A Crucial Space Weather Effect: Meteors and Meteoroids

Lars Dyrud, **Sigrid Close, Diego Janches, Meers Oppenheim, John Plane, John Mathews, Julio Urbina, Mihaly Horanyi, Jorge Chau, Jonathan Fentzke, Mike Sulzer, Sixto A. González, Shikha Raizada**

Introduction

Every day billions of meteoroids impact and disintegrate in the Earth's atmosphere. Current estimates for this global meteor flux vary from 20,000-300,000 tons per year and estimates for the average velocity range between 14 km/s to 55 km/s, depending on sizes, masses and composition distributions. These particles arrive both during intense showers and as a nearly constant rain of sporadic meteors. Understanding the interplanetary meteoroid environment is important for several fields of study from solar system evolution, upper atmospheric physics, planetary atmospheres and ionospheres, planetary geology, and most critically to accurately asses the risk that these particles present to manned and unmanned space flight. Yet, the basic properties of this global meteor flux, such as the particle mass and velocity distributions and their chemical composition remain poorly constrained. It is known that at least four satellites have been severely damaged by meteoroids and one was destroyed during a meteor shower in the last 20 years; the shuttle's windows have been hit by over 20 meteoroids with enough energy to require replacement; and the Hubble telescope has received more than 5000 meteoroid impacts. A more accurate picture of the distribution of particle orbits and masses would help not only spacecraft designers but also scientists who model the outer solar system and its evolution based on the material observed near Earth, Earth and planetary atmospheric scientists and heliosphere scientists.

The largest uncertainties surround the most frequent meteors, mostly small (sand grain and dust size) sporadic meteors. We believe much of the mystery surrounding the basic parameters of the interplanetary meteor flux exists for the following reasons: the barely understood sampling characteristics of the different meteor observation techniques, and the scarcity of ground and spaced based measurements of meteors and interplanetary dust, which are used to derive or constrain most models.

Meteor physics is important to a broad range of disciplines. Meteors affect upper atmospheric and ionospheric physics and chemistry because meteoric material seeds the upper atmosphere with metallic atoms, ions, and dust [*McNeil et al*., 2002, Plane, 2003]. These particles affect conductivities, create metal layers near 100 km altitude, and provide the condensation nuclei for noctilucent clouds [von Zahn, 2002]. Klekociuk et al. [2005], and subsequent press releases have recently suggested that meteoritic dust effects cloud formation and may influence weather, and large dust clouds from bollide explosion may initiate abrupt climate change. Meteor radars have been used for decades to monitor winds in the mesopause and lower thermosphere [*Chang et al.,* 1999] and more recent attempts have been made to monitor temperatures [*Tsutsumi*, 1994]. This information is crucial for the understanding of the effects of global stratospheric warming in the MLT region and also acts as coupling between different regions of the atmosphere. Characterizing the high-speed meteoroid population is essential to understanding the current distribution of mass in the solar system and, by inference, its evolution and origin. The highest-speed meteors generally arrive from outside the solar system and characterizing this intergalactic population is of interest to astronomers [Meisel et al., 2002]. Meteor burst communication relies on the reflectivity of meteor trails, bouncing high bandwidth radio signals off them.

Observing Micro-meteoroids

For decades, meteor observations were typically made with photographic and TV cameras and specular meteor radars. Specular radars only detect reflection from the trails of ionization formed *perpendicular* to the radar beam [*Ceplecha et al.*, 1998]. The resulting meteor parameters deduced from these radar observations are sensitive to this condition.

The last decade has seen a resurgence in US meteor research largely due to the increased attention from the Leonid Meteor Shower of 1998, which prompted numerous, large, military and civilian atmospheric radars to train in on the storm radiant. As a result, two new types of radar meteor reflections have become known and increasingly used. These reflections are known as meteor head echoes and non-specular trails and are largely observed and studied with high power and large aperture (HPLA) radars designed for incoherent scattering sensing of the ionosphere, and example of which is shown in Figure 1 . Because these observations produce such detailed spectral signatures, they have stimulated intense study, they last few years of which has focused on using these observations for deriving more complex parameters about meteoroids and the atmosphere they interact with [*Dyrud et al.*, 2005; *Zhou et al.*, 2001, *Malhotra* et al., 2007,*Close et al.*, 2002; *Janches et al.*, 2000, 2009; *Mathews et al.*, 2001, Janches et al. 2008, *Chau and Galindo, 2008, Dyrud et al. 2008, Oppenheim et al.* 2003a,b, 2009]. These observations have also shown that these small dust and sand grain sized micrometeoroids are considerably more numerous than previously measured, and are in largely retrograde orbits, unlike their larger sized counterparts. Additionally, it is becoming clear that observing radar meteors at two or more frequencies in common volume yields much more information on the details—e.g., meteoroid fragmentation [Mathews et al., 2010].

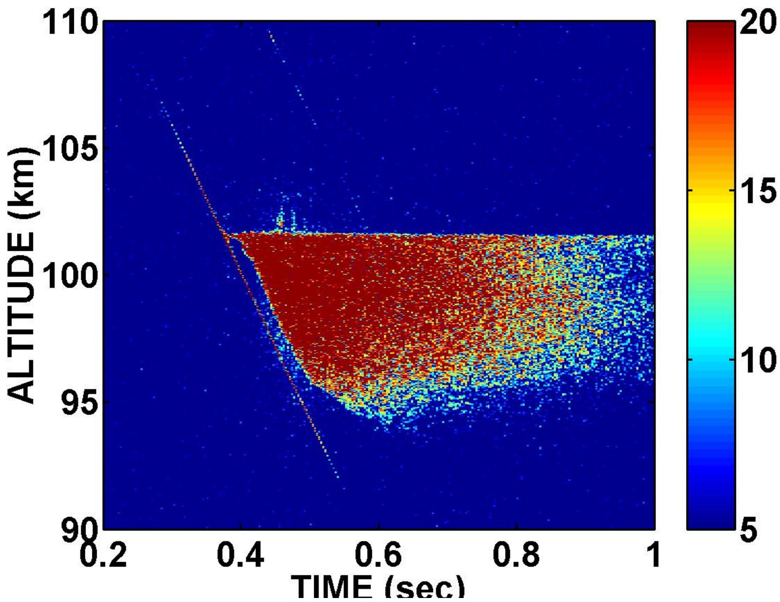

Figure 1 Altitude-time-intensity image of a head and subsequent non-specular echoes over extended range from ALTAIR VHF Radar. The diagonal line to the left is called a head echo, while the echoes spread in range and time to the right are the non-specular trail. Figure reproduced from [Close et al. (2002]

Another driving force behind the resurgence in meteor research is the growing understanding of the impacts of meteoroids in planetary atmospheres. Starting with the Earth, meteoric ablation is the source of the global layers of metals atoms such as iron and sodium around 90 km altitude [*Plane*, 2003]. Metallic ions are the major constituents of sporadic E layers, which have important effects on radio communications. The metallic vapors also recondense to form nanometer size "smoke" particles, which provide condensation nuclei for noctilucent H_2O-ice clouds. Smoke also removes acidic gases and affects the formation of aerosols in the lower stratosphere, which impact on the ozone layer. The meteoroid flux probably explains the following recent observations in the atmospheres of other solar system bodies: sporadic layers on Mars and Venus; "noctilucent" CO_2-ice clouds around 80 km on Mars; and the detached haze layer on Titan around 500 km. We have just recently begun to understand the direct connection between the variability of the meteor flux with that of mesospheric layered phenomena [Gardner et al., 2010].

Recent work has demonstrated the importance of meteoric dust interaction with the solar wind flow [Mann et al., 2010]. Small nanometer scale particles are polarized and charged and interact with the solar wind and interplanetary medium, yet there is little modeling that exists on the overall influence both dust has on the solar wind, and the role that solar wind plays in the dust distribution.

Meteors as Space Weather-Space Craft Hazard

Although much emphasis has been placed on the space debris problem, which clearly dominates in low-Earth orbit (LEO), the meteoroid population travels at least twice the speed of debris and typically is a factor of 10 faster. In middle-Earth orbit (MEO) and geosynchronous-Earth orbit (GEO), the meteoroid and debris populations are at least comparable if not dominated by meteoroids. To determine an approximate satellite impact rate, we can extrapolate flux measurements from ground-based radar. For example, the ALTAIR radar detects meteors formed by meteoroids with masses greater than 1 μg. A typical measured sporadic peak meteoroid flux (~6 AM local time) is 192 meteoroids/km^2/hr for particles greater than 1 μg. This detection rate, however, is highly dependent on the altitude of ablation and does not include small meteoroids that do not heat up enough to form meteors. If we instead look at the impact rate on LDEF, we find that microgram-sized particles impact at a rate of 360 meteoroids/km^2/hr. Since the number of particles decreases (conservatively) as $1/m^2$ (where m is meteoroid mass), particles weighing 1 ng will impact a 1 m^2 spacecraft at least once per day. Furthermore, since meteoroids travel fast enough to ionize upon impact, they pose a risk of causing damage to satellites through electrical effects that depend more strongly on velocity than on mass.

The most common type of satellite damage is "mechanical," which describes the penetration through the outer layer of a spacecraft. The electrical effects associated with an impacting meteoroid include electrostatic discharges (ESDs) and electromagnetic pulses (EMPs). An ESD occurs when there is a sudden discharge of accumulated electric charge on a satellite. This is usually caused when a satellite has a large buildup of charge that exceeds a voltage breakdown limit. ESDs are believed to occur frequently on spacecraft and are attributed to imbalances of surface currents in the space plasma charging process. In comparison, EMPs occur from the direct vaporization of an impacting meteoroid due to either radiation or charge transport mechanisms (Fig. 1). Although the link between meteoroid-induced EMP and satellite failure is not understood, the plasma production associated with a hypervelocity (i.e. meteoroid) impact has been studied for over 30 years using ground-based experiments. It is believed that both the meteoroid as well as a fraction of the target is vaporized and ionized, forming a plasma cloud instantaneously. This plasma cloud then expands into the surrounding vacuum with a separated charge caused by the different mobilities of the electrons and ions. The charge separation can cause an initial vehicle potential pulse, followed by plasma oscillations as the particles oscillate at their characteristic frequency. Since an asymmetry exists (such as a hemispherical plasma expanding away from a satellite), there will be an associated radiated power that may interfere with satellite operations or even cause catastrophic damage. Spacecraft lost due to electrical effects associated with meteoroid impact include Olympus in 1993, and SEDS and MSTI in 1994. In addition, the Landsat 5 satellite lost gyro stability during the peak of the Perseid shower in 2009 – similar to the Olympus satellite and suggestive of a meteoroid-induced electrical effect. Some of the spacecraft losses generically attributed to ESD may also be due to meteoroid impacts, since the catalyst for electrical anomalies typically remains undetermined.

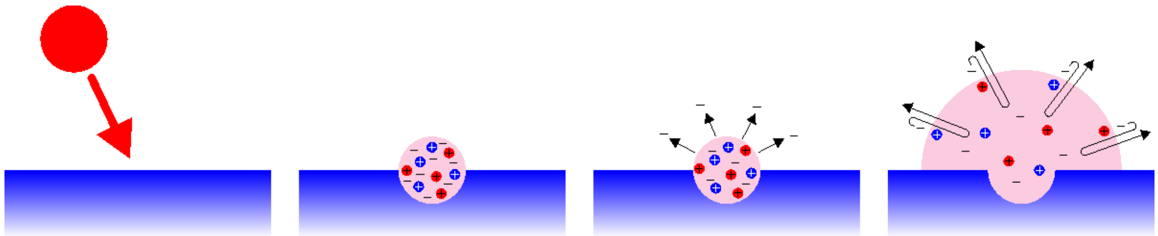

Figure 2. Depiction of plasma expansion process.

Recommendations

Because of the growing need from many within the Heliophysics and operational communities for an improved understanding of the interplanetary meteor and dust populations, we are strongly recommending funding for observations that support and constrain models of these populations. Further recognition of the interdisciplinary nature of this field of study via joint solicitations should also be prioritized in the coming decade.

1. In order to better understand meteor physics and to provide valuable observational constraints to meteoroid flux models, NSF should expand ground based utilities such as radars for observing meteors and meteoroids. This is necessary because each location and local time on Earth will preferentially view different sources of the meteoroid populations. Multi-frequency common-volume radars such as those available at Arecibo Observatory are particularly valuable. It is important to recognize that that while these large radars are typically funded from NSF Geospace Facilities section (formerly Upper Atmospheric Facilities) the value of meteoroid observations extends well beyond and includes planetary science and heliophysics as well.
2. NASA should prioritize space-based methods for observing small meteors, meteoroids, and interplanetary dust in part to establish relationship between ground based observables and properties of interest such as meteoroid and dust composition and density.
3. Relevant agencies should establish cross-cutting solicitations and programs that facilitate the naturally multi-disciplinary nature of scientists with an interest and requirement to understand the dust and particle population and its effects. This will overcome programmatic hurdles that arise when the scientific motivation to understand the meteoroids/dust distribution possesses atmospheric, planetary, heliophysics, and space craft threat motivations.
4. NASA should facilitate and expand cooperation between basic researchers and space flight stake holders for improved characterization of the sporadic meteoroid and dust flux and threat to spacecraft well bellow the oft cited 1 cm particle size.
5. A relevant agency should establish, maintain, and distribute a meteoroid flux model to be used for scientific purposes by both Earth and planetary and heliophysics researchers that is

independent of engineering models, but with shared result to the benefit of improved space-craft threat models.

References

D. W. R. McKinley. Meteor Science and Engineering, pages 1–309. McGraw Hill, New York, 1961.

V. Bronshten. Physics of meteoric phenomena. d. Reidel Publishing Co., 1983.

Z. Ceplecha, J. Borovicˇka, W. Elford, D. Revelle, R. Hawkes, V. Porubcˇan, and M. Sˇimek. Meteor phenomena and bodies. Space Sci. Rev., 84:327–471, 1998.

Oppenheim, M. M., Y. Dimant, and L. P. Dyrud, Large-scale simulations of 2-D fully kinetic Farley-Buneman turbulence, *Annales Geophysicae*, *26* , 543–553, 2008a.

P. Wiegert, J. Vaubaillon, and M. Campbell-Brown. A dynamical model of the sporadic meteoroid complex. Icarus, 201:295–310, May 2009.

D. Janches, C. J. Heinselman, J. L. Chau, A. Chandran, and R. Woodman. Modeling the global mi- crometeor input function in the upper atmosphere observed by high power and large aperture radars. J. Geophys. Res., 111(A10):7317, jul 2006.

S. Close, M. Oppenheim, S. Hunt, and L. Dyrud. Scattering characteristics of high-resolution meteor head echoes detected at multiple frequencies. J. Geophys. Res., 107(A10):1295, doi:10.1029/2002JA009253, 2002.

L. Dyrud, E. Kudeki, and M. Oppenheim. Modeling long duration meteor trails. Journal of Geophysical Research, 112(A12), 2007

M. M. Oppenheim, L. P. Dyrud, and A. F. vom Endt. Plasma instabilities in meteor trails: 2-D simulation studies. Journal of Geophysical Research (Space Physics), 108:1064–+, 2003.

J. Plane. A new time-resolved model for the mesospheric Na layer: constraints on the meteor input function. Atmos. Chem. Phys., 4:39–69, 2004.

T. Vondrak, J. Plane, S. Broadley, and D. Janches. A chemical model of meteoric ablation. Atmos. Chem. Phys, 8:7015–7031, 2008

J. Jones. Micrometeoroid engineering model-final report. Technical Report SEE/CR-2004-400, NASA, MSFC, June 2004.

Mann, I., A. Czechowski, N. Meyer-Vernet, Dust in the interplanetary medium – interactions with the solar wind, Solar Wind 12, AIP CP 1216, eds. M. Maksimovic, K. Issautier, N. Meyer-Vernet, M. Moncuquet, F. Pantelliniet, 491-496, 2010

M. Rapp, I. Strelnikova, and J. Gumbel. Meteoric smoke particles: Evidence from rocket and radar techniques. Adv. Space Res., 40:809–817, 2007.

J. Gumbel and L. Megner. Charged meteoric smoke as ice nuclei in the mesosphere: Part 1-A review of basic concepts. J. Atmos. Sol. Terr. Phys., 71:1225–1235, Aug. 2009.

D. M. Hunten, R. P. Turco, and O. B. Toon. Smoke and dust particles of meteoric origin in the mesosphere and stratosphere. J. Atmos. Sci., 37:1342–1357, 1980.

S. Love and D. E. Brownlee. A direct measurement of the terrestrial mass accretion rate of cosmic dust. Science, 262:550–553, October 1993.

Z. Y. Fan, J. M. C. Plane, and J. Gumbel. On the global distribution of sporadic sodium layers. Geophys. Res. Lett., 34:15808–+, 2007.

J. Gumbel, Z. Y. Fan, T. Waldemarsson, J. Stegman, G. Witt, E. J. Llewellyn, C. She, and J. M. C. Plane. Retrieval of global mesospheric sodium densities from the Odin satellite. Geophys. Res. Lett., 34:4813–+, 2007.

M. Pätzold, S. Tellmann, B. H □ausler, D. Hinson, R. Schaa, and G. L. Tyler. A Sporadic Third Layer in the Ionosphere of Mars. Science, 310:837–839, Nov. 2005.

P. G. Brown, R. W. Whitaker, D. O. ReVelle, and E. Tagliaferri. Multi-station infrasonic observations of two large bolides: signal interpretation and implications for monitoring of atmospheric explosions. Geophys. Res. Lett., 29(13):130000–1, 2002.

B. W. Grime, T. J. Kane, S. C. Collins, M. C. Kelley, C. A. Kruschwitz, J. S. Friedman, and C. A. Tepley. Meteor trail advection and dispersion; preliminary lidar observations. Geophys. Res. Lett., 26:675–678, mar 1999.

Tsutsumi, M., Tsuda, T. and Nakamura, T., 1994. Temperature fluctuations near the mesopause inferred from meteor observations with the middle and upper atmosphere radar. *Radio Science* **29**, pp. 599–610.

U. von Zahn, J. H □offner, and W. J. McNeil. Meteor trails as observed by lidar. In E. Murad and I. P. Williams, editors, Meteors in the Earth’s Atmosphere, pages 149–187. Cambridge University Press, 2002.