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A sporadic layer in the Venus lower ionosphere of meteoric origin

M. Pätzold,[1] S. Tellmann,[1] B. Häusler,[2] M. K. Bird,[3] G. L. Tyler,[4] A. A. Christou,[5] and P. Withers[6]

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[1] The Venus Express Radio Science (VeRa) experiment aboard Venus Express has detected, by means of radio occultation, distinct, low-lying layers of electron density below the base (115 km altitude) of the ionosphere of Venus. A plausible origin of these lowest layers is ionization by the influx of meteoroids into the atmosphere. The layers appeared only occasionally during the 2006 and 2007 Venus Express occultation seasons, could be identified only on the dayside and seem to be geographically localized as they usually occur in either the northern or southern hemisphere of the same orbit; they are detected at all latitudes, but only at solar zenith angles between 55° and 90°. Typical peak plasma densities of 10^{10} m^{-3} are reached between 110 and 120 km altitude. Peak meteor layer electron densities increase with decreasing solar zenith angle. Layer shapes are symmetric with respect to peak altitude. The present observational statistics and lack of dedicated models prevents definite statements to be made on the origin of the source meteoroids. **Citation:** Pätzold, M., S. Tellmann, B. Häusler, M. K. Bird, G. L. Tyler, A. A. Christou, and P. Withers (2009), A sporadic layer in the Venus lower ionosphere of meteoric origin, *Geophys. Res. Lett.*, *36*, L05203, doi:10.1029/2008GL035875.

1. Introduction

[2] The ionosphere of Venus was first detected by the radio science experiment on Mariner 5 in 1967 [*Kliore et al.*, 1967]. Several instruments on the Pioneer Venus Orbiter (PVO) returned in situ information on ionospheric composition [*Taylor et al.*, 1980]; height profiles of the electron density distribution were measured by the PVO Radio Occultation experiment (see, e.g., the review by *Brace and Kliore* [1991]).

[3] The Venus Express Radio Science Experiment, VeRa (see *Häusler et al.* [2006] for details) onboard the ESA Venus Express (VEX) spacecraft sounds the Venus atmosphere and ionosphere using coherent, highly-stable, radio carrier downlink signals at frequencies of 2.3 and 8.4 GHz, driven by an Ultra-Stable Oscillator (USO). Radio occultations, as seen from a terrestrial tracking station, occur as the spacecraft disappears behind the planetary disk and later emerges from behind the opposite limb. These events occur once per VEX orbit of 24 hours over a period of some months or weeks, referred to as a "season", which depends on the geometry of the spacecraft orbital plane relative to the positions of Earth and Venus. At ingress, the radio ray path moves downward from the top of the ionosphere and atmosphere to a minimum altitude approaching the physical limit near 32 km, the level at which the atmosphere is critically refractive [*Fjeldbo et al.*, 1971]. Refraction by the neutral atmosphere and ionosphere alters the path of the radio signal, leading to a frequency shift as received by the ground station. A vertical profile of the refractive index in the Venusian atmosphere/ionosphere is derived from the measured frequency. Vertical ionospheric electron density profiles are derived from the respective refractive index profiles between 50 and 1500 km altitude. Derived ionospheric electron densities typically exceed their uncertainties of $2{,}000 \cdot 10^6$ m^{-3} from 100 to 400 km.

2. Observations

[4] During the first three VEX occultation seasons of 2006–2007 the VeRa experiment retrieved 118 profiles, equally divided between occultation ingress and egress, of pressure, temperature, and neutral number density from the lower atmosphere (<90 km) together with profiles of electron density from the overlying ionosphere [*Pätzold et al.*, 2007]. Within the southern hemisphere the height profiles are well-distributed in latitude, whereas the northern hemisphere observations are restricted to latitudes above 65°. About half of all profiles are nighttime profiles with solar zenith angles ranging from 90° to 113°.

[5] Figure 1 shows daytime electron density profiles from the first occultation season. These profiles were observed on DOY 204, 2006, for occultation ingress (Figure 1, left) and egress (Figure 1, right). In addition to the main layer at ≈140 km altitude, V2, a secondary layer, V1, at the lower altitude of ≈125 km is readily identified.

[6] We report here the presence of a sporadic layer below ≈115 km altitude, i.e., below the base of the V1 layer. An example of the additional layer is presented in Figure 1 (left), well below and distinctly separate from V1; no such layer is present in the corresponding egress profile (Figure 1, right) obtained at high northern latitude. This new layer has a peak electron density of $10{,}000 \cdot 10^6$ m^{-3} at ≈110 km altitude, well above the noise level ($2{,}000 \cdot 10^6$ m^{-3}). *Witasse and Nagy* [2006] pointed out that such a layer may be visible in two profiles from the PVO Radio Occultation Experiment. Similar features are present in the dayside ionosphere profile from Mariner 10 [*Fjeldbo et al.*, 1975] and in some ionospheric electron density profiles at Mars [*Pätzold et al.*, 2005].

[1]Rheinisches Institut für Umweltforschung, Abteilung Planetenforschung, Universität zu Köln, Cologne, Germany.
[2]Institut für Raumfahrttechnik, Universität der Bundeswehr München, Neubiberg, Germany.
[3]Argelander Institut für Astronomie, Universität Bonn, Bonn, Germany.
[4]Department for Electrical Engineering, Stanford University, Stanford, California, USA.
[5]Armagh Observatory, College Hill, Armagh, UK.
[6]Center for Space Physics, Boston University, Boston, Massachusetts, USA.

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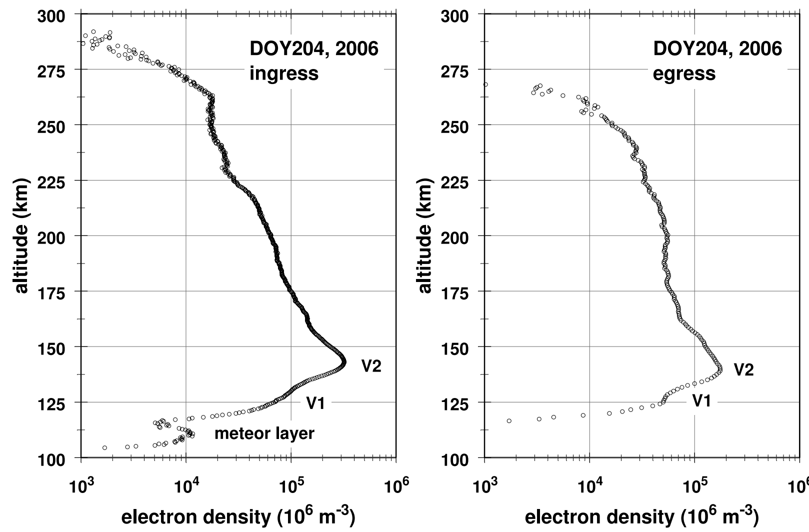

Figure 1. Electron density profiles from 2006 DOY 204 occultation (left) ingress at Lat. = 42°S, SZA = 63°, (right) egress Lat. = 78°N, SZA = 83°. An additional layer is present in the southern hemisphere profile at an altitude near 110 km, possibly of meteoric origin. This layer is absent in the egress profile from the northern hemisphere.

[7] Figure 2 shows three further examples of layers below V1 from 2007 DOY 016, 164 and 173. None of the corresponding profiles from the opposite hemisphere display a lower layer. Figure 2a (top) and Figure 2a (bottom) show a layer well detached from V1, in contrast to the additional layer in Figure 2b, which is clearly merged with the V1 base. Finally, double peaks below V1, illustrated in Figure 2c, are observed in several profiles; these double layers are well resolved and distinct from each other, although the upper layer partially merges with V1.

3. Analysis and Interpretation

[8] Sporadic plasma layers below the expected lower boundary of the ionosphere were predicted prior to these observations [e.g., *Pesnell and Grebowsky*, 2001; *Pesnell et al.*, 2004; *Grebowsky et al.*, 2002]. They are believed to be caused by the surface ablation of metallic atoms from impacting meteoroids and subsequent ionization. This well-known phenomenon in the Earth's ionosphere occurs at altitudes of 95 to 100 km [e.g., *McNeil et al.*, 2001]. A "meteor layer" containing metallic ions, predicted at Mars at altitudes between 80 and 100 km, was recently detected [*Pätzold et al.*, 2005]. The Martian meteor layer typically has a peak electron density of $8{,}000 \cdot 10^6$ m^{-3} at altitudes between 70 and 100 km. While the observed number density of metallic ions in the Martian meteor layers agrees well with previous models [*Pesnell and Grebowsky*, 2000; *Molina-Cuberos et al.*, 2003], the observed density peak in the Venus layers reported here is many times larger [*Grebowsky et al.*, 2002] and at different altitudes [*Molina-Cuberos et al.*, 2008] than predicted.

[9] Three processes have been proposed to form ions from the ablated atoms [*Pesnell and Grebowsky*, 2000; *Molina-Cuberos et al.*, 2003]: (i) photoionization and photoelectron impact ionization, (ii) charge exchange, and (iii) direct ionization by hyperthermal collisions. Since the VeRa observations clearly show an increase in the electron density, photoionization is the likely dominant daytime process for creating the extra layer. On the other hand, charge exchange between short-lived (O_2^+) and long-lived metal species (Mg^+; Fe^+) may decrease the recombination loss rate. Electrons can thus accumulate in "bottleneck" fashion, increasing their density even if their production rate (by CO_2 photoionization) is unchanged.

[10] Figure 2 (bottom) shows the result of separating the low layers from V1. The contribution of V1 has been removed by fitting and subtracting a Chapman function from the observed profiles. The density distributions of the additional layers are symmetric in altitude about their peak, the residuals—observed electron density minus the fits—scattering randomly about zero.

[11] The density and deposition altitude of the ablated metal atoms depend on the relative impact speed into the atmosphere. Fast meteors ablate considerably more metal atoms, and at higher altitudes, than do slower meteors of the same mass. Hence, the double peaks below V1 (Figure 2c) may represent two different meteoric populations.

[12] *Molina-Cuberos et al.* [2008] predict a peak metal atom deposition altitude at Venus of 110–120 km and a metal ion peak altitude of 120–130 km. The ionized meteor layer would be very difficult to detect in this altitude range because it would merge directly with V1. The VeRa observations, however, show the peak of the meteor layer at an average altitude of 113 ± 4 km (see Table S1 in the auxiliary material)[1], well below the predicted lower limit of 120 km. Table S1 lists the observational characteristics of all detected low lying layers.

[13] Plotting the meteor layer peak density versus solar zenith angle shows that the peak density tends to increase with decreasing SZA (Figure 3). No low-lying layers have been observed outside the range 59° < SZA < 91°, which may indicate that impacts preferentially occur near the terminator. Compared with the total number of observed electron density profiles per 10° solar zenith angle range (Figure 3), about 30% of all observed profiles in the range

[1]Auxiliary materials are available in the HTML. doi:10.1029/2008GL035875.

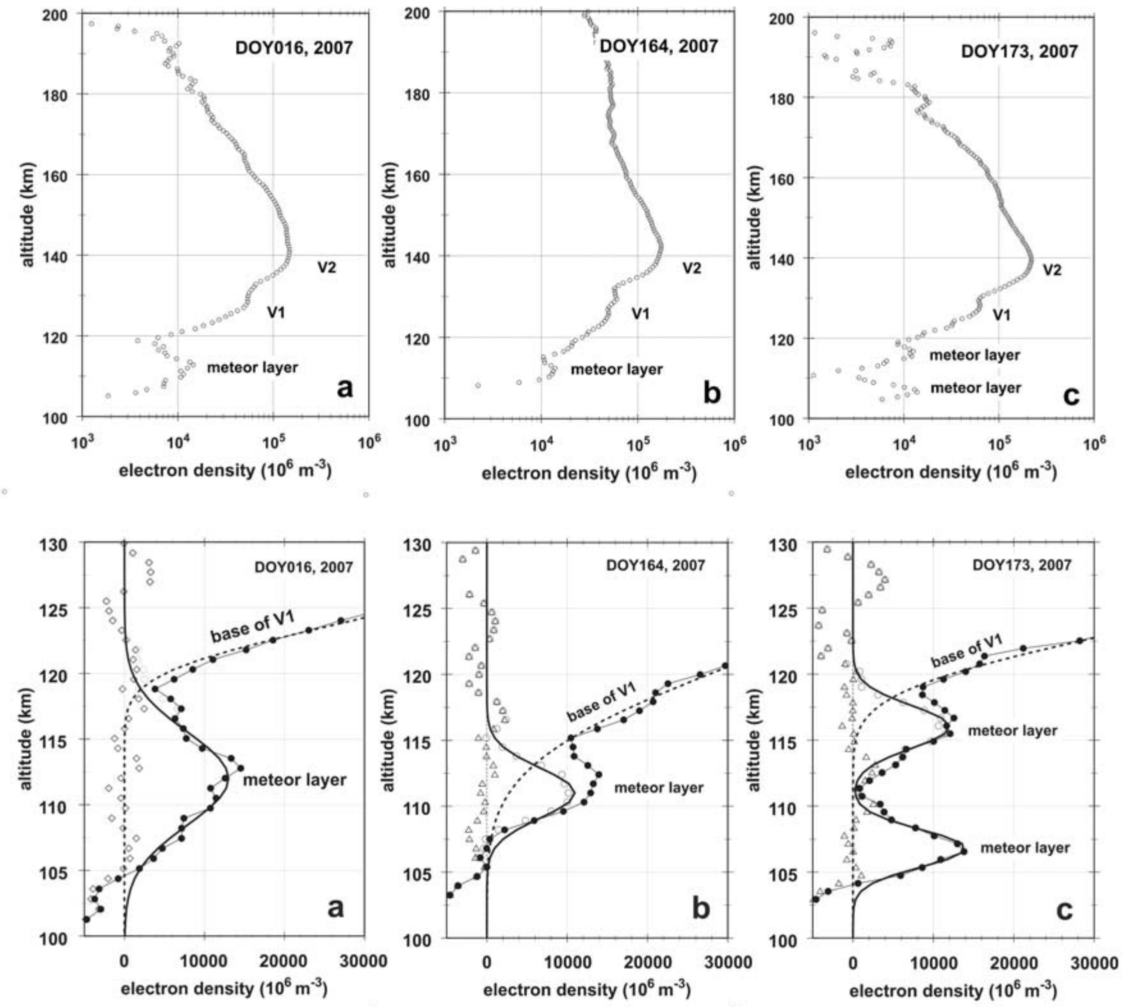

Figure 2. Meteor layers from three days in 2007: DOY 016 (Lat. = 29°S, SZA = 67.3°), DOY 164 (Lat. = 89°N, SZA = 83.7°) and DOY 173 (Lat. = 72.4°N, SZA = 76.8°). These three examples demonstrate (a) a layer well detached from V1, (b) a layer merged with V1, and (c) a double layer where the upper layer merges with V1, but both are well separated from each other. (top) The entire profiles and (bottom) details in the altitude range 100–130 km. The solid circles connected by a thin line are the observations of electron density. Clearly visible is the bottom side of the V1 layer, which usually forms the lower boundary of the ionosphere. Additional electron density of the meteor layers are evident in all three panels. Dashed lines are Chapman function fits to V1. Open circles denote observations minus the Chapman fit. A Gaussian function symmetric about the maximum of the meteor layer is fit to this residual. Open diamonds, scattered randomly about zero denote the observed layer minus the Gaussian fit. Note the low residuals above and below the labelled 'meteor layer.'

60° < SZA < 90° contain a meteor layer. A similar correlation of the peak altitude with solar zenith angle, however, could not be verified but, as already mentioned, the deposition altitude is controlled by the relative impact speed of the meteors [*Molina-Cuberos et al.*, 2008].

[14] It is very difficult to identify a meteor layer in the nighttime profiles with unstructured ionization. Although there is significant ionization below 120 km in many of the nightside profiles [*Pätzold et al.*, 2007], it is not a distinct layer as on the dayside (Figures 1 and 2). It is premature to conclude that the lower peak of this structure [*Kliore et al.*, 1979; *Pätzold et al.*, 2007] is formed by meteors because the altitude does not agree with the VeRa dayside meteor layer observations, the shape of the layer is not symmetric as on the dayside and the peak amplitude is comparable to the fluctuation of the electron density within the entire profile.

[15] The VeRa data show the observed meteor layers to be a sporadic phenomenon with regard to the sensitivity of the radio science method, rather than a permanent dayside feature. We note two instances, 2007 DOY 014 and DOY 016, where the meteor layer was observed on both the ingress and egress occultations of an individual orbit.

4. Meteoroid Source Regions: Discussion

[16] Annual meteor activity at the Earth consists of the sporadic background and showers. The sporadic background flux is continuous but is neither constant nor isotropic. It mainly originates from discrete sources near the ecliptic plane [*Campbell-Brown and Jones*, 2006]. The principal seasonal and latitudinal trends in sporadic meteor activity as observed by radars over several years have been attributed to the geometric effects of the Earth's obliquity

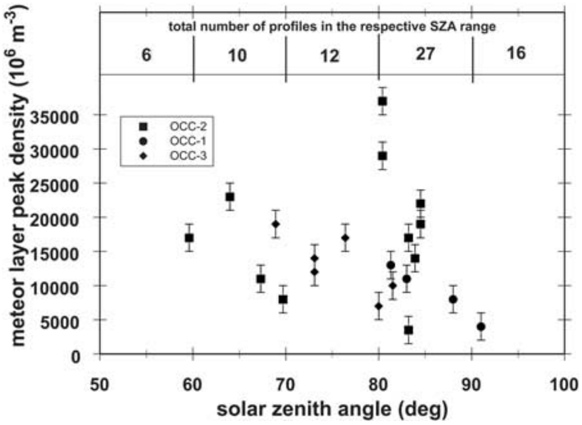

Figure 3. Peak density of the low-lying additional ionospheric layers versus SZA. Different symbols are used for each occultation season. The peak density increases with decreasing SZA. All observed layers fall in the range 59° < SZA < 91°. The total number of observed electron density profiles in the SZA range 50° < SZA < 100° per 10° interval is given in the top of the figure. In the range 60° < SZA < 90°, about 30% of all observed electron density profiles have a low lying meteor layer.

[e.g., *Janches et al.*, 2004]. Neutral magnesium atoms and sporadic E layers show similar trends [*Haldoupis et al.*, 2007; *Correira et al.*, 2008]. Showers, on the other hand, are only expected to produce short-lived increases in meteoric layer plasma density [*McNeil et al.*, 2001]. The observed variability of terrestrial meteor layers has so far prevented definite statements on the effect of showers in the ionosphere. It is possible, for example, that the occurrence of all major meteor showers in the June-January period could produce or mimic a seasonal effect similar to that of the sporadic flux; we know of no works that have explored this possibility. Models have not yet addressed how either meteor showers or a non-isotropic sporadic fux affect Venusian meteor layers. Thus, any conclusions from terrestrial observations and simulations can be applied to Venus only with care until more data and relevant models become available. We note, however, that the orbits of several comets as well as known meteoroid streams do cross the Venusian orbit. These are provided in Table S1. Finally, we propose that the lack of a significant obliquity at Venus significantly simplifies the assessment of the importance of the sporadic meteor source population for these plasma layers.

[17] In summary, the question of whether Venusian meteor layers are produced primarily by sporadic or shower meteoroids remains unanswered at present, but is important because of its implications for understanding the meteoroid environment, its characteristics and effects on the planetary bodies of our solar system.

5. Conclusions

[18] The VeRa radio science experiment on Venus Express has detected distinct, low-laying layers of electron density at a mean altitude of 113 ± 4 km, well below the nominally stable base of the Venus dayside ionosphere. The origin of these layers is attributed to electron production associated with the influx of meteors into the atmosphere. The observed altitude is similar to the altitudes where ablating meteoroids should deposit metallic species into the Venusian atmosphere but does not agree with the predicted ionization peak. The electron density enhancement is due to photoionization of the ablated metallic atoms and/or charge exchange with short-lived ions (O_2^+) to create long-lived ions (Mg^+, Fe^+), thereby decreasing the ion/electron recombination rate. The observed "meteor layers" do occur near expected Venus crossings of comet and meteoroid stream orbits—events that would produce meteor showers in the atmosphere. However, we cannot as yet say whether the dominant source for the meteoric layer material is showers or the sporadic meteor flux. Table S1 also lists four cases of meteor layers where a relation to a candidate comet or meteor steam is not obvious.

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M. K. Bird, Argelander Institut für Astronomie, Universität Bonn, D-53121 Bonn, Germany.

A. A. Christou, Armagh Observatory, College Hill, Armagh BT61 9DG, UK.

B. Häusler, Institut für Raumfahrttechnik, Universität der Bundeswehr München, D-85577 Neubiberg, Germany.

M. Pätzold and S. Tellmann, Rheinisches Institut für Umweltforschung, Abteilung Planetenforschung, Universität zu Köln, D-50931 Cologne, Germany. (martin.paetzold@uni-koeln.de)

G. L. Tyler, Department for Electrical Engineering, Stanford University, Stanford, CA 94305-9515, USA.

P. Withers, Center for Space Physics, Boston University, Boston, MA 02215, USA.