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The Interaction of Electrons in the Optical Umbra of Venus With the Planetary Atmosphere—The Origin of the Nighttime Ionosphere

K. I. GRINGAUZ, M. I. VERIGIN, AND T. K. BREUS

Space Research Institute, USSR Academy of Sciences, Moscow, USSR

T. GOMBOSI

Central Research Institute for Physics, Hungarian Academy of Sciences, Budapest, Hungary

The ionization produced by electrons having energies of several tens of electron volts in the nighttime Venusian atmosphere is investigated on the basis of plasma measurements made on board Venera 9 and 10. We conclude that electron fluxes are sufficient to produce a nighttime ionosphere with a maximal electron density of 10^4 cm^{-3}. Calculated density profiles of the Venusian nighttime ionosphere show shapes closely resembling measured ones with closely agreeing values of maximal density and corresponding altitudes as well.

1. INTRODUCTION

The information now available on the nighttime ionosphere of Venus has been deduced from radio occultation observations during the short time intervals when the Mariner 5 and 10 space probes passed Venus [*Mariner Stanford Group*, 1967; *Howard et al.*, 1974] and from a number of observations of the same kind made by the Venera 9 and 10 satellites [*Aleksandrov et al.*, 1976*a*, *b*]. The results show considerable variability of the nightside ionosphere of Venus: the height distributions of the electron density have one or sometimes two maxima at altitudes of about 120–140 km. The electron number density in the upper maximum usually (though not always) exceeds n_e measured in the lower maximum.

It is rather difficult to interpret the origin, structure, and variability of the nightside ionosphere of Venus. Solar wind proton fluxes which were made turbulent behind the near-Venus bow shock and partially penetrate the nightside atmosphere of the planet, cosmic radiation, scattered solar electromagnetic radiation, CO_2 charge exchange with He^+ ions transported from the dayside ionosphere, and meteoric ionization have been discussed as possible sources of ionization in the nighttime atmosphere of Venus [*Mariner Stanford Group*, 1967; *Gringauz et al.*, 1968; *McElroy and Strobel*, 1969; *Butler and Chamberlain*, 1976]. These hypotheses either were unable to interpret satisfactorily the observed profiles or did not use measured ionization sources.

Direct measurements of electron plasma components made on Venera 9 and 10 in the optical umbra of Venus at altitudes of about 1500–2000 km revealed the existence of intense electron fluxes with energies exceeding several tens of electron volts [*Gringauz et al.*, 1976*a*, *b*, 1977]. These electrons, colliding with the neutral atoms in the nighttime atmosphere of the planet, can ionize them and therefore can be one of the sources of the nightside ionosphere. The assumption that these electron fluxes are responsible for the existence of the nighttime ionosphere was first mentioned by *Gringauz et al.* [1976*a*, *b*]. Summarizing the preliminary scientific results of the Venera 9 and 10 mission, *Keldysh* [1977] mentioned this possibility too. As *Gringauz et al.* [1977] pointed out, the detected $j_e \approx 10^8$ cm^{-2} s^{-1} electron fluxes are sufficient to produce a nighttime ionosphere with a maximum electron density $n_{em} \approx 10^4$ cm^{-3} which coincides with the data of radio occultation experiments. On the basis of the concept published by *Keldysh* [1977], that electron currents can serve as sources of ionization in the nighttime atmosphere, *Chen and Nagy* [1978], using their upper atmosphere model, also pointed out that nighttime ionosphere may be produced by a $j_e \approx 10^7$ cm^{-2} s^{-1} flux of ≈400-eV electrons or a $j_e \approx 3 \cdot 10^6$ cm^{-2} s^{-1} flux of ≈700-eV electrons.

It will be shown in this paper that the maximal electron density obtained by the radio occultation method in the nighttime ionosphere depends on the intensity of electron fluxes with energies of several tens of electron volts measured at altitudes of 1500–2000 km. This implies that these electron fluxes reach ionospheric altitudes and do play an essential role in nighttime ionosphere formation. Preliminary results of the radio occultation measurements were partly published by *Aleksandrov et al.* [1976*a*, *b*] and partly provided by M. Kolesov, N. Savich, and their colleagues.

2. CALCULATION OF ELECTRON DENSITY PROFILES

The q ion production rate due to electron fluxes measured in the optical umbra of Venus was calculated under the assumption of a flat and one-component nighttime atmosphere containing neutral CO_2 molecules. The density of neutrals $n_n(h)$ can be written near a height h_0 (which is approximately equal to the altitude of maximal electron density) in the form

$$n_n(h) = n_{n0} \cdot \exp\,[-(h - h_0)/H_0] \qquad (1)$$

where n_{n0} and H_0 are the density and scale height, respectively, of neutrals at altitude h_0. This approximation is justified for the calculation of q, since CO_2 is the major component of the atmosphere at ionospheric altitudes [*Marov and Ryabov*, 1974; *Chen and Nagy*, 1978]. In our previous work [*Gringauz et al.*, 1977], only the ionization of CO_2 by electrons was considered with an energy independent cross section, while ionization by electrons having undergone nonelastic collision was neglected. The present calculation, however, takes into account the energy dependent cross sections $\sigma_i(E)$ of various excitation processes and $S_i(E, T)$ of ionization ones (E and T represent the energy of primary and secondary electrons, respectively) which were taken from the work of *Sawada et al.* [1972]. Additionally, we assumed in our calculations that the velocity of primary electrons did not change their direction in elastic and inelastic collisions, while in our previous work we as-

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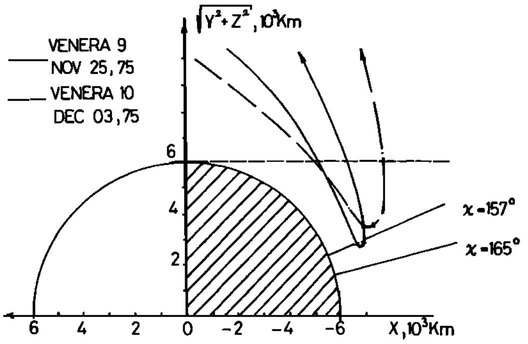

Fig. 1. Sections of trajectories of Venera 9 (on November 25, 1975) and Venera 10 (on December 3, 1975) close to the planet's surface. The X axis points toward the sun along the Venus-sun line. The zenith angle where radio occultation measurements were carried out is represented by χ.

sumed a nearly isotropic angular distribution of primary electrons as a result of multiple collisions [*Gringauz et al.,* 1977].

We have done calculations with two extreme assumptions, i.e., the nearly isotropic and totally anisotropic (this work) cases, as there is only rather poor experimental material on the angular distribution of electrons in the Venusian atmosphere. The results of both calculations will be compared in section 4.

The elastic collisions can be neglected in what follows, since the energy loss due to elastic collisions is very small ($\leq (4m/M)\cdot E \approx 5\cdot 10^{-5}\cdot E$, where m is the electron, M is the CO_2 molecule mass [*Landau and Lifshits,* 1973]) and we use the approximation that the velocity of an electron does not alter its direction after collision. The variation of the electron distribution function $f(E, \theta, h)$ through a layer with thickness dh can be written

$$\frac{df(E,\theta,h)}{dh} = \frac{n_n{}^{(h)}}{\cos\theta}\left\{f(E,\theta,h)\left[\sum_i \sigma_i(E) + \sum_i \int_0^{(E-I_i)/2} S_i(E,T)\,dT\right] - \sum_i f(E+W_i,\theta,h) \cdot (1+W_i/E)\sigma_i(E+W_i) - \sum_i \int_0^E f(E+I_i + T,\theta,h)[1+(I_i+T)/E]\,S_i(E+I_i+T,T)\,dT\right\} \tag{2}$$

where θ is the angle of incidence of the primary electron into the atmosphere, W_i is the average energy loss of the electron in the ith excitation process, and I_j is the threshold energy of the jth ionization process taken from the work of *Sawada et al.* [1972]. The first and second terms in (2) describe the decrease of the number of electrons with energy E due to energy losses by excitation and ionization. The third and fourth terms describe the increase of the number density of electrons with energy E from electrons initially having higher energies and losing energy W_i in excitation and energy $I_i + T$ in ionization processes. In (2) we neglected the electrons produced by ionization and, consequently, the additional ionization produced by them.

Equation (2) was solved numerically by using the Euler method. The initial electron distribution was assumed to consist of two groups of electrons having n_1, n_2 and T_1, T_2 densities and temperatures, respectively:

$$f(E,\theta,h)\,|_{h\to\infty} = (m/2\pi k)^{3/2}[n_1 T_1{}^{-3/2} \exp(-E)kT_1/ + n_2 T_2{}^{-3/2}\exp(-E/kT_2)] \tag{3}$$

As a consequence of (2), the f function has to be known at a given h altitude up to energies equal to $\max(E + W_i, 2E + I_i)$ to determine the values of f with E energy at altitude $h - dh$. Hence at high energies a supplementary condition was included:

$$f(E,\theta,h)|_{h\to\infty} = 0 \qquad E > E_{\max} \tag{4}$$

In our calculations the value $E_{\max} = 300$ eV was used, since the electron measurements on Venera 9 and 10 were carried out with retarding potentials $U_R \leq 300$ V; thus ionization of the Venusian atmosphere due to electrons of energies of >300 eV was neglected.

After the determination of $f(E, \theta, h)$ the ion production rate at altitude h was calculated:

$$q(h) = (4\pi n_n(h)/m^2)\cdot\int_0^\infty E\left[\sum_i \sigma_i(E)P_{i,\mathrm{auto}} + \sum_i \int_0^{(E-I_i)/2} S_i(E,T)\,dT\right]\cdot\int_0^{2\pi} f(E,\theta,h)\sin\theta\, d\theta\, dE \tag{5}$$

where $P_{i,\mathrm{auto}}$ is the efficiency of autoionization in the ith excitation process [*Sawada et al.,* 1972]. The density of ionospheric electrons was deduced from the condition of local equilibrium of ion production and recombination $q - \alpha n_e{}^2 = 0$; thus

$$n_e(h) = [q(h)/\alpha]^{1/2} \tag{6}$$

where $\alpha = 3.8\cdot 10^{-7}$ cm³ s⁻¹ is the $CO_2{}^+$ dissociative recombination coefficient [*Bardsley and Biondy,* 1970].

In this calculation the electron temperature dependence of α was neglected. We neglected the possibility that $O_2{}^+$ might be the major ion component in the atmosphere if atomic oxygen is abundant enough. In this case, (6) gives an electron density which is about 30% smaller than that for $CO_2{}^+$ ions ($\alpha_{O_2{}^+} = 2.2\cdot 10^{-7}$ cm³ s⁻¹ [*Bardsley and Biondy,* 1970]). As the main aim of our model is the understanding of the importance of electrons with energies of several tens of electron volts in the formation of the nighttime ionosphere, the neglect of components other than CO_2 in the neutral atmosphere does not affect our final conclusions.

3. COMPARISON OF CALCULATED AND MEASURED ELECTRON DENSITIES IN THE NIGHTTIME IONOSPHERE

Orbits of spacecrafts Venera 9 and 10 near the planet's surface are shown in Figure 1, while the plasma spectra mea-

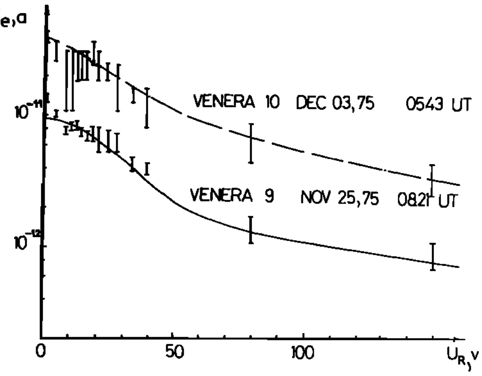

Fig. 2. I_e currents recorded by electron analyzer with various values of retarding potential. The parameters of the fitting curves are $n_1 = 0.8$ cm⁻³, $T_1 = 13$ eV, $n_2 = 0.04$ cm⁻³, $T_2 = 100$ eV for Venera 9 and $n_1 = 3.3$ cm⁻³, $T_1 = 15$ eV, $n_2 = 0.2$ cm⁻³, $T_2 = 100$ eV for Venera 10 measurements.

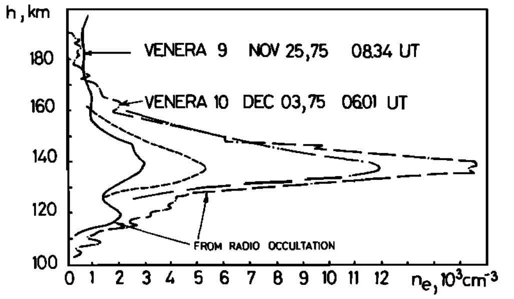

Fig. 3. Comparison of $n_e(h)$ profiles calculated from radio occultation measurements on November 25 and December 3, 1975, with the profiles deduced from the data of electron measurements.

sured at the deepest penetration into the optical umbra are presented in Figure 2 (heavy parts of lines in Figure 1 refer to corresponding parts of the orbits). Vertical bars in Figure 2 represent the interval within which the I_e current varied in 10 s, while the U_R retarding potential of the analyzing grid remained constant. I_e was recorded by a wide angle electron detector (±40°) pointing toward the antisolar direction. Supposing isotropic distribution of electrons around the satellite and approximating it by (3), similarly to *Gringauz et al.* [1974*b*], we calculated the values of the I_e taking into consideration the electron analyzer characteristics measured by *Gringauz et al.* [1976*a*]. Fairly good agreement between the estimated and measured I_e values over a wide range of U_R potential indicates the applicability of (3). Starting from the (3) initial distribution function (with parameters shown in Figure 2), we calculated the electron density profiles $n_e(h)$. Calculating the ionospheric electron density profiles in (1) we used the following parameters of the Venusian nightside neutral atmosphere: $n_{n0} = 2.10^9$ cm^{-3}, h_0 = 140 km, H_0 = 5 km. Figure 3 illustrates calculated and measured profiles. Radio occultation measurements were carried out for 12 min on November 25 and for 18 min on December 3 beginning from the deepest penetration in the optical umbra.

Inspection of Figure 3 shows that $n_e(h)$ profiles calculated by using the above mentioned parameters of the Venusian atmosphere and the measured profiles agree in the altitude of maximal electron density, in the density at the maximum, and in the width of profiles as well.

We have made a detailed analysis of estimated and measured maximal values of the electron density profiles. In Table 1 the cases in which both radio occultation and plasma electron component measurements were nearly simultaneously carried out are listed. For each case the date and universal time, the parameters of electron distribution function (n_1, n_2, T_1, T_2), determined from electron spectra measured in the deepest part of the optical umbra, the maximal value of the calculated electron density profile, and the average height and zenith angle χ_e of this measurement, and the time, the maximal density value, and the zenith angle of the radio occultation measurement are given.

In Figure 4 the calculated $n_{em}{}^c$ values are plotted against the measured n_{em} data. The correlation coefficient between the two quantities turns out to be 0.6, approximately, although the slope, estimated by the least squares method, is ~0.4 rather than the 1 that is indicated by the dashed line. Nevertheless, in view of the small number of measurements we feel that the degree of proportionality shown should be considered as additional evidence in favor of our mechanism.

4. DISCUSSION

Calculations described in the previous section as well as the results of *Gringauz et al.* [1977] show that measured electron fluxes in the optical umbra of Venus can produce the nighttime ionosphere with a maximal electron density of about 10^4 cm^{-3} in accordance with the radio occultation measurements of the *Mariner Stanford Group* [1967], *Howard et al.* [1974], and *Aleksandrov et al.* [1976*a*, *b*].

The correlation of the ionization source intensity with the radio occultation measurements gives some evidence that electrons having energies of several tens of electron volts are important ionization sources in the Venusian atmosphere and seem to be responsible for the upper maximum at altitudes of ≈140 km. These electrons, however, cannot penetrate as far as the height of the lower maximum, which was observed to be lower than the upper one [*Aleksandrov et al.*, 1976*a*, *b*], and to explain this, other ionization sources should be taken into consideration.

The agreement of $n_{em}{}^c$ and n_{em} suggests that electrons with energies of several tens of electron volts get down to the altitudes of maximal ionospheric electron density; consequently, there exists no mechanism effective enough to prevent the ionizing electrons from penetrating into the nightside atmosphere. If a magnetic field parallel to the planet's surface existed, it could serve as such a preventing mechanism. Although there were no magnetic field measurements at ionospheric altitudes (the trajectory of Venera 9 and 10 made measurements possible only beyond 1500 km), the magnetic field behind the planet is stretched along the sun-Venus line depending on the interplanetary magnetic field [*Dolginov et al.*, 1977]; this fact together with the correlation of $n_{em}{}^c$ and

TABLE 1. Cases in Which Nearly Simultaneous Radio Occultation and Plasma Electron Component Measurements were Carried Out

		Electron Measurements								Radio Occultations		
Date	Satellite	UT	n_1, cm^{-3}	T_1, eV	n_2, cm^{-3}	T_2, eV	$10^{-3}\cdot n_{em}{}^c$, cm^{-3}	h, km	χ_e, deg	UT	χ_R, deg	$10^{-3}\cdot n_{em}$, cm^{-3}
Oct. 28, 1975	Venera 9	0348	1.4	13	0.09	100	7.2	1700	142	0359	150	16.0
Oct. 30, 1975	Venera 9	0408			0.6	70	9.4	1600	143	0418	151	5.3
Oct. 31, 1975	Venera 10	0705			0.38	50	7.0	1800	152	0720	146	7.4
Nov. 1, 1975	Venera 9	0426	1.3	17	0.16	100	9.0	1500	143	0436	152	7.9
Nov. 23, 1975	Venera 9	0802			0.07	100	3.3	1300	157	0813	162	5.4
Nov. 25, 1975	Venera 9	0821	0.8	13	0.04	100	5.3	1200	158	0834	165	2.9
Dec. 3, 1975	Venera 10	0543	3.3	15	0.2	100	11.9	1700	154	0601	157	15.5
Dec. 5, 1975	Venera 10	0708	1.1	9	0.16	100	7.1	1800	155	0728	159	7.0
Dec. 7, 1975	Venera 10	0833	0.6	13	0.18	70	6.5	2100	157	0854	160	8.8*

*In the upper maximum.

n_{em} indicates that apparently there is no stable magnetic field parallel to the planet's nightside surface below 1500 km.

Both the estimates obtained by *Gringauz et al.* [1977] and the results given above show that electrons with energies of several tens of electron volts interacting with the CO_2 neutral atmosphere produce maximal ionization at heights where $n_n \approx 2 \cdot 10^9$ cm^{-3}. As a consequence of this, the density of the nighttime neutral atmosphere at the altitude of the ionization maximum ($\approx$140 km) can be estimated as $\approx 2 \cdot 10^9$ cm^{-3}. In spite of the fact that this value definitely differs from that predicted by most existing upper atmosphere models (this difference is smaller for models constructed recently), it is not in contradiction with the newest experimental results on the nighttime atmosphere of Venus. The upper atmosphere model of *Marov and Ryabov* [1974] and the model of *Izakov et al.* [1976] predict the density value of $2 \cdot 10^9$ cm^{-3} at altitudes of 165–170 km as a consequence of the T_∞ = 450°–380°K temperatures. On the other hand, T_∞ has a considerable daily variation; according to the models of *Izakov and Morozov* [1975] and *Dickinson and Ridley* [1972], T_∞ decreases from 700°–800°K (daytime value) to 300°K at night, while in the latest model of *Dickinson and Ridley* [1977] it varies from 330°K to 170°K at night. The neutral density can be measured by the radio occultation method only up to 90 km, so one can determine the neutral atmosphere density at altitudes above 90 km only by using the temperature of the neutral atmosphere. *Ivanov-Khalodnii et al.* [1977] deduced from the dual-frequency radio occultation measurements a temperature of about 180°K at altitudes of 120–140 km. Using the results of *Yakovlev et al.* [1976] obtained by a radio occultation experiment ($n_n \approx 10^{17}$ cm^{-3} at h = 82–84 km), one can conclude that in order to obtain $2 \cdot 10^9$ cm^{-3} neutral density at h = 140 km, it is necessary to suppose an average temperature of about 150°K between 80 and 140 km (for a pure CO_2 atmosphere). This T_n is in agreement with the T_n = 170°K value measured for $n_n = 10^{17}$ cm^{-3} [*Yakovlev et al.*, 1977] and with the measurements of *Ivanov-Khalodnii et al.* [1977] as well as with the newest theoretical calculations of *Dickinson and Ridley* [1977].

The only experiment that is inconsistent with the $2 \cdot 10^9$ cm^{-3} neutral density value at a 140-km altitude was carried out in 1959 during the occultation of Regulus by Venus. The difference might be explained by the different solar activity at the moment of the occultation of Regulus ($F_{10.7} = 220 \cdot 10^{-22}$ W m^{-2} Hz^{-1}) and during the flights of Venera 9 and 10 ($F_{10.7} = 70 - 77 \cdot 10^{-22}$ W m^{-2} Hz^{-1} (Solar Geophysical Data 373). We suppose that as a result of the variation of thermal structure of the upper Venusian atmosphere, the level where the neutral density was $2 \cdot 10^9$ cm^{-3} was definitely higher in 1958 than it was during the Venera 9 and 10 mission.

Some discrepancy can be observed in certain cases listed in Table 1 between the height of calculated maximum $h_m{}^c$ and the radio occultation profile maximum height h_m ($h_m{}^c - h_m$ = 5 km on October 31 and $h_m{}^c - h_m$ = 15 km on October 3 and November 1. In our opinion, this discrepancy has no physical meaning: it is associated with the uncertainty of height estimation in radio occultation measurements, which can reach ±10 km [*Aleksandrov et al.*, 1976*a*].

Ionization produced by meteors in the nighttime atmosphere is sufficient to cause a maximal ionospheric electron density corresponding to experimental data [*Butler and Chamberlain*, 1976]. According to this calculation the meteoric ionization maximum takes place at an altitude where n_n is approximately 10^{12}–10^{13} cm^{-3}. As was shown above, electrons with energies of several tens of electron volts can produce an ionization maximum at altitudes where n_n is approximately $2 \cdot 10^9$ cm^{-3}; consequently, meteors can contribute only to the production of the lower maximum.

One possible reason for the deviation between calculated and measured maximal electron density values is the time variation of the source intensity. Time intervals of electron spectrum and radio occultation measurements are shifted by 10–20 min (see Table 1). The relaxation time, within which the density of ionosphere follows the changes of source intensity, is $\tau = (\alpha n_{em})^{-1} \approx 6$ min (with $n_{em} = 7 \cdot 10^3$ cm^{-3}); hence the ionosphere can be considerably changed in the time interval between plasma and radio occultation measurements as a consequence of the variation of ionizing electron fluxes. Time variations of plasma density along the radio occultation path and possible horizontal ionospheric gradients also cause errors in electron density estimation (see, for example, *Gringauz and Breus* [1976]). On the other hand, the calculated values of $n_{em}{}^c$ contain errors due to neglecting the dynamical effects in the atmosphere and the inaccuracy of the neutral atmosphere model.

Our ionospheric parameter estimations, obtained by different calculation methods, are compared below. Ionosphere parameters on November 25 and December 3, 1975, were assessed by *Gringauz et al.* [1977]. On the basis of electron currents recorded by the electron analyzer with U_R = 40 V retarding potential (Figure 2) and taking into account the characteristics of the analyzer [*Gringauz et al.*, 1974*a*] and assuming the angular distribution of electrons to be isotropic, one can determine the omnidirectional electron flux $j_{e0}(E \geq 40$ eV), which turned out to be $0.8 \cdot 10^8$ cm^{-2} s^{-1} and $2.4 \cdot 10^8$ cm^{-2} s^{-1}, respectively. Equation (9) in the paper of *Gringauz et al.* [1977] makes it possible to estimate the height h_m with the nightside atmosphere parameters used above, the result being h_m = 139 km. Similarly, from (11) in the work of *Gringauz et al.* [1977], maximal density values $6 \cdot 10^3$ cm^{-3} and 10^4 cm^{-3} were obtained on November 25 and December 3, respectively. These values differ from those listed in Table 1 by less than 20%. The half width of the $n_e(h)$ profile calculated by the method described in section 3 is greater ($3.9H_0$) than that obtained by *Gringauz et al.* [1977] ($3.6H_0$), owing to slower decay of the density profile below the maximum height. The slower decay is associated with the fact that ionization produced by electrons in repeated nonelastic collisions at lower altitudes was taken into account. Present calculations give a lower ionization maximum height than does the work of *Gringauz et al.* [1977]; the difference is 0.2–$0.4H_0$.

Thus changing the calculation method in the present paper with respect to our previous calculation [*Gringauz et al.*, 1977]

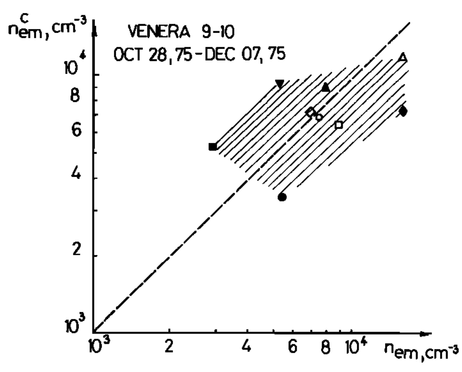

Fig. 4. Comparison of calculated and measured maximal values of electron density profiles.

has had only a slight effect on the estimation of ionospheric parameters and on the correlation between n_{em}^c and n_{em}.

5. CONCLUSIONS

1. Electron fluxes measured in Venusian umbra are sufficient to produce a nighttime ionosphere with $n_{em} \approx 10^4$ cm^{-3}.
2. A correlation is revealed between the electron fluxes in the planet's umbra and maximal electron density values obtained by radio occultation measurements.
3. Electrons with energies of several tens of electron volts are apparently responsible for the upper maximum in the electron density profile.
4. The density of neutral particles at the altitude of the upper maximum (about 140 km) is about $2 \cdot 10^9$ cm^{-3}.

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