

REPORT DOCUMENTATION PAGEForm Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. **PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.**

1. REPORT DATE (DD-MM-YYYY)
 11-05-2004

REPRINT

4. TITLE AND SUBTITLE
 Evaporation of High Speed Sporadic Meteors
5a. CONTRACT NUMBER**5b. GRANT NUMBER****5c. PROGRAM ELEMENT NUMBER**
6. AUTHOR(S)
 E. Murad and C. Roth*

5d. PROJECT NUMBER
 5021

5e. TASK NUMBER
 RS

5f. WORK UNIT NUMBER
 A1

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
 Air Force Research Laboratory/VSBX
 29 Randolph Road
 Hanscom AFB MA 01731-3010

8. PERFORMING ORGANIZATION REPORT NUMBER

20040518 081

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
11. SPONSOR/MONITOR'S REPORT NUMBER(S)

AFRL-VS-HA-TR-2004-1072

12. DISTRIBUTION / AVAILABILITY STATEMENT
 Approved for Public Release; Distribution Unlimited.

*RADEX, Inc., Bedford, MA

13. SUPPLEMENTARY NOTES
 REPRINTED FROM: ATMOSPHERIC CHEMISTRY AND PHYSICS, Vol 4, pp 1-4, 2004
[www.atmos-chem-phys.org/acp/4/1/SRef-ID 1680-7324/acp/2004-4-1](http://www.atmos-chem-phys.org/acp/4/1/SRef-ID%201680-7324/acp/2004-4-1)
14. 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 ~20 km/s and ~50 km/s). The particles have a maximum mass of ~1 µg. This paper will present an analysis of the ablation of 1 µg 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 µg 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.

15. SUBJECT TERMS
 Meteors Meteoroids Evaporation Chemical Model
16. SECURITY CLASSIFICATION OF:
a. REPORT
 UNCLAS

UNCLAS

c. THIS PAGE
 UNCLAS

17. LIMITATION OF ABSTRACT
 SAR

18. NUMBER OF PAGES
 4

19a. NAME OF RESPONSIBLE PERSON
 Edmond Murad

19b. TELEPHONE NUMBER (include area code)
 781-377-3176

Evaporation of high speed sporadic meteors

E. Murad¹ and C. Roth²

¹Air Force Research Laboratory, Space Vehicles Directorate, Hanscom AFB, MA 01731, USA

²Radex, Inc., 3 Preston Court, Bedford, MA 01730, USA

Received: 22 September 2003 – Published in Atmos. Chem. Phys. Discuss.: 18 December 2003

Revised: 23 April 2004 – Accepted: 23 April 2004 – Published:

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 ~ 20 km/s and ~ 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 (≥ 50 km/s), very light ($1 \mu\text{g}$) meteoroids (Janches et al., 2000, 2001; Mathews et al., 2001, 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, 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, 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 nec-

essary for meteoroids of radius < 1 mm; in other words for such meteoroids the temperature is uniform, and, presumably, a thermal equilibrium 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 point 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 of 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).

1.1 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

Correspondence to: E. Murad
(ed.murad@hanscom.af.mil)

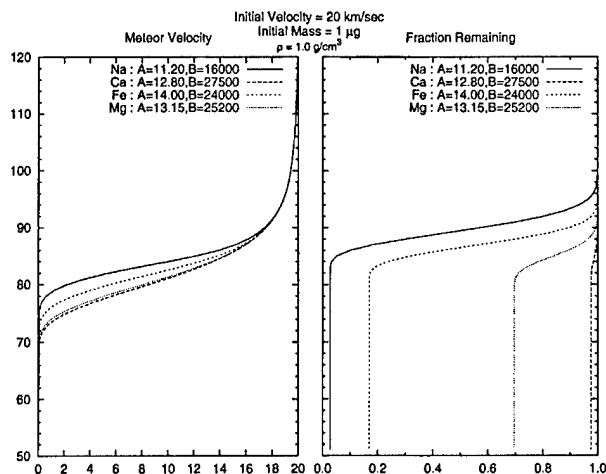


Fig. 1. The ablation of a $1 \mu\text{g}$ particle entering the atmosphere at 20 km/s.

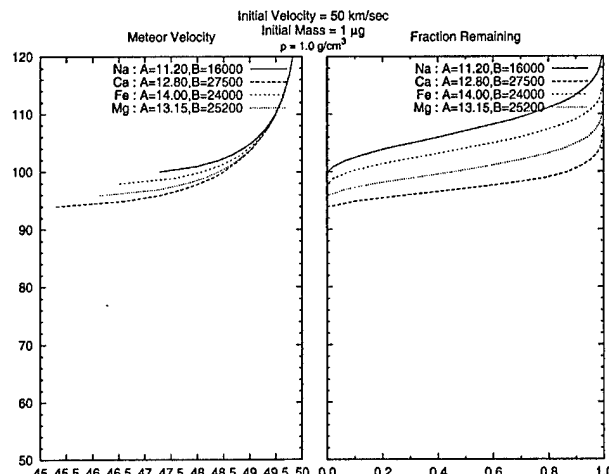


Fig. 3. The ablation of a $1 \mu\text{g}$ particle entering the atmosphere at 50 km/s.

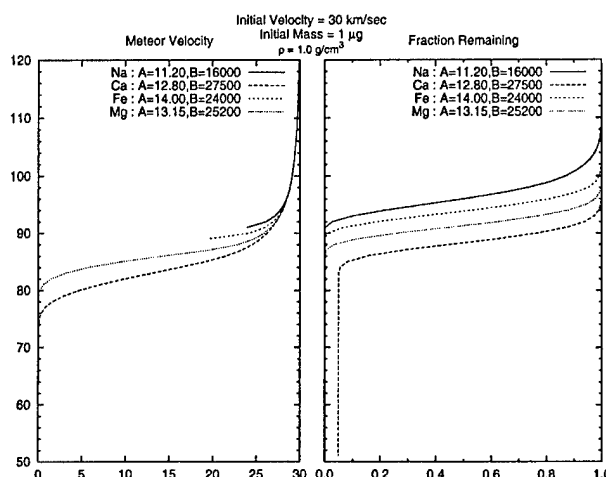


Fig. 2. The ablation of a $1 \mu\text{g}$ particle entering the atmosphere at 30 km/s.

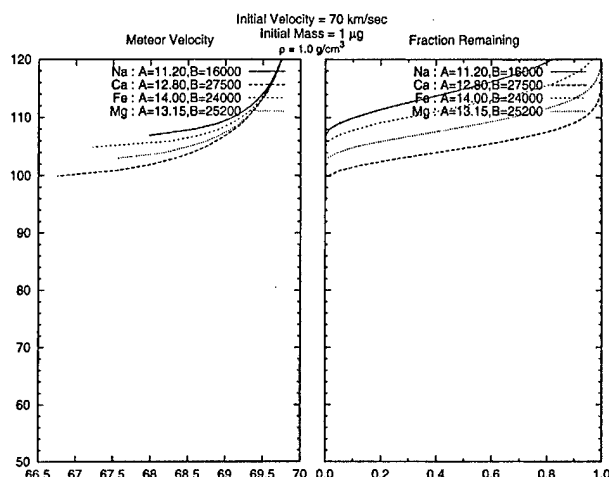


Fig. 4. The ablation of a $1 \mu\text{g}$ particle entering the atmosphere at 70 km/s.

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 of the form $\ln P_{eq} = A - B/T$. 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 ≥ 50 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 ≥ 120 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

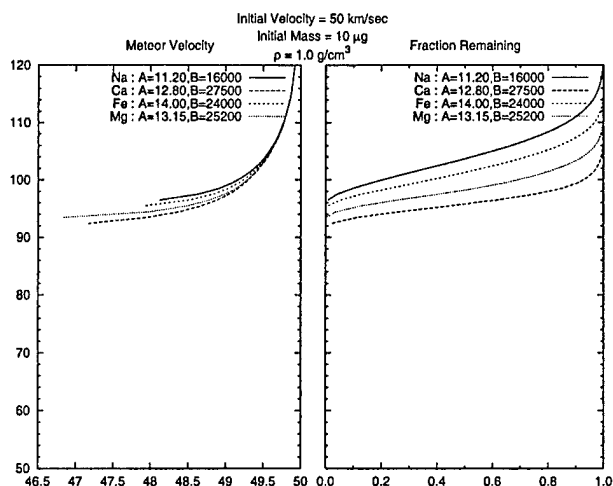
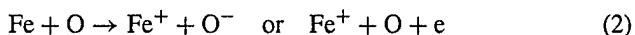
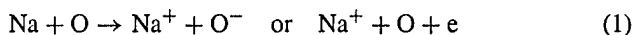


Fig. 5. The ablation of a $10 \mu\text{g}$ particle entering the atmosphere at 50 km/s.

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 $\sim 10^{-15} \text{ cm}^2$. There is no estimate for the cross section of reaction (2). However, the reaction of Fe with O_2 to give ionic products (undetermined) is $\sim 10^{-16} \text{ cm}^2$ (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 Fe^+ and 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 $\sim 0.1 \text{ ms}$.

The implication of the above discussion is that for 1 and $10 \mu\text{g}$ meteoroids the beginning height would be at $\sim 120 \text{ km}$ and the end height would be at $\sim 90 \text{ km}$, in agreement with the observations (Janches et al., 2000, 2001; Mathews et al., 2001, 1997).

2 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 U.S. Air Force contract F19628-98-C-0054. We also thank the reviewer for helpful comments.

Edited by: J. Plane

References

- Alexander, C. M. O. D.: Exploration of the quantitative kinetic models for the evaporation of silicate melts in vacuum and in hydrogen, *Meteoritics Planet. Sci.*, 36, 255–283, 2001.
- Bukhteev, A. M. and Bydin, Y. F.: Loss of electrons by fast Ca, Mg, Si and Fe atoms in encounters with N_2 and O_2 , *Bull. Acad. Sci. USSR, Phys. Ser.*, 27, 985, 1963.
- Bukhteev, A. M., Bydin, Y. F., and Dukel'skii, V. M.: *Soviet Phys.-Tech. Phys.*, 6, 496, 1961.
- Chase Jr., M. W.: NIST-JANAF Thermochemical Tables, in *J. Physical Chemical Ref. Data*, American Institute of Physics, Woodbury, NY, 1998. **Please give the page numbers.**
- Dressler, R. A. and Murad, E.: The gas phase chemical dynamics associated with meteors, in *Chemical Dynamics in Extreme Environments*, edited by Dressler, R. A., World Scientific, Singapore, 268–348, 2001.
- Fegley, J. B. and Cameron, A. G. W.: A vaporization model for iron/silicate fractionation in the Mercury protoplanet, *Earth Planet. Sci. Lett.*, 82, 207–222, 1987.
- Flynn, G. J.: Atmospheric entry heating of micrometeorites, in 19th Lunar and Planetary Science Conference, Lunar and Planetary Institute, Houston, TX, 673–682, 1989.
- Friichtenicht, J. F., Slattery, J. C., and Hansen, D. O.: Ionization from Fe atoms incident on various gas targets, *Phys. Rev.*, 163, 1, 75–80, 1967.
- Grebowsky, J. and Aikin, A. C.: In situ measurements of meteoric ions, in *Meteors in the Earth's Atmosphere*, edited by Murad, E. and Williams, I. P., Cambridge University Press, Cambridge, UK, 2002. **Please give the page numbers.**
- Hawkes, R. L. and Jones, J.: A quantitative model for the ablation of dustball meteors, *Mon. Not. R. Astr. Soc.*, 173, 339–356, 1975.
- Janches, D., Mathews, J. D., Meisel, D. D., and Zhou, Q.: Micrometeor Observations using the Arecibo 430 MHz Radar: I. Determination of the Ballistic Parameters from Measured Doppler Velocity and Deceleration Results, *Icarus*, 145, 53–63, 2000.
- Janches, D., Meisel, D. D., and Mathews, J. D.: Orbital properties of the Arecibo micrometeoroids at Earth interception, *Icarus*, 150, 206–218, 2001.
- Janches, D., Pellinen-Wannberg, A., Wannberg, G., Westman, A., Hägerström, I., and Meisel, D. D.: Tristatic observations of meteors using the 930 MHz EISCAT radar system, *J. Geophys. Res.*, 107, (11A), SIA 14-1–14-14, 2002.
- Jones, J. and Kaiser, T. R.: The effects of thermal radiation, conduction and meteoroid heat capacity on meteoric ablation, *Mon. Not. R. Astron. Soc.*, 133, 411–420, 1966.
- Love, S. G. and Brownlee, D. E.: Heating and thermal transformation of micrometeoroids entering the Earth's atmosphere, *Icarus*, 89, 26–43, 1991.
- Love, S. G. and Brownlee, D. E.: Peak atmospheric entry temperatures of micrometeorites, *Meteoritics*, 29, 69–71, 1994.
- Mathews, J. D., Janches, D., Meisel, D. D., and Zhou, Q.-H.: The micrometeoroid mass flux into the upper atmosphere: Arecibo

- results and a comparison with prior estimates, *Geophys. Res. Lett.*, 28, 10, 1929–1932, 2001.
- Mathews, J. D., Meisel, D. D., Hunter, K. P., Getman, V. S., and Zhou, Q.: Very high resolution studies of micrometeors using the Arecibo 430 MHz radar, *Icarus*, 126, 157–169, 1997.
- McNeil, W. J., Dressler, R. A., and Murad, E.: Impact of a major meteor storm on Earth's ionosphere: A modeling study, *J. Geophys. Res.*, 106, (A6), 10 447–10 465, 2001.
- McNeil, W. J., Lai, S. T., and Murad, E.: Differential ablation of cosmic dust and implications for the relative abundances of atmospheric metals, *J. Geophys. Res.-D.*, 103, 10 899–10 911, 1998.
- McNeil, W. J., Murad, E., and Plane, J. M. C.: Models of meteoric metals in the atmosphere, in *Meteors in the Earth's Atmosphere*, edited by Murad, E. and Williams, I. P., Cambridge University Press, Cambridge, UK, 265–287, 2002.
- Öpik, E. J.: *Physics of Meteor Flight in the Atmosphere*, Interscience Publishers, New York, 174, 1958.
- von Zahn, U., Höffner, J., and McNeil, W. J.: Meteor trails as observed by lidar, in *Meteors in the Earth's Atmosphere*, edited by Murad, E. and Williams, I. P., Cambridge University Press, Cambridge, UK, 2002. **Please give the page numbers.**
- Whipple, F.L.: Meteors and the Earth's upper atmosphere, *Rev. Mod. Phys.*, 15, 246–264, 1943.