Simulating meteor showers in the Martian atmosphere

Jonathan P. McAuliffe,

Armagh Observatory, College Hill, Armagh, BT61 9DG, Northern Ireland. E-mail jma@arm.ac.uk

Apostolos A. Christou

In an attempt to begin to quantify the Martian meteor year, we have simulated meteor shower detection in the Martian and terrestrial atmospheres. Assuming a meteoroid stream flux, size distribution and velocity based on current knowledge of Earth streams as well as the proximity of certain comets' orbits to that of Mars, we numerically integrate meteoroid ablation in model Martian and terrestrial atmospheres. Using the same baseline detector characteristics (limiting magnitude, sky coverage) we have generated detection statistics for the two planets. We present results for four showers, including strong annual activity and velocity extremes from Halley-type comets at both planets. We show that for high speed showers similar detection rates can be expected at both planets but for showers with low approach velocities very low mass indices would be required to produce detection rates greater than 10 per hour at Mars. Finally we will comment on what these findings mean in terms of monitoring the Martian atmosphere for meteor activity.

1 Introduction

For over a century, science has sought to explain meteoric phenomena in the Earth's atmosphere. As early as the mid 19^{th} century the work of Schiaparelli and Kleiber began to extricate *shooting stars* from the superstitions and mythology that had previously surrounded them. Throughout the 20^{th} century much work was done on explaining the physical and dynamical properties of meteors, the meteoroids that produce them and the meteorites that they sometimes leave behind. With the advent of space exploration, however, the possibility of extending our knowledge of the Solar System's dust-complex presented itself and science began to look at the feasibility of detecting meteor phenomena in the atmospheres of other planets. Mars, in particular, appeared as the most likely candidate in whose atmosphere meteors could be detected, due to the fact that its atmosphere is thick and relatively stable, it has a solid surface, is close by, and is the focus of an ever growing number of spacecraft missions.

Over the past ten years, among the works that have looked at using the Martian atmosphere as a meteor detector, are studies of how the brightness of sporadic background meteors would differ between the Earth and Mars (Adolfsson et al., 1996). Christou and Beurle (1999) determined which minor bodies (comets and asteroids) could potentially produce recurrent showers or even storms on Mars due to the close approach of the two objects' orbits. While Ma et al. (2002) looked at the velocity distribution of periodic comets at Mars, in light of the fact that the brightness and therefore the detectability of a meteor is highly dependent on its entry velocity (Bronshten, 1983).

Although single meteors have already been detected at Mars (Selsis et al., 2005), the characterization of the Martian meteor year will require a large number of detections. Experience on Earth suggests that data storage and bandwidth resources to conduct such surveys will be substantial, and perhaps even prohibitive — novel image storage and transfer techniques will be needed.

2 Statistical shower simulator

To begin to quantify meteor shower observability at Mars we have developed a shower simulator in order to compare shower phenomena at Mars and the Earth. We have generated statistical distributions of

IMO bibcode IMC-2005-mcauliffe-martiansimulation

initial mass, arrival times and atmospheric interface position based on current knowledge of streams at the Earth and adopted entry velocities corresponding to the approach velocities of certain comets' orbits to that of Mars (Christou, 2005).

Arrivals of individual meteoroids are assumed to be random, and should therefore follow Poisson's distribution. Consequently their arrival times will be exponentially distributed. The cumulative distribution function of an exponential distribution is given by

$$D(r;\lambda) = \begin{cases} 1 - e^{-\lambda x}, & r \geq 0; \\ 0, & r < 0, \end{cases} \tag{1}$$

where r is a random variable and λ, often called the rate parameter, is the product of the meteoroid flux F_M and the projected interface area at the top of the atmosphere $A\cos\Theta_z$. Here Θ_z is the zenith entry angle. Inverting equation 1 we have a means to generate a distribution of arrival time differences Δt_i, in terms of a predefined rate parameter λ, and computer generated random variable r_i.

$$\Delta t_i = -\frac{\ln(1 - r_i)}{\lambda}\ , \qquad 0 < r_i < 1. \tag{2}$$

In our simulations the entry zenith angle used in determining λ is set to 45° and the interface area at the top of the atmosphere depends on the field of view of our simulated camera. The flux of meteoroids entering this interface area is calculated according to

$$F_M = kM^{-\alpha}, \tag{3}$$

where k and α are shower dependent constants as in McDonnell et al. (2001). While the arrival times of individual meteors follow Poisson's distribution, the arrival locations at the top of the atmosphere are uniformly distributed over the interface area, such that

$$x_i,\ y_i = d_{\alpha,h}\left(r_{i_{x,y}} - 0.5\right) \tag{4}$$

where x_i and y_i are the coordinates of the i$^{\text{th}}$ meteoroid with respect to an arbitrary origin centered on our camera. The $r_{i_{x,y}}$ in equation 4 represent two different random variables while $d_{\alpha,h}$ (a function of camera angle α, and height h), is the diameter of a circular interface area (see Figure 1).

The third statistical set of initial values generated were those for the masses of the incident meteoroids. Meteoroid masses are found to follow power law distributions of the form shown in equation 3 (Jenniskens, 1994). In the case of equation 3 F_M represents the flux of meteoroids with masses equal to or greater than M. Therefore if M_0 and M_i are two masses such that $M_0 < M_i$ the flux of meteoroids with masses between these two limits is given by

$$F_{(M_0,M_i)} = F_{M_0} - F_{M_i} = kM_0^{-\alpha} - kM_i^{-\alpha}. \tag{5}$$

Dividing equation 5 by F_{M_0} we obtain a value r_i, between zero and one that defines the probability of a particular meteoroid (belonging to a distribution with parameters k and α) having a mass of M_i.

$$r_i = \frac{kM_0^{-\alpha} - kM_i^{-\alpha}}{kM_0^{-\alpha}} \tag{6}$$

Rearranging equation 6 we get an expression for individual meteoroid masses in terms of the distribution parameter α[1], a random variable r_i, and a lower mass limit M_0.

$$M_i = \left(M_0^{-\alpha}\,(1 - r_i)\right)^{-1/\alpha}. \tag{7}$$

[1] α is also known as the mass index, and is proportional to the magnitude distribution index χ : $\alpha = 2.3\log\chi$; (McDonnell et al., 2001).

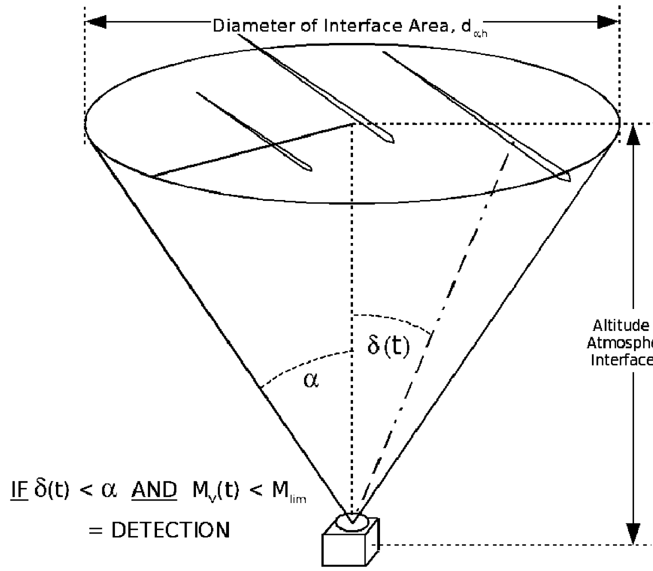

Figure 1 – Simulated detection geometry. If at any time t, the zenithal distance of the meteor $\delta(t) < \alpha$ (the half angle of the detector) **AND** its current apparent magnitude $M_V(t) < M_{\rm lim}$ (the camera's limiting magnitude), a detection is recorded.

Using equations 2, 4 and 7 we generate lists of arrival times, interface positions and initial masses for simulated observing periods of 1 hour. For showers linked to Halley-type parent bodies these 1 hour lists contain in the order of 25 000 meteoroids. The ablation of each member of such a list is then numerically integrated using M.A.S.S. (McAuliffe & Christou, 2005) — our in-house meteor ablation simulation software, running on 15 nodes of the Armagh Observatory's 3.0 GHz 64 bit *Beehive* cluster.

Typically, such a simulation takes about 10 hours. For each meteoroid integrated if at any time t, the zenithal distance of the meteor $\delta(t) < \alpha$ (the half angle of the detector), and its current apparent magnitude $M_V(t) < M_{\rm lim}$ (the camera's limiting magnitude), a detection is recorded. A detection results in the creation of a detailed output file containing (as a function of time) height, mass, magnitudes, velocity, acceleration, size, etc. Each output file is continually amended as long as the meteor remains visible to our camera.

3 Annual shower simulations

In this work we have simulated four annual showers associated with Halley-type parent bodies. On Earth, August's Perseids are one of the strongest annual showers with ZHRs regularly reaching 100. The high approach velocity of its parent body 109P/Swift-Tuttle of 60.4 km s^{-1} results in a high ratio of bright to faint meteors. At Mars comet 13P/Olbers approaches the planet to within 0.03 AU (Christou, 2005) at 26.9 km s^{-1}. Such a close approach may produce activity at Mars similar to the terrestrial Perseids. On these grounds we use the mass distribution parameters from McDonnell et al. (2001) for the terrestrial Perseids (109P/Swift-Tuttle) for what would be the β Canis Majorids (13P/Olbers) at Mars (see Table 1) to compare detection rates.

We have also simulated extreme-velocity showers for both the Earth and Mars. On Earth the maximum velocity at which an object bound to the Sun at 1 AU can enter the atmosphere is $\sim$ 72 km s^{-1}. Fortunately, Nature provides us with just such a high velocity shower in the form of November's Leonids associated with comet 55P/Temple-Tuttle. Assigning the mass distribution parameters given for the Leonids in (McDonnell et al., 2001) to a hypothetical extreme-velocity shower at Mars we again look at how detection counts vary between the two planets. The entry velocity upper limit at Mars is 58.5 km s^{-1}.

Planet	Shower	Parent Body	α	k	Velocity
Earth	Perseids	109P/Swift-Tuttle	0.92	1.2×10^{-17}	60.4 km s^{-1}
Mars	β Canis Majorids	13P/Olbers	0.92	1.2×10^{-17}	26.9 km s^{-1}
Earth	Leonids	55P/Temple-Tuttle	1.22	3.4×10^{-20}	71.7 km s^{-1}
Mars	N/A	N/A	1.22	3.4×10^{-20}	58.5 km s^{-1}

Table 1 – Characteristics of four Halley-type cometary showers. The parent body and velocity data are taken from Christou (2005), while the α and k values are as in McDonnell et al. (2001).

Planet	Shower	Parent Body	Velocity	No. Detected	$M_{V,\max}$ Height
Earth	Perseids	Swift-Tuttle	60.4 km s^{-1}	73 (0.25%)	$\sim$ 100 km
Mars	β Canis Majorids	Olbers	26.9 km s^{-1}	8 (0.03%)	$\sim$ 50 km
Earth	Leonids	Temple-Tuttle	71.7 km s^{-1}	29 (0.14%)	$\sim$ 95 km
Mars	N/A	N/A	58.5 km s^{-1}	20 (0.10%)	$\sim$ 40 km

Table 2 – Detection rates for four Halley-type cometary showers. The percentages next to the detected counts are the percentages of incident meteoroids that produced detectable meteors. $M_{V,\max}$ Height is the average height of maximum apparent magnitude for those meteors detected.

The detector characteristics that we have chosen for these simulations are based on those of one of the cameras of the newly installed Armagh Observatory automated meteor monitoring system. These are a limiting apparent magnitude of +2 and a field of view of $60° = 2\alpha$ (see Figure 1). The pointing direction of the camera was toward the zenith.

4 Detection comparison

Martian meteors reach maximum ablation and therefore maximum brightness at lower altitudes than would similar objects in the Earth's atmosphere (Adolfsson et al., 1996). In the case of ground based observations, lower altitudes mean, for the most part, smaller detector–meteor distances. So it may be reasoned that the inherent lower entry velocities of Martian meteoroids may be compensated for by the fact that the resulting fainter meteors reach maximum magnitude closer to the detector. Table 2 shows this to be true for extreme-velocity meteors as we see similar counts and detection percentages for Leonid-type meteors at both planets.

The smaller the value of the mass index α, the higher the ratio of large-to-small initial masses. However the relatively low mass index for our hypothetical β Canis Majorids does not provide enough large particles to compensate for their low entry velocity and this is reflected in their low detection rate. We would expect such showers on Mars to be far less active than the Perseids on the Earth. If low speed is indeed the culprit for the fewer detections of Olberids, we would expect comet 1P/Halley (54 km s^{-1} at Mars) to be a more prolific source of meteors on Mars. This comet also makes close approaches to the Earth (May's Eta Aquarids & October's Orionids) as well as to Venus (Christou, 2004) — a potential yardstick for shower-parent body calibration. The potential of 1P/Halley to produce detectable meteor activity on Mars will be the focus of future work.

As these estimates are for a camera with a limiting magnitude of +2 and field of view of 60° we suggest that a camera such as the Mars Exploration Rovers' PANCAM, with a field of view of $16° \times 16°$ and a limiting stellar magnitude of +5 (Lemmon, 2005) should at least be capable of similar detection rates under clear sky conditions and appropriate proximity to the radiant. A conservative conversion of a stellar magnitude of +5 to a meteor magnitude would give about +2. A camera similar to the Rovers' NAVCAM, which has a larger field of view of $45° \times 45°$ but a brighter limiting stellar magnitude of -1 (meteor magnitude ~ -4), would be suitable for detecting meteors resulting from larger faster particles. Meteoroids of $\sim 1.4 \times 10^{-3}$ kg entering at 40 km s^{-1} would produce meteors of about -4 at Mars, with this initial mass requirement decreasing to $\sim 2 \times 10^{-4}$ kg for an initial velocity of 58 km s^{-1}.

5 Summary

We have developed a meteor shower simulator in order to estimate likely detection rates at Mars based on current knowledge of the terrestrial meteor calendar. We simulated four Halley-type showers, the Perseids on Earth and the β Canis Majorids potentially produced by the close approaching 13P/Olbers at Mars; the Leonids at the Earth and a hypothetical extreme-velocity shower at Mars. For a camera field of view of 60° and a limiting magnitude of +2, high velocity meteor showers such as the Leonids should produce detection rates of ∼20–30 per hour at both planets, even with a relatively high mass index. However, as perhaps should be expected, a low velocity shower such as the β Canis Majorids would require a very low mass index (i.e., a high large-to-small initial mass ratio) to produce counts of more than 10 per hour.

As instruments currently on the surface of Mars have already detected meteor activity (Selsis et al., 2005) a more active campaign to quantify the Martian meteor year is not beyond the capabilities of today's detector technology. Future missions to Mars should consider the inclusion of wide-angle detectors with faint limiting magnitudes to study atmospheric phenomena including meteors (Koschny et al., 2004).

6 Acknowledgments

The authors thank Mark Lemmon for specifics regarding the Mars Exploration Rovers' cameras. Astronomical research at Armagh Observatory is funded by The Northern Ireland Dept. of Culture, Arts and Leisure. The Armagh Observatory's *Beehive* cluster is funded by a PRTLI research grant for Grid-enabled Computational Physics of Natural Phenomena (Cosmogrid).

References

Adolfsson L. G., Gustafson B. A. S., and Murray C. D. (1996). "The Martian atmosphere as a meteoroid detector". *Icarus*, **119**, 144–152.

Bronshten V. A. (1983). *Physics of meteoric phenomena.* (Fizika meteornykh iavlenii, Moscow, Izdatel'stvo Nauka, 1981) Dordrecht, D. Reidel Publishing Co., 372 pages. Translation.

Christou A. A. (2004). "Prospects for meteor shower activity in the Venusian atmosphere". *Icarus*, **168**, 23–33.

Christou A. A. (2005). "Predicting Martian and Venusian meteor shower activity". *Earth, Moon and Planets.* In Press.

Christou A. A. and Beurle K. (1999). "Meteoroid streams at Mars: possibilities and implications". *Planetary and Space Science*, **47**, 1475–1485.

Jenniskens P. (1994). "Meteor stream activity I. The annual streams". *Astron. Astrophys.*, **287**, 990–1013.

Koschny D., di Martino M., and Oberst J. (2004). "Meteor observation from space – The Smart Panoramical Optical Sensor (SPOSH)". In *Proceedings of the IMC 2003, Bollmannsruh, Germany*, pages 64–69. International Meteor Organization.

Lemmon M. (2005). Private communication.

Ma Y., Williams I. P., Ip W. H., and Chen W. (2002). "The velocity distribution of periodic comets and the meteor shower on Mars". *Astron. Astrophys.*, **394**, 311–316.

McAuliffe J. P. and Christou A. A. (2005). "Modelling meteor ablation in the Venusian atmosphere". *Icarus.* In Press.

McDonnell T., McBride N., Green S. F., Ratcliff P. R., Gardner D. J., and Griffiths A. D. (2001). "Near Earth environment". *Interplanetary Dust (Eds: Grün, E., Gustafson, B. Å. S., Dermott, S. F., Fechtig, H.)*, pages 163–231.

Selsis F., Lemmon M. T., Vaubaillon J., and Bell J. F. (2005). "Extraterrestrial meteors – A Martian meteor and its parent comet". *Nature*, **435**, 581–+.

Discussion

Jean-Marc Wislez: *Do you expect a larger number of big meteoroid chunks on Mars, due to the proximity of the asteroid belt?*

Detlef Koschny: There is a consensus that large sporadics may be present due to the proximity of the asteroid belt, however many simulations relate to specific streams.