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ON THE POSSIBLE SOURCE OF THE IONIZATION IN THE NIGHTTIME MARTIAN IONOSPHERE
1. PHOBOS 2 HARP ELECTRON SPECTROMETER MEASUREMENTS

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Abstract. The measurements of electron spectra in the Martian magnetosphere by the HARP instrument on board the Phobos 2 orbiter are presented. The energy of the electrons (a few tens of electron volts) is sufficient for the impact ionization of the planetary neutral gas, and the characteristic flux of electrons (~ 10^8 cm^{-2} s^{-1}) could produce the nightside ionospheric layer with a peak density of a few thousands of electrons per cubic centimeter, which corresponds to densities observed earlier during radio occultations of the Mars 4 and 5 and Viking 1 and 2 spacecraft. The possibility of magnetospheric electron precipitation into the nightside atmosphere of Mars is in agreement with the mainly induced nature of the magnetic field in the planetary magnetotail (as at Venus), while the variability of the Martian nightside ionosphere may be explained by the partial screening of the atmosphere by a weak intrinsic magnetic field of the planet.

Introduction

The first measurements of electron spectra by the hyperbolic retarding potential analyzer (HARP) on board the Phobos 2 orbiter revealed the permanent presence of electron fluxes deep in the Martian magnetosphere including the shadow of the planet [Shutte et al., 1989]. The characteristic energy of these electrons was quite different in the plasma sheet (hundreds of electron volts) and in the magnetotail lobes (tenths of an electron volt), but in any case this energy was sufficient for impact ionization of the Martian neutrals.

It is known and generally accepted now that electrons precipitating from the induced magnetotail of nonmagnetic Venus are the main (during solar cycle minimum and high solar wind pressure solar cycle maximum conditions) and permanently operating source of the ionization maximum of the nightside ionosphere of this planet [Gringauz et al., 1977, 1979; Chen and Nagy, 1978; Breus et al., 1985; Knudsen et al., 1987; Zhang et al., 1990]. Recent magnetic measurements on board Phobos 2 revealed that the magnetic field in the Martian magnetotail is mainly induced also (though the possible existence of a weak intrinsic planetary magnetic field has not been ruled out) [Yeroshenko et al., 1990]. In this case, it is reasonable to assume that the Martian magnetospheric electrons could precipitate in the nightside atmosphere of the planet, resulting in collisional ionization of the neutral atmosphere

In the present paper, after a brief description of HARP observations on board Phobos 2, the electron density in the nightside ionosphere will be estimated using the measured fluxes of ionizing electrons. Comparison of these estimations with available radio occultation measurements of the nighttime Martian ionosphere permits us to conclude that the magnetospheric electrons could play an essential role in the formation of the nighttime ionosphere of Mars.

Observations

In the first two orbits during a high temporal resolution mode of operation, the HARP instrument on board the Phobos 2 orbiter measured differential electron spectra in the energy range from 3 to 480 eV in 25 logarithmically spaced energy windows. Electrons were measured simultaneously in eight sectors (20° x 20° each) symmetrically arranged relative to the antisolar axis, so behind Mars this instrument registered the fluxes of electrons moving toward the planet. The peculiarities of the HARP instrument are described in more detail by Szucs et al. [1990].

In Figure 1 the second elliptic orbit of Phobos 2 is given in Mars-centered aberrated solar ecliptic (ase) coordinates rotated by 2.5 deg to take into account the aberration of solar wind with a velocity of ~ 550 km/s [Rosenbauer et al., 1989] due to orbital motion of the planet with a velocity of ~ 24.1 km/s. Points along the orbit mark 10-min intervals of time. The highlight of electron measurements during this orbit is shown in Figure 2 [Shutte et al., 1989]. This figure presents 2-min averages of energy spectra measured by the HARP instrument in one of the eight angular sectors (~ 56 deg from the symmetry axis). The baselines in Figure 2 correspond to the instrument count rate of 1 count per second.

In Figures 1 and 2 those parts of the trajectory where the spacecraft passed through the solar wind are indicated by light solid lines, the foreshock region is indicated by wavy lines, shocked solar wind is marked by heavy solid lines, and the passage through the Martian magnetosphere is indicated by dashed lines. Crosses on the

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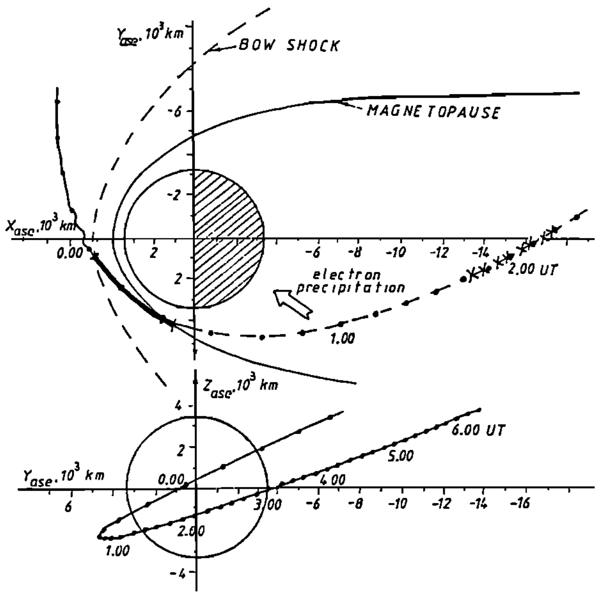

Fig. 1. The second elliptic orbit of Phobos 2 in Mars-centered aberrated solar ecliptic (ase) coordinates. Points along the orbit mark 10-min intervals of time. Light solid lines indicate parts of the orbit when the spacecraft was in the solar wind, wavy lines indicate when it passed through the foreshock region, shocked solar wind is marked by heavy solid lines, the passage through the Martian magnetosphere is indicated by dashed lines, and the crosses on the dashed lines show the positions where the plasma sheet was observed.

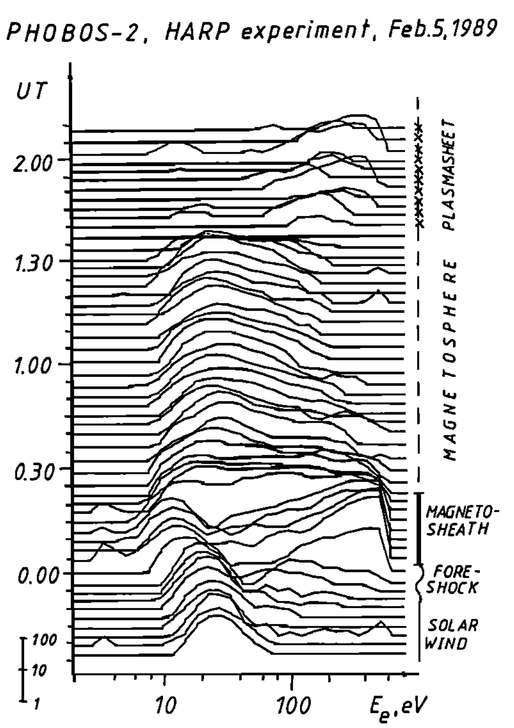

Fig. 2. The highlight of electron spectra during the orbit shown in Figure 1. The different plasma regions in the near-Martian space are indicated by the same marks as in Figure 1.

dashed lines show the parts of the trajectory where the plasma sheet was observed. In Figure 1, approximate positions of the most important boundaries, the bow shock and the magnetopause, are shown by dashed and solid lines, respectively. The positions of all boundaries and regions were derived from the specific changes in the proton spectra measured by the TAUS instrument (proton and alpha particle spectrometer) [Rosenbauer et al., 1989], in the electron spectra measured by HARP [Shutte et al., 1989], in the magnetic field [Riedler et al., 1989], and in plasma waves [Grard et al., 1989].

An important feature of the HARP measurements is the existence of noticeable fluxes of electrons everywhere in the Martian magnetosphere [Shutte et al., 1989]. The characteristic energy of the electrons was quite different in different parts of the magnetosphere. In the plasma sheet region, in the vicinity of magnetic field reversal, it reached some hundreds of electron volts while in the magnetosphere tail lobes the electrons were colder, with energies of a few tenths of an electron volt [Shutte et al., 1989]. In any case the energy of the main magnetospheric electron population was sufficient for impact ionization of neutral gas.

Figure 3 presents the spectrum of ionizing electron fluxes f(E) averaged over a 20-min interval, characteristic of the magnetotail lobes (the main volume of the magnetotail). In the lobes maximal electron fluxes of ~ 10^6 cm^{-2} s^{-1} sr^{-1} eV^{-1} were observed for the electrons with ~ 20 eV energy. Since the main population of electrons in the magnetosphere was more or less isotropic (except the high-energy tail of spectra), the total omnidirectional flux of electrons can be estimated to be $j \sim 4\pi\int f(E)\,dE \sim 3.8 \times 10^8$ cm^{-2} s^{-1} from the data of Figure 3. It includes the omnidirectional flux of electrons with energy E > 30 eV of $j_o \sim 2 \times 10^8$ cm^{-2} s^{-1}.

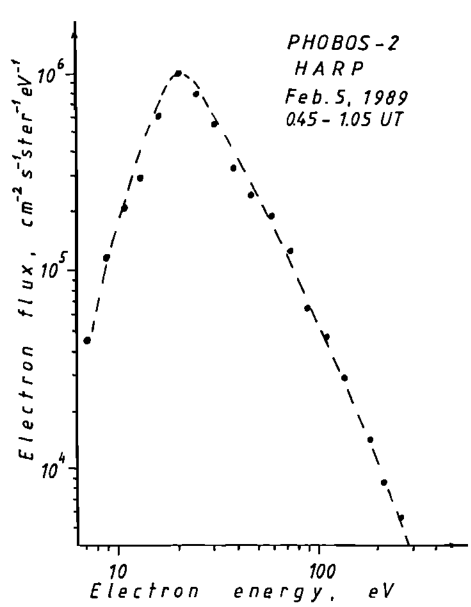

Fig. 3. The spectrum of electron fluxes averaged over a 20-min interval, characteristic of the Martian magnetotail lobes. The omnidirectional flux of electrons with energy E > 30 eV is approximately $j \sim 2 \times 10^8$ cm^{-2} s^{-1}.

Although part of the electrons observed in the magnetosphere are moving toward the planet, it is unclear whether they could actually reach ionospheric heights and produce the principal ionization layer. The realization of such a precipitation was observationally proved for nonmagnetic Venus by Spenner et al. [1981]. If Mars possesses a weak intrinsic magnetic field, some part of the nightside planetary atmosphere could be screened from the electron precipitation. To proceed with an estimate of the ionospheric layer produced by electron impact, we will assume that electrons could finally reach ionospheric heights.

Electron Density Estimation

There are a number of theoretical approaches to account for the electron energy degradation in the Martian atmosphere, the continuous slowing down approximation of Green and Barth [1967], the diffusion approach of Nisbet [1968], the two-stream method of Banks and Nagy [1970], the Monte Carlo calculations of Cicerone and Bowhill [1971], the analytical yield approximation of Green and Singhal [1979], and so forth. In the present paper we will use the simple analytical approach of Gringauz et al. [1977], which is reasonable in cases where the characteristic energy of the precipitating electrons is a few times larger than the ionization threshold (~ 13.8 eV for CO_2) and the electron fluxes are rapidly decreasing with increasing energy (see Figure 3).

The total electron impact ionization cross section σ_i of CO_2 rapidly grows with electron energy from ~ 4 x 10^{-17} cm^2 for E ~ 20 eV to ~ 1.5 x 10^{-16} cm^2 for E ~ 30 eV, then slowly increases to a value nearly 2 times the latter for E ~ 100 eV, and then decreases to ~ 1.4 x 10^{-16} cm^2 for e ~ 1000 eV [Sawada et al., 1972]. Taking into account that the electron flux rapidly decreases with energy for E > 20 eV (Figure 3), in further estimations we will assume σ_i ~ 1.5 x 10^{-16} cm^2 for E > 30 eV and σ_i ~ 0 for E < 30 eV. The energy loss for the excitation before the ionization collision of electrons with energies of 30 - 100 eV is 4 - 6 eV according to Sawada et al. [1972], which is small compared to the energy loss for the ionization. We will neglect this process hereinafter.

The impacting electrons are effectively isotropized by the elastic scattering with CO_2 molecules, (we assume that CO_2 is the only neutral gas component in the altitude region of interest) whose typical cross section is nearly σ_c ~ 1.5 x 10^{-15} cm^2 [e.g., McDaniel, 1964]. So the electron distribution function $F(\vec{v},\vec{r})$ can be reasonably well approximated by two terms of the expansion over spherical functions:

$$F(\vec{v}) = F_o(v) + \vec{v}/v\vec{F}_1(v) + \ldots \quad (1)$$

In a steady state with the external electric and magnetic fields being neglected, the electron kinetic equation can be reduced to the following system of equations (see, for example, Akhiezer et al. [1974]):

$$\begin{aligned} &1/3\, v\nabla\vec{F}_1(v) - J_o = 0, \\ &v\nabla F_o(v) - \vec{J}_1 = 0, \end{aligned} \quad (2)$$

where

$$J_o = \int \left(\frac{\partial F}{\partial t}\right)_c \frac{d\Omega}{4\pi}$$

and

$$\vec{J}_1 = 3\int \left(\frac{\partial F}{\partial t}\right)_c \frac{\vec{v}}{v}\frac{d\Omega}{4\pi}$$

are the first and second moments of a collisional integral.

Because of collisions during the time dt the number of electrons whose velocities are in the interval $(\vec{v}, \vec{v} + d\vec{v})$ will be changed in the following way:

$$\begin{aligned} \left(\frac{\partial F}{\partial t}\right)_c v^2 dv d\Omega dt = n_n v[&-\sigma_c F(\vec{v}) + \sigma_c F_o(v) \\ &-\sigma_i F(\vec{v}) + \sigma_i F_o(\sqrt{v^2 + 2E_i/m_e})\,(1 \\ &+2E_i/m_e v^2)]\, v^2 dv d\Omega\, dt, \end{aligned} \quad (3)$$

where n_n is the CO_2 number density. The first and the third terms in (3) describe the electron outflow from the velocity interval mentioned as a result of elastic and ionizing collisions, respectively; the second term is the inflow of electrons which underwent elastic scattering to the interval $(\vec{v}, \vec{v} + d\vec{v})$, while the last term is the inflow of electrons which lost energy E_i through the ionization. It was assumed that the electron energy does not change in the case of elastic scattering, while during ionization, scattering decreases by E_i, and that after collisions of both types all directions of electron velocities are equally probable.

In a case where electron fluxes are decreasing rapidly enough with increasing energy,

$$F_o(v) >> F_o(\sqrt{v^2 + 2E_i/m_e}), \quad (4)$$

the last term in (3) can be neglected. This means that we will neglect ionization produced by electrons which have already undergone an ionizing collision. Taking relations (3) and (4) into account, $\vec{F}_1(v)$ can be eliminated from equations (2), thus leading to [Gringauz et al., 1977]

$$\begin{aligned} &\Delta F_o - (\nabla n_n, \nabla F_o)/n_n \\ &-3n_n^2 \sigma_i(\sigma_i + \sigma_c) F_o = 0. \end{aligned} \quad (5)$$

Assuming that in the atmosphere n_n and F_o depend only on altitude h, the CO_2^+ ion production rate q(h) can be derived by using the solution of (5), which falls monotonically with decreasing h [Gringauz et al., 1977]:

$$\begin{aligned} &q(h) = j_o \sigma_i n_n(h) \exp \\ &[-\sqrt{3\sigma_i(\sigma_i+\sigma_c)}\int_h^\infty n_n(h)\, dh]. \end{aligned} \quad (6)$$

The CO_2^+ ions are quickly removed by the reaction with atomic oxygen, thus leading to O_2^+ formation [Fox and Dalgarno, 1979; Nagy et al., 1983], which is the major ion in the vicinity of the dayside (and probably nightside) maximum. Under local equilibrium conditions between the ion production rate and O_2^+ dissociative recombination, the electron density in the nightside ionosphere can be estimated as

$$n_e(h) = \sqrt{q(h)/\alpha}, \quad (7)$$

where α = 1.9×10^{-7} $(300/T_e)^{1/2}$ [Mul and McGowan, 1979].

The height of the ionization maximum h_m is obtained from the condition $dn_n(h_m)/dh = 0$, and hence using the relation (3), we get

$$dn_n(h_m)/dh = -\sqrt{3\sigma_i(\sigma_i+\sigma_c)}\,n_n^2(h_m)\,. \tag{8}$$

Using the exponential approximation of n_n (h) in the vicinity of h:

$$n_n(h) = n_n(h_m)\exp[-(h-h_m)/H(h_m)]\,,$$

where $n_n(h_m)$ and $H(h_m)$ are the density and the scale height of CO_2 at h_m, from (8) it follows that

$$\sqrt{3\sigma_i(\sigma_i+\sigma_c)}\,n_n(h_m)H(h_m) = 1\,. \tag{9}$$

Additionally, in the vicinity of h_m, instead of (7) we can use the following expression:

$$n_e(h) = \sqrt{\frac{j_o\sigma_i n_n(h_m)}{\alpha}}\exp\{-\tfrac{1}{2}(h-h_m)/H(h_m) - \tfrac{1}{2}\exp[-(h-h_m)/H(h_m)]\}. \tag{10}$$

This permits us to estimate the electron density n_{em} at the electron density maximum as

$$n_{em} = \sqrt{\frac{j_o\sigma_i n_n(h_m)}{\alpha e}}\,. \tag{11}$$

Applying the recent model of the Martian neutral atmosphere constructed by Bougher et al. [1988] specifically for the period of Phobos 2 measurements, one can show that condition (9) is fulfilled at $h_m \sim 165$ km (equator, midnight), where $n_n \sim 10^9$ cm^{-3} and H ~ 10 km. Then in accordance with (11) the maximum electron density can be estimated as $n_{em} \sim 7 \times 10^3$ cm^{-3}. The electron density profiles calculated by (10) with n_{em} mentioned above are shown in Figures 4a and 4b by dot-and-dashed lines.

Discussion

First of all, it is reasonable to compare the calculated electron density profiles with the available information on the properties of the nightside ionosphere. The only source of such information is the radio occultation experiments which permit the study of the Martian nightside ionosphere with solar zenith angles χ less than ~ 125°.

The single-frequency radio occultations carried out in 1971-1972 during the primary and extended Mariner 9 missions [Kliore et al., 1972, 1973] did not provide clear evidence of the existence of the ionosphere above the nightside of Mars.

The existence of the Martian nightside ionosphere was reliably shown by more sensitive dual-frequency radio experiments on board the Mars 4 and 5 orbiters in February 1974 [Vasiliev et al., 1974, 1975]. From these measurements, two electron density profiles were obtained [Savich and Samovol, 1976] which are shown in Figure 4a by solid and dashed lines.

The nighttime ionosphere measurements during ~ 50 dual-frequency radio occultations of Viking 1 and 2 in 1977 were recently reevaluated by Zhang et al. [1990]. According to these data, in ~ 40% of the profiles the sensitivity of the experiment was sufficient to detect a peak of ionization in the Martian nightside ionosphere with peak density of $n_{em} \sim 5 \times 10^3$ cm^{-3}. Two of the three Viking 1 and 2 nighttime electron density profiles published by Zhang et al. [1990] are shown in Figure 4b (see also one profile in the work by Lindal et al. [1979]).

Just after the first radio occultation measurements it became clear that a source of ionization is required to produce the nighttime ionosphere of Mars [Savich and Samovol, 1976].

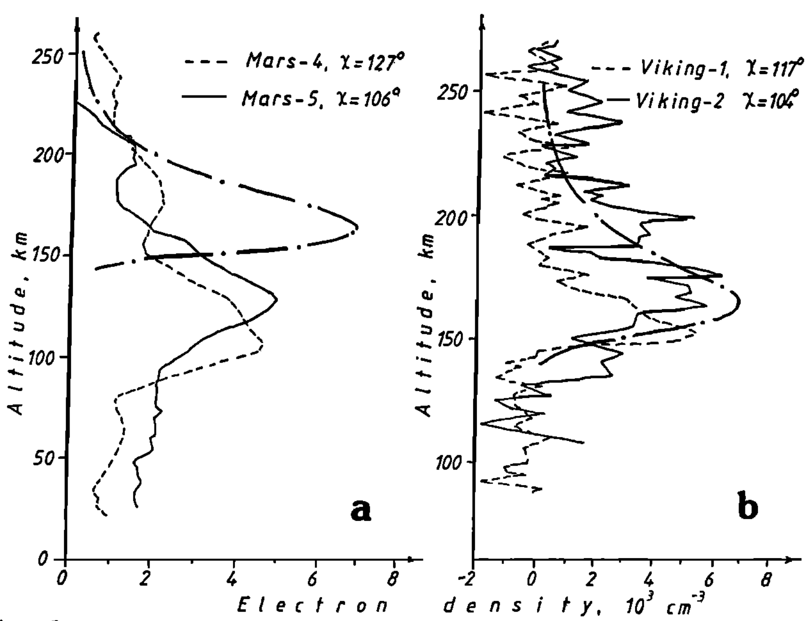

Fig. 4. The electron density profiles in the Martian nighttime ionosphere (solid and dashed lines) from the radio occultations of (a) Mars 4 and 5 and (b) Viking 1 and 2 compared with the electron density profiles calculated in the present paper (dot-and-dashed lines) with the use of the electron spectrum measured in the Martian magnetosphere (Figure 3).

This follows directly from a comparison of the specific recombination time of the nightside peak ~ $1/(\alpha n_{em})$, ~ 20 min, with the planetary rotation period of 24.6 hours. However, in some publications the necessity for such a source was questioned. For example, the nightside ionization layer was considered by Kolosov et al. [1976] as a simple layer being deformed by some mechanism and being moved to the dark side, while the evening ionization layer was supposed to consist primarily of electrons and ions formed during the daytime which have not yet had time to recombine [Lindal et al., 1979].

The ionization of the atmosphere by cosmic rays [Vasiliev et al., 1975; Kolosov et al., 1975] cannot be a source of the main peak of the Martian nighttime ionosphere, as this source mainly produces ionization at lower heights than the height of the main dayside maximum, i.e., essentially lower than the observed heights of the nightside peak [Zhang et al., 1990]. Two other possible sources of the Martian nighttime ionosphere, similar to those operating above the nightside of Venus, were mentioned recently by Zhang et al. [1990]. They are the competing processes of ionization transport from the dayside and of electron precipitation. There is no observational information on the intensity of the ionization sources mentioned above.

From the data presented in Figure 4 it is seen that the nightside electron density profiles of both Mars 4 and 5 and Viking 1 and 2 and those calculated from Phobos 2 HARP measurements have similar peak n_{em} values. The height of the peak of the calculated profiles, h_m ~ 165 km, is similar to that observed by Viking 1 and 2 (h_m ~ 140 - 180 km [Zhang et al., 1990]) but different from that (h_m ~ 110 - 130 km) observed by Mars 4 and 5.

The reasonably good coincidence of the measured and calculated n_{em} values (Figure 4) means that the intensity of electron fluxes observed in the magnetotail of Mars by the Phobos 2 HARP spectrometer is sufficient to support the Martian nighttime ionosphere, provided such electrons are actually precipitating into the planetary atmosphere.

The reason for the large difference between the peak heights observed by Mars 4 and 5 and the calculated peak height (Figure 4a) could be one of the following:

1. If the peak of ionospheric electron density in some nightside regions (or in the period of Mars 4 and 5 measurements) is caused by more energetic electrons which can provide multiple ionization (e.g., precipitating from plasma sheet; see Figures 1 and 2), it should be located a few tens of kilometers (a few scale heights) lower than the calculated peak.

2. A global dust storm could change the (dayside) ionosphere peak altitudes by 20 - 30 km due to heating effects in the lower atmosphere [Kliore et al., 1973; Martin, 1984].

3. The scale height of the topside Martian atmosphere is unusually sensitive to the variations of solar activity ($F_{10.7}$ index [Bauer and Hantsch, 1989]).

Both of the last two effects can lead to the variation of the density distribution in the thermosphere, so that the neutral gas density (n_n ~ 10^9 cm^{-3}) corresponding to the peak ionization rate is at different heights during different observational periods.

On the average the peak electron density of the nightside ionosphere of Mars (~ 5 x 10^3 cm^{-3}) is 2 times less than that of Venus (~ 10^4 cm^{-3} [Zhang et al., 1990]). If the nightside peak originates from the electrons precipitating from the magnetotail, which probably in turn originates from the solar wind electrons, this fact can be explained by the 2 times greater heliocentric distances of Mars compared to Venus. At the Martian orbit the solar wind electron fluxes are 4 times less, on average, than these fluxes at the orbit of Venus. Taking into account the square root dependence of n_{em} on the electron fluxes (equation (11)), we will get the necessary factor.

Why was the peak of nightside ionization observed in 100% of the spacecraft radio occultations at Venus but in only 40% of the spacecraft radio occultations at Mars? The reason may be connected with the partial screening of the Martian nightside atmosphere by a weak intrinsic magnetic field of the planet which is completely absent in the case of Venus. That this screening really exists might be checked by simultaneous measurements of magnetic field and three-dimensional electron spectra during the planned Mars Observer and the Mars-94 mission. Also, useful information on the distribution of the ionosphere density in the nightside hemisphere of Mars can be obtained by the topside-sounder experiment RLK on board Mars-94. We hope that the above mentioned missions will finally clarify the problem of the ionization sources in the nighttime ionosphere of Mars.

Conclusions

The measurements of electron spectra by the HARP instrument on board the Phobos 2 orbiter revealed the permanent presence of electron fluxes in the Martian magnetosphere with sufficient energy for impact ionization of planetary neutral gas. The characteristic omnidirectional flux of such electrons is of the order of 10^8 cm^{-2} s^{-1}. Because the Martian magnetotail is mainly induced, it is reasonable to assume that the magnetospheric electrons can precipitate into the nightside atmosphere, similar to the situation which has been observed behind Venus.

For Mars, the magnetospheric electrons will produce a layer of ionization at a height where the atmosphere density reaches ~ 10^9 cm^{-3}. The estimated peak density in this layer - several thousand electrons per cubic centimeter - corresponds to that observed by radio occultations of the Mars 4 and 5 and the Viking 1 and 2 spacecraft. Therefore the magnetospheric electrons can be considered as a possible source of ionization in the nighttime ionosphere of Mars, and the Phobos 2 HARP measurements as the first observations of such a source.

Further studies of the electron density distribution in the nightside ionosphere of Mars with simultaneous measurements of magnetic field and electron fluxes are necessary for the final solution of the problem of the ionization sources in the nighttime ionosphere of Mars.

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