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**Evaporation of high  
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E. Murad and C. Roth

# Evaporation of high speed sporadic meteors

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## Abstract

Recent measurements conducted at the Arecibo Observatory report high-speed sporadic meteors having velocities near 50 km/s. The results seem to indicate a bimodal velocity distribution in the sporadic meteors (maxima at  $\sim 20$  km/s and  $\sim 50$  km/s). The particles have a maximum mass of  $\sim 1 \mu\text{g}$ . This paper will present an analysis of the ablation of  $1 \mu\text{g}$  meteoroids having velocities of 20, 30, 50, and 70 km/s. The calculations show that there is fractionation even for the fast meteoroids, the effect being particularly noticeable for the  $1 \mu\text{g}$  sporadic particles, and less so for the heavier particles. The relevance of the calculations to the radar observations of the sporadic meteors will be discussed.

## 1. Introduction

Sporadic meteors studied using the Arecibo Observatory have indicated the presence of a component that consists of very fast ( $\geq 50$  km/s), very light ( $1 \mu\text{g}$ ) meteoroids (Janches et al., 2000; Janches et al., 2001; Mathews et al., 2001; Mathews et al., 1997). These observations were confirmed in a subsequent study, also conducted at the Arecibo Observatory (Janches et al., 2002). The ablation of meteoroids has been treated in detail by a number of authors (Flynn, 1989; Hawkes and Jones, 1975; Love and Brownlee, 1991; Love and Brownlee, 1994; Öpik, 1958; Whipple, 1943). We will discuss in this paper the ablation of meteoroids of the mass and velocity that have been observed at Arecibo within the framework of differential ablation (McNeil et al., 1998; McNeil et al., 2002).

Before proceeding to the analysis and discussion of the results, it is worth outlining the basis for differential ablation. Analysis of the vaporization process of meteoroids (Jones and Kaiser, 1966) has indicated that consideration of thermal conductivity in the heating meteoroids is not necessary for meteoroids of radius  $< 1$  mm; in other words for such meteoroids the temperature is uniform, and, presumably, a thermal equilib-

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rium is established. The establishment of a thermally-equilibrated meteoroid is the basic assumption behind differential ablation, even though the transit time through the atmosphere is very short. The evaporation and the consequent abundance of the elements would then be according to their thermodynamic properties. The alternative to thermal equilibration is that the meteoroid undergoes pulse heating and all components are deposited as vapor irrespective of the thermal properties. Qualitatively, the difference between the two models can be summarized as follows: thermal equilibration would lead to evaporation of low boiling metals when the meteoroid temperature reaches 900 K (Na and K), while in the case of non-equilibrated or pulse-heated meteoroids, evaporation would occur when the temperature of the meteoroid reaches some average temperature, perhaps 1800–2000 K. The consequences of these models are that the thermal equilibrium model would lead to beginning heights that are higher than the pulse-heated model, and that the composition of metal vapor layer in the upper atmosphere (whether ionic or neutral) would show altitude profiles that are different for each for the metals.

Composition data obtained with rocket-borne mass spectrometers (see the review in (Grebowsky and Aikin, 2002) seem to support the idea of differential ablation, namely that the different atomic ions have their peak intensities at different altitudes. Moreover, lidar measurements of meteor trails give results that are readily interpretable within the framework of differential ablation (von Zahn et al., 2002).

## 2. Analysis and discussion

The processes that are included in the differential ablation (equilibrium) model for meteoroids entering the Earth's atmosphere have been published elsewhere (McNeil et al., 2002). The thermodynamic properties were taken either from the JANNAF Tables (Chase, 1998) or were calculated from the MAGMA model (Fegley and Cameron, 1987). Our model is similar to the Pure Component Reference (PCR) recently described (Alexander, 2001). The pressure of a component is described by an equation

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of the form  $\ln P_{\text{eq}} = A - B/T$ . In Figs. 1–4 we show the ablation of a meteoroid of  $1 \mu\text{g}$  mass entering the atmosphere at velocities of 20, 30, 50, and 70 km/s. Assuming a density of  $\sim 1 \text{ g/cm}^3$  such a meteoroid corresponds to a radius of  $\sim 6 \mu\text{m}$ , well below the radius at which thermal conductivity has to be included in the calculation of ablation properties of meteoroids (Jones and Kaiser, 1966). What is clear from the figures is that the evaporation begins at higher altitudes, that the ablation is complete for all these elements. It is worth noting that fractionation is more pronounced for meteoroids of the size discussed here ( $1 \mu\text{g}$ ) than for the larger ones, as is shown in Fig. 5 for the ablation of a  $10 \mu\text{g}$  meteoroid. The calculations indicate that as the meteoroid velocity increases, its loss of the metals increases; for the  $1 \mu\text{g}$  meteoroid most of the Ca survives transit through the atmosphere at 20 km/s. Even for Ca, the most refractory of the metal oxides, ablation is nearly complete at velocities  $\geq 50 \text{ km/s}$ . Also worth mentioning is that the density is an important parameter in modeling the ablation of meteoroids. For a given size and velocity, an increase in density leads to a higher temperature being reached at a given altitude.

At 50 km/s deposition of the metals begins at altitudes  $\geq 120 \text{ km}$ . Since the ablating atoms collide with the atmospheric constituents at the initial meteoroid velocity (50 km/s), the net center-of-mass collision energy with O is very high. Na and Fe likely account for most of the ionization seen by the radars. The hyperthermal processes leading to ionization have been discussed in other publications (Dressler and Murad, 2001; McNeil et al., 2001) and may be summarized:



The cross section for reaction (1) is estimated to be  $\sim 10\text{--}15 \text{ cm}^2$ . There is no estimate for the cross section of reaction (2). However, the reaction of Fe with  $\text{O}^2$  to give ionic products (undetermined) is  $\sim 10\text{--}16 \text{ cm}^2$  (Bukhteev and Bydin, 1963; Bukhteev et al., 1961; Friichtenicht et al., 1967); the cross section for reaction with O atoms (i.e. reaction 2) is likely to be greater because of the ready occurrence of resonances in

the formation of  $\text{Fe}^+$  and  $\text{O}^-$ . In any case, with  $[\text{O}] \sim 10^{12} \text{ cm}^{-3}$ , the time constant for reaction of either Na or Fe with O atoms is  $\sim 0.1$  ms. The implication of the above discussion is that for 1 and  $10 \mu\text{g}$  meteoroids the beginning height would be at  $\sim 120$  km and the end height would be at  $\sim 90$  km, in agreement with the observations (Janches et al., 2000; Janches et al., 2001; Mathews et al., 2001; Mathews et al., 1997).

### 3. Conclusions

Perhaps the most important conclusion is that the Arecibo data are explainable in terms of fundamental physical properties of meteoroids. Thus the necessary condition is met, but the calculations are not sufficient to show that the observations are not biased.

*Acknowledgements.* The work at Radex, Inc. was supported by the US Air Force contract F19628-98-C-0054. We also thank the reviewer for helpful comments.

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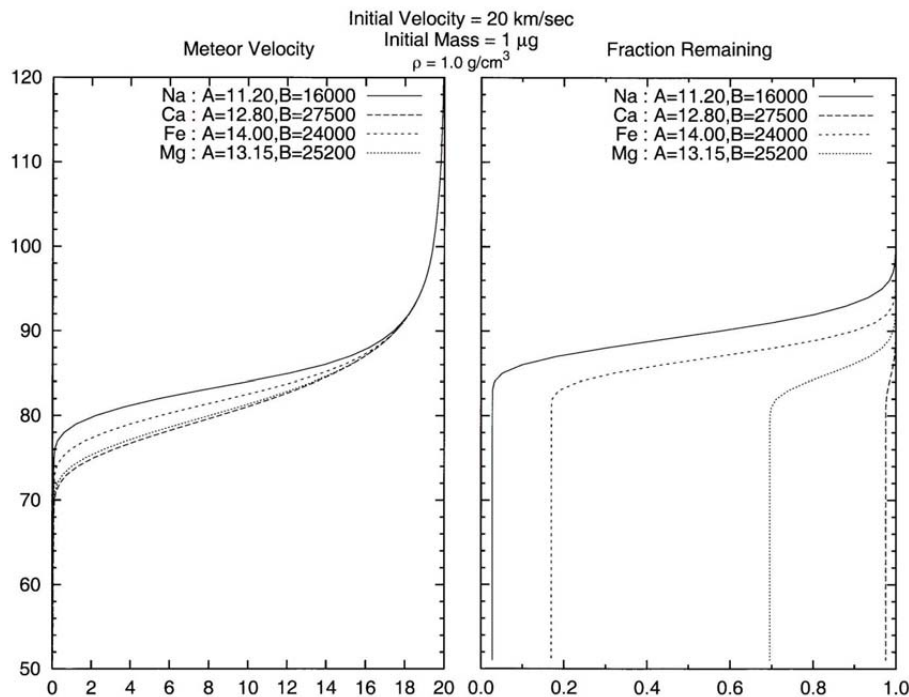
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**Fig. 1.** The ablation of a 1  $\mu\text{g}$  particle entering the atmosphere at 20 km/s.

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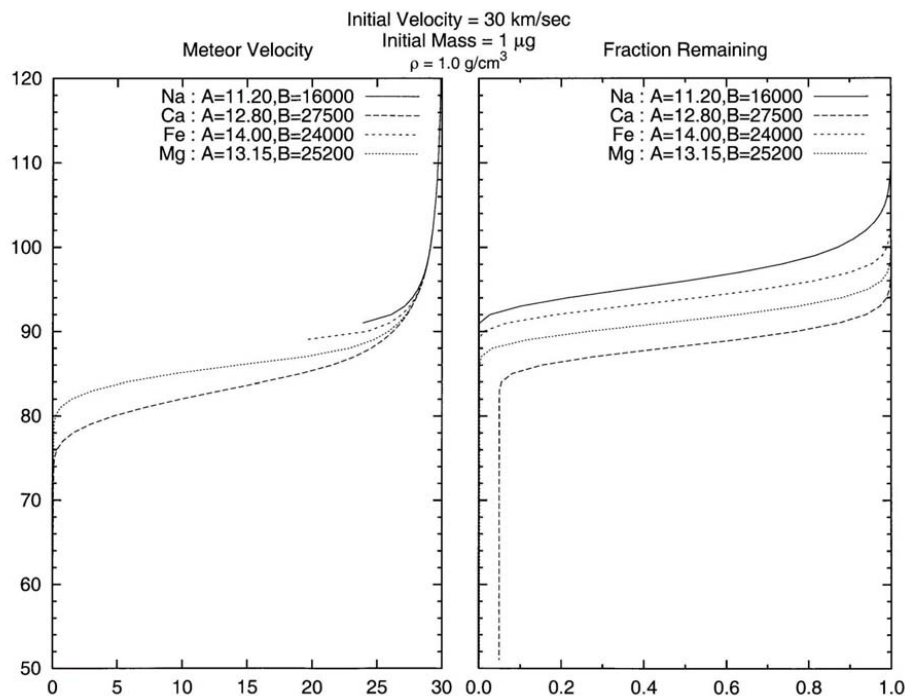
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**Fig. 2.** The ablation of a 1  $\mu\text{g}$  particle entering the atmosphere at 30 km/s.

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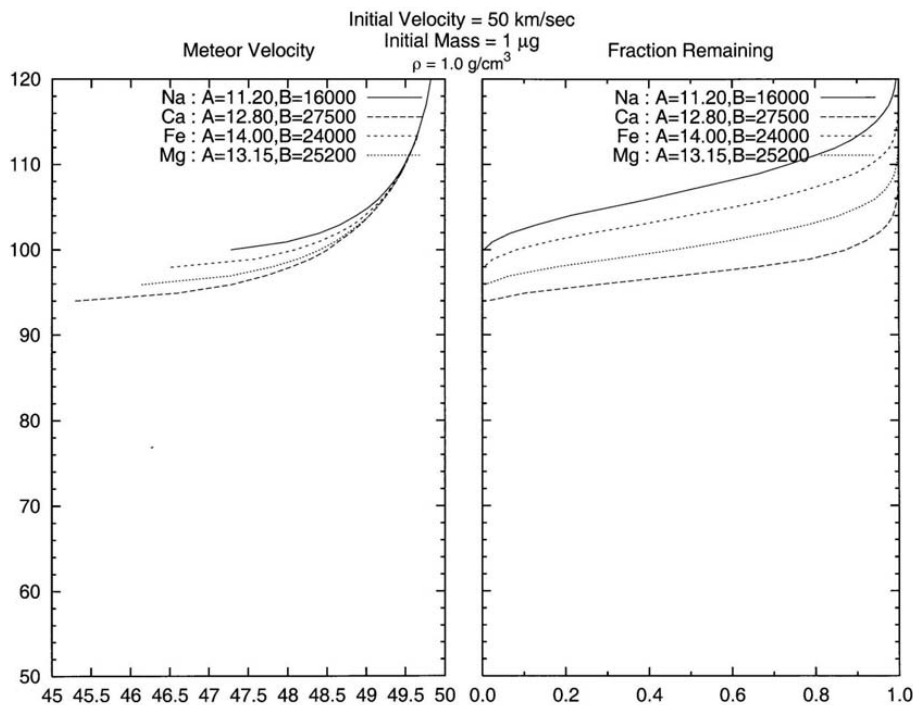


Fig. 3. The ablation of a 1 µg particle entering the atmosphere at 50 km/s.

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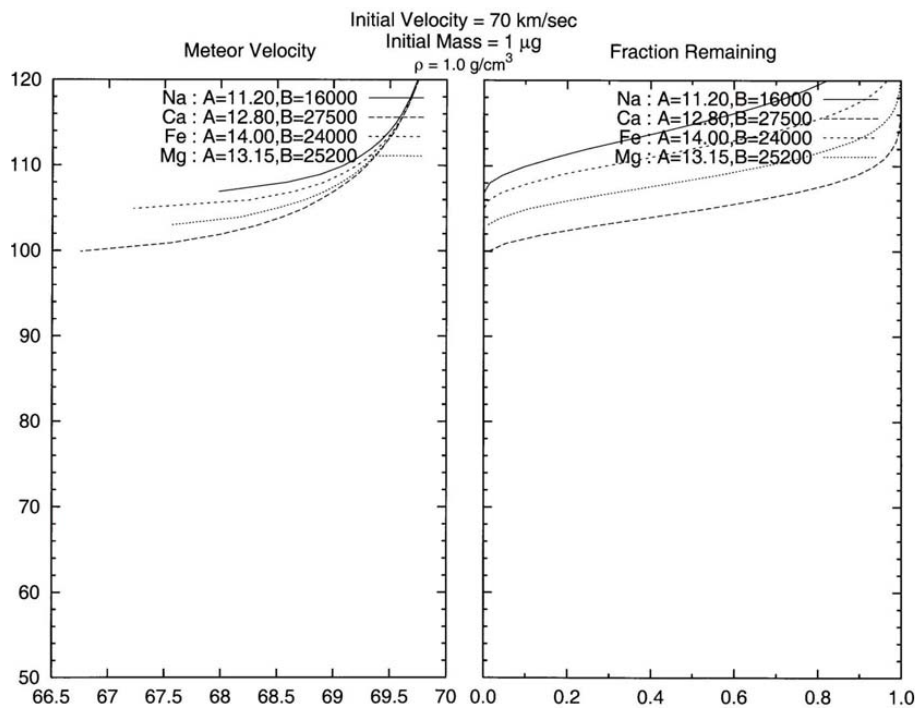
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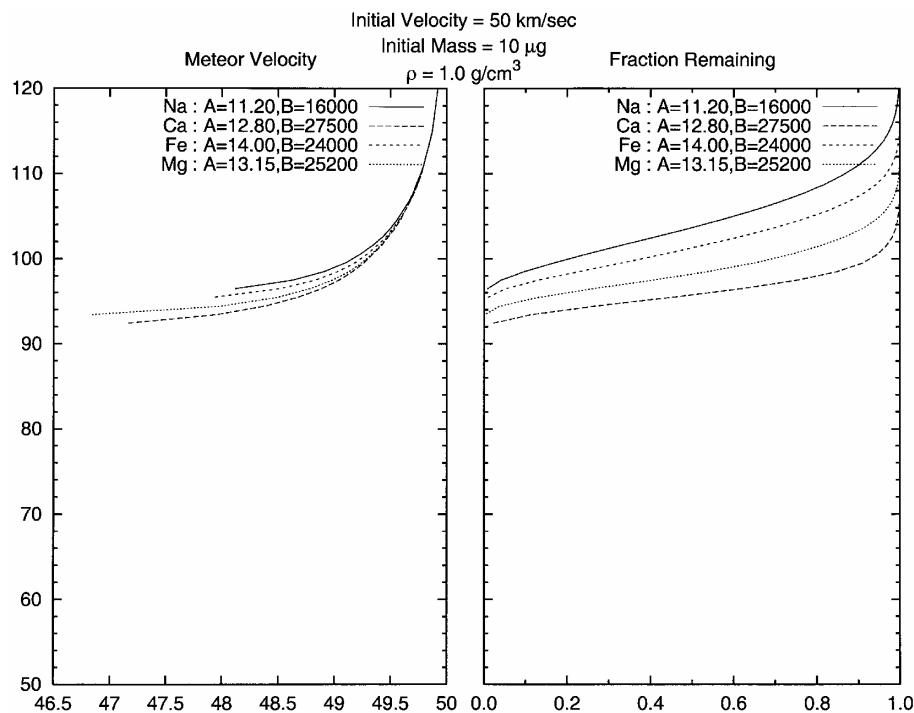
**Fig. 4.** The ablation of a 1  $\mu\text{g}$  particle entering the atmosphere at 70 km/s.

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**Fig. 5.** The ablation of a 10  $\mu\text{g}$  particle entering the atmosphere at 50 km/s.

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