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Calculated Ionization Rates, Ion Densities, and Airglow Emission Rates Due to Precipitating Electrons in the Nightside Ionosphere of Mars

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The calculations presented in this paper clearly establish that the electron fluxes measured by the HARP instrument, carried on board Phobos 2, could cause significant electron impact ionization and excitation in the nightside atmosphere of Mars, if these electrons actually do precipitate. The calculated peak electron densities were found to be about a factor of 2 larger than the mean observed nightside densities, indicating that if a significant fraction of the measured electrons actually precipitate, they could be the dominant mechanism responsible for maintaining the nightside ionosphere. The calculated zenith column emission rates of the O I 5577-Å and 6300-Å and CO Cameron band emissions, due to electron impact and dissociative recombination mechanisms, were found to be significant.

Introduction

The mechanism(s) responsible for maintaining the nightside ionosphere of Venus, where the effective night lasts about 58 Earth days, have been intensively discussed and studied, ever since Mariner 5 found a significant ionosphere to be present back in 1967 [cf. *Nagy et al.*, 1983; *Brace and Kliore*, 1991]. It is now fairly well accepted that electron impact ionization is the major source mechanism during solar cycle minimum conditions, while at solar maximum, transport from the dayside and electron precipitation combine to maintain the nightside ionosphere, depending on solar wind conditions. The corresponding problem for Mars has received practically no attention until recently, because (1) the measured nighttime peak densities are of the order of 5×10^3 cm^{-3}, which are significantly smaller than at Venus (also the data base is limited) and (2) the night is much shorter (nearly the same as that at Earth). However, two papers were recently published which deal with the nightside ionosphere of Mars, and these generated new interest in this topic. *Zhang et al.* [1990] collected all the nightside electron density data available; they found that the peak electron density is highly variable and at times is below the detection threshold. *Verigin et al.* [1991] showed that the electron fluxes measured in the magnetotail of Mars, by the hyperbolic electrostatic analyzer (HARP) electron spectrometer carried aboard the Phobos 2 spacecraft, are of the right magnitude to cause sufficient impact ionization to more than account for the measured nighttime electron densities.

The preliminary calculations published by *Verigin et al.* [1991] used a simple analytic method, developed by *Gringauz et al.* [1977], to calculate the ionization rates resulting from a representative measured electron energy distribution. The resulting ion density altitude profiles were calculated, assuming chemical equilibrium conditions, and compared to the nightside electron density profiles obtained by radio occultation techniques. In the work to be presented in this paper we extend the preliminary calculations of *Verigin et al.* [1991] by (1) considering electron energy distributions measured by the HARP carried on Phobos 2 in both the magnetotail and the plasma sheet, (2) using the more quantitative two-stream method to carry out the calculations, and (3) calculating the optical emission rates of a number of different airglow features, due to both electron impact and dissociative recombination processes.

Model Calculations

The hyperbolic electrostatic analyzer (HARP) carried by Phobos 2 measured the electron flux within the energy range of about 3-480 eV in eight angular sectors arranged symmetrically in the antisolar direction [*Szucs et al.*, 1990]. Figure 1 shows the characteristic electron spectra measured on February 5, 1990, in the magnetotail lobes (curve a: 0045-0105 UT) and in the plasma sheet (curve b: 0150-0210 UT) during the second elliptic orbit of Phobos 2. The position of Phobos 2 during these measurements is shown in Figure 1 of the *Verigin et al.* [1991] paper.

As indicated earlier, the electron impact ionization rate calculations to be presented in this paper were carried out using the two-stream method [*Nagy and Banks*, 1970]. This approach has been well documented in the literature and will not be discussed in this paper. The elastic and inelastic electron impact cross sections used in the two-stream calculations are given by *Gan et al.* [1990] and *Gan* [1991]. The differential cross sections for elastic collision with CO_2 were taken from *Trajmar et al.* [1983]. The inelastic cross sections were those given by *Strickland and Green* [1969] and then updated by *Sawada et al.* [1972*a*]. The elastic differential cross sections for CO are summarized by *Trajmar et al.* [1983]. The inelastic cross sections were taken from *Sawada et al.* [1972*b*] and *Jackman et al.* [1977]. The elastic cross sections used for O were obtained from *Sunshine et al.* [1967] and *Wedde and Strand* [1974]. The excitation cross sections for O were collected from the values given by *Green*

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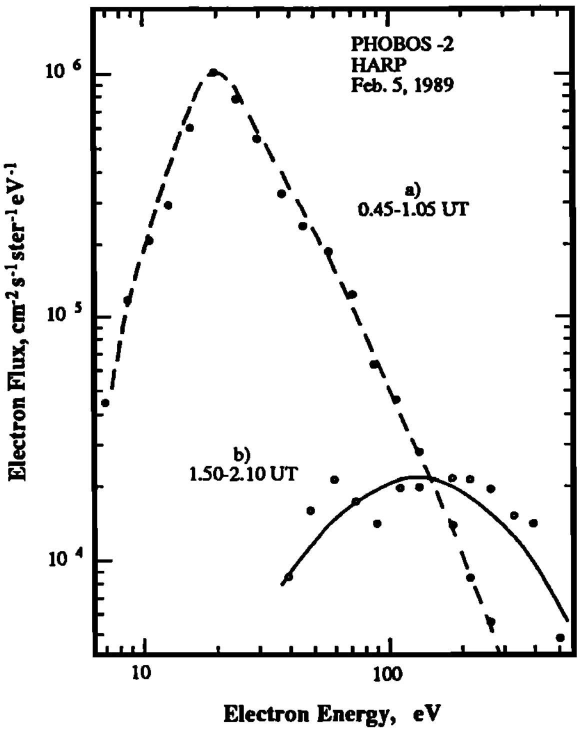

Fig. 1. Electron spectra measured by the Phobos 2 HARP instrument, during the second orbit in (curve a) the magnetotail lobe and (curve b) the plasma sheet.

and Stolarski [1972], *Stone and Zipf* [1974], *Jackman et al.* [1977], *Zipf and Erdman* [1985], and *Vaughan and Doering* [1987]. The ionization cross sections are from *Jackman et al.* [1977], but were adjusted to match *Burnett and Roundtree* [1979].

The cross sections used for the airglow calculations were from the compilation of *Fox and Stewart* [1991]; the normalization for the Cameron band emission from electron impact on CO_2 is the one suggested by *Conway* [1981].

The neutral atmosphere model used in the calculations was adopted from that of *Bougher et al.* [1990], for midnight and equatorial conditions. The atmospheric constituents considered were CO_2, CO, O, and N_2 (S. W. Bougher, private communication, 1992).

The ion densities resulting from the calculated impact ionization rates are obtained by assuming chemical equilibrium conditions, a reasonable assumption below about 200 km. The calculated ionization rates were used to calculate the densities of five ionic species: CO_2^+, O_2^+, O^+, CO^+ and NO^+. The reaction rates used in these calculations were given in Table 1 of Kim et al. [1989].

RESULTS

The impact ionization rates calculated for the two different electron energy spectra by the two-stream technique are shown in Figures 2 and 3, respectively. As expected, the altitude of the ionization peak for the more energetic plasma sheet electron spectrum is lower, at about 144 km, than the

TABLE 1. Zenith Intensities

	Cameron Band	5577Å			6300Å		
		Total	Impact	Dissociative Recombination	Total	Impact	Dissociative Recombination
Magnetotail electrons	59.6	37.6	20.4	17.2	32.8	5.7	27.1
Plasma sheet electrons	87.3	56.7	30.0	26.7	18.9	3.5	15.4

Values are in rayleighs.

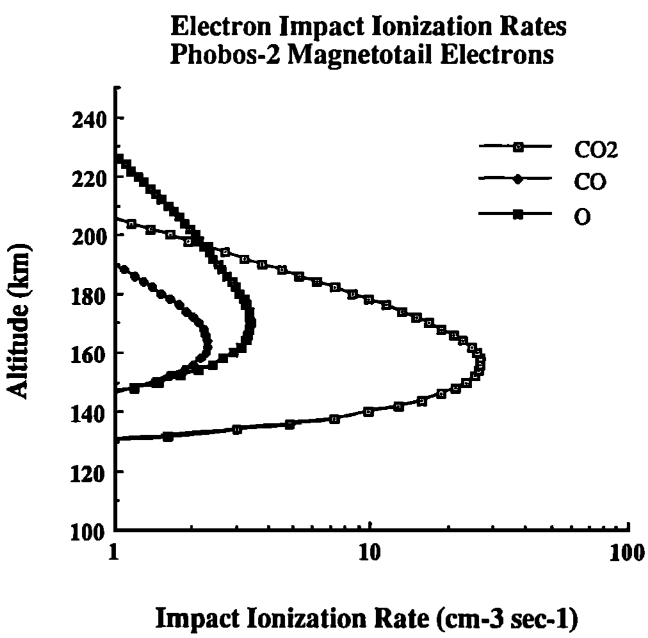

Fig. 2. Calculated electron impact ionization rates (magnetotail electrons).

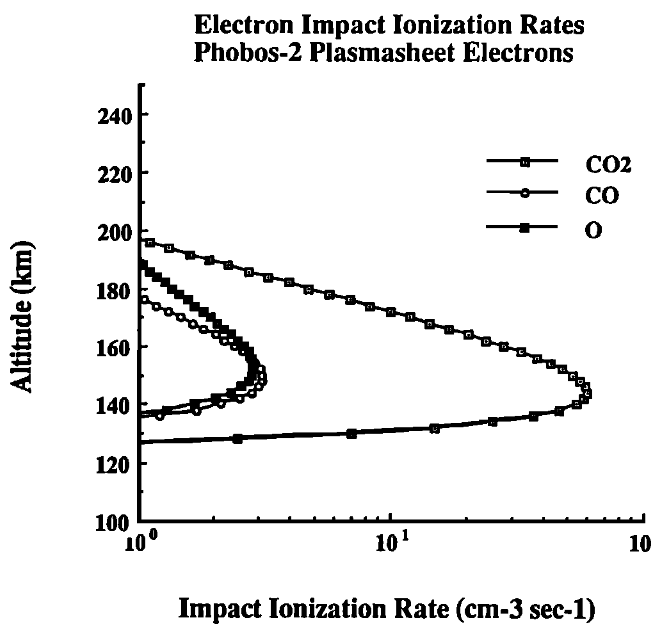

Fig. 3. Calculated electron impact ionization rates (plasma sheet electrons).

softer magnetotail one, which is at about 158 km. The peak total ionization rates for magnetotail and plasma sheet spectra are 3.14×10^1 and 6.53×10^1 cm^{-3} s^{-1}, respectively. The calculated ion density profiles, for the two cases, are shown in Figures 4 and 5. The major ion, as is the case for the dayside, is O_2^+. Among the minor ions, CO_2^+ is the most important in this altitude range. The calculated peak electron densities are 1.20×10^4 and 1.68×10^4 cm^{-3} for the magnetotail and plasma sheet cases, respectively. These peak densities are greater than the observed densities, which have been presented by *Zhang et al.* [1990], corresponding to solar cycle minimum conditions. The solar zenith angle limit

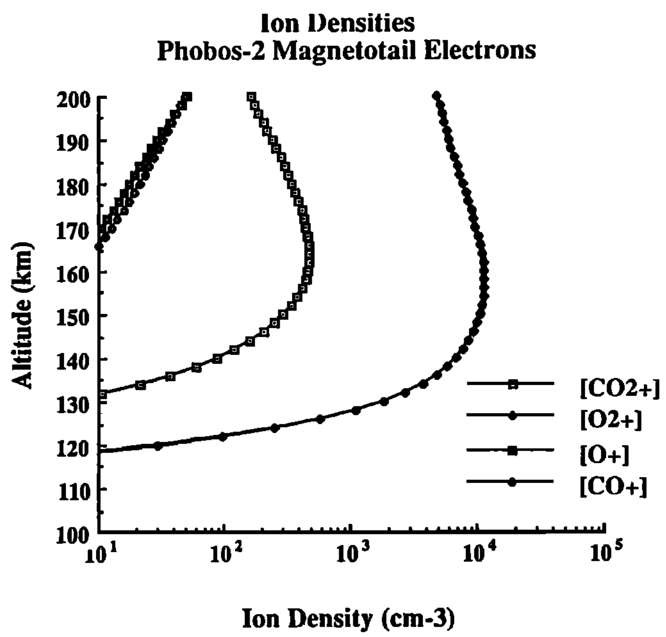

Fig. 4. Ion density profiles calculated assuming chemical equilibrium conditions (magnetotail electrons).

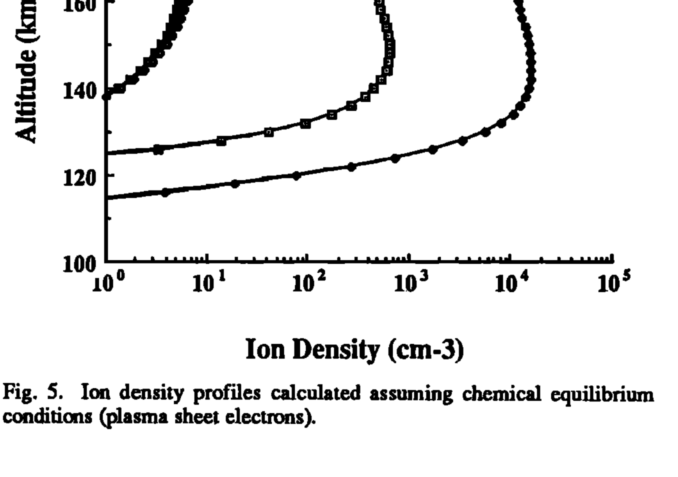

Fig. 5. Ion density profiles calculated assuming chemical equilibrium conditions (plasma sheet electrons).

of these radio occultation measurements is 125°. The average peak densities are ~5×10^3 cm^{-3}, but on numerous occasions no detectable densities were found. These observations are not in contradiction with the notion that the electron fluxes measured by Phobos 2, during solar cycle maximum conditions, are totally or partially responsible for the nightside ionosphere. It should be remembered that the electron fluxes were measured in the magnetotail and plasma sheet, and there is no way to establish what fraction of these electrons actually precipitate into the ionosphere.

It is not known at this time whether there is a small intrinsic field at Mars or not. The Phobos observations only indicated that the magnetic field strength is of the order of about 30 nT near the top of the ionosphere, and not whether it is induced or intrinsic [*Riedler et al.*, 1989]. This magnetic field strength is similar to that found at Venus [cf. *Luhmann and Cravens,* 1991], where auroral measurements have clearly demonstrated the presence of electron precipitation [*Fox and Stewart,* 1991]. What has been demonstrated by the calculations presented here is that if a significant fraction of these electrons do precipitate, the resulting impact ionization is sufficiently large to result in electron densities consistent with those observed. One can actually speculate further by assuming that on those occasions when the nightside electron density drops below the detection threshold, the magnetic configuration is such as to exclude the electrons from the ionosphere.

Electrons precipitating into the nightside atmosphere/ionosphere result in optical emissions. A weak but detectable aurora was observed on Venus and is believed to be the result of low-energy electron precipitation [*Fox and Stewart,* 1991]. There have been a number of different observations of optical emissions at Mars, but they concentrated on measurements of the UV dayglow [cf. *Barth et al.,* 1992]. The only published results which are relevant to the nightside of Mars are those of *Krasnopolsky and Krysko* [1976], who had a spectrometer on board Mars 5, covering the wavelength region 3000-8000 Å, with a spectral resolution of 20 Å; this instrument placed an upper limit of about 50 rayleighs (R) on the nightglow emissions in this wavelength range. We used our two-stream program to calculate the electron impact excitation rate of the 6300- and 5577- Å atomic oxygen line (the ^1S source due to electron impact on CO_2, as well as the direct excitation of O, was included) and the Cameron band of CO, the most intense emission in the ultraviolet dayglow. We also calculated the 6300- and 5577- Å and Cameron band excitation rates due to dissociative recombination.

The values for the branching ratios leading to $O(^1D)$ and $O(^1S)$ in the dissociative recombination of O_2^+ were taken from *Solomon and Abreu* [1989]. For the Cameron band, in the dissociative recombination of CO_2^+, we took the value given by *Wauchop and Broida* [1972]. We found that the dissociative recombination contribution to the Cameron band emissions is negligible for the cases considered here. In calculating the 6300- Å emission rates we took into account quenching by O and CO_2, with rate coefficients of 2×10^{-12} (*A. Dalgarno,* private communication, 1991) and $6.8 \times 10^{-11} \exp(117/T)$ cm^3 s^{-1} [*Streit et al.,* 1976], respectively. The calculated altitude profiles of these three emission rates, corresponding to the Phobos magnetotail and plasma sheet spectra, are shown in Figures 6 and 7. As an indication of the relative importance of electron impact excitation as compared to dissociative recombination, we

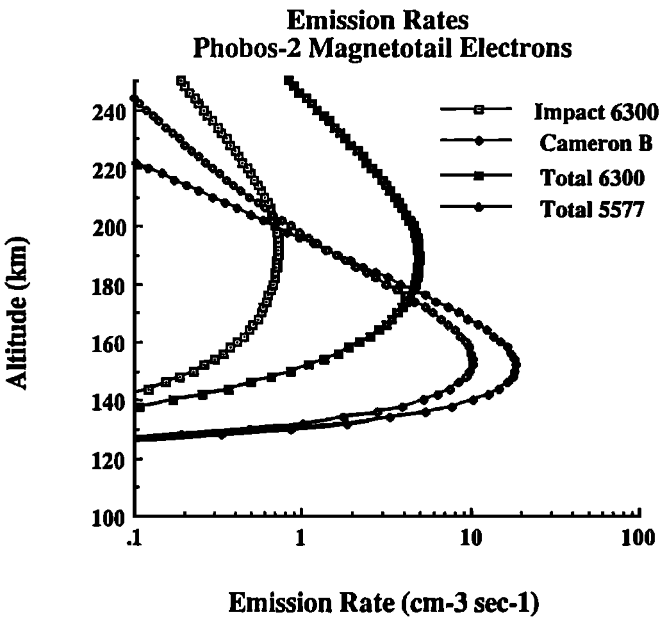

Fig. 6. Calculated airglow emission rates (magnetotail electrons).

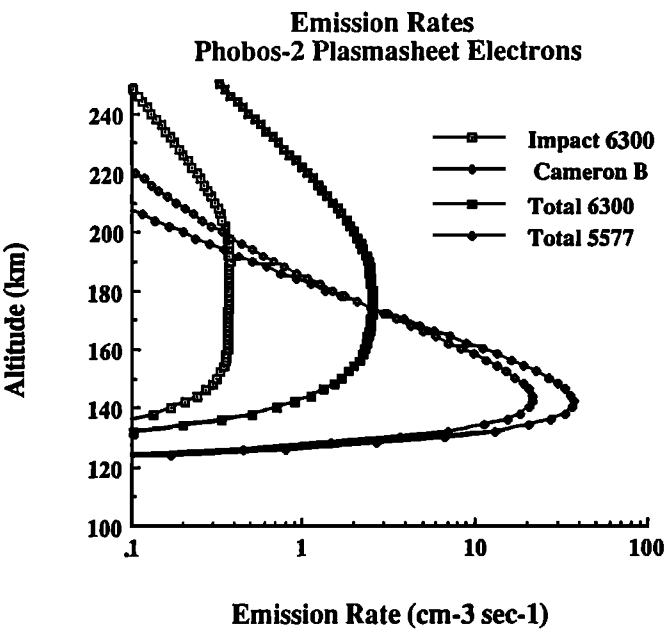

Fig. 7. Calculated airglow emission rates (plasma sheet electrons).

show the 6300- Å emission rates due to electron impact excitation as well as the total emission rates in Figures 6 and 7, respectively. The calculated zenith intensities are given in Table 1 for the two cases studied; for comparison the contributions from electron impact and dissociative recombination are also given. The total zenith intensities for the 5577- and 6300- Å emission are 37.9 and 32.8 R for the magnetotail case and 56.7 and 18.9 R for the plasma sheet, basically within the constraint set by the Mars 5 observations [*Krasnopolsky and Krysko*, 1976].

CONCLUSIONS

The calculations presented in this paper have clearly established that the electron fluxes measured by the HARP instrument, carried on board Phobos 2, could cause significant electron impact ionization and excitation in the nightside atmosphere of Mars, if these electrons actually do precipitate. More specifically, two representative electron spectra, observed in the magnetotail lobes and the plasma sheet, respectively, during the second orbit of Phobos 2 were used in calculating ionization rates and optical emission rates. The ionization rates were then used with a chemical equilibrium model to calculate the corresponding ion density profiles. The calculated peak electron densities were found to be about a factor of 2 larger than the mean observed nightside densities, indicating that if a significant fraction of the measured electrons actually precipitate, they could be the dominant ionization source responsible for maintaining the nightside ionosphere. The calculated emission rates of the 5577- Å, 6300- Å, and Cameron band emissions, due to electron impact and dissociative recombination mechanisms, were found to be significant. They have not been observed so far, but are detectable with present instrumentation technology.

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