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Meteoric ion layers in the ionospheres of venus and mars: Early observations and consideration of the role of meteor showers

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Abstract

Layers of metal ions produced by meteoroid ablation have been known in Earth's ionosphere for decades, but have only recently been discovered at Venus and Mars. Here we report the results of a search for meteoric layers in earlier datasets from Venus and Mars. We find 13 candidates at Venus in Mariner 10, Venera 9/10, and Pioneer Venus Orbiter data that augment the 18 previously identified in Venus Express data. We find 8 candidates at Mars in Mariner 7 and Mariner 9 data that augment the 71 and 10 previously identified in Mars Global Surveyor and Mars Express data, respectively. These new findings extend the ranges of conditions under which meteoric layers have been observed, support studies of the temporal variability of meteoric layers, and (for Venus) independently confirm the existence of meteoric layers. One of the proposed causes of temporal variations in the occurrence rate of meteoric layers is meteor showers. This possibility is controversial, since meteor showers have minimal observed effect on meteoric layers in Earth's ionosphere. In order to aid progress towards a resolution of this issue, we present a series of tests for this hypothesis.

Keywords: Comets; Meteors; Ionospheres; Venus; Mars

1. Introduction

The chemistry of a planetary atmosphere, an environment dominated by species derived from atoms found in the first row of the periodic table, such as N_2, O_2, or CO_2, is disrupted by meteoroids. The ablation of meteoroids, also known as interplanetary dust particles, due to atmospheric drag and associated heating deposits cosmochemically abundant, but atmospherically deficient, species like Mg and Fe into the atmosphere (Grebowsky et al., 2002; Murad and Williams, 2002). Metallic species are easily ionized, so meteoroid ablation affects the state of the ionosphere. In the absence of meteoroids, the ionosphere at altitudes where meteoroids would be ablated is dominated by non-metallic molecular species, such as O_2^+, whose primary loss mechanism is dissociative recombination with an electron (i.e., $XY^+ + e \rightarrow X + Y$). Metals tend to form atomic ions (e.g. Mg^+), which cannot be neutralized via this fast mechanism for quantum mechanical reasons and are consequently long-lived. As a result, even relatively small production rates of atomic metal ions can maintain a significant plasma population. Hence meteoroids affect the structure, chemistry, dynamics, and energetics of planetary ionospheres.

The existence of a layer of meteoric ions in Earth's ionosphere has been well-known for decades (Grebowsky and Aikin, 2002; Murad and Williams, 2002). Attempts to find analogous meteoric layers on Venus and Mars were frustrated by the scarcity of data: electron density data from other planets are rare and compositional data at the appropriate altitudes are non-existent. Pätzold et al.

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(2009) convincingly identified meteoric layers in Venus observations, although possible candidates were discussed earlier by Witasse and Nagy (2006). Similarly, Pätzold et al. (2005) convincingly identified meteoric layers in Mars observations, reinforced by later, independent identifications by Withers et al. (2008), although possible candidates were discussed earlier by Fox (2004). On Venus, Earth, and Mars, meteoric ions form layers below the main ionospheric peaks.

Meteoric layers form in poorly-understood regions of the ionospheres and neutral atmospheres of Venus and Mars (Brace et al., 1983, 1992; Fox and Kliore, 1997), so these layers can be used as diagnostic tools of these regions. For example, their physical properties are sensitive to the eddy diffusion coefficient of the neutral atmosphere and the chemical composition of the ionosphere (Grebowsky et al., 2002). They are also sensitive to the meteoroid influx rate, something that reflects the dust population of the solar system yet is poorly constrained beyond Earth (Janches et al., 2006; Fentzke and Janches, 2008; Wiegert et al., 2009; Gardner et al., 2011; Nesvorný et al., 2011; Nesvorný et al., 2011). Meteoric layers are only sporadically present in ionospheric observations at Venus and Mars, something that has not been explained to date. This sporadic occurrence could be caused by internal factors, such as changes in neutral atmospheric dynamics that affect layer formation, or external factors, such as meteoroid influx rate. Many discussions of this variability have centered on the possible role of meteor showers, which are visibly impressive at Earth, but do not affect observed properties of Earth's meteoric layers (Kopp, 1997; Grebowsky et al., 1998; Molina-Cuberos et al., 2008).

This manuscript has two main objectives. First, to find additional examples of meteoric layers on Venus and Mars by examining early ionospheric observations. Second, to develop specific tests for the hypothesis that meteor showers influence the occurrence rate of meteoric layers.

2. Early observations

There are few reported examples of meteoric layers at Venus and Mars. Finding additional meteoric layers will better define the physical properties of meteoric layers, increase the likelihood of finding atypical examples, increase the range of conditions at which meteoric layers have been observed, support studies of inter-annual repeatability, and independently confirm the existence of meteoric layers. Datasets from the Venus Express (VEX), Mars Global Surveyor (MGS) and Mars Express (MEX) radio occultation experiments have been carefully examined for meteoric layers in recent work (Pätzold et al., 2005, 2009; Withers et al., 2008). Many earlier datasets exist from similar experiments, but have not been systematically surveyed. At least, they have not been systematically surveyed since these recent observations revealed what meteoric layers on Venus and Mars actually look like. Here we report the results of a search for meteoric layers in earlier datasets from Venus and Mars.

We examined electron density profiles shown in published figures and used subjective criteria to determine whether a profile contained a meteoric layer. These procedures are not optimal, but result from the lack of archived digital electron density profiles from many planetary radio occultation experiments. Since previous work has demonstrated that meteoric layers are present near 110 km on Venus and 90 km on Mars (Pätzold et al., 2005, 2009; Withers et al., 2008), regions where electron density usually increases monotonically with altitude (Brace et al., 1983; Barth et al., 1992; Fox and Kliore, 1997; Withers, 2009), we first identified local maxima in electron density near these altitudes. With a few exceptions that are discussed in Sections 2.1 and 2.2, all of these local maxima were interpreted as possible meteoric layers. The identification of possible meteoric layers was not influenced by the measurement uncertainties, since these are rarely shown on the available figures. Anyway, published electron density profiles generally include only datapoints that exceed the measurement uncertainty. Meteoric layers in published profiles generally occur only a short vertical distance above the bottom of the profile, which might be considered to indicate that electron densities in meteoric layers are close to the detection limit and should be viewed with caution. However, this is not necessarily true as vertical gradients in electron density at the bottom of typical published profiles are very large, similar to the bottomside of a Chapman layer.

2.1. Results for Venus

Pre-1995 dayside ionospheric electron density profiles were obtained by Mariner 5, Mariner 10 (M10), Venera 9/10 (V9/10), Pioneer Venus Orbiter (PVO) and Venera 15/16. Mariner 5 recorded 1 dayside profile on 19 Oct 1967 (Kliore et al., 1967; Fjeldbo and Eshleman, 1969; Fjeldbo et al., 1975). Mariner 10 recorded 1 dayside profile on 5 Feb 1974 (preliminary profile in Howard et al. (1974), revised profile in Fjeldbo et al. (1975)). Venera 9/10 recorded at least 16 dayside profiles from 27 Oct to 7 Dec 1975 (Ivanov-Kholodnyi et al., 1977, 1979; Keldysh, 1977; Aleksandrov et al., 1977, 1978; Iakovlev et al., 1977; Kolosov et al., 1978; Savich, 1981; Savich et al., 1982). Venera 15/16 recorded 29 dayside profiles from 12 Oct to 1 Nov 1983, 20 from 19 Mar to 3 Apr 1984 and 24 from 29 Aug to 24 Sep 1984; 12 profiles have been published (Samoznaev, 1991). PVO recorded 148 dayside profiles from 1979 to 1989 (Cravens et al., 1981; Kliore and Luhmann, 1991). 7 are plotted in Kliore et al. (1979) and 90 are plotted in Kliore and Luhmann (1991). 20 of these 90 profiles are also plotted in Kliore (1992). Magellan (Steffes et al., 1994; Jenkins et al., 1994) recorded 14 dayside profiles from 1992 to 1994; one on 7 Dec 1992, one on 24 Jun 1994, three on 16 Jul 1994 and nine on 9 Aug 1994 (pers. comm, Jenkins, 2008). These have not been published and are not discussed here.

Table 1
Possible meteoric layers on Venus. Lat is latitude, z is altitude, and Ne is electron density.

Spacecraft	Orbit	N/X[a]	Lat (°N)	Date	ψ_V[b] (°)	SZA (°)	z (km)	Ne (cm^{-3})
M10[c]	–	X	−56.0	5 Feb 1974	144.4	67.0	115	3E3[d]
V9[e]	?	X	81	23 Nov 1975	114.9	85	120	1E4
V10[f]	?	X	56	1 Dec 1975	127.9	58	100	7E3
V9[f]	?	X	?	7 Dec 1975	137.7	74	100	4E3
PVO[g]	26	N	88.3	30 Dec 1978	130.4	91.7	100	1E4
PVO[h]	353	N	64.8	22 Nov 1979	294.5	76.4	105	1E4
PVO[h]	2850	N	79.4	24 Sep 1986	336.1	77.3	115	5E3
PVO[h]	2853	N	77.4	27 Sep 1986	340.9	75.1	115	5E3
PVO[h]	2856	X	−50.2	30 Sep 1986	345.6	62.0	110	1E4
PVO[h]	2862	N	72.2	6 Oct 1986	355.2	70.5	115	5E3
PVO[h]	?	?	?	Sep–Dec 1986	−60 to 133	83.6	100	5E3
PVO[h,i]	?	?	?	Sep–Dec 1986	−60 to 133	85.6	110	5E3
PVO[h,i]	?	?	?	Sep–Dec 1986	−60 to 133	91.6	115	5E3

[a] N = ingress, X = egress.

[b] Heliocentric ecliptic longitude from the JPL Horizons system at UTC noon on specified date (Giorgini et al., 1996).

[c] Fjeldbo et al. (1975, Fig. 3).

[d] Read 3E3 as 3×10^3.

[e] Aleksandrov et al. (1977, Fig. 3).

[f] Kliore et al. (1979, Fig. 1).

[g] Kliore et al. (1979, Fig. 3).

[h] Kliore (1992, Fig. 4). Dates from Kliore and Luhmann (1991) and from ephemeris data at the Planetary Plasma Interactions node of the Planetary Data System. Latitudes, N/X and orbit numbers for SZA < 80° from Kliore and Mullen (1989). Values not stated for SZA>80°.

[i] Previously suggested to be a meteoric plasma layer by Witasse and Nagy (2006).

First, all profiles except those in Kliore and Luhmann (1991) were examined. Those with possible meteoric layers are listed in Table 1. A good example is the Mariner 10 egress profile, shown in Fig. 1, where peak electron density in this layer (10^4 cm^{-3}) is more than an order of magnitude larger than the experimental uncertainty (200 cm^{-3}). Other examples of possible meteoric layers, from Venera 10 and PVO respectively, are shown in Figs. 2 and 3.

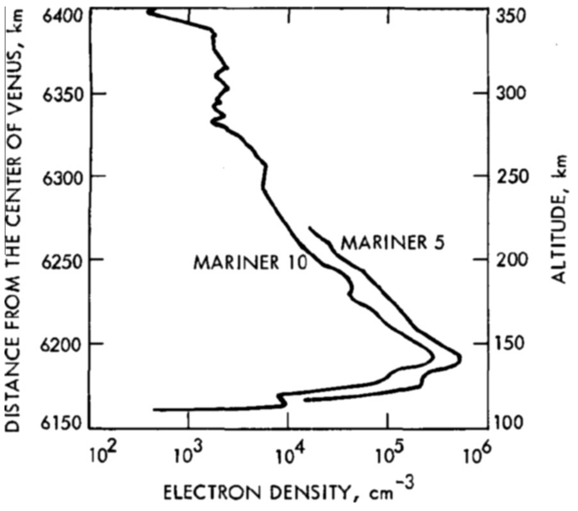

Fig. 1. Venus. Electron density profile of the ionosphere of Venus from the Mariner 10 radio occultation experiment (egress). The layer at 110 km is a possible meteoric layer. The Mariner 5 egress profile is also shown. Reproduced with permission from Fig. 3 of Fjeldbo et al. (1975).

Next, the >100 PVO and Venera profiles published in Kliore and Luhmann (1991) were examined. Unfortunately, these figures do not show the bottomside ionosphere clearly. Possible meteoric layers cannot be identified with confidence from these figures, so these figures did not provide any entries for Table 1. However, it is statistically improbable that the meteoric layer is absent from all of these profiles. Some of them appear to have large electron densities or local maxima at 110 km, suggestive of meteoric layers, but our visual inspections are inconclusive. These profiles are 4a/53.9, 4a/67.6, 4a/89.5, 4b/69.1, 5a/79.2, 5a/90.7, 6a/82.7, 8b/84.6 and 8b/87.2, where X/Y refers to the profile in Fig. X of Kliore and Luhmann (1991) that is labeled with solar zenith angle of Y degrees. These are listed here in order to support possible future investigations of these profiles, if the long-lost profiles ever become accessible, but they are not tabulated in Table 1.

2.2. Results for Mars

Dayside profiles from the pre-1995 datasets listed in Table 1 of Mendillo et al. (2003) were examined. Profiles with possible meteoric layers are listed in Table 2. All are ingress occultations.

The Mariner 4 dayside profile contains three narrow layers below 100 km that appear to be noise, not plasma layers (Fjeldbo and Eshleman, 1968). Fjeldbo et al. (1966) show a preliminary and much smoother version of this profile that does not extend below 100 km. The Mariner 6 dayside profile does not contain any plasma layers below 100 km (Fjeldbo et al., 1970). The Mariner 7 (M7) dayside profile, shown in Fig. 4, contains a plasma layer at 80 km (Fjeldbo et al., 1970). This layer is broader than the spurious layers in the Mariner 4 profile and is similar in altitude, electron

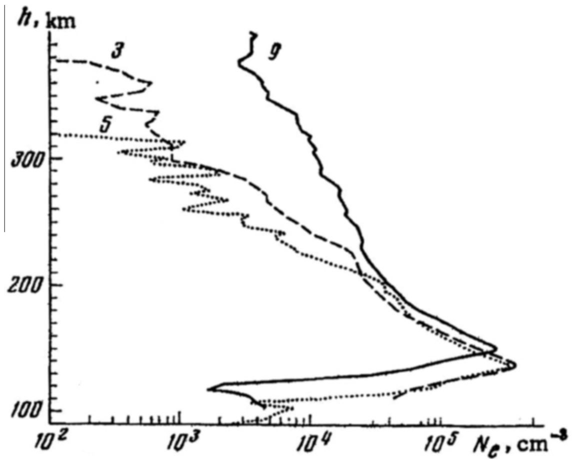

Fig. 2. Venus. Three electron density profiles of the ionosphere of Venus from the Venera 9 and 10 radio occultation experiments. Profile #5 (dotted line, Venera 10) contains an example of a possible meteoric layer at 100 km. Reproduced with permission from Fig. 1 of Kolosov et al. (1978).

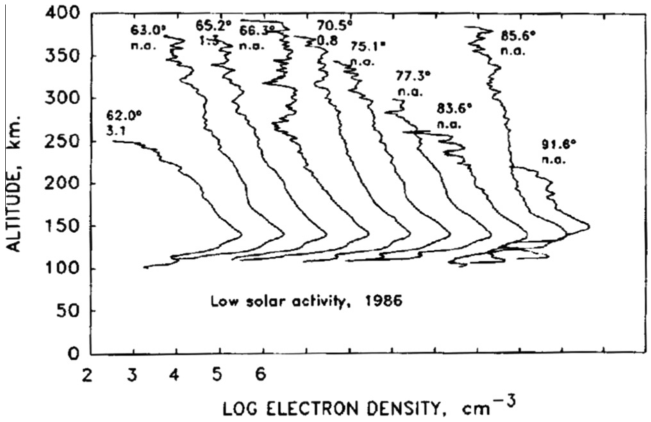

Fig. 3. Venus. Ten electron density profiles of the ionosphere of Venus from the PVO radio occultation experiment. The horizontal scale refers to the first profile on the left. Electron densities in each profile are increased by one order of magnitude with respect to the preceding profile. SZA (degrees) is shown next to each profile. The first profile (SZA = 62.0°) contains an example of a meteoric layer at 110 km. Reproduced with permission from Fig. 4b of Kliore (1992).

density, width and shape to layers found in MGS and MEX profiles (Pätzold et al., 2005; Withers et al., 2008). The profile appears realistic at the other altitudes where the electron density is the same as in this layer, namely the bottomside at 100 km and the topside at 300 km. We accept it as a possible meteoric layer. The Soviet missions Mars 2, 4, 5 and 6 returned <10 profiles. Kolosov et al. (1979) show three dayside electron density profiles from Mars 2. Two of the profiles contain apparent plasma layers below 80 km, yet they are unusually broad and have unusually low altitudes. All three profiles have electron densities of 10^4 cm^{-3} at 50 km, unlike any other observations or models. The results below 100 km are not reliable, so we do not consider these layers to be possible meteoric layers. A possible explanation for spurious results below 100 km is that a key assumption of the differential Doppler radio occultation method—that the two radio signals, which have different wavelengths, follow the same path through the atmosphere—is violated here (Withers et al., 2012). Mars 4 and Mars 6 each observed one dayside profile; neither profile contains a meteoric layer (Moroz, 1976). Mars 5 did not observe any dayside profiles (Savich and Samovol, 1976).

95 profiles from Mariner 9 (M9) are shown in Kliore (1992). Meteoric layers were identified in orbits 5, 6, 10, 30, 31, 43 and 67. Orbit 30, shown in Fig. 5, and orbit 43 are good examples. In fact, the M9 profiles are available at the National Space Science Data Center (NSSDC), albeit as microfilmed sets of tables. A Boston University group is in the process of extracting these data and preparing them for delivery to the Planetary Data System (PDS). As that work is still ongoing, the images from Kliore, 1992 were used in this work.

Kliore, 1992 also showed 40–50 profiles from Viking Orbiter 1 and <20 profiles from Viking Orbiter 2. Additional profiles were published by Zhang et al., 1990 in figures that do not extend below 100 km and are consequently not appropriate for studies of meteoric layers. The complete set of ~150 Viking radio occultation electron density profiles has not been published yet. Table 2 does not contain any possible meteoric layers from Viking Orbiters 1 or 2. The absence of meteoric layers is significant. Given the Mariner 9 occurrence rate, four meteoric layers should have been identified in the Viking profiles. However, published Viking profiles appear noticeably smoother at low alitudes than Mariner 9 profiles. Kliore (1992) comments that the Viking profiles, which were obtained from a dual frequency experiment, provide more reliable measurements of small plasma densities than the Mariner 9 profiles, which were obtained from a single frequency experiment. Without either the ability to manipulate the data or knowledge of the uncertainties associated with each profile, we are not able to quantify the confidence with which the Mariner 9 meteoric layers are identified.

Electron densities around 90 km appear large, consistent with meteoric layer electron densities, on orbits 4, 17, 25, 27, 36, 40, 41, 46, 59 and 61 for Mariner 9 and orbits 610 and 639 for Viking Orbiter 1 (Kliore, 1992). However, these are not listed in Table 2 as possible meteoric layers. In some cases, lines in the printed figures are entangled at 90 km and it is unclear which line belongs to which profile. In other cases, the printed figure contained half of a layer at 90 km. That is, the profile contained what might have been the topside of a layer, but did not extend below the apparent peak of the layer. In such cases it is unclear whether this is a possible meteoric layer or not.

2.3. Implications of early observations

In summary, meteoric layers are visible in 13 early observations of the ionosphere of Venus and 8 early observations of the ionosphere of Mars. Nine additional possible, but not definitive, layers are present in Venus

Table 2
Possible meteoric layers on Mars. Lat is latitude, Lon is longitude, z is altitude, and Ne is electron density.

Spacecraft	Orbit	Lat (°N)	Lon (°E)	Date	L_s[a] (°)	SZA (°)	z (km)	Ne (cm^{-3})
M7[b]	–	−58	30	5 Aug 1969	202.5	56	80	6E3[c]
M9[d]	5	−38.6	34.8	16 Nov 1971	293.8	55.6	90	1E4
M9[d]	6	−38.2	219.6	17 Nov 1971	294.5	55.5	90	3E3
M9[d]	10	−36.3	239.2	19 Nov 1971	295.7	54.7	100	1E4
M9[d]	30	−25.8	340.3	29 Nov 1971	301.7	51.0	90	3E3
M9[d]	31	−25.2	165.2	29 Nov 1971	301.7	50.9	90	2E4
M9[d]	43	−17.6	223.1	5 Dec 1971	305.2	48.9	90	8E3
M9[d,e]	67	3.8	340.3	17 Dec 1971	312.2	47.2	90	1E4

[a] Martian seasons are described by L_s, the areocentric longitude of the Sun, which is defined as the angle between the Mars–Sun line and the Mars–Sun line at the northern hemisphere vernal equinox (Zurek et al., 1992). Values of L_s were calculated from the tabulated dates, assuming times of UTC noon, using Forget (2008).

[b] Fjeldbo et al. (1970, Fig. 7).

[c] Read 6E3 as 6×10^3.

[d] Kliore (1992, Fig. 2). Data from Kliore et al. (1972), Lindal et al. (1979) and Zhang et al. (1990).

[e] Discussed orally by Witasse et al. (2002) (pers. comm., Witasse, 2008).

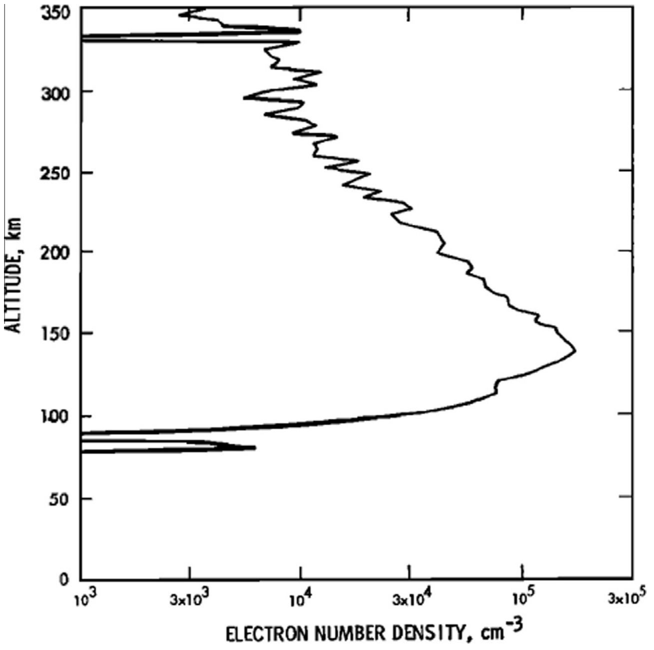

Fig. 4. Mars. Electron density profile of the ionosphere of Mars from the Mariner 7 radio occultation experiment (ingress). It contains a possible meteoric layer at 80 km. Reproduced with permission from Fig. 7 of Fjeldbo et al. (1970).

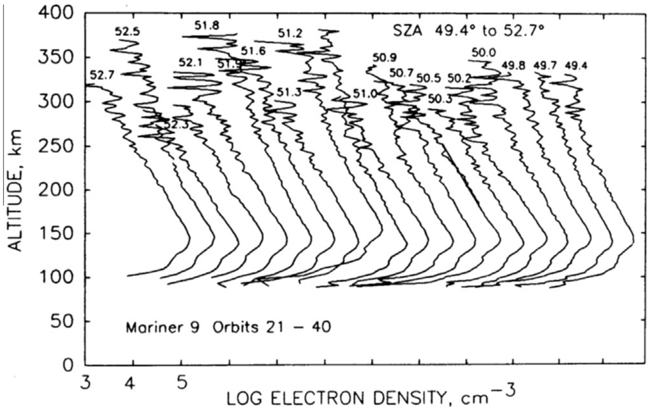

Fig. 5. Mars. 20 electron density profiles of the ionosphere of Mars from the Mariner 9 radio occultation experiment (ingress). These profiles are from orbits 21–40. The horizontal scale refers to the first profile on the left. Electron densities in each subsequent profile are increased by half an order of magnitude with respect to the preceding profile. Solar zenith angle (degrees) is shown next to each profile. Profile 30 (center of the figure) contains an example of a meteoric plasma layer at 90 km. Reproduced with permission from Fig. 2c of Kliore (1992).

observations and twelve are present in Mars observations. Since the published figures in which these layers were identified do not provide electron density uncertainties, it is not possible to address confidently the question of how these uncertainties influence the contents of Tables 1 and 2.

The statistical properties of the 13 venusian observations listed in Table 1 can be compared to the 18 meteoric layers identified in VEX profiles by Pätzold et al. (2009). In both sets, all meteoric layers have solar zenith angles greater than or equal to 58 degrees. None are identified at smaller solar zenith angles, despite many profiles being available there. It is possible that the altitudes of the V1 layer and the meteoric layer are too similar at small solar zenith angles for the meteoric layer to be distinguished and identified. Pätzold et al. (2009) reported peak altitudes of 110–120 km; here we report peak altitudes of 100–120 km. The challenges inherent in measuring peak altitudes from published figures may be responsible for differences between our range and the range of Pätzold et al. (2009). Pätzold et al. (2009) reported peak densities of up to 4×10^4 cm^{-3}; here we report peak densities of 0.3–1.0 × 10^4 cm^{-3}. This difference seems larger than can be explained by inaccuracies in our data processing and is a promising topic for future investigations. It is unfortunate that Pätzold et al. (2009) did not show images of any profiles with meteoric densities greater than 1.5×10^4 cm^{-3}.

Compared to the 71 meteoric layers identified in MGS profiles by Withers et al. (2008), the 8 martian observations listed in Table 2 are too few to be used for meaningful statistical studies of correlations with season or solar zenith angle.

3. The possible importance of meteor showers

3.1. Shower meteoroids at Earth

There are two populations of meteoroids in the solar system, sporadic and shower meteoroids (Grün et al., 2001). Shower meteoroids belong to a stream of cometary ejecta. Particles ejected from a comet during a perihelion passage form a *trail*, a narrow, dense structure that can remain cohesive for tens of orbital revolutions. The accumulation of several trails, mixed together by planetary scattering, forms the broader *stream background*. Both structures are typically close to, but not superimposed upon, the comet's orbit. Annual meteor showers at Earth are caused by Earth encountering the stream background. Intense meteor storms, or outbursts, occur when Earth encounters a trail within a stream. For example, Earth encounters the Leonid meteor stream every year, but only encounters a major trail every ~33 years (Asher, 1999).

The meteoroid streams and parent comets that contribute to the shower meteoroid flux at Earth have been determined from centuries of observations (Jenniskens, 1994). Predictions of the parent comets that contribute to the shower meteoroid flux at Venus and Mars have been made by several groups e.g. (Christou, 2004; Treiman and Treiman, 2000; Ma et al., 2002; Selsis et al., 2004). Although the dynamical aspects of these predictions, namely the simulation of the trajectory of a test particle ejected from a comet, are likely to be reasonably accurate, uncertainties in cometary dust production rates, size distributions, and ejection speeds lead to uncertainties in the predicted shower meteoroid flux. Extrapolation of the shower meteoroid flux and its variation with heliocentric longitude from 1 AU to other heliocentric distances is therefore challenging.

Observations have not shown any convincing changes in the terrestrial ionosphere due to a meteor shower, although Kopp (1997) noted that the metallic ion column density was one order of magnitude greater than usual for a rocket flight shortly after the Perseid meteor shower in August 1976. Grebowsky et al. (1998) identified 18 measurements of metallic ion concentrations between 30° and 55° (both hemispheres), 4 of which were made during meteor showers. The three highest column densities belonged to three of the four flights during meteor showers. Also, the highest concentration measured in each of the four flights during meteor showers exceeded the highest concentration measured at the same altitude during any other flight. Grebowsky et al. (1998) also identified 18 measurements of metallic ion concentrations between 55° and 90° (both hemispheres), 2 of which were made during meteor showers. No enhancement during meteor showers was detected. "The evidence points toward an enhancement of the metal layer ion concentrations during [meteor] showers at mid-latitudes. However, the number of data samples is limited and the effects of different ionospheric and atmospheric conditions under which the rocket measurements were made have not been investigated …Further studies are needed to establish definitively the impact of showers on the ionospheric metal ion distributions." (Grebowsky and Aikin (2002)).

The lack of a strong observational response to meteor showers is not wholly unexpected: shower meteoroids contribute only a small fraction of the total meteoric mass incident upon Earth and the critical time constants governing the loss of metal ions are longer than the duration of meteor showers. Nevertheless, the implications of numerical models are clear. They predict that metallic ion column densities should increase by factors of a few during meteor showers and by two orders of magnitude during a meteor storm comparable to the 1966 Leonids (Carter and Forbes, 1999; McNeil et al., 2001).

3.2. Sporadic meteoroids at Earth

Over time, shower meteoroids become sporadic meteoroids as their orbits gradually diffuse away from the orbit of their parent body due to gravitational perturbations from the planets, Poynting–Robertson drag, solar wind drag, and collisions. Sporadic meteoroids cannot be easily associated with a parent body or meteoroid stream. Sporadic meteoroids belong to a background population of interplanetary dust whose characteristic number density, mass and speed vary on large spatial scales and who have a broad range of directions of motion. However, their radiants are not uniformly distributed across the sky or within the ecliptic plane.

On Earth, sporadic meteoroids predominantly come from six apparent sources that are tens of degrees across. These are called the helion, anti-helion, north apex, south apex, north torodial and south torodial sources e.g. (Jones and Brown, 1993; Taylor and Elford, 1998; Galligan and Baggaley, 2005). Their locations are fixed in a Earth-centred coordinate system that is defined by the two vectors of Earth's velocity and the Earth–Sun line. The flux of sporadic meteoroids for an observer at Earth consequently depends on which of these apparent sources is above the horizon, although the flux from a given source may also vary with Earth's position along its orbit.

It is commonly assumed that the population of sporadic meteoroids seen at Earth is composed of meteoroids from many parent bodies, but recent work by Wiegert et al. (2009) surprisingly suggested that only a small number of comets are significant sources of sporadic meteoroids. They predicted that low speed sporadic meteoroids are dominated by material from bodies with orbits similar to comet 2P/Encke, the parent body of Taurid meteor showers, and that high speed sporadic meteoroids are dominated by material from bodies with orbits similar to comet 55P/Tempel-Tuttle, the parent body of the Leonid meteor shower.

3.3. Predictions of shower and sporadic meteoroid fluxes at Venus and Mars

Substantially more effort has been devoted to predicting the meteor shower environment at Venus and Mars (Kolmakov, 1991; Beech, 1998; Christou and Beurle, 1999; Christou, 2004,, 2010; Christou et al., 2007, 2008; Treiman and Treiman, 2000; Ma et al., 2002; Selsis et al., 2004) than the sporadic meteor environment, despite the vast majority of meteoric mass incident on Earth coming from sporadic, not shower, meteoroids. This situation may reflect the fact that the orbital dynamicists performing such simulations are primarily interested in the evolving dynamics of cometary ejecta, rather than the impact of these meteoroids on the planets they impact.

The implications of the work on sporadic meteoroids of Wiegert et al. (2009) for other planets have not yet been established. Is the meteoroid flux at other planets dominated by sporadic meteoroids, as it is at Earth? Do sporadic meteoroids at other planets come from a small number of apparent sources? Do sporadic meteoroids at other planets come from a small number of comets and, if so, which comets? To the best of our knowledge, studies have not yet addressed how the sporadic meteoroid flux at Venus varies during a Venus orbit nor at Mars during a Mars orbit.

3.4. Relationships between variations in meteoric layer properties and variations in meteoroid flux

If the lifetime of metal ions is short by comparison to the timescale over which meteoroid flux varies, then variations in meteoric layer properties might be expected to follow variations in meteoroid flux. Thus a short metal ion lifetime on the order of a day is essential if ionospheric responses to meteor showers are to be detectable. A longer metal ion lifetime of, say, a week would mask the ionospheric response to meteor showers.

Despite the lack of an unambiguous and strong ionospheric response to meteor showers, some data do demonstrate that variations in meteoroid influx affect the abundance of metallic ions in the terrestrial ionosphere. The properties of sporadic E layers, which are composed of metal ions and routinely observed by extensive networks of ground-based ionosondes, vary seasonally. In a comprehensive review of these layers, Whitehead (1989) concluded that the wind shear theory “does not explain the overall morphology of sporadic E, in particular the large summer maximum.” In response, Haldoupis et al. (2007) compared radar data on meteor count rates and sporadic E plasma densities to show that “the marked seasonal dependence of sporadic E correlates well with the annual variation of sporadic meteor deposition in the upper atmosphere.” The annual variations referred to here are variations caused by changes in the visibility of particular sources of sporadic meteoroids as high-obliquity Earth progresses around its orbit, not variations in the intrinsic strength of a sporadic source with heliocentric longitude.

Variations in meteoric layer occurrence rate have been observed at Venus and Mars, but have not been convincingly attributed to variations in meteoroid flux (Withers et al., 2008; Pätzold et al., 2009; Pandya and Haider, 2012). The lack of independent, observationally-based knowledge of the meteoroid environment at these planets and of reliable models for how ionospheric characteristics depend on meteoroid flux properties are obstacles to testing whether variations in meteoroid flux have observable and verifiable ionospheric consequences.

In theory, Venus is an excellent test case for studying possible relationships between variations in meteoric layer properties and variations in meteoroid flux, since many planet-specific factors that may influence meteoric layer properties are fixed or absent. It has neither a core dynamo that generates a strong, global dipolar magnetic field nor crustal magnetic fields. It has near-zero orbital eccentricity and obliquity, which eliminates seasonal variations in atmospheric dynamics.

3.5. Do meteor showers influence meteoric layers on Venus and Mars?

As discussed in Section 3.1, simulations predict that meteor storms should, and meteor showers might, significantly alter properties of meteoric layers on Earth, although tests of these predictions have been inconclusive. It is clearly possible that meteor storms and showers could affect properties of meteoric layers on Venus and Mars. If so, ionospheric observations would become of great interest to orbital dynamicists. It is tempting to search for evidence of meteor showers in ionospheric data from Venus and Mars simply by looking for seasonal variations in the occurrence rate of meteoric layers, but that alone is not sufficient to establish that meteor showers are responsible. Variations in the sporadic meteoroid flux or variations in the neutral atmosphere could also be responsible.

Specific tests of the hypothesis that meteor showers influence the occurrence rate of meteoric layers on Venus and Mars are needed. In order to enable better evaluation of this hypothesis, here we list eight such tests. Any of the following observations would favor meteor showers over changes in the sporadic meteoroid flux as a cause of variations in the occurrence of meteoric layers.

1. High occurrence rates of meteoric layers occur when the planet crosses the orbit of an identifiable small body, such as a comet or asteroid.
2. The radiants of optical meteors observed during an interval with a high occurrence rate of meteoric layers are consistent with the orbit of a candidate parent body.
3. The small body highlighted by item 1 at a particular time is the same as the small body highlighted by item 2 at that time.

4. Year-to-year variations in the season at which an interval with high occurrence rates of meteoric layers occurs are consistent with the orbital dynamics of the associated meteoroid stream and its constituent trails, since a given meteor shower should not occur at precisely the same season and intensity each year e.g. (Christou et al., 2007).
5. The occurrence rate of meteoric layers during an identified interval with high occurrence rate of meteoric layers increases significantly in some years. That is, some meteor showers should be meteor storms in which the planet encounters a meteoroid trail within the meteoroid stream.
6. Meteoric layers associated with an identified meteoroid stream occur at latitudes within the stream's sub-radiant hemisphere and do not occur at other latitudes.
7. The detection rate of optical meteors in the planetary atmosphere increases during intervals of high occurrence rates of meteoric layers. The effects of cosmic rays on cameras complicate such observations (Selsis et al., 2005; Domokos et al., 2007).
8. The timescale for variations in the occurrence rate of meteoric layers is much shorter than the planet's year.

Conversely, if any of these anticipated observations is shown not to occur, this would favor changes in the sporadic meteoroid flux over meteor showers as a cause of variations in the occurrence of meteoric layers.

At Mars, one particularly interesting opportunity to explore the importance of shower meteoroids will be presented by comet 2013 A1 (Siding Spring), which is currently predicted to pass within 300,000 km (0.002 AU) of the planet on 19 October 2014 (http://www.nasa.gov/mission_pages/asteroids/news/comet20130305.html). This exceptionally close encounter may result in very high fluxes of shower meteoroids onto Mars.

4. Summary

Meteoric layers are visible in 13 early observations of the ionosphere of Venus and 8 early observations of the ionosphere of Mars. The pre-Venus Express detections reported here constitute a significant fraction of all reported examples at Venus (13 of a total of 31, or 42%). Coming from four different spacecraft, they exclude the possibility that the previously published detections, which were all associated with Venus Express radio occultations, were some kind of instrumental malfunction.

The hypothesis that meteor showers influence the occurrence and properties of meteoric layers at Venus and Mars is eye-catching, but challenged by the lack of evidence for any such influences at Earth. However, many Earth-based expectations have crumbled when tested in other environments and there are enough noteworthy differences between conditions at Earth and conditions at Venus and Mars for that outcome to be possible here. We have presented eight ways to distinguish between meteoric layer variations caused by meteor showers and by changes in sporadic meteoroid flux. These should permit future studies to tackle this highly visible issue.

There is a compelling need for improved models or data concerning the sporadic meteoroid environment at Venus and Mars. Without some knowledge of the input rate of metallic species, it will be difficult to transform observations of the properties of meteoric layers into understanding of the processes that create, maintain, and destroy these layers. Improved constraints on the sporadic flux will also be valuable for testing whether shower meteoroids have significant ionospheric effects or not.

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