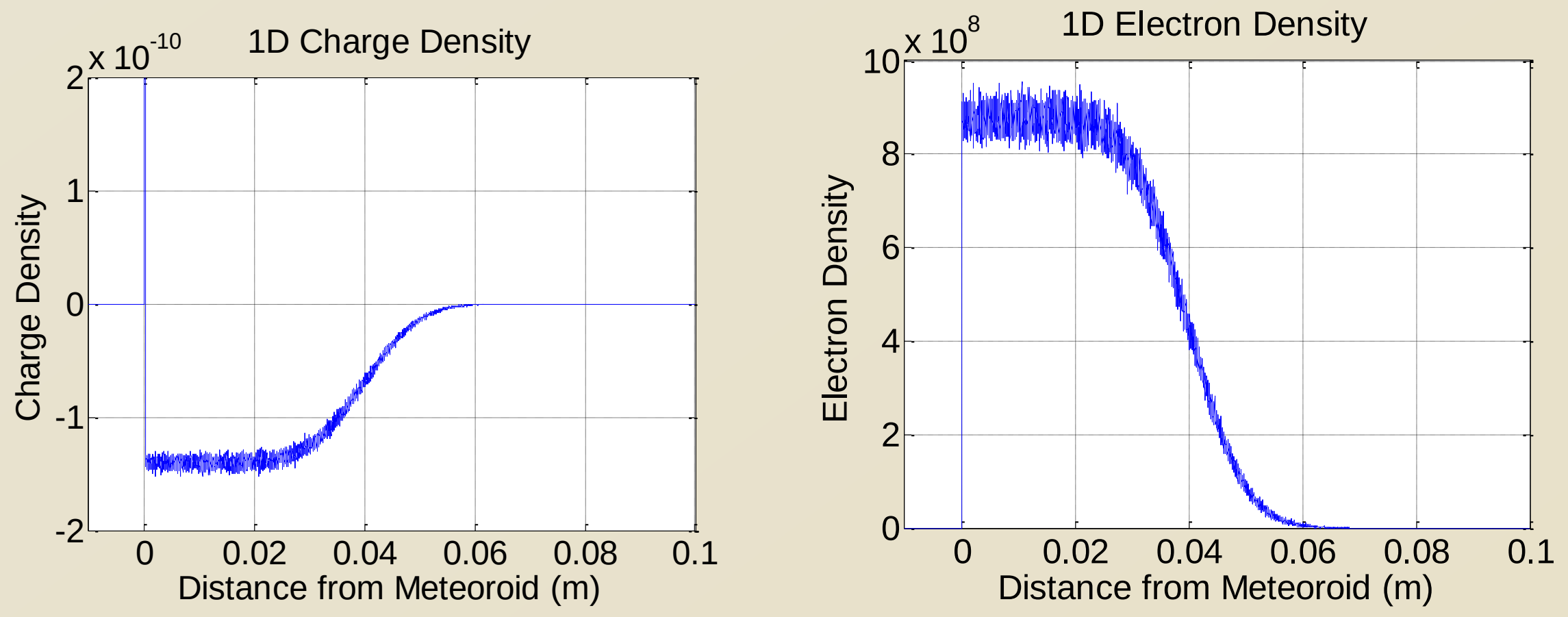
Collision Energy Book Keeping:

We assume the total energy of a collision is the kinetic energy of a diatomic Nitrogen molecule moving at the speed of the meteoroid (60 km/s). While meteor spectra show emission lines at for various metals and atmospheric molecules, some of the strongest emission lines are those of monatomic Nitrogen. For simplicity, we assume all collisions are with N_2 molecules and the energy is distributed between dissociation, ionization, ablation, and heating. The remaining energy is then split between the kinetic energy of the ion and electron.

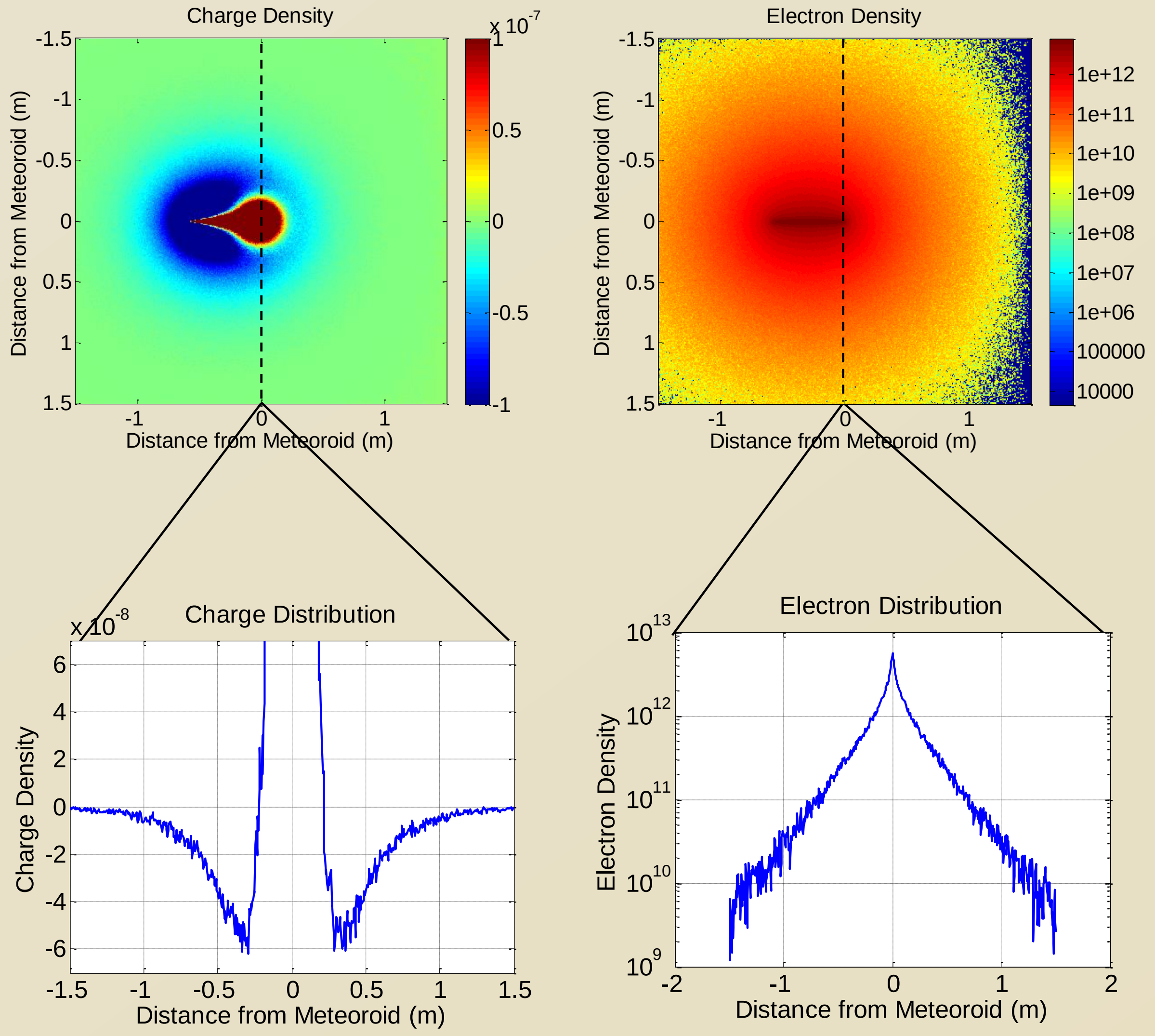
Process	Energy (eV)
N_2 Dissociation	9.8
N^+ Ionization	14.5
Surface Binding Energy [2]	5.7
Heating	2
Total Collision	523
Remaining	491

[2] Tielens, A. G. G. M., et al. The Physics of Grain-Grain Collisions and Gas-Grain Sputtering in Interstellar Shoacks, Astrophys. J. 1994.

Small Scale (1D) Results



Large Scale (2D) Results



Future Work

The next steps are to run longer simulations to determine the density distribution once the ion front catches up to the electrons. We will also investigate the effects of a background magnetic field, Coulomb collisions, multiple ion species, as well as meteoroid fragmentation on plasma density distribution. In the long term, an electromagnetic scattering simulation (possibly FDTD) will be used to relate the meteor plasma to a radar cross section.

Acknowledgements

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