ON THE MECHANISM OF EARLY RAPID REMOVAL OF ELECRONS FROM POSTADIABATICALLY EXPANDING OVERDENSE METEOR TRAINS

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1. INTRODUCTION

Overdense meteors (electron line density $10^{16} \leq q \leq 10^{19}$ electrons m^{-1} and diameters $d_m \geq 4$ mm up to small fireballs) are in the size regime of the meteoroids capable of generating shockwaves (**Fig. 1**) during the lower transitional flow regimes and prior to their terminal stage in the MLT (Mesosphere-Lower Thermosphere) region of the atmosphere, at altitudes between 75 km and 100 km [1].

However, small scale physico-chemical processes that accompany the early evolution of the high T meteor train remain poorly understood.

Primarily it is of interest to understand the mechanism behind subsequent rapid and intense electron removal from the postadiabatically expanding meteor train within the first 0.1 s after its formation **(Fig. 2)**. A comprehensive background on the topic can be found in [2].

We examine subsequent hyperthermal chemistry occurring on the early diffusing boundary of the high temperature postadiabatically formed meteor train and the shock modified ambient atmosphere in the MLT region.

This study has been motivated by the recent observational evidence [3] that suggest slower thermalization times of the postadiabatically formed meteor trains which is conducive for hyperthermal chemistry.

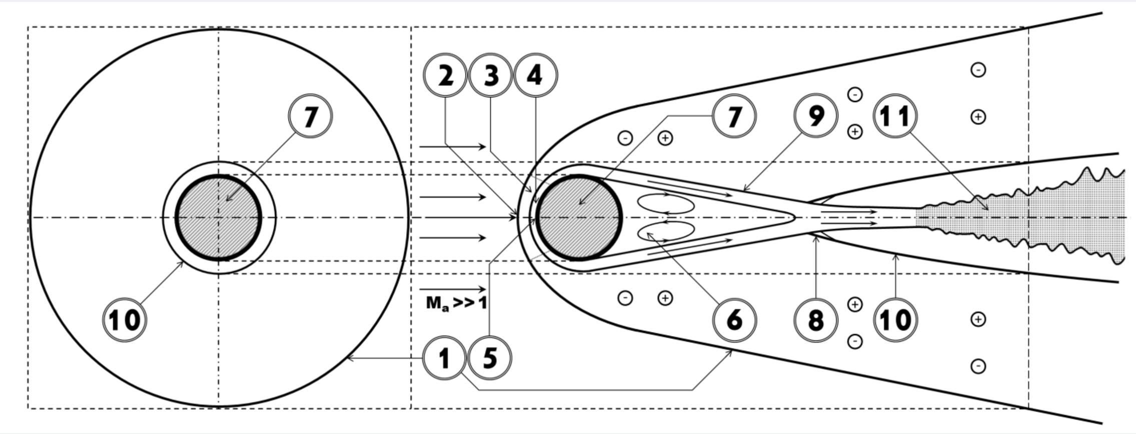

Figure 1: Schematics of the meteor shock wave(s), flow fields and near wake. The meteoroid is considered as a blunt body (with the spherical shape) propagating at hypersonic velocity. (1) Bow (cylindrical) shock wave front; (2) The "ballistic" shock front; (3) Sonic region; (4) Boundary layer; (5) Stagnation point; (6) Turbulent region (in some older literature, this is referred as the dead water region); (7) Meteoroid; (8) The neck and recompression region; (9) The 'free' shear layer; (10) The recompression vapour (or a true cylindrical) shock wave front; (11) The region of turbulent vapour flow and adiabatic expansion. Note that small circles with positive and negative signs indicate regions affected by the presence of ions and electrons respectively. The diagram is only for the illustrative purpose and is not to scale.

2. THEORETICAL & MODELING APPROACH

A theoretical approach was applied to approximate the temperature of the ambient atmosphere near the meteor train, which is heated by the passage of the overdense meteor cylindrical shock wave. This was accomplished by considering the meteor velocity and energy deposition, and evaluating the pressure ratios between the ablation amplified shock front and the ambient atmosphere (see **Fig. 3** and [2] for further details about this treatment). We have modeled hypersonic meteor flow in the MLT region using a simplified model without ablation, incorporated into the computational fluid dynamics (CFD) software package ANSYS Fluent (**Figs. 4, 5**). The computation was performed using O_2 and N_2 as the only major species, at an altitude of 80 km. A spherically shaped meteoroid is assumed to have velocity of 35 km/s (M_{80km} = 124.6). Two meteoroid sizes were modeled, d_m = 2.5 cm and d_m = 10 cm. Further details about the model are given in [2].

3. RESULTS

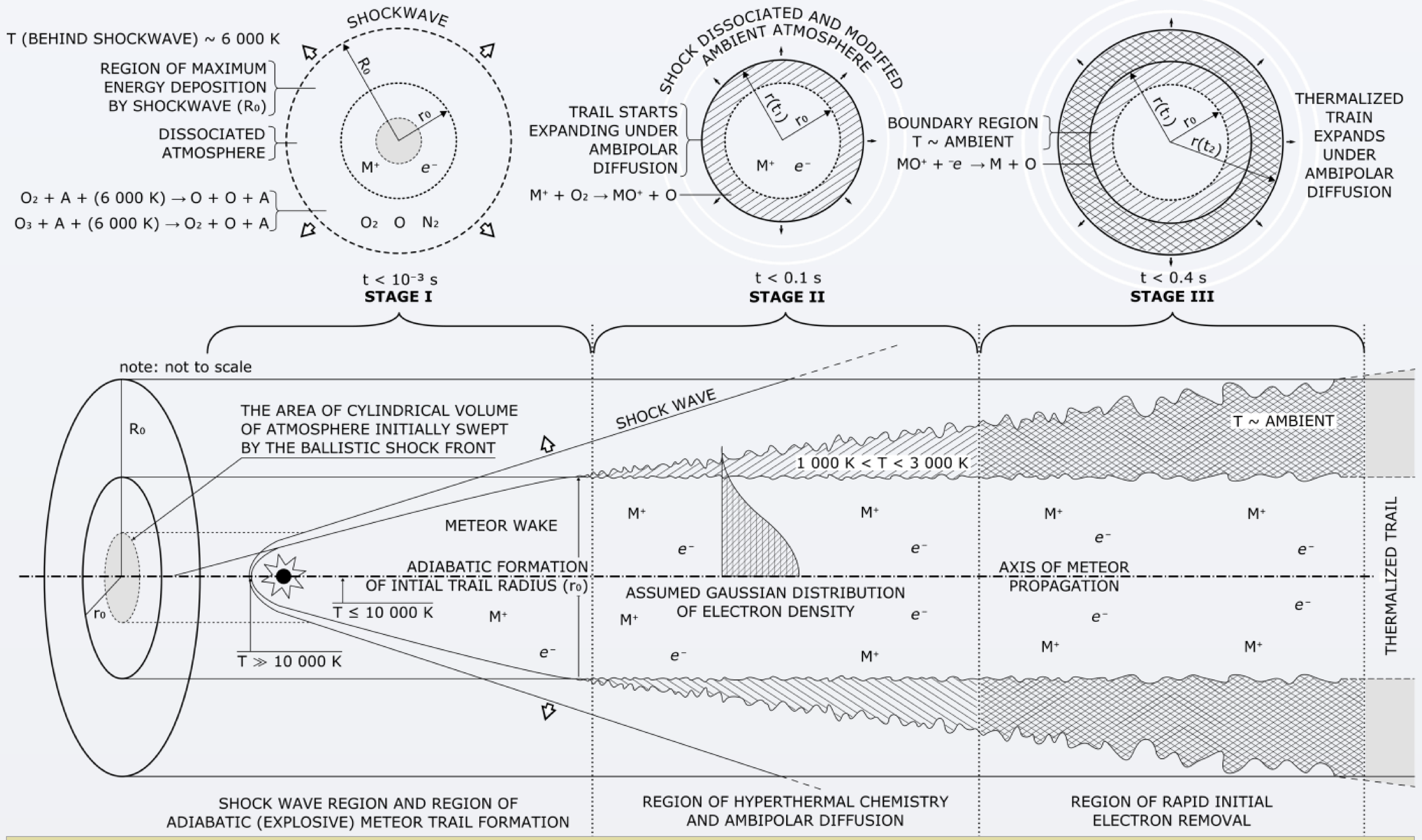

Figure 2: Schematic depiction of an overdense meteor's early evolution, in which three distinct stages can be recognized. In the first stage, the ablating meteoroid with the shock front in front sweeps the cylindrical volume of ambient atmosphere (depicted by the small gray circle), ionizing and dissociating atmospheric gasses. This stage also coincides with the cylindrical shock wave expanding radially outward, perpendicular to the meteor axis of propagation, with enough energy deposited within R_0 to dissociate O_2 and O_3 in the ambient atmosphere, but not enough for N_2 dissociation (see [2] for the extended discussion). In stage two, the adiabatically formed meteor train (which can be approximated as quasineutral plasma with the Gaussian radial electron distribution), begins to expand under ambipolar diffusion and thermalizes. This stage coincides with formation of metal ion oxides which takes place and is appreciable between approximately (3,000 – 1,500 K) at the boundary region of the diffusing trail. In this reaction, an ablated meteoric metal ion will react in a thermally driven reaction with the shock-dissociated product of ozone (O_2 in ground and excited states). In the stage three, in the almost thermalized train, the newly formed metal ion oxide will consume electrons rapidly by temperature independent dissociative recombination (see [2] for discussion).

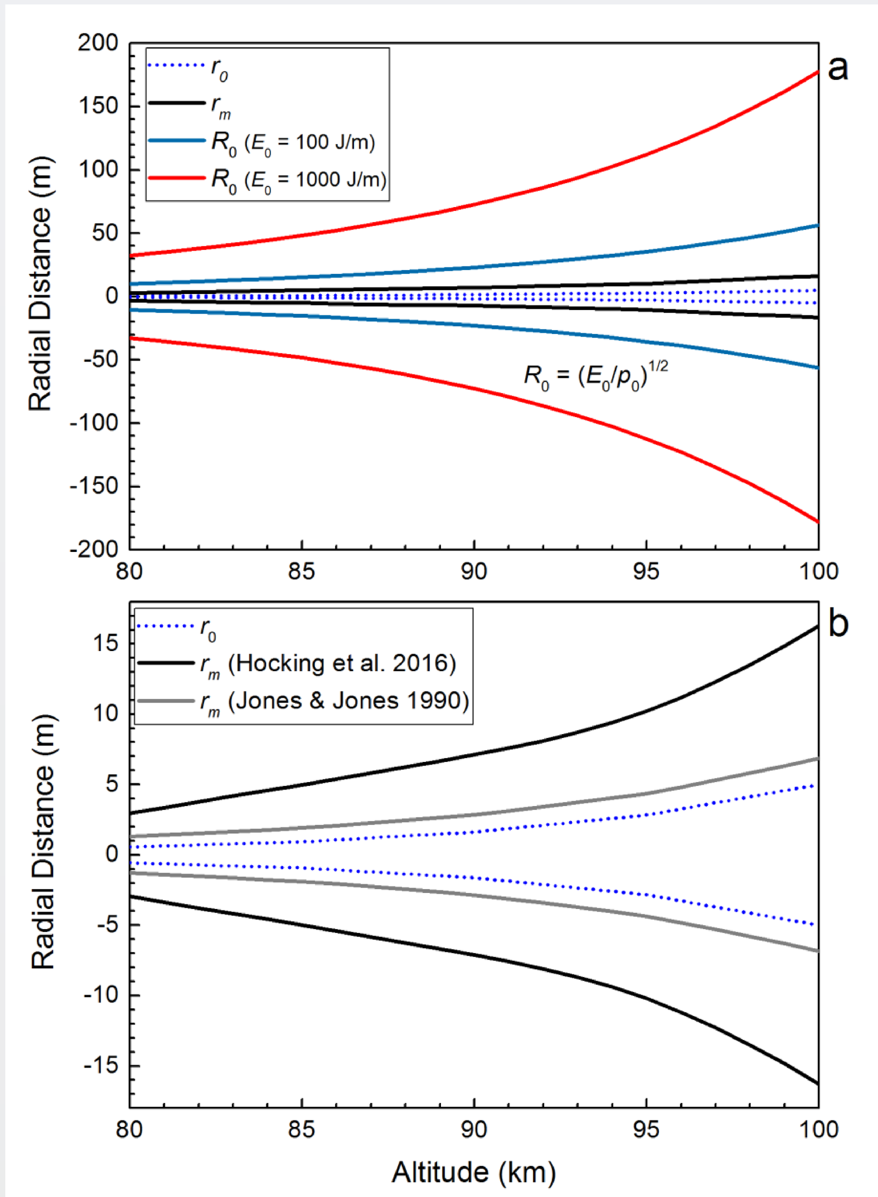

Figure 3: (a) Plotted are the initial radius (r_0) of a typical bright overdense meteor (from [4]) and the radius of the meteor (r_m) trail after t = 0.3 s. These are compared to R_0 as a function of constant energy deposition (see eq (1) in [2]) for altitudes from 80 km to 100 km. For r_m at 0.3 s, we applied the geometrically averaged hot plasma and ambient atmosphere ambipolar diffusion coefficients as per [5]. (b) The initial radius r_0, plotted along r_m at t = 0.3 s [6]. Here, shown is the comparison between r_m as calculated in panel (a), and r_m as calculated using the Massey's formula for the theoretical diffusion coefficient.

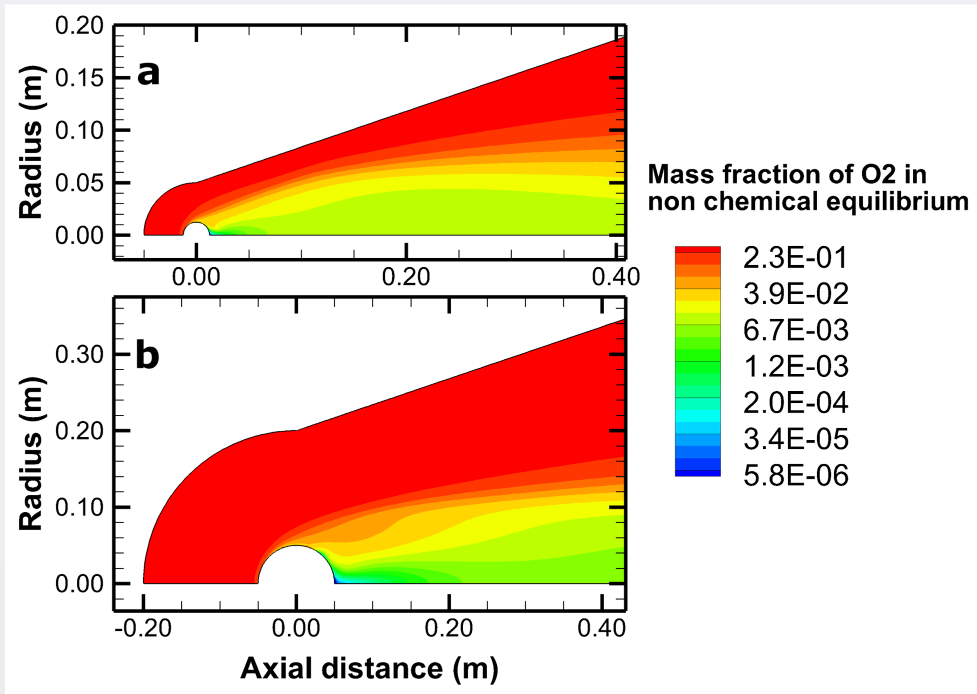

Figure 4: The mass fraction of O_2 as a function of radial distance from the propagation axis of the (a) 2.5 cm and (b) 10 cm meteoroid. The top boundary ("white space" in the plot) represents a numerical boundary condition without any physical significance (it is set up to be far enough away from the body (meteoroid), such that the influence of the body (meteoroid) no longer has any effect. Note that (a) and (b) have different axes scaling. The colour scheme is represented in log scale.

3. RESULTS – CONT'D

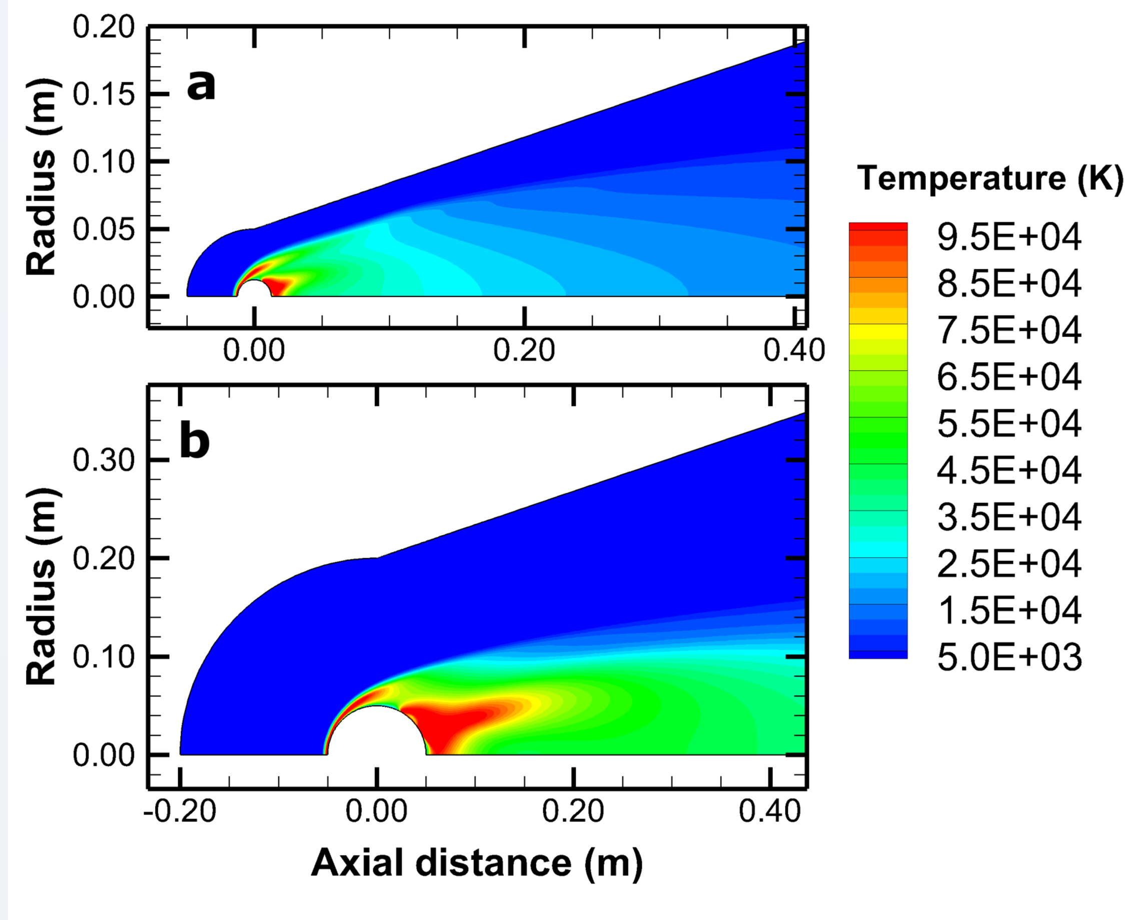

Figure 5: The temperature distribution around the (a) 2.5 cm and (b) 10 cm meteoroid. Note that (a) and (b) have different axes scaling.

4. DISCUSSION AND CONCLUSION

The cylindrical shock waves produced by overdense meteors are strong enough to heat the ambient atmosphere to temperatures of ~6,000 K in the near field and subsequently dissociate oxygen and minor species such as O_3, but insufficient to dissociate N_2. This substantially alters the considerations of the chemical processes taking place at the meteor train boundary. We demonstrate that ambient O_2 which survives the cylindrical shockwave, along with small quantities of O_2 that originates from the shock dissociation of O_3, participate primarily in high temperature oxidation of meteoric metal ions, forming metal ion oxide. For the case of overdense meteor trains, the subsequently formed meteoric metal oxide ions are predominantly responsible for the initial intense and short lasting electron removal from the boundary of the expanding meteor train, through a process of fast temperature independent dissociative recombination. This altitude dependent process is typically completed within 0.1 - 0.3 s, which in good agreement with the results suggesting substantially slower cooling of meteor wakes [3]. The rate of this process is also strongly dependent on the second Damköhler number. The potential implications of results presented here, toward the behavior of strong underdense radio meteors, should be further investigated. The full scope of implications of this work is presented in [2].

5. REFERENCES

[1] Bronshten V.A. (1983) *Physics of meteoric phenomena*. Dordrecht, D. Reidel. [2] Silber E.A. et al. (2017), *MNRAS*, 469(2), 1869-1882 (and references therein). [3] Jenniskens P. et al. (2004) *AsBio*, 4(81). [4] Baggaley W. and Fisher G. (1980) *PSS*, 28, 575 [5] Hocking W.K. et al (2016) *AnGeo*, 34, 1119, [6] Jones W. and Jones J. (1990) *JSTP*, 52, 185.

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