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Upper Limits to the Nightside Ionosphere of Mars

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Abstract. The nightside ionosphere of Mars could be produced by electron precipitation or by plasma transport from the dayside, by analogy to the Venus, but few measurements are available. We report here model calculations of upper limits to the nightside ion densities on Mars that would be produced by both mechanisms. For the auroral model, we have adopted the downward traveling portions of the electron spectra measured by the HARP instrument on the Soviet Phobos spacecraft in the Martian plasma sheet and in the magnetotail lobes. For the plasma transport case, we have imposed on a model of the nightside thermosphere, downward fluxes of O^+ , C^+ , N^+ , NO^+ and O_2^+ that are near the maximum upward fluxes that can be sustained by the dayside ionosphere. The computed electron density peaks are in the range $(1.3 - 1.9) \times 10^4 \text{ cm}^{-3}$ at altitudes of 159 to 179 km. The major ion for all the models is O_2^+ , but significant differences in the composition of the minor ions are found for the ionospheres produced by auroral precipitation and by plasma transport. The calculations reported here provide a guide to the data that should be acquired during a future aeronomy mission to Mars, in order to determine the sources of the nightside ionosphere.

INTRODUCTION

Since its discovery by the radio occultation experiment on Mariner 5 [Kliore *et al.*, 1967], the major mechanisms for maintenance of the nightside ionosphere of Venus have been much disputed. The major source at high solar activity is now generally believed to be transport of atomic ions from the dayside [e.g., Knudsen *et al.*, 1980; Cravens *et al.*, 1983], and at low solar activity, precipitation of electrons that have been detected at high altitudes in the umbra [e.g., Gringauz *et al.*, 1979; Knudsen and Miller, 1985; Knudsen, 1988; Kliore *et al.*, 1991]. From a study of the densities and inferred production rates of mass-28 ions, the source of which is mainly electron precipitation, Fox and Taylor [1990] showed, however, that the precipitation source was highly variable over the first 600 Pioneer Venus (PV) orbits, which occurred during a period of high solar activity.

In contrast, much less is known about the nightside ionosphere of Mars. Some Viking radio occultation profiles from 90 to 125° solar zenith angle were recently examined by Zhang *et al.* [1990]. They found that, for about 60% of the available profiles at low solar activity, a well-defined electron density peak does not appear. For those cases in which it was detected, the average nightside peak density, about $5 \times 10^3 \text{ cm}^{-3}$, was significantly smaller than that of the Venus

nightside ionosphere. Most of the detectable Martian nightside peaks fall in the altitude range 150 to 180 km, compared to a dayside maximum near 130 km, and thus are higher relative to the dayside peak than those of Venus. Both the dayside and nightside peaks on Venus usually appear at 140–150 km. The Soviet spacecraft Mars 4 also obtained electron density measurements at low solar activity and 127° solar zenith angle [e.g., Vasil'ev *et al.*, 1975]. A two-peaked profile was inferred, with an upper peak of about $2 \times 10^3 \text{ cm}^{-3}$ at 190 km, and a lower peak of about $5 \times 10^3 \text{ cm}^{-3}$ at 110 km.

No information is available, however, about the identity of the ions, and their sources are uncertain. The HARP instrument on the Phobos spacecraft measured large fluxes of electrons in the vicinity of Mars. Verigin *et al.* [1991] and Haider *et al.* [1992] reported spectra measured in the plasma sheet and magnetotail lobes. Haider *et al.* [1992] used a two-stream electron transport code to compute the ionization rates that would result if the electrons precipitated into the nightside atmosphere. They also carried out a photochemical equilibrium calculation of the resulting electron density profile. Their computed maximum electron densities were 1.7×10^4 and $1.2 \times 10^4 \text{ cm}^{-3}$, at altitudes of 144 and 158 km, for the plasma sheet and magnetotail lobe spectra, respectively.

In addition to electron precipitation, it is also possible that some nightside ionization on Mars could be produced by transport of ions from the dayside, as suggested by Zhang *et al.* [1990]. Although nightward fluxes of ions have not been measured in situ at Mars, modelers [Shinagawa and Cravens, 1989, 1992; Fox, 1993] have found it necessary to impose a loss process for ions at the top of the dayside ionosphere in order to reproduce the ion densities measured by the RPA on Viking [Hanson *et al.*, 1977]. Shinagawa and Cravens [1989] suggested that the loss process is the divergence of the horizontal ion fluxes, by analogy to the Venus ionosphere. If those ions do not escape from the gravitational field of the planet, they may converge and flow downward on the nightside, producing a nightside ionosphere.

In this letter, we report model calculations of upper limits to the nightside ionosphere of Mars that would be produced by electron precipitation (the auroral model) and by ion transport from the dayside (the plasma transport model). The auroral model is similar to that of Haider *et al.* [1992]. For the ion fluxes from the dayside, we have imposed the dayside upward fluxes of O^+ , C^+ , N^+ , NO^+ and O_2^+ derived by Fox [1993] in the downward direction on a model of the neutral atmosphere near the midnight equator (including CO_2 , N_2 , CO and O) provided by S. Bougher [private communication, 1992; see also Bougher *et al.*, 1990]. In addition, we have assumed that the atomic nitrogen mixing

ratio is the same as that computed by Fox [1993] for the dayside, and we discuss the effects of this assumption on the model. Since our goal is to derive upper limits, high solar activity is assumed for all the models.

CALCULATIONS

The chemical scheme that we use here is essentially the same as that of Fox [1992]. For the precipitation calculations we employ a multi-stream electron transport code developed by H. S. Porter, which includes electron-neutral elastic and inelastic scattering, and electron-electron elastic scattering [e.g. Porter *et al.*, 1987]. We fitted the magnetotail lobe spectrum to a Maxwellian distribution with a characteristic energy of 20 eV, and the plasma sheet spectrum to a Gaussian centered at 180 eV with a standard deviation of 150 eV. The fraction of the observed electron flux that actually reaches the atmosphere is uncertain. On Venus, other evidence for precipitating electrons has appeared in nightside images at 1304 and 1356 Å that were recorded by the PV orbiter ultraviolet spectrometer. Fox and Stewart [1991] suggested that the average intensities could be reproduced if 8 to 28% of the electron flux measured by the PV retarding potential analyzer [Knudsen and Miller, 1985] at high altitudes in the wake did, in fact, find its way to the atmosphere. That fraction has been refined to 23% in a subsequent, more accurate calculation [Fox *et al.*, 1992].

For our ion transport model, the assumed downward ion fluxes are equal to the dayside upward fluxes derived by Fox [1993] for a high solar activity model, and are equal to 6.8×10^7 , 1.6×10^7 , 4.2×10^6 , 9.1×10^5 , and 2.0×10^5 $\text{cm}^{-2} \text{s}^{-1}$, for O_2^+ , O^+ , NO^+ , N^+ , and C^+ , respectively. The adopted upward fluxes were close to the maximum values that the dayside ionosphere could sustain.

On Venus, only atomic ions are assumed to be transported nightward in significant numbers. O^+ is the dominant ion at high altitudes (greater than 200 km) where the flow is assumed to occur. Because they are efficiently destroyed by dissociative recombination, the molecular ion lifetimes are short, and their densities are small. On the Martian dayside, however, where the electron and atomic ion densities are smaller, the lifetimes of O_2^+ and NO^+ are quite long, about 8400 and 3600 s, respectively, at 250 km. We have assumed here that these molecular ions survive transport to the nightside. Although we imposed upward fluxes of the molecular ions N_2^+ and CO_2^+ at the upper boundary of our dayside model, the chemical lifetimes of those ions at 250 km are more than an order of magnitude less than that of O_2^+ . We have assumed that these ions are destroyed in chemical reactions before they are transported a significant distance. They cannot be definitively excluded, however, without some knowledge of the altitude and velocity of the flowing ions. Their inclusion or exclusion does change the density profiles (mostly of the species themselves), but does not affect the magnitude or altitude of the electron density peak.

RESULTS

Figure 1 shows the ion densities computed for the plasma transport model. The major ion over the whole altitude range is O_2^+ , which attains a maximum density in this model of $1.27 \times 10^4 \text{ cm}^{-3}$ at an altitude of about 179 km. Even if no O_2^+ is assumed to be transported, the dominant ion at high altitudes on the nightside is O^+ , but the maximum density is reduced by about a factor of about two.

Fig. 1. Ion density profiles calculated for the plasma transport model of the nightside ionosphere.

Figures 2a and 2b show the ion production rate and the resulting steady state ion densities computed for the magnetotail auroral model. The production rate maximum is about 20 CO_2^+ ions $\text{cm}^{-3} \text{s}^{-1}$ at an altitude of about 169 km. The computed O_2^+ maximum density appears at a slightly higher altitude, about 172 km, with a value of about $1.4 \times 10^4 \text{ cm}^{-3}$. The electrons detected in the plasma sheet were more energetic, thus they are predicted to penetrate further into the atmosphere. Figures 3a and 3b show that the peak production rate is about $52 \text{ cm}^{-3} \text{s}^{-1}$ near 157 km, about 12 km below the peak for the magnetotail spectrum. The peak in the computed density of O_2^+ is about 2 km higher than the peak in the production rate, with a magnitude of about $1.9 \times 10^4 \text{ cm}^{-3}$.

The maximum production rates and peak densities agree fairly well with the calculations of Haider *et al.* [1992], but our computed auroral peak densities are 14–15 km above theirs. The assumption of photochemical equilibrium, which we show below is not appropriate, accounts for about 3 km of the difference for the magnetotail spectrum. Most of the difference, however, arises from our use of a high solar activity model rather than the moderate solar activity model employed by Haider *et al.*, and from the use of the CO_2 elastic cross sections of Shyn *et al.* [1978], rather than those of

Fig. 2. (a) Ion production rates, and (b) ion densities computed for the magnetotail auroral model.

Fig. 3. (a) Ion production rates, and (b) ion densities computed for the plasma sheet auroral model.

Register *et al.* [1980], which are smaller by a factor of about two. Also, Haider *et al.* used the measured fluxes from the plasma sheet spectrum, whereas we fit the spectrum to a Gaussian, which underestimated some of the higher energy points.

We have also computed the resulting ion densities for combined ion transport and precipitation by electrons. The results for the magnetotail lobe and plasma sheet spectra are shown in Figures 4a and 4b, respectively. For the magnetotail lobes, the O_2^+ peak is near 177 km, with a density of

Fig. 4. (a) Altitude profiles of ion densities computed for the case of plasma transport combined with magnetotail auroral precipitation. (b) Ion densities computed for the case of plasma transport combined with plasma sheet auroral precipitation.

about $1.8 \times 10^4 \text{ cm}^{-3}$. The plasma sheet spectrum produces a broad peak with a lower shoulder in the O_2^+ profile, which is really the superposition of the upper transport peak and the lower electron precipitation peak. The maximum density is about $1.9 \times 10^4 \text{ cm}^{-3}$ at 173 km.

DISCUSSION AND CONCLUSIONS

Fox [1992] analyzed six Pioneer Venus nightside orbits near the antisolar point and, from the measured O^+ maximum densities, derived an average downward O^+ flux of about $1 \times 10^8 \text{ cm}^{-2} \text{ s}^{-1}$, approximately 30% of the maximum upward flux that could be imposed at the upper boundary of a dayside Venus model. It is likely that on Mars also, the actual downward flux on the nightside is only a fraction of the maximum possible flux. Thus even if plasma transport is a source, the true nightside electron densities at high solar activity are likely to be smaller than the upper limits of $(1-2) \times 10^4 \text{ cm}^{-3}$ that we have computed here.

On the Martian nightside, the predicted total electron densities are small and the lifetimes of molecular ions against loss by dissociative recombination are long. Moreover, the peaks occur high in the atmosphere where the lifetimes against diffusion are much shorter than at the dayside ion peak. For example, the lifetime against dissociative recombination of O_2^+ near 172 km is about 450 s, compared to a diffusion lifetime of 900 s. In the auroral models the altitude of the peak electron density changes when the magnitude of the electron flux is varied, showing that diffusion plays a role in determining the altitude profiles. If the magnetotail lobe fluxes are reduced by a factor of 10, the computed peak altitude is about 4 km lower. For 10% of the plasma sheet spectrum, the peak rises by 9 km to 168 km.

There are significant differences between the compositions of the ionospheres produced by plasma transport and by auroral precipitation. The most striking difference in the two models is between the density profiles for CO_2^+ and for the mass-28 ions, N_2^+ and CO^+ . Figure 1 shows that for the plasma transport ionosphere the CO^+ peak density is more than three orders of magnitude smaller than the electron (or O_2^+) density peak, and there is no N_2^+ . In the aurorally produced ionospheres in Figures 2 and 3, the sum of CO^+ and N_2^+ is about an order of magnitude larger. There is no N_2^+ in the plasma transport model because none of the transported ions is capable of producing it in chemical reactions. An important source of N_2^+ in the Venus nightside ionosphere is charge transfer from He^+ to N_2 . The helium mixing ratio in the Martian atmosphere is unknown; consequently, the He^+ densities, and thus the source of N_2^+ due to charge transfer from He^+ could not be modeled.

Even larger differences are seen in the peak density of CO_2^+ , which is about a factor of 600 smaller than the electron density peak in the transport model. In both of the auroral models, the difference is only about a factor of 20. Significant but smaller differences are observed in the O^+ profiles, and those of the other atomic ions, which are larger in the plasma transport model than in the auroral model. For example, the peak O^+ density is a factor of 20 less than the electron density peak in the transport model, but it is a factor of 60–140 smaller in the auroral models.

The upper NO^+ peak density is smaller by a factor of 2–3 in the auroral models compared to that in which the NO^+ is assumed to be transported in, but the lower NO^+ peak is relatively invariant for the auroral and transport models. Because it is produced mainly in the reaction of

O_2^+ with N, and destroyed by dissociative recombination, the NO^+ densities are directly proportional to the assumed N densities, and to the ratio of $[\text{O}_2^+]$ to $[\text{e}]$, which is similar for both models. If the nightside N densities are smaller than those assumed here, the magnitude of the lower peak would also be proportionately smaller.

The Viking measured electron density profiles are for low solar activity, and the peak electron densities are smaller than our calculated upper limits [Zhang et al., 1990]. A solar activity variation of about a factor of two has been observed in the Venus nightside electron densities [e.g. Kliore et al., 1991]. The upper peak in the Mars 4 profile may be consistent with precipitation of electrons of lower energy than the Phobos magnetotail lobe spectrum into the nightside thermosphere. The lower peak is, however, difficult to explain. The altitude of the peak at 110 km is about 50 km or 5 scale heights below our lowest peak. Our calculations show that such a peak is unlikely to arise from either electron precipitation or plasma transport. It is not known whether it could represent an artifact arising from deviations from spherical symmetry.

The aim of these calculations has been to predict the maximum possible nightside ionosphere on Mars. Both the transport of ions from the dayside and precipitation of electrons that have been observed at high altitudes by the Phobos spacecraft have been included. Assuming that the electrons measured by the HARP instrument on Phobos actually precipitate into the atmosphere, and/or that the downward fluxes of ions are near the maximum upward fluxes that the dayside can sustain, we find that the maximum electron density is in the range $(1.3 - 1.9) \times 10^4 \text{ cm}^{-3}$. These are extreme assumptions, and we do not expect that these conditions actually prevail on average. In situ measurements from a future aeronomy mission to Mars will probably be necessary to determine the actual conditions in the nightside ionosphere. Furthermore, given the uncertainties in the electron spectra and in the neutral atmosphere, radio occultation data alone will not be sufficient to determine the origin of the nightside ionosphere.

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