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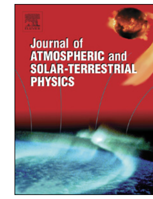

The diffusion of multiple ionic species in meteor trails

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ABSTRACT

Meteor trails are composed of a number of different types of ions that are produced during the meteoroid ablation process. The diffusion of meteoric plasma is usually presented in terms of the diffusion of a single ionic species, but this ignores the possibility of non-linear diffusion due to complex meteor trail composition. This study uses numerical simulations to investigate what effect multi-ion diffusion has on the time-decay of meteor radar echoes, and whether multi-ion diffusion could be responsible for the anomalous diffusion coefficient estimates produced by radars operating at different frequencies. It is found that the diffusion of different species of ions in meteor trails does not produce the same discrepancies seen in estimates of the ambipolar diffusion coefficient made using meteor radar.

1. Introduction

Meteor radars detect the trails of ionization left in the atmosphere around 70–110+ km by ablating meteoroids. These thin columns of plasma provide targets for radar scatter that can be used to obtain radial velocities for wind estimates. Furthermore, meteor trails expand over time due to diffusion, which for trails satisfying the underdense condition results in a characteristic exponential decay in meteor echo strength (see, e.g., McKinley, 1961). If diffusion is the only mechanism governing meteor trail development, the duration of meteor radar echoes is inversely proportional to the ambipolar diffusion coefficient of the atmosphere.

As diffusion is a function of atmospheric temperature and pressure, the diffusion coefficient obtained from meteor radar echo decay times can be used as a diagnostic parameter to characterize the atmosphere. Given appropriate data for temperature or pressure, the remaining term can be inferred using the diffusion coefficient (Tsutsumi et al., 1994). Alternatively, the hydrostatic relation can be combined with a value of the vertical temperature gradient to infer temperature (Hocking, 1999). Both of these methods provide a day-night, all-weather capability to measure temperature in the mesosphere/lower thermosphere (MLT) region of the atmosphere.

Recent studies of meteor diffusion coefficients have revealed substantial deviations from expected behavior. It has been shown by Younger et al. (2008) that the estimate of the diffusion coefficient differs between radars with different operating frequencies. Specifically, it was found that VHF radars with longer wavelengths produce larger estimates of the ambipolar diffusion coefficient, even when simultaneously observing the same meteors with smaller wavelength radars. Singer et al. (2008) reported that the diffusion coefficient is also dependent on the strength of the meteor echo, which corresponds to the density of electrons in the meteor trail. Kim et al. (2010) and Kumar and Subrahmanyam (2012) also found that temperatures derived from meteor radar diffusion coefficient estimates differ significantly from temperatures obtained from satellite and airglow measurements.

It is clear from these studies that additional mechanisms are governing the evolution of meteoric plasma, beyond the existing diffusion-only model. In order to determine what is causing the deviation of meteor radar diffusion coefficients from established theory, it is necessary to consider what processes have been left out of the original theoretical framework. Among the omissions made in the interest of a simple analytic solution is the presence of more than one species of ion in meteoric plasma. The following work will describe the diffusion of multiple ionic species in a meteor trail and determine if this mechanism is contributing to the anomalous decay of meteor radar echoes. In the event that the presence of multiple ionic species in meteor trails is not responsible for observed discrepancies in meteor radar observations efforts can be focused on better understanding other mechanisms governing the development of meteoric plasma, such as electron loss to recombination and attachment.

2. Radial diffusion

If diffusion is the only mechanism affecting meteoric plasma, the movement of electron density, n_e, away from the meteor trail

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axis is described by

$$\frac{dn_e}{dt} = -D\nabla^2 n_e(r,t), \tag{1}$$

where D is the ambipolar diffusion coefficient of the atmosphere and r is the distance from the trail axis. This leads to the Gaussian analytic solution for electron density at all times

$$n_e(r,t) = \frac{q}{\pi(4Dt + r_0^2)} \exp\left(-\frac{r^2}{4Dt + r_0^2}\right), \tag{2}$$

where q is the linear density of electrons in the trail and r_0 is the radius of the trail at the time of formation.

The Gaussian solution to Eq. (1) indicates that the time taken for a radar echo to decay by a factor of e^{-1} is given by

$$\tau = \frac{\lambda^2}{32\pi^2 D}, \tag{3}$$

where λ is the wavelength of the radar. The diffusion coefficient, D, is a function of the reduced ionic mobility, K_0 and the atmospheric temperature and pressure, T and p, as given by

$$D = 6.39 \times 10^{-2} \frac{T^2}{p} K_0. \tag{4}$$

The reduced ionic mobility is defined (Massey et al., 1971) in terms of the reduced mass of the neutral atmospheric molecules and ions, μ, and the average polarizability of the atmospheric molecules, $\overline{\alpha}$, as

$$K_0 = 1.14 \times 10^{-4} (\overline{\alpha}\mu)^{-1/2}. \tag{5}$$

As illustrated in Fig. 1, Eq. (5) dictates that lighter ions have higher reduced mobilities, which results in higher values of the ambipolar diffusion coefficients.

3. Ion collisional cross-section

In order to define the meteor trail initial radius for a given species, we must consider the kinetic properties of the ions as they collide with atmospheric molecules. Specifically, the ion-molecule collisional cross section in conjunction with meteoroid velocity determines the initial radius.

The precise value of r_0 depends on the speed of the meteor and the mean free path of atmospheric molecules, the latter being primarily an expression of atmospheric density. The mean free path of ions in the meteor trail, given by $l = (n_a \sigma_d)^{-1}$ is inversely proportional to the density of atmospheric molecules, n_a, and the collisional cross-section of the ions and atmospheric molecules, σ_d. This dictates that some consideration must be given as to what species are present in meteor trails when developing a description of the diffusion of meteoric ions.

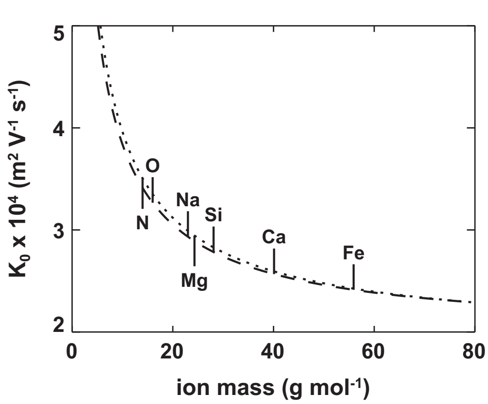

Fig. 1. Reduced mobility of ions in a background of O_2 (dotted) and (N_2) (dashed). Labels show the locations of some common ions present in meteor trail spectra (Ceplecha et al., 1998).

Portnyagin and Tokhtasyev (1974) use in their model the Langevin cross section, defined by

$$\sigma_d = \frac{2.2 \times 10^{-5}}{v} \left(\frac{\overline{\alpha}}{N_a \mu}\right)^{1/2}, \tag{6}$$

where v is the velocity of the meteoroid, $\overline{\alpha}$ is the average polarizability of the atmospheric molecules, and N_a is Avogadro's number. Bronshten (1983) subsequently suggested $\sigma_d = 1.4 \times 10^{15} v^{-0.8}$ as the collisional cross-section for some nominally average meteor composition, but it is not specified how he arrived at the values of the constant of proportionality or the exponent of v. Specifically, it is not stated how the values are determined by the properties of the ions present in meteor trails. As the purpose of this study is to examine the diffusive behavior of meteor trails composed of multiple ion species, we have opted to use the Langevin cross section from Eq. (6) in our simulations, as it affords us control over the specific species of ion being considered.

4. Multiple species diffusion

If there is more than one species of ion in the meteor trail, Eq. (1) for each ion species becomes

$$\frac{dn_i(r,t)}{dt} = -D_i \nabla \cdot [\nabla n_i((r,t) + c_i(r,t)\nabla n_e(r,t)], \tag{7}$$

where c_i is the fractional concentration of species i. Assuming that the condition of quasi-neutrality is satisfied, the electron density is given by

$$n_e = \sum_i c_i n_i. \tag{8}$$

This system no longer admits an analytic solution.

In regards to the initial distribution of ions about the trail axis, it is necessary to link the collisional cross-section of the ions with the initial radius of the trail, which is a measure of the width of the trail following the rapid thermalization of electrons and ions. Bronshten (1983) and Jones (1995) both provide relations with what they describe as average values for meteoric material, but they and their source material do not specify how the constants were arrived at. For this reason, the older relation

$$r_0 = \left(\frac{4}{3} N l^2\right)^{1/2} \tag{9}$$

was used. Here, l is the mean free path, as described above, and N is the number of collisions at which thermalization occurs.

Jones (1995) modeled the formation of a meteor trail by simulating the collisions of 10,000 particles diffusing away from the axis of meteor trails, starting at meteoric velocities. It was found that particles were slowed to thermal velocity within 10 collisions, regardless of the initial velocity. Following this example, a value of $N = 10$ collisions was used in our calculations to define the point of thermalization and hence, initial radius of the trail.

The problem of the initial radius is further confused by the differing collisional cross-sections of the different ions in a multi-species trail. We may posit two distinct scenarios for the relative distributions of different ion species at the onset of ambipolar diffusion. Firstly, it may be the case that the different ion species are well mixed throughout the entire evaporation and scattering process, producing a single common initial radius for all species at time $t = 0$ when diffusion commences. Alternatively, the scattering of different ion species independently of one another following ejection from the surface of the meteoroid may result in different initial radii for the initial distributions of each ion species.