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The meteoroid environment and impacts on Phobos

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ABSTRACT

We review current knowledge of the flux of meteoroids on Phobos, a key to interpreting its cratering record and understanding the origin of the Martian satellite system. Past observational attempts to estimate the flux of small (mm to cm) meteoroids as meteors in the Martian atmosphere highlight the need for customised instrumentation onboard future missions bound for Mars. The temporal distribution of cometary meteoroid streams as predicted by recent work is non-uniform; we advocate emplacing seismic stations on Phobos or cameras optimised to monitor the Martian atmosphere for meteors as a means to elucidate this and other features of the meteoroid population. We construct a model of the sporadic flux of metre-sized or larger meteoroids and use it to predict a leading/trailing ratio in crater density of ~ 4 if crater production by asteroidal meteoroids dominates over that by cometary ones. It is found that the observed distribution of craters ≥ 100 m as determined from spacecraft images is consistent with a 50/50 contribution from the two meteoroid populations in our model. A need for more complete models of the meteoroid flux is identified. Finally, the prospects for new observational constraints on the meteoroid environment are reviewed.

1. Introduction

As with every other body in the solar system, the Martian system is subject to a continuous influx of meteoroids ranging in size from under a μm to several km. Their effect on the Martian atmosphere is to produce ionisation layers (Pätzold et al., 2005) and meteors (Adolfsson et al., 1996) with the larger ones reaching the Martian surface and creating impact craters, crater clusters or meteorites (Flynn and McKay, 1989; Popova et al., 2003; Chappelow and Sharpton, 2006). Impacts of “large” (metre-sized or larger) meteoroids on the airless surface of Phobos is the primary process for producing the craters seen in spacecraft images. In addition, seismic shaking and the production of ejecta contribute to the displacement and transport of surface material. On the other hand, impacts by “small” (decimetre or smaller) meteoroids can launch ejecta in circum-martian space, contributing to the dust environment in the orbital vicinity of this moon (e.g. Krivov and Hamilton, 1997). Consequently, as can be read in the relevant chapters of this volume, an independent determination of the meteoroid flux is needed to compare with models of the production rate of craters and boulders on Phobos, the impact flux on Mars itself now and in the past as well as the dust torus that is postulated by several studies.

A study of the Phobos meteoroid environment also has value in itself. It represents an opportunity to learn more about the population of meteoroids which do not intersect the Earth's orbit. The physical properties of meteoroids causing meteors in the Earth's atmosphere have been studied theoretically in a number of works (Lebedinets, 1987; Babadzhanov, 1994; Kikwaya et al., 2006). According to the classical physical theory of meteors, these are considered to be solid bodies similar to meteorites of stony/iron composition with bulk densities ranging from 3.5 g cm^{-3} to 7.7 g cm^{-3} (Levin, 1956). Lebedinets (1987) and Babadzhanov (1994) obtained an average bulk density of 3.3 g cm^{-3} with values for individual cases in the range from 0.1 g cm^{-3} to 8.0 g cm^{-3}. Bellot Rubio et al. (2002) gave even lower estimates ranging from 0.1 g cm^{-3} to 4.5 g cm^{-3}. In contrast, a wide range of the laboratory measurements for meteorites, micrometeorites and interplanetary dust particles did not confirm such a low limit for the bulk

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density. A selection effect may be at work here since fragile, low density material is likely to ablate and consume itself high in the Earth's atmosphere rather than land as a meteorite. The same is true for the Martian atmosphere (Christou and Beurle, 1999; McAuliffe, 2006) but not for airless Phobos where such objects would impact directly onto the surface.

This work is concerned with the meteoroid environment and impact effects at Phobos, particularly crater production. In the section that follows we review past attempts to constrain the meteoroid flux in the Martian system while in Section 3 we consider the particular question of the existence and detectability of meteoroid streams. In Section 4 we present a model of the "sporadic" (i.e. non-stream) flux of large meteoroids at Phobos. This is used to predict relative crater abundances over its surface through the procedure described in Section 5. Section 6 describes the results of this model and a comparison with observationally determined crater counts from *in situ* spacecraft data. Finally, Section 7 contains our main conclusions and outlines prospects for future development in the field.

2. Observations to-date

No direct *in situ* measurements of the meteoroid flux at Mars exist to-date. Since meteoroids obey a size distribution, the flux of particles larger than a few tens of microns across is too low to be picked up by contemporary instrumentation for dust detection *in situ*. Rather, such particles can be detected as meteors in the Martian atmosphere (Adolfsson et al., 1996; McAuliffe and Christou, 2006). Adolfsson et al. (1996) estimated the flux of meteoroids producing so-called "photographic" meteors – i.e. in the absolute visual magnitude range -1 m to $+4$ m – at Mars to be 50% of that at the Earth. Domokos et al. (2007) concluded that the negative result of their meteor search in nighttime images taken by the MER rovers, which they translated into an upper flux limit of $4.4 \times 10^{-6}\ \mathrm{km}^{-2}\ \mathrm{h}^{-1}$ for a mass lower limit of 4 g, was broadly consistent with the Adolfsson et al. prediction of $\sim 4 \times 10^{-7}\ \mathrm{km}^{-2}\ \mathrm{h}^{-1}$ derived by their scaling of the Earth flux according to the Grün et al. (1985) model. No imaging system suitable for the routine detection of meteors in the Martian atmosphere has yet flown but many of the key technologies are now available (Oberst et al., 2011). A detection of a meteor associated with a known Jupiter-family comet by the dual-eye Pancam imager onboard the Spirit rover on Mars was claimed by Selsis et al. (2005). Later work by Domokos et al. (2007) quantified the effects of cosmic ray hits (CRHs) on the Spirit Pancam as part of a dedicated meteor search and placed the 2005 detection in doubt.

3. Streams

Many cometary meteoroids remain close to the orbit of the parent comet for up to $\sim 10^5$ yr forming dense *streams* (McIntosh, 1991). These create meteor showers in the atmospheres of the Earth, where they dominate the bright ($+0$ m to -4 m) meteor flux (Hughes, 1987; Atreya and Christou, 2009). The majority of observational and theoretical work to-date concerns this class of meteoroids. Their orbits retain a memory of their birth, with the result that, if observed and recorded, they can be associated with their specific comet of origin.

In addition, the high particle density within *trails*, which results in short-lived outbursts (of duration a few hour) in meteor activity when these trails encounter the Earth's atmosphere (e.g. McNaught and Asher, 1999), produce a proportionate increase in meteoroid flux on the surfaces of airless bodies. For example, the flux corresponding to a Leonid-type meteor storm translates into 400 meteoroids ≥ 1 mm in size impacting the surface of a body with the dimensions of Phobos every hour (Christou and Beurle, 1999) exceeding the sporadic flux of same-sized objects at the Earth by ~ 4 orders of magnitude.

In the absence of observations, arguments for the existence of Mars-intersecting meteoroid streams have been primarily based on orbital geometry considerations (Terentjeva, 1993; Christou and Beurle, 1999; Treiman and Treiman, 2000; Larson, 2001; Selsis et al., 2004; Neslusan, 2005; Jenniskens, 2006). Christou (2010) re-examined the problem of meteor shower parenthood in light of the tendency for strong meteor showers at the Earth to be associated with certain types of comets (e.g. Halley-type) rather than others. He identified 19 Intermediate Long Period (ILPCs) and Halley Type Comets (HTCs) that are potentially responsible for meteor showers at Mars. In addition, that author found that most of the meteoroid streams associated with Encke-type comets and responsible for shower activity at the Earth are likely to also intersect the orbit of Mars. Expected characteristics of these showers such as speed and radiant location – but not their intensity or particle population properties – can be determined in a straightforward way from the planet-approaching geometry and are illustrated in Fig. 1. Filled circles correspond to Halley-Type (HTCs) and Intermediate Long Period Comets (ILPCs) while open circles correspond to Encke-Type Comets (ETCs). The size of the circle is proportional to the impact speed in the Martian atmosphere while the colour indicates either a radiant near the Sun (bright red), along the terminator (dark red) or in the anti-Sun direction (black). The location corresponding to $L_S = 0°$ is indicated by the grey arrow. It is noted that the temporal distribution of these putative streams is non-uniform with twice as many stream encounters occurring during the period $180° \lesssim L_S \lesssim 360°$.

Christou and Vaubaillon (2011) refined the results of Christou by simulating numerically these meteoroid streams. They found

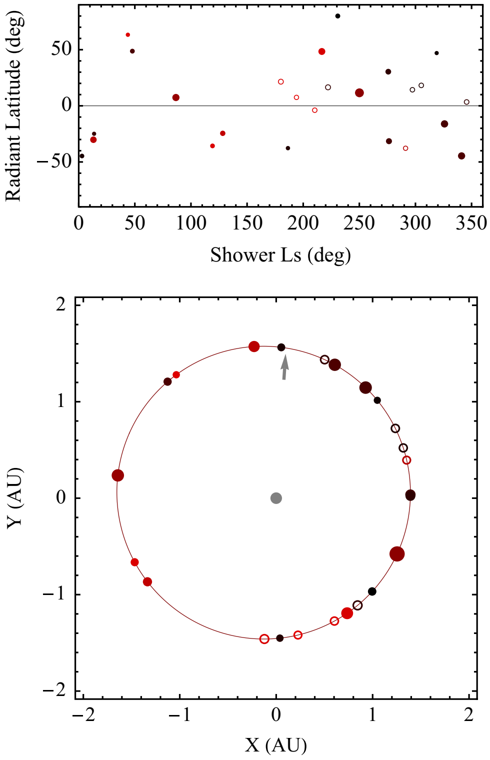

Fig. 1. Top: Areocentric latitudes referenced to the Martian equator as a function of L_S for the radiants of the shower candidates given in Christou (2010). Bottom: Location of the shower candidates along the Martian orbit. See the text for details. (For interpretation of the references to colour in the main text the reader is referred to the web version of this article.)

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