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Some Characteristic Features of the Ionospheres of Near-Earth Planets.

By

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With 22 Figures.

1. Introduction. The atmosphere of a planet is largely responsible for the degree of influence solar radiation exerts on the planet's surface. It determines the type of interaction of the interplanetary medium with a planet and it is upon this that the physical characteristics of the circumplanetary space depend. The ionospheres of planets, being the substantial parts of their atmospheres, interact with these by the ionization-recombination cycle as well as by the dynamical processes of heat and mass transfer and by energy exchange between charged and neutral particles. It is very difficult to understand the heat balance in the atmospheres and their dynamics without knowing the structure of the ionospheres and the processes involved in their formation. In addition, this structure of the ionosphere determines the propagation of radio waves near the planet.

The first attempts to explore the vicinity of the planets of the terrestrial group (Mars and Venus) by space probes were made some time ago (Venera 1, 1961; Mars 1, 1962; Mariner 2, 1963).

From the beginning the ionospheric parameters were thought to be interesting planetary characteristics [*1*]. It was assumed intuitively that Venus, which has a dense atmosphere and is closer to the Sun than the Earth, would have a denser ionosphere than Earth, while Mars, which has a tenuous atmosphere and is farther from the Sun, would correspondingly have a less dense ionosphere.

Radioastronomy and radar investigations of Venus and determinations of the brightness temperatures of the Venusian radio emission at wavelengths between 4 mm and 40 cm led to the hypothesis that the electron density in the ionosphere of Venus could exceed the terrestrial ionospheric electron density[1–3] by a factor of about 10^3.

Models of the Martian ionosphere have been extremely controversial. The lack of data on planetary atmospheres and magnetic fields, other than those obtained from indirect measurements, has, of course, been the main reason for the difficulties experienced in constructing models of the ionospheres of planets.

Measurements in the vicinity of the planets were carried out during the descent of the Soviet space probes Venera 4, 5 and 6 in the atmosphere of Venus, during the landing of Venera 7 on the surface of the planet, and also during experiments carried out on the American space probes Mariner 2, 4, 5, 6, 7 and 9 when they were passing relatively close to Mars and Venus. These measurements provided information about the density, temperature, pressure and composition

[1] D. E. JONES: Planet. Space Sci. **5**, 166 (1961).
[2] A. D. DANILOV and S. P. JATCENKO: Kosmič. Issled. **22**, No. 2, 276 (1964).
[3] A. D. DANILOV and S. P. JATCENKO: Dokl. Akad. Nauk SSSR **162**, 774 (1965).

of the neutral lower atmospheres, about the distribution of charged particles, density and temperature in the upper atmospheres, and about magnetic fields and plasma in the vicinity of the planets. On the basis of these data several tentative physical and aeronomical models have been constructed of the atmospheres and ionospheres but also models of the interaction of the solar wind with the planets.

Some interesting phenomena were observed. Thus the maxima of electron density in the ionospheres of Mars, Earth and Venus appear to be of the same order of magnitude. At lower heights, the neutral atmospheres of Mars and Venus (unlike the atmosphere of Earth) consist mainly of CO_2, the density of N_2 at upper heights is negligible and the density of O and CO is very small, though due to dissociation of CO_2 these components must be created at some altitude.

It was found that Venus has practically no intrinsic magnetic field determining environmental conditions or charged-particle dynamics in the vicinity of the planet. In spite of this a disturbance of the solar wind plasma was observed near Venus, similar to the bow shock near the Earth. It is, however, known that the Earth's bow shock is the result of the interaction of the solar wind with the magnetic field of the Earth. Most of the observed properties of the circumplanetary regions of Venus and Mars, their similarities with and differences from circumterrestrial space, were unexpected. Some of these observational results are still unexplained; to some degree the conclusions depend on assumptions made during the processing and interpretation of data and hence require further specification and verification.

For a better appreciation of the observed phenomena and their reliability, one should consider the results of direct measurements in the Venusian and Martian ionospheres, the methods used, and the models constructed on the basis of these results.

I. Methods for investigating planetary ionospheres by means of spacecraft.

2. General characteristics. Both the ionospheres of planets and the plasma fluxes of the solar wind consist of particles of comparatively small energies ranging from fractions of an eV to several keV. Probes and radiomethods appear to be the most useful tools for investigating such plasmas.

The choice of method depends on the purpose of the experiment as well as on the conditions and technical difficulties likely to be encountered.

For instance, the use of the method of pulse sounding with the aid of an artificial orbiting ionospheric station at a sufficiently close distance (a method now widely used for exploring the terrestrial ionosphere) would permit systematic observations of space- and time-dependent variations in the electron density of the planetary ionosphere. However, this method involves great difficulties when used as the first stage of investigation. The station has to operate over a wide range of wavelengths since the critical frequencies of the relevant ionospheres are initially unknown, and this means that the weight of the receiving and transmitting equipment is even greater than for Earth-orbiting ionospheric stations and hence restricts other scientific measurements to be made on the same vehicle.

Using probe methods cuts down the weight of the instrumentation; probes are more easily combined with a whole set of other physical studies. Probes, installed aboard a spacecraft designed to penetrate into the planetary atmosphere and land on the planet's surface in theory enable the characteristics of the ionospheres to be measured *in situ* with high space and time resolution. Of course, the different probe methods, like the method of pulse sounding, require the presence of special instruments on the spacecraft.

The cheapest and simplest method is that of investigating the radio waves propagating between a space vehicle and Earth and passing through the atmosphere of the planet. Particularly during the radio-occultation of the spacecraft by the planet one obtains reliable data. This method does not require any special instrumentation: one may use radio waves emitted from the spacecraft for telemetry purposes or beacon transmission as currently used for radio location. However, when radio methods are used for investigation of planetary ionospheres they record only approximate and averaged properties of the medium and it is sometimes difficult to interpret the relevant results.

3. Charged-particle traps. Among the great variety of probes now in use for direct measurements in the vicinity of Earth and in the interplanetary space, ion traps were the first choice for investigating the planetary environment.

An ion trap consists of a system of several electrodes, mostly grids, and a collector. By setting one of the grids at different potentials (fixed, sweeping or alternating), one obtains a voltage/current characteristic which enables one to analyse the trapped charged particles. The particular method of analysis and the trap geometry (plane, spherical or hemispherical) depend on the experimental conditions, for example, on the capacity of the available telemetry channel, on the type of craft and its orientation, etc.

Traps with fixed potentials on the grids may be used for measuring the fluxes of charged particles with energies above some well-defined level given by the potential of one of the grids.

By varying the retarding potential at one of the grids it is possible to determine the energy distribution of the charged particles.

Hemispherical and plane charged-particle traps with fixed electrode potentials have been installed on several Soviet spacecrafts. For instance, the solar wind was recorded for the first time with such traps on Luna 2 and 3 in 1959 (Gringauz *et al.*, 1960).[1] The same traps were used in exploring the plasmasphere, which is the extension of the Earth's ionosphere between altitudes of 1000 and 15000 to 20000 km.[1,2]

In order to measure the plasma characteristics of the ionosphere of Venus, and ionization in the vicinity of this planet hemispherical and plane ion traps were installed on Venera 4, 5 and 6. A sophisticated ion trap will be applied with the USA Viking mission to Mars in 1976.[3]

4. Radio methods.

α) The *radio-occultation method* was used in American space probes to study the charged (and neutral) particle density distribution in the atmospheres of Mars and Venus.

Fig. 1 is a diagram showing the principle of the method of radio-occultation of a spacecraft by a planet.

Frequency, phase and amplitude of the radio waves propagating through the atmosphere and ionosphere of the planet are influenced by the properties of the medium.[1] Changes in the amplitude of the radio signals are caused by focusing, defocusing and possibly by absorption of the radio waves in the atmosphere and ionosphere of planet and Earth.

[1] K. I. Gringauz, V. V. Bezrukih, V. D. Ozerov, and R. E. Rybčinskij: Dokl. Akad. Nauk SSSR **133**, No. 5, 1069 (1960).

[2] V. V. Bezrukih and K. I. Gringauz: Issledovanija Kosmičeskogo prostranstva [Space Research], p. 394 (1965).

[3] A. O. Nier, W. B. Hanson, M. B. McElroy, A. Seiff and N. W. Spencer: Icarus **16**, No. 1, 74 (1972).

[1] K. Rawer and K. Suchy: This Encyclopedia, Vol. 49/2, Sects. 52—55.

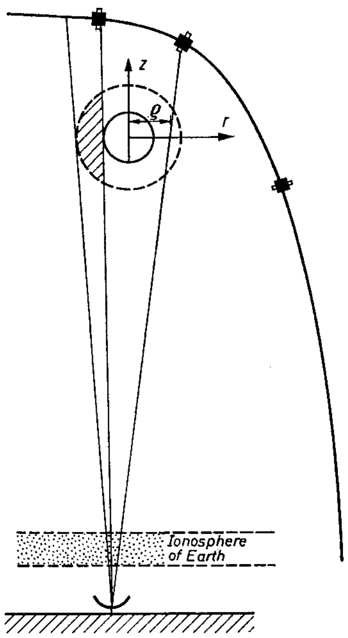

Fig. 1. Schematic representation of radio-occultation of a spacecraft by a planet. The z axis passes through the centres of Earth and the planet; ϱ is the distance from this axis to the radio beam [2].

When radio waves reach the atmosphere or ionosphere of the planet, their velocity of propagation changes relative to that recorded in the interplanetary medium (which is close to the velocity in vacuum) with other words, the refractive indices of neutral and ionized media differ from unity. The height gradient of the refractive index in the atmosphere and ionosphere produces a bending of the radio ray. According to the wavelength, these two phenomena may significantly influence the phase and group path. Unfortunately, the time-dependent variations of the refractive indices in the Earth's troposphere and ionosphere and in the interplanetary medium also influence the phase and group path. Thus the continuous increase of the phase path measured during the occultation of a spacecraft by a planetary atmosphere is partly due to the motion of the spacecraft in the planetary atmosphere and partly to changes in the refractive index along the propagation path of the radio waves.[2] We thus have one contribution due simply to the increasing distance between the spacecraft and the groundbased receiving point (which would take place if the refractive index along the entire path were unity) and another contribution due to changes in the refractive index in the Earth's ionosphere and in interplanetary space. If both contributions are subtracted from the measured total increase of the phase of the received radio waves, then the experiment will under certain assumptions yield the height profile of the refractive index in the planetary atmosphere. In the altitude range where the refractive index is less than unity it is possible to determine the dependence of electron density on altitude. In the lower part of the atmosphere of a planet the refractive index exceeds unity; this section of the refractive index profile can be used to determine the characteristics of the neutral atmosphere of the planet. For instance, when the composition of the neutral atmosphere is known, it is possible to calculate from this profile the neutral density profile in the lower atmosphere because the refractive index of a mixture of gases is equal to the sum of the refractive indices of all its components, and the contribution of each component is proportional to its density so that both density and temperature profiles can be derived.

β) Experiments using the radio-occultation of a spacecraft by a planet can be modified in various ways, as it is feasible to use radio waves on one frequency or on two or more frequencies.

The use of *one frequency* does not permit a clear separation between the contributions to the phase path of the neutral and charged particles which may be mutually compensating. One may obtain a reasonable solution by assuming that the lowest range of a planetary atmosphere contains no appreciable amount of charged particles, so that changes in the refractive index may be attributed to the neutral atmosphere. The total increase of the phase path in a planetary atmosphere and ionosphere may be written as indicated by FJELDBO *et al.*[2] These authors use a cylindrical coordinate system, with the zero point at the center of the planet, and the z-axis directed along the Earth-planet line (Fig. 1); they suppose further that outside the planetary atmosphere and ionosphere the refraction index is unity. The reliability of this assumption is illustrated by the experimental data shown in Fig. 2. The equation for the phase difference as compared with vacuum is:

$$\Delta\varphi(\varrho, f) = \frac{2\pi}{\lambda}\int_{-\infty}^{\infty}(\mu_n - 1)\,\mathrm{d}z + \frac{2\pi}{\lambda}\int_{-\infty}^{\infty}(\mu - 1)\,\mathrm{d}z \tag{4.1}$$

where ϱ is the height coordinate, λ the wavelength in vacuum, μ_n the refractive index in the neutral atmosphere and μ the refractive index in the ionosphere. If we assume that the frequency f is much greater than the electron cyclotron frequency and the plasma frequency (and is also large compared with the frequency of collision of the electrons with neutral particles), then we may use the SELLMEIER equation[3]

$$\mu^2 = 1 - 0.806\cdot 10^{-10}\left(\frac{N_e}{\mathrm{m}^{-3}}\right)\Big/\left(\frac{f}{\mathrm{MHz}}\right)^2$$

which may be approximated by (4.2)

$$\mu \approx 1 - 0.403\cdot 10^{-10}\,\frac{N_e}{\mathrm{m}^{-3}}\Big/\left(\frac{f}{\mathrm{MHz}}\right)^2$$

It is assumed that in the lower atmosphere $\mu = 1$ so that the profile with altitude h, namely $\mu_n(h)$ can be determined unambiguously, whereas in the upper atmosphere $\mu_n = 1$ due to the low density; this allows the profile $\mu(h)$ and hence the profile $N_e(h)$ to be determined. Plasma refraction can be ignored if

$$0.403\cdot 10^{-10}\,\frac{N_e/\mathrm{m}^{-3}}{(f/\mathrm{MHz})^2} \ll 1\,.$$

The altitude profile of the refractive index can be obtained by inverting[4] the integral equation, Eq. (4.1). In order to do this, either one chooses a profile satisfying the measured increase of the phase path, or one replaces it by the sum

[2] G. FJELDBO, V. R. ESHLEMAN, O.K. GARIOTT, and E. L. SMITH: J. Geophys. Res. 70, 15, 3701 (1965).
[3] K. RAWER and K. SUCHY: This Encyclopedia, Vol. 49/2, Sect. 6.
[4] K. RAWER and K. SUCHY: This Encyclopedia, Vol. 49/2, Sects. 30—32.

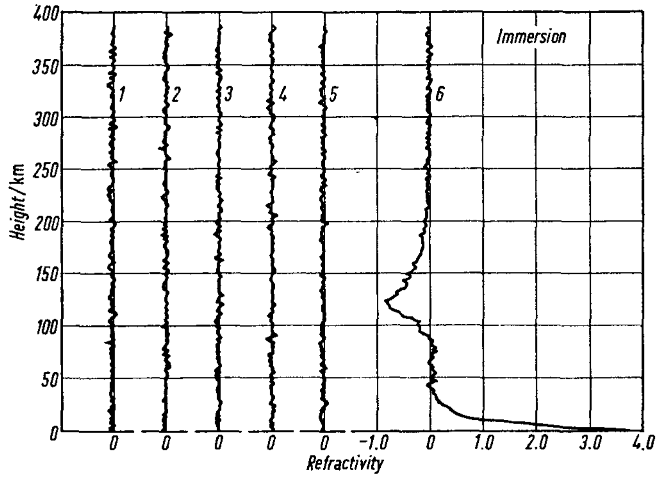

Fig. 2. Profiles of refractivity $\mathcal{N} \equiv (\mu - 1) \cdot 10^6$ recorded before the beginning of the occultation (*1, 2, 3, 4* and *5*) and during the immersion (*6*) of Mariner 4 into occultation by the atmosphere of Mars (the ordinate scales of curves *1* to *5* are arbitrary).[5]

of the increases in a finite number of layers, each of which is characterized by a constant refraction index. Both methods presuppose that the ionosphere and atmosphere are spherically symmetric. While with the first method the profile shape is assumed *a priori*, the second method yields a less arbitrary profile of the refractive index and consequently may reveal some features of the fine structure of the atmosphere.

γ) In an experiment where *two radio frequencies* are used the unambiguity due to the simultaneous influence of the neutral and charged particles is ruled out by the fact that the dispersive effect is different for neutral gas and plasma. The contribution of the ionosphere can be isolated by comparing a high and a low frequency. The higher frequency is usually a multiple of the low frequency ($f_2 = mf$); the relevant increase of phase path is then (with $\mu_n = 1$) given by[2]

$$\Delta\varphi(\varrho, mf) = \frac{2\pi m}{\lambda} \int_{-\infty}^{\infty} (\mu - 1)\, dz = -\frac{2\pi}{c_0} \frac{0.403 \cdot 10^{-4}\,\text{Hz}}{m\,(f/\text{MHz})} \int_{-\infty}^{\infty} \frac{N_e}{\text{m}^{-3}}\, dz\,. \quad (4.3)$$

This equation may also be written as

$$\Delta\varphi = -\frac{0.844 \cdot 10^{-9}}{m\,(f/\text{MHz})} \int_{-\infty}^{+\infty} \frac{N_e}{\text{m}^{-3}} \frac{dz}{\text{km}}\,. \quad (4.3\,\text{a})$$

The system of equations, Eqs. (4.1) and (4.3), allows us in principle to determine the two unknowns, μ_n and N_e. It is important to mention that multipath propagation is assumed to be negligible.

δ) Such *experiments* can be performed by one of *two methods*: emission of radio waves from a spacecraft with reception on Earth; or triggered re-transmission of radio waves received in the spacecraft from a terrestrial station, usually with transposition of the frequency. In the second case the frequency of

[5] G. FJELDBO and V. R. ESHLEMAN: Planet. Space Sci. **16**, No. 8, 1035 (1968).

the radio waves will be more stable, since it is determined by ground-based frequency standards and this improves the accuracy of phase measurements.

5. Analysis of radio data.

α) *Phase path measurements* have produced the greater part of the information concerning the structure of the Martian and Venusian atmospheres and ionospheres obtained from the experiments of Mariner 4, 5, 6, 7 and 9.

The electron density distribution may also be obtained from radio-wave absorption by fitting the observed amplitude data to the model. An often used model is the Chapman-layer[1] model, which has to be adapted to the maximum of the ionosphere. This procedure has to be used with caution when no additional information is available, because horizontal gradients of N_e or any other irregularities can make the results ambiguous. For similar reasons measurements of the group delay of radio waves have also been shown to be not always reliable.

Let us now consider in more detail how the refractivity may be determined from phase data.

As stated above, values of $\Delta\varphi$ measured during the passage of the waves through the planet's atmosphere, contain a contribution due to the orbital increase in the distance of the spacecraft, variations in the Earth's ionosphere and that of the interplanetary medium, as well as influences due to the particular radio system (phase deviations of the reference signal, etc.). Before its occultation by the atmosphere the trajectory of the vehicle is calculated from Doppler measurements. Subsequently, when the occultation begins, the trajectory is extrapolated, (this can be done with high accuracy since the spacecraft moves ballistically). The phase path increase due to the increase of the vehicle's geometrical path (on the extrapolated trajectory) is calculated, usually with the assumption that the motion takes place in vacuum.

To take into account the influence [on the measured increase of the phase path during the occultation] of variations in the terrestrial ionosphere and the interplanetary medium, and the instability of the radio system, the following two procedures are employed.

β) Variations in the phase of the received radio waves are determined during suitably chosen time intervals *preceding the final measurement*, i.e. before the passage of radio waves through the planetary atmosphere; each of these intervals is chosen so as to be equal to the duration of the occultation. The observed variations are then averaged and subtracted from the phase variation measured during the subsequent occultation. The effects on the increase in the radio phase of the Earth's ionosphere and the interplanetary medium are generally much less than the effects produced by the planetary ionosphere and neutral atmosphere. The reason for this is clear if one bears in mind that during the occultation the change in the direction of the radio beam in the Earth's ionosphere is very small (see Fig. 1) and that only time variations of the integrated electron density in the Earth's ionosphere will have an appreciable effect. These variations are quite small compared with the variation of the electron density along the beam due to the influence of the planetary ionosphere, which produces (during the total period of final observation) a change corresponding to more than twice the integrated electron density in the planet's ionosphere (see Fig. 1).

Fig. 2 shows the refractivity profile $\mathcal{N} \equiv (\mu - 1)\, 10^6$ in the dayside atmosphere of Mars (profile 6) as obtained from the Doppler residual observed during the occultation of Mariner 4, and several other profiles of $\mathcal{N}$ obtained prior to the occultation (the scale along the y axis is arbitrary and the data were obtained

[1] K. Rawer and K. Suchy: This Encyclopedia, Vol. 49/2, Eq. (9.26), p. 97.

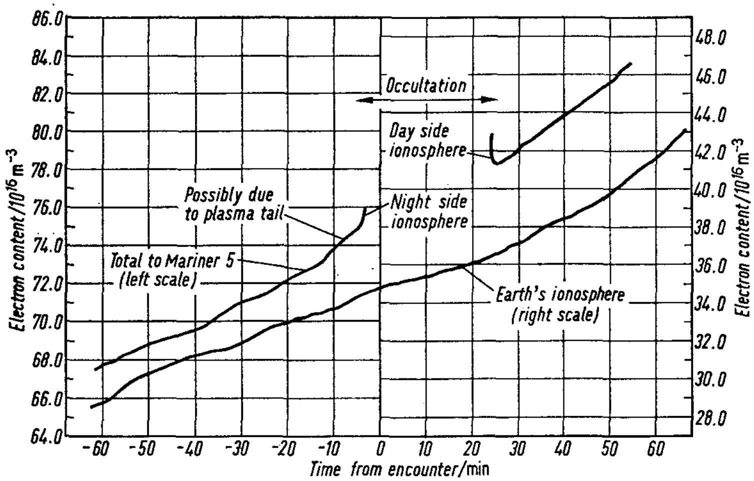

Fig. 3. Total electron content along the propagation path from Stanford to Mariner 5, and contribution by the Earth's ionosphere versus time from closest approach (periapsis).[3]

during equal time intervals).[2] These profiles clearly demonstrate how the refractivity deviates from unity when radio waves propagating from the Earth to the spacecraft reach the planetary atmosphere.

γ) By *linear extrapolation:* the point on Fig. 3 which corresponds to the instant when the measured electron content along the propagation path begins to increase, i.e. the beginning of the radio-occultation, is connected by a straight line to the point corresponding to the end of the radio-occultation. The total electron content corresponding to this straight line is taken as *the zero reference level*, and deviations from it are interpreted as due to the influence of the planetary atmosphere and ionosphere.[3]

The total electron content of the Earth's ionosphere was measured simultaneously by the authors of [3]; a geostationary satellite was used so as to exclude variations in the zero level due to the Earth's ionosphere. The lower curve in Fig. 3 represents the measured electron content of the Earth's ionosphere between the Application Technology Satellite ATS and Stanford (Cal., USA) at the time of the experiment.

6. Difficulties and limitations of the different methods.

α) *Charged particle traps* are rather simple to build and have proved to be very reliable for determining plasma properties in situ. There are, however, some drawbacks, the most important being the following.

(i) As mentioned above and demonstrated earlier [*1*] traps with fixed potential do not permit one to determine the contribution to the measured collector current which is due to photoemission from the electrodes. One needs data from other experiments to find this contribution.

This peculiarity of traps is rather critical when measuring interplanetary

[2] G. FJELDBO and V. R. ESHLEMAN: Planet. Space Sci. **16**, No. 8, 1035 (1968).

[3] G. FJELDBO and V. R. ESHLEMAN: The Atmosphere of Venus as Studied with the Mariner 5 Dual Radio-frequency Occultation Experiment, Final Report, Part 1, Radio Sci. Lab. Stanford, Electronics Lab., Stanford Univ., California (SUSEZ 69-003), 1969.

plasma, but less so for ionospheric plasma because in the ionosphere the wanted current greatly exceeds the photocurrent.

(ii) For a correct determination of the ionospheric plasma properties by means of such a trap one further needs to know the electrical potential of the spacecraft relative to the surrounding plasma.

Charged particle traps using variable electrode potentials greatly reduce these difficulties.

β) The *radio-occultation method* also has a number of drawbacks. Thus, as previously noted, when only one frequency is used the contributions of the neutral and charged particles to the measured phase path variation cannot be clearly distinguished. There are also some general difficulties.

(i) When deriving the electron density profile by inverting Eq. (4.1) it is always assumed that the ionosphere is regularly stratified, i.e. spherically symmetric. Usually one supposes that it consists of a number of layers, each of constant refractivity. It is obvious that this assumption is not quite correct. For example, the 1967 maximum of the Venusian daytime electron density, obtained with Mariner spaceprobes by the Stanford Group, exceeds the maximum of the night-time density by a factor of approximately 15, and the thickness of the night-time ionosphere exceeds that of the dayside ionosphere by nearly 3000 km. Hence considerable horizontal gradients must exist in the Venusian ionosphere. With such data it is possible to evaluate roughly the deviation of the electron density distribution from the above assumption.

Assuming photochemical equilibrium, the variation of the maximum electron density N_e with solar radiation intensity may be approximately represented by a cosine law; this is true at least for equatorial and middle latitudes where the occultation observations were made (30° N to 30° S). To a first approximation one thus obtains the following horizontal variation of electron density:

$$N_e(R, \varphi) = N_{e0}(R) + N_{e1}(R) \cos\varphi. \tag{6.1}$$

Here φ is a "longitude" measured from the line Venus-Sun (Fig. 4).

$$N_{e0}(R) = \frac{N_{\text{day}} + N_{\text{night}}}{2}; \quad N_{e1}(R) = \frac{N_{\text{day}} - N_{\text{night}}}{2\cos\alpha}$$

where α is the longitude at which the occultation occurs. Then the electron density difference between the point of entrance of the radio-beam to the ionosphere maximum region and the point of its exit from this region (see Fig. 4) is as follows:

$$\Delta N_e = N_{e1}(R)\,[\cos(\alpha + \varphi_0) - \cos(\alpha - \varphi_0)] = -2N_{e1}(R)\sin\alpha\sin\varphi_0. \tag{6.2}$$

Here φ_0 is the angle between the line connecting the center of the planet to the point where the radio ray contacts the lower boundary of the region under consideration and the line connecting the center of the planet to the point at which the beam enters (or leaves) the spherical layer which is considered.

$$\tan\varphi_0 = \frac{\sqrt{2Rh}}{R}, \tag{6.3}$$

h being the height of the ionization maximum in the Venusian ionosphere (about 140 to 170 km). Consequently $\varphi_0 \sim 12$ to 13° and the change of electron density, ΔN_e, in the layer is of the order of $6 \cdot 10^{10}\,\text{m}^{-3}$ whereas $N_{e\,\text{day}} \approx 5 \cdot 10^{11}\,\text{m}^{-3}$ and $N_{e\,\text{night}} \approx 10^{10}\,\text{m}^{-3}$. Thus the assumption of spherical symmetry produces an ambiguity concerning the maximum electron density as evaluated from data obtained during radio-occultation experiments.

Considerable fluctuations in radio-signal amplitude were observed during the experiment on Mariner 5, indicating the existence of great irregularities in the Venusian ionosphere. Since the horizontal gradients of N_e were not taken into account when the observed radio-occultation data were interpreted, the magnitude of local electron density determined from integral measurements must be considered somewhat unreliable. Only where these gradients are negligible may the data be taken as accurate.

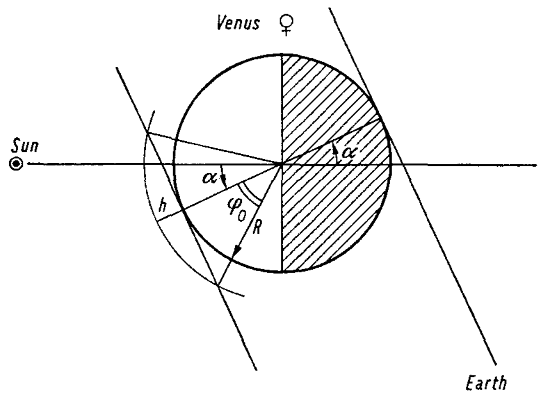

Fig. 4. Influence of lack of spherical symmetry of the ionosphere on the radio-occultation experiment (explains notations used in the text).

(ii) The possibility of multipath propagation, which may also provoke ambiguous results, was neglected in deriving the refractivity profile from phase measurements.

It is impossible to determine whether the observed amplitude fluctuations are related to horizontal irregularities or to a horizontal stratification of the ionosphere. Existing amplitude computations are based on ray theory, and this does not provide an accurate representation, particularly in regions where the scale of the structure of the ionosphere is small against the radio wavelength. The limitations of ray theory are particularly obvious at the caustics, where it predicts infinite signal amplitudes.

(iii) The electron density profile derived for the outer part of the ionosphere (above the maximum) is greatly influenced by the correctness of the determination of the zero reference level, i.e. the magnitude of the variations in electron content in the Earth's ionosphere and in the interplanetary medium during the radio-occultation. This uncertainty may provoke errors when determining the structure of the outermost planetary ionosphere.

(iv) The above difficulties might in principle be avoided by using radio-occultation of a planetary satellite, which provides much more data.

It is in principle possible to have two spacecraft on different trajectories near the planet: one to be used for radio-occultation measurements, and the other orbiting around the planet without occultation to provide data on the variations of electron density in the interplanetary space and the Earth's ionosphere. Such an experiment was planned in 1971 with two USA spacecraft for exploration of the Martian atmosphere but the launching of one of them (Mariner 8) was unsuccessful.

II. Experimental results of the exploration of the ionospheres of Mars and Venus.

7. The ionosphere of Mars.

α) In July 1965 radio-occultation of Mariner 4 by the martian atmosphere was observed; thus for the first time it became possible to measure the properties of the atmosphere and ionosphere of this planet.[1,2]

[1] A. J. KLIORE, D. L. CAIN, G. S. LEVY, V. R. ESHLEMAN, G. FJELDBO, and F. D. DRAKE: Science 149, No. 3689, 1234 (1965).

[2] G. FJELDBO and V. R. ESHLEMAN: Planet. Space Sci. 16, No. 8, 1035 (1968).

On 31 July 1969 Mariner 6 passed behind Mars and was followed on 5 August 1969 by Mariner 7 and their radio-occultations were observed.[3-5] Thus, four years after the first experiment, data concerning the neutral and ionized components of the martian atmosphere were again obtained for different solar activity and above another region of the planet's surface.

During these three experiments phase, amplitude and frequency variations of radio signals in the S-band (~2100 MHz) were measured and their propagation in the planetary atmosphere was studied. On the basis of the phase measurements atmospheric height profiles of refractivity, $\mathcal{N} \equiv (\mu - 1) \cdot 10^6$, were derived for night- and day-time conditions on Mars.

In November 1971 two artificial Mars satellites were launched: Mariner 9 (period of orbital revolution: 12.5 h; inclination of the orbit against the ecliptic plane: $-65°$; pericenter: about 1300 km; apocenter: about 17900 km), Mars 2 (period of orbital revolution: about 17 h; orbital inclination: about 40°; pericenter: about 1100 km; apocenter: about 28000 km). By means of these satellites measurements of the ionospheric parameters were also carried out viz. with a radio-occultation method in the S-band on Mariner-9[6,7] and with the Doppler shift method on the harmonic combination of 937.5 and 3750 MHz on Mars-2, Mars-4 and Mars-6[8,9]. Table 1 summarizes data concerning these experiments, their realization conditions and the results on martian ionosphere parameters.

β) A method has been described for obtaining *refractivity profiles* from phase measurements which takes into account phase variations due to the influence of the interplanetary medium, the Earth's ionosphere and the radiosystem (see Sect. 4 where the height profile of $\mathcal{N}$ in the atmosphere of Mars as derived from

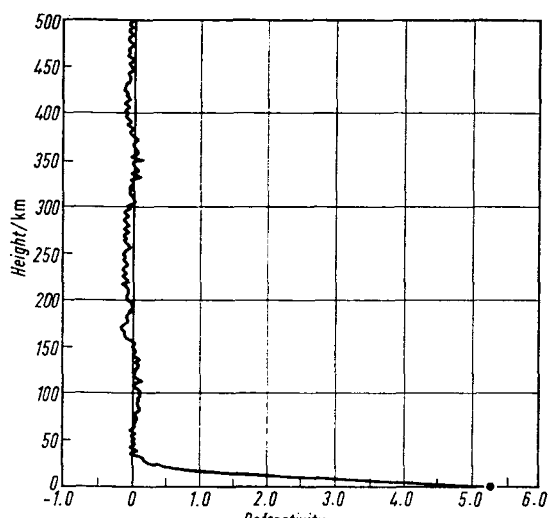

Fig. 5. Refractivity $[\mathcal{N} \equiv (\mu - 1) \cdot 10^6]$ profile obtained during the immersion of Mariner 6 on the nightside of the planet Mars.[3]

[3] G. Fjeldbo, A. J. Kliore, and B. L. Seidel: Radio Sci. **5**, No. 2, 381 (1970).

[4] V. R. Eshleman: Science 5, No. 2, 325 (1970).

[5] A. J. Kliore, G. Fjeldbo, and B. L. Seidel: Science **166**, No. 3911, 1393 (1969).

[6] A. J. Kliore, G. Fjeldbo, B. L. Seidel, D. L. Cain, and J. M. Sykes: Icarus **17**, No. 12, 484 (1972).

[7] A. J. Kliore, G. Fjeldbo, B. L. Seidel, and M. J. Sykes: Science **175**, 313 (1972).

[8] M. A. Kolosov, N. A. Savich *et al.*: Radiotehnika i Elektronika **18**, No. 10, 2009 (1973).

[9] M. B. Vasiliev, A. S. Višlov *et al.*: Kosmič. Issled. **13**, 48 (1975).

Table 1. *Immersion, day.*

Vehicle	Date	Location	Zenith angle	Local time	Season	Height of main maximum/km	Electron density, main maximum N_e/m^{-3}	Height of 2nd maximum/km	Electron density, 2nd maximum N_e/m^{-3}	Plasma scale Hp height above main maximum/km	Temperature in the main maximum T_p/K
Mariner 4	July 1975	50° S 177° E	67°	13 h	end of winter	120 ± 5	$(0.9 \pm 0.1) \times 10^{11}$	100 ± 5	$2.5 \cdot 10^{10}$	20…25	250…300 (100% CO_2^+)
Mariner 6	July 1969	4° N 5° W (equator)	57°	15 h 40 min	beginning of spring	135 ± 5	$(1.5 \div 1.7) \times 10^{11}$	110 ± 5	$(6 \div 8) \times 10^{10}$	45 (at $h = 140$ …250 km)	400…500 (100% CO_2^+)
Mariner 7	August 1969	58° N 30° E (middle latitude)	56°	14 h 20 min	beginning of spring	135 ± 10	$(1.5 \div 1.7) \times 10^{11}$			38.5 (av.) (at $h > 250$ km $H_p \div (70 \pm 25)$ % greater than at $h = 250$ km)	
	November 1971	$-40.8° \div 29.9°$	57…47°	14…17 h		134…148	$(1.5 \div 1.7) \times 10^{11}$	110 ± 5	$(6 \div 7) \times 10^{10}$		
Mariner 9 (satellite)	May to June 1972	$86° \div (-40°)$	0…17°	4…5 h	spring in the Northern hemisphere	$135 \div 145$ km ($x = 45…60°$) $125 \div 145$ km ($x = 70…90°$)	$(1.3 \div 1.8) \cdot 10^{11}$ ($x = 45…60°$) $(0.4 \div 1.0) \cdot 10^{11}$ ($x = 70…90°$)			39 (later between 30 and 50)	
Mars 2 (satellite)	December 1972					138	$1.5 \cdot 10^{11}$			37 (at $h = 150$ …210 km) 54 (at $h = 210$ …310 km)	

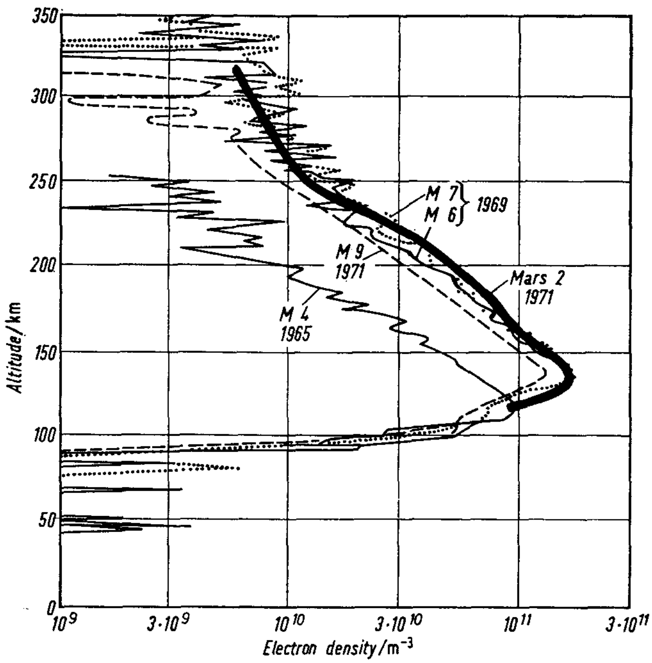

Fig. 6. The Martian ionosphere as observed during the Mariner 4, 6 and 7 missions and with the Mars-2 occultation experiment.[10]

Mariner 4 data is shown in Fig. 2). Fig. 5 represents the $\mathcal{N}$ profile in the night-time atmosphere of Mars plotted from Mariner 6 data.[3]

Obviously the night-time Martian ionosphere could not be detected from the refractivity profiles as well as it was during the experiments on Mariner 4 and Mariner 7. S-band observations are not sensitive enough for measuring the night-time ionosphere of Mars. Apparently the electron density[3] in the night-time ionosphere was less than $5\cdot 10^9\ \mathrm{m}^{-3}$. $N_e(h)$-profiles of the night time Martian ionosphere were determined by the Mars-4 and -6 Spacecrafts.[9] It was found that at the peak altitude of about 110 km the electron density was about $4.6\cdot 10^9\ \mathrm{m}^{-3}$. Ionisation of density up to $10^9\ \mathrm{m}^{-3}$ may even appear at quite low altitudes.

γ) Fig. 6 represents *electron density height profiles*[6] while Figs. 7a and b show plasma temperature profiles. The profiles in Fig. 6 were derived from refractivity profiles recorded on Mariner 4, 6, 7 and 9, and on Mars-2. The plasma temperature profiles were derived from refractivity profiles recorded on Mariner 4 and 6 assuming temperature equilibrium (i.e. the temperatures of neutral particles, ions and electrons are supposed to be equal, $T_n = T_i = T_e$). Further, the ionosphere was supposed to be in diffusive equilibrium, and at a certain starting level ion masses and temperatures were assumed so as to start the computations.[2,3] A comparison of the electron density profiles plotted in Fig. 6 reveals that the Martian ionosphere in 1969—1971 differs slightly from the ionosphere in 1965: the height of the ionization maximum has increased as have also the maximum electron density, the scale-height above the maximum, and the plasma temperature at the level of maximum electron density. The upper boundary [due to inadequate experimental sensitivity in the S-band] was also at a greater height in 1969, thus showing that the top-side electron density was also greater when the solar activity was more important.

δ) The coordinates of the occultations in 1965 and 1969 (local time, season and solar activity level) show that Mars was nearer to the Sun during the period 1965—1969 so that an increased solar radiation flux was entering the Martian

[10] J. S. Hogan, R. W. Stewart and S. I. Rasool: Radio Sci. 7, No. 5, 525 (1972).

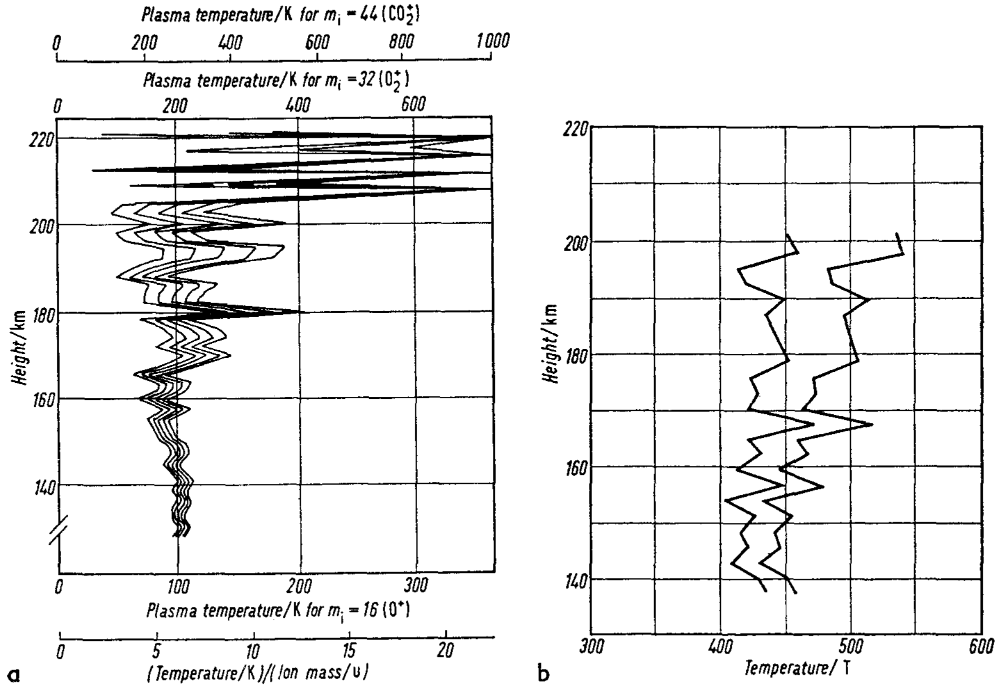

Fig. 7a and b. Plasma temperature profiles for the Martian atmosphere calculated from occultation data obtained (a) by Mariner 4[2] and (b) by Mariner 6[3]. The bottom abscissa scale of Fig. 7a gives the measured quantity. Interpretation as temperature depends upon the identification of the principal positive ion (three different scales).

atmosphere. The magnitude of the ultraviolet radiation flux, which is the main source of ionization and heating in the atmosphere, increased between 1965 and 1969 by a factor of two. From an analysis of the change in the experimental conditions between 1965 and 1969, even before the results of the experiments became known, it was predicted that variations would be found in certain martian ionospheric characteristics, e.g. the value of the maximum electron density, the corresponding height and exospheric temperatures.[11]

ε) The height refractivity profiles obtained from the experiments aboard Mariner 4, 6 and 7 were obtained with a single frequency method. As stated, this procedure is not completely reliable in the lower atmosphere. In particular, it has been shown[12] that an important plasma density might exist at a very low altitude, about 15 km above the surface. The relevant density is said to be about the same or an order of magnitude smaller than that at the peak of the ionosphere. If this interpretation is proved to be correct, it will be necessary to revise the data previously determined, e.g. the scale height of the lower Martian atmosphere (varying within the limits of 9 to 15 km). Thus the measured altitude profile of the refractive index could be interpreted with different profiles. In Fig. 8 the electron density profile for scale height $H_n = 9$ km is indicated by curve 1 and that for $H_n = 15$ km by curve 4.

[11] R. W. STEWART and J. S. HOGAN: Science **165**, No. 3891, 386 (1969).

[12] J. V. HARRINGTON, M. D. GROSSI and B. M. LANGWORTHY: J. Geophys. Res. **73**, No. 9, 3039 (1968).

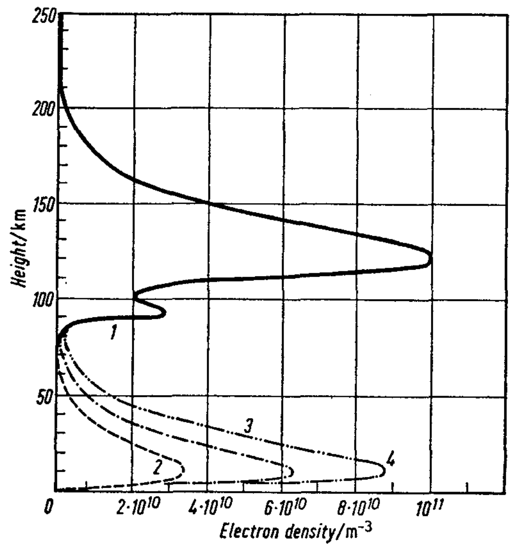

Fig. 8. Plausible electron density profiles in the Martian ionosphere corresponding to the following scale heights of the atmosphere: ① 9 km; ② 11 km; ③ 13 km; ④ 15 km.[12]

It is probable that there is a region of *enhanced electron density near the surface of Mars*, since there are no appreciable amounts of O_3 and O_2 in the martian atmosphere. Ozone would be able to absorb the solar ultraviolet radiation while molecular oxygen with its high affinity for electrons would reduce the free electron density in the lower atmosphere by binding them. All these features are quite different from the conditions in the terrestrial ionosphere.

8. The ionosphere of Venus.

α) The first attempt to measure *local conditions* in the ionosphere of another planet was carried out with the space probe Venera 4 on 18 October 1967. The spacecraft descended into the Venusian atmosphere on its night side. The scientific instruments aboard included plane and hemispheric charged particle traps.[1] The planar traps were designed to measure low ion densities in the outermost part of the Venusian ionosphere, in the range $5 \cdot 10^7$ to $5 \cdot 10^9\,m^{-3}$.

During the period when the vehicle was approaching the planet the total collector current of the plane traps was measured every 7 s. To separate the (thermal) ionospheric ions and the (high-speed) ions of non-ionospheric origin, e.g. solar wind ions, one grid of the plane trap was fed every 14 s by a potential of +50 V relative to the spacecraft in order to remove the thermal (ionospheric) ions; in this mode, only energetic (non-ionospheric) ions could reach the collector. Varying the grid potential from 0 to 50 V enabled the contribution of non-ionospheric ions to the total current to be evaluated. Near the surface of the planet the spacecraft velocity was about 10^4 m/s so that the measurements made with plane traps gave one data point every 150 km.

The hemispherical traps were intended for measuring the positive ion density near the peak of the Venusian ionosphere, i.e. near the main ionization maximum.

[1] K. I. Gringauz, V. V. Bezrukih, L. S. Musatov, and T. K. Breus: Kosmič. Issled. 6, No. 3, 11 (1968).

According to the models of the Venusian ionosphere available at that time,[2-4] the maximum charged particle density had been estimated to be of the order of 10^{15} m^{-3}. For this reason the sensitivity of these traps had been chosen in the range 10^{10} to 10^{13} m^{-3}. To give more measuring points on the ion density profile, these measurements were planned to be carried out every 0.8 s.

These measurements made by the hemispherical traps showed that the ion density in the night-time ionosphere nowhere exceeded $1 \cdot 10^{10}$ m^{-3}. As mentioned above, the low ion density measurements were made at 150 km intervals. Due to radio interference the data from the last two planar trap measurements at lower altitudes could not be decoded, so that the upper limit of 10^9 m^{-3} applies only to the ion density at heights above 300 km.

β) On 19 October 1967 Mariner 5 passed near Venus in a trajectory which permitted the radio-occultation of the spacecraft by the planetary atmosphere to be observed. At the beginning of the radio-occultation the latitude was 37° N and the solar zenith angle was 142°. The latitude of immersion, (i.e. vanishing reception) was 32° S at a solar zenith angle of −37°.

One of the experiments to determine the properties of the Venusian ionosphere carried out by the Stanford University group[5] consisted in making dispersive Doppler measurements on two harmonically combined frequencies: 49.8 and 423.3 MHz. In this experiment a signal propagated on one of the frequencies

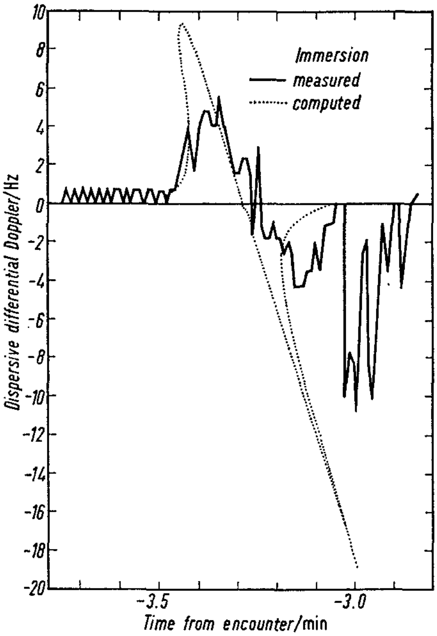

Fig. 9.

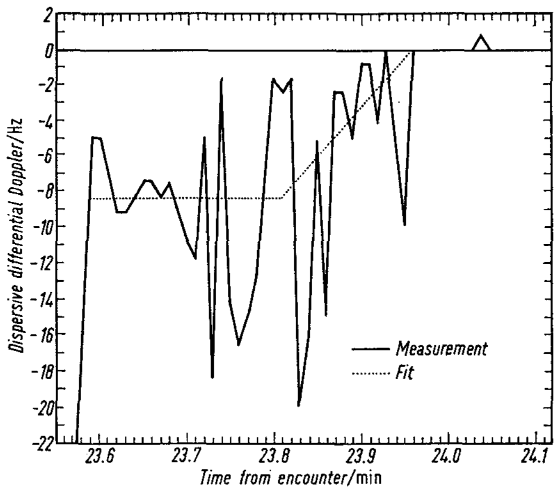

Fig. 10.

Fig. 9. Observed and computed differential Doppler effect during immersion of Mariner 5.[7]

Fig. 10. Dispersive differential Doppler effect versus time from closest approach, day side.[7]

[2] D. E. JONES: Planet. Space Sci. **5**, 166 (1961).
[3] A. D. DANILOV and S. P. JATCENKO: Kosmič. Issled. **2**, No. 2, 276 (1964).
[4] A. D. DANILOV and S. P. JATCENKO: Dokl. Akad. Nauk SSSR **162**, 774 (1965).
[5] Mariner Stanford Group: Science **158**, 1678, 1683 (1967).

from Earth to the spacecraft and returned to Earth on the other frequency; phase and amplitude as well as the group delay of the signals were measured. It seems, however, that measurement of group delay achieved only modest accuracy, and its results have not been analysed.

Simultaneously another experiment was carried out on 2298 MHz, a frequency in the S-band;[6] in this experiment the signal propagated only from the spacecraft to the Earth; signal frequency, phase and amplitude were measured. Unfortunately, this experiment was not sensitive enough to detect the rather low night-time electron density in the Venusian ionosphere.

As in the case of the Martian radio-occultation experiments, the S-band experiment did not clearly distinguish the contributions of the charged and neutral components of the lower atmosphere. However, as will be discussed later, by combining the two experiments data were obtained which allowed a determination of some parts of the electron density profiles in the ionosphere of Venus, for day and night-time.

γ) Figs. 9 and 10 show the variation in the rate of change of the *phase path* on two frequencies ($\Delta\varphi$) due to dispersion in the ionosphere of Venus as a function of orbital time (counted from the moment when the spacecraft was closest to the planet).[7] Data have been obtained for day and night conditions on Venus. The curves show steep dips and oscillations, indicating that multipath propagation was present with different rays being received at different moments. This multipath propagation was attributed to the 49.8 MHz signal; for this reason in the vicinity of the peak of the Venusian ionosphere the phase measurements could not be reduced and so were abandoned. Only the data from amplitude measurements could be used, although the method of constructing the profile from amplitude data is less accurate, as explained above.

Fig. 11 shows samples of the observed and calculated variations in the

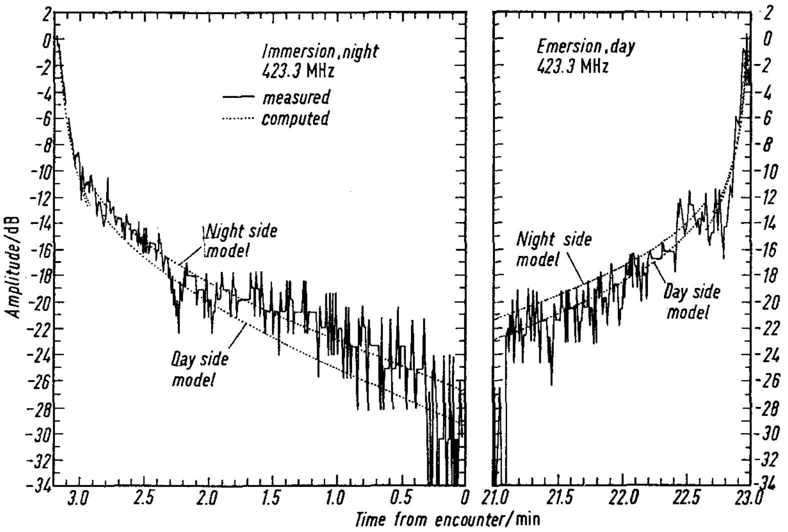

Fig. 11. Observed and computed amplitude variations illustrating the difference between day- and nightside atmospheres.[7]

[6] A. J. Kliore, G. S. Levy, D. L. Cain, G. Fjeldbo, and S. I. Rasool: Science **158**, 1683 (1967).

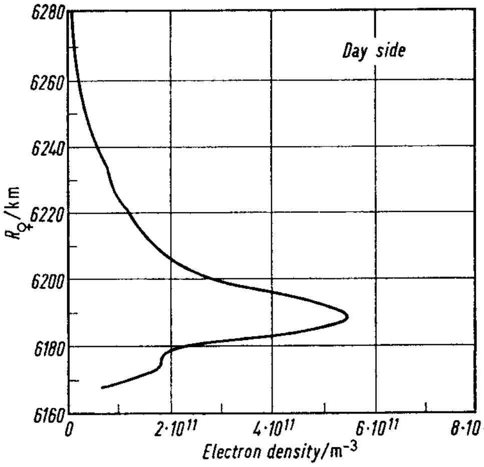

Fig. 12. Electron density in the daytime ionosphere of Venus obtained from data of the Mariner 5 single-frequency experiment in the S band.[6]

423.3 MHz *signal amplitude* for the day- and night-time Venusian ionospheres.[7] It is clear that the amplitude is fluctuating strongly due to the presence of inhomogeneities, or of horizontal gradients in the electron density. Consequently, when interpreting the results of amplitude measurements, the S-band experiment data were invoked. Starting with the Doppler-phase measurements in the S-band, an electron density profile of the daytime Venusian ionosphere was first computed (see Fig. 12); this profile was then used as a model for calculating the amplitude variations at 423.3 MHz.

δ) Fig. 13 shows day- and night-time *electron density profiles* in the Venusian ionosphere obtained by interpreting both experiments.[7,8] Obviously, that part of the electron density profile which is just below the ionization maximum (dotted line) is less reliable than other parts. This is the height range where amplitude measurements on 423.3 MHz and S-band phase data have been combined. In daytime at heights between 200 and 250 km no signals were received at all, probably because of caustic refraction in this height range.

The steep descent of the phase curve near about 500 km (see the data after 23.95 min in Fig. 10) is apparently due to refraction of the 49.8 MHz signal in the region of sharply increasing electron density (continuous line in Fig. 13). The zero Doppler readings preceding the last dip of the phase difference (see Fig. 10) correspond to a ray passing straight through the outer boundary of this region.[7]

By analogy with the boundary of thermal plasma in the Earth's ionosphere this boundary is called the plasmapause (Fig. 13).

In the region from 250 to 500 km the dotted curve had to be interpolated since due to multipath propagation of the 49.8 MHz signal the original data could not readily be interpreted.

The night-time electron density profile in the vicinity of the maximum has been determined from amplitude data obtained for the 423.3 MHz signal by fitting the profile to a

[7] G. FJELDBO and V. R. ESHLEMAN: The Atmosphere of Venus as Studied with the Mariner 5 Dual Radio-frequency Occultation Experiment, Final Report, Part 1, Radio Sci. Lab. Stanford, Electronics Lab., Stanford Univ., California (SUSEZ 69-003), 1969.

[8] T. K. BREUS and K. I. GRINGAUZ: In: Fizika Luni i Planet. Moskva: Nauka 1972, pp. 279–283.

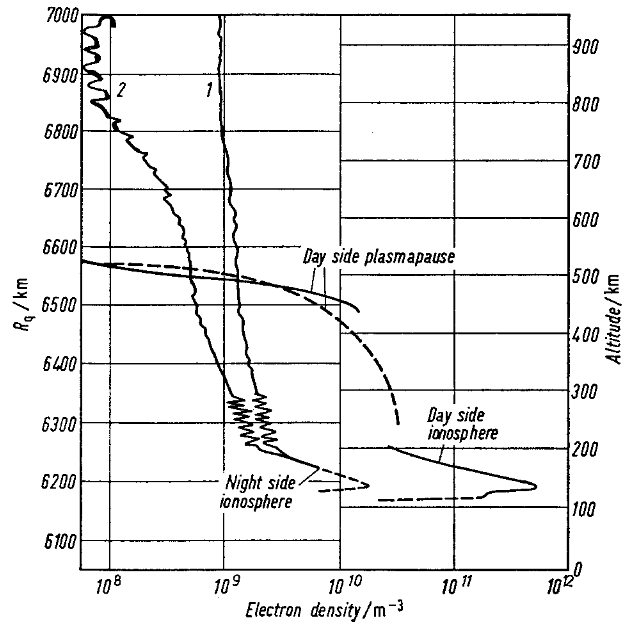

Fig. 13. Altitude profiles of the electron number density in the day and night ionosphere of Venus, obtained from data of the Mariner 5 dual-frequency experiment, and upper limits of the ion density in the atmosphere of Venus from data obtained by the Venera 4 probe (see text for explanation).

Chapman-layer model. It is important to note that the observed amplitude fluctuations in the lower ionosphere (from -3.26 to -3.18 min) could be due either to horizontal irregularities in the ionization profile near the 142 km level (as observed quite often in the terrestrial E region), or to propagation of the signal through four thin layers, each with electron density of the order of 10^{10} m^{-3} in the height range 87 to 120 km.

As stated, the shape of the night-time profile above 200 km essentially depends on the accuracy with which the contributions of the interplanetary medium and the Earth's ionosphere are interpreted.

ε) When at the beginning of the occultation the radio beam first contacted the night-time ionosphere (Fig. 3) the electron content did increase but only slowly. This increase could be explained by the presence of a certain *tail* in the electron density profile at *great heights* in the night-time planetary ionosphere. (It could otherwise be explained by a 1.3% increase of the electron content outside the planetary ionosphere, but this increase must then be attributed to the interplanetary space because during this period no sufficient variations occurred in the Earth's ionosphere as can be seen from Fig. 3.) If the increase is due to an ionized "tail" in the night-time ionosphere, extending high up in the planetary environment, then the shape of the electron density profile deeper in the planetary ionosphere necessarily depends on the assumed electron density distribution in the "tail". Fig. 13 represents two profiles: profile 1 obtained on the assumption that the plasma density in the "tail" was constant, while for profile 2 an exponential law has been assumed along the axis of symmetry coincident with the direction of the solar wind.[7]

The daytime maximum of electron density in the Venusian ionosphere is $(5 \pm 0.5)\ 10^{11}$ m^{-3} and lies at a radial distance of about 6190 km, i.e. near 140 km height. Apparently an additional maximum lies 15 km lower. The scale height above the main peak is about 13 to 15 km, which corresponds to a temperature T_p of 300 to 400 K (if the main ion component of the Venusian ionosphere is CO_2^+). Higher up, the scale height is different as a consequence of a different temperature and ion composition; at such heights lighter ions are beginning to predominate.

The night-time maximum of electron density in the Venusian ionosphere was found at a height of about 170 km; maximum electron density was 10^{10} m^{-3}. The scale height just above the main maximum is of the order of 10 km.

Let us remind that according to Venera 4 data the upper limits of N_i were 10^9 m^{-3} above 300 km and 10^{10} m^{-3} below this altitude. So the measured N_i and N_e in the night-time ionosphere of Venus are not in contradiction. If we take into account the limitations of the radio occultation method for determining the electron density profile (see Sect. 6), it is clear that the uncertainty of the radio data may be reduced by comparing them with the results of direct measurements in the night-time Venusian ionosphere.

9. Comparison of electron density and temperature profiles in the Martian, terrestrial and Venusian ionospheres. To give one an idea of the extension of the Martian and Venusian ionospheres as compared with that of the Earth the electron density profiles obtained for the Martian and Venusian ionospheres are plotted[1] in Figs. 14 and 15, together with typical electron density profiles in the terrestrial ionosphere obtained for the same solar activity.

It is apparent that the Earth, though it occupies an intermediate position between these planets relative to the Sun, has a much thicker and denser ionosphere than either Mars or Venus. This is so in spite of the fact that the Earth's

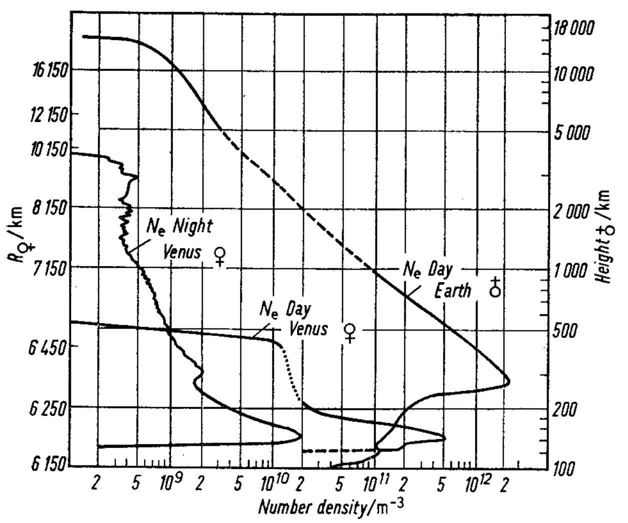

Fig. 14.

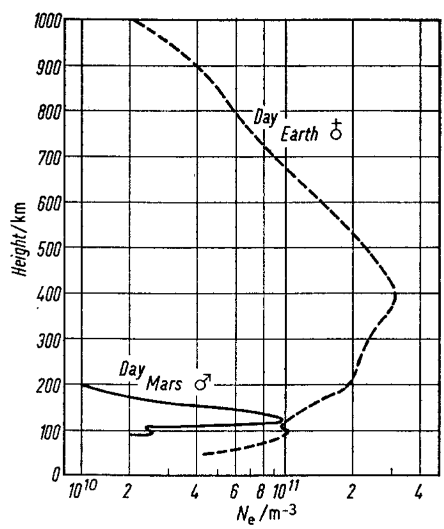

Fig. 15.

Fig. 14. Altitude distributions of the electron density in the ionospheres of Venus and the Earth.[1]

Fig. 15. Altitude distributions of the electron density in the ionospheres of Mars and the Earth.[1]

[1] K. I. GRINGAUZ and T. K. BREUS: Sp. Sci. Rev. **10**, No. 6, 743 (1970).

atmosphere receives solar ionizing radiation of smaller intensity than the atmosphere of Venus. Resuming the main findings:

1. The fact that for all these planets the shapes of electron density profiles are similar is striking enough. For example, below the main maximum of ionization a second maximum is seen in all three profiles. Above the main peak, in the daytime as well as in the night-time Venusian ionosphere (and in the Earth's ionosphere) one observes a sharp rise of the rate of electron density decrease with altitude—"a knee" or "plasmapause" as this phenomenon is called in the Earth's ionosphere. This "knee" occurs, however, at much greater height in the Earth's ionosphere than in the Venusian ionosphere. The phenomenon may be explained by the boundary of the thermal plasma envelope thought to be situated here. Perhaps in the ionosphere of Mars the "knee" in the electron density profile has not yet been found because of the lack of experimental sensitivity to smaller electron densities.[2]

2. The maximum electron densities in the ionospheres of Mars and Venus are of the same order as the maximum density in the daytime ionosphere of Earth.

3. Peak altitudes are considerably lower than the ionospheric peak altitude in the Earth's ionosphere, which lies between 270 and 500 km.

4. The electron temperature at peak altitude in the daytime terrestrial ionosphere may reach 3000 K, and 1000 K in the night-time ionosphere; the electron and ion temperatures in the plasmapause are much higher, tens of thousands K. The corresponding temperatures in the Martian and Venusian ionospheres appear to be much lower.[3-5]

III. Models of the Martian and Venusian ionospheres.

10. Generalities: the influence of neutral composition.

α) First attempts to analyze and describe the structures of the Martian and Venusian ionospheres were made in a similar way as for the Earth's ionosphere, especially as the ionospheres of these planets have many similar features. Major difficulties are encountered when constructing such models, due to the lack of data concerning the upper neutral atmospheres.

Direct *composition measurements* have been carried out only in the lower Venusian atmosphere. The determination of the refractivity by the radio-occultation method allows only the neutral particle density in the lower atmosphere to be determined with the degree of accuracy with which it is possible to determine the chemical composition from other data. Figs. 16 and 17 represent the results of measurements of neutral particle density and temperature in the lower atmospheres of Mars and Venus.[1] For comparison, typical curves of the same parameters for the Earth's atmosphere are also plotted.

Composition, temperature and density in the upper neutral atmosphere have been obtained by extrapolation of the direct measurements in the lower atmosphere. The extrapolation was made in such a way that the models of the ionosphere so constructed were in agreement with the observed electron density/height profiles. Certainly, such a procedure is questionable, since the ion composition,

[2] S. J. Bauer and R. E. Hartle: J. Geophys. Res. **78**, 3169 (1973).

[3] J. V. Evans: In: Solar-Terrestrial Physics (ed. J. W. King and W. S. Newman), London-New York: Academic Press 1967, 289.

[4] K. I. Gringauz: In: Solar Terrestrial Physics (ed. J. W. King and W. S. Newman), London-New York: Academic Press 1967, 341.

[5] G. P. Serbu and E. J. R. Maier: J. Geophys. Res. **75**, 31, 8102 (1970).

[1] V. R. Eshleman: Radio Sci. **5**, No. 2, 325 (1970).

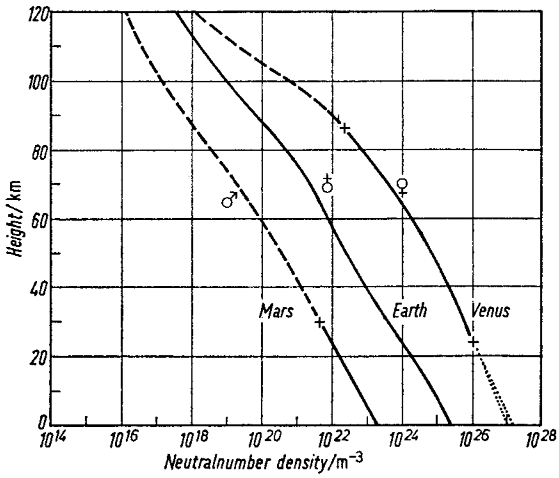

Fig. 16. Altitude profiles of neutral particle number densities in the Martian and Venusian atmospheres (solid line-experimental data, dashed curve-extrapolation). For comparison the neutral particle density in the Earth's atmosphere is also given.[1]

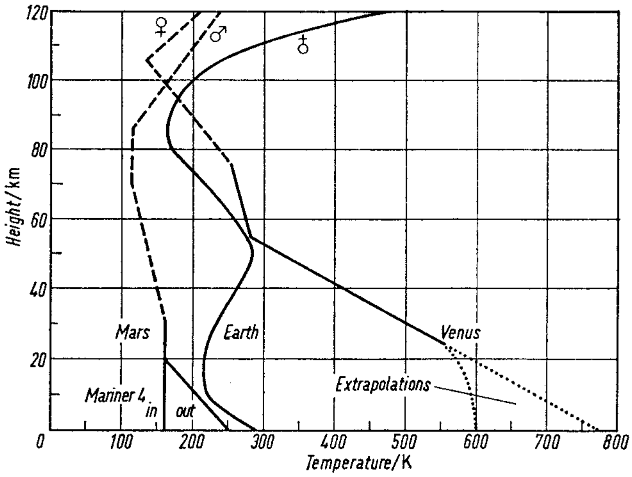

Fig. 17. Altitude profiles of temperatures in the Martian and Venusian atmospheres (solid line-experimental data, dashed curve-extrapolation). For comparison the neutral temperature in the Earth's atmosphere is also given.[1]

which depends on the composition of the neutral gas at the height of the ionosphere, determines the processes which play the main role in forming the ionospheric maximum.

β) An ionization maximum of the type of the terrestrial F1 or E region may be expected if the ionosphere is in photochemical equilibrium. The main ionization maximum of the terrestrial F2 region, however, is formed far above the level of maximum rate of ionization. This is due to the neutral component, namely atoms which prevail at greater altitude in the neutral atmosphere (oxygen atoms in the Earth's atmosphere). If neutral molecules are present at all in the atmosphere, ion losses must occur in the F2 region due to ion-molecule reactions with subsequent dissociative recombination of the molecular ions formed in this way. With increasing height the density of the molecular components of the neutral atmosphere (and hence the rate of ion recombination which is proportional to this density) decreases more rapidly than the atomic component density and hence than the rate of ion formation. It follows that the level of the electron density maximum is higher than that of maximum ion production. The equilibrium is maintained by downward transfer of the ions formed at greater height, down to the region of rapid recombination through ambipolar diffusion.

It is obvious that a knowledge of the atmospheric composition in the region where the maximum of ionization usually appears is extremely important in chosing a correct model of the ionosphere.

11. Problems involving the range near the main peak of the profile. The uncertainty regarding the properties of the neutral planetary atmosphere has consequences for the choice of a suitable model of the ionosphere. This can be seen from an analysis of the first Martian and Venusian ionosphere models constructed on the basis of preliminary data yielded by the experiments of the Mariner 4, Venera 4 and Mariner 5 spacecrafts.

α) Three types of model have been proposed for the Martian ionosphere in analogy with the terrestrial ionospheric layers F2[1-3], F1[4] and E[5,6].

These models are very different. As for the neutral upper atmosphere model, derived from ionospheric parameters fitting the ionospheric models of types E and F2, the corresponding neutral densities differ by four orders of magnitude. The neutral particle temperature in the vicinity of the main ionization peak differs by a factor of five. In the F2-type models atomic oxygen is taken to be the main component of the upper atmosphere while in the E-type model the main component is a mixture of CO_2 and N_2 (see Fig. 18). Available experimental data at that time did not allow the percentage of CO_2 to be derived with the degree of accuracy necessary to distinguish between the different proposed models. The Mariner 4 observations are compatible with a CO_2 content of 80 to 100% in the lower Martian atmosphere.

The models of types F2 and E are in fact contradictory in many respects.

From Mariner 5 data two preliminary models (Fig. 19) of types F1 and E[7] have been proposed under the assumption that the ionospheric ions are all CO_2^+. In the vicinity of the ionization peak the neutral particle densities of these two models differ by two orders of magnitude, while the temperatures differ by a factor of two.

The results of measurements[8,9] carried out on Mariner 6 and 7 confirmed that CO_2 is indeed the main component of the Martian neutral atmosphere. No traces of nitrogen were found so that models with an appreciable N_2 content had to be discarded. Atomic oxygen, O as well as CO and hydrogen H were also found to be practically negligible. For instance, the ratio of O and CO_2 densities[9,10] in the vicinity of the ionospheric peak is of the order of 10^{-3}.

[1] G. Fjeldbo, W. C. Fjeldbo, and V. R. Eshleman: J. Geophys. Res. **71**, No. 9, 2307 (1966).

[2] F. S. Johnson: Science **150**, 1455 (1965).

[3] F. S. Johnson: The atmosphere of Mars. Presented at 7-th Int. Space Sci. Symp. Comm. on Space Res. (COSPAR), Vienna, Austria, 11–17 May 1966.

[4] T. M. Donahue: Science **152**, 763 (1966).

[5] J. W. Chamberlain and M. B. McElroy: Science **152**, 21 (1966).

[6] M. B. McElroy: J. Geophys. Res. **74**, No. 1, 29 (1969).

[7] A. J. Kliore, G. S. Levy, D. L. Cain, G. Fjeldbo, and S. I. Rasool: Science **158**, 1683 (1967).

[8] C. A. Barth *et al.*: Science **165** (Sept. 5, 1969).

[9] M. B. McElroy and D. M. Hunten: J. Geophys. Res. **75**, No. 7, 1188 (1970).

[10] D. E. Anderson and C. W. Hord: J. Geophys. Res. **76**, 6666 (1971).

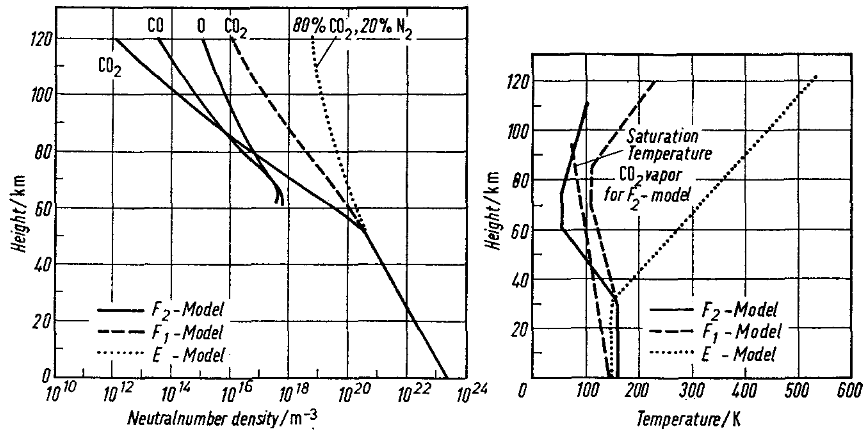

Fig. 18. Models of the Martian neutral atmosphere calculated from experimental data obtained by Mariner 4, assuming ionosphere models of the type of the terrestrial F2 and F1 layers. Left: number densities, right: temperatures, for three different models (see text). Thermal equilibrium is supposed to exist in the neutral atmosphere (model E).*

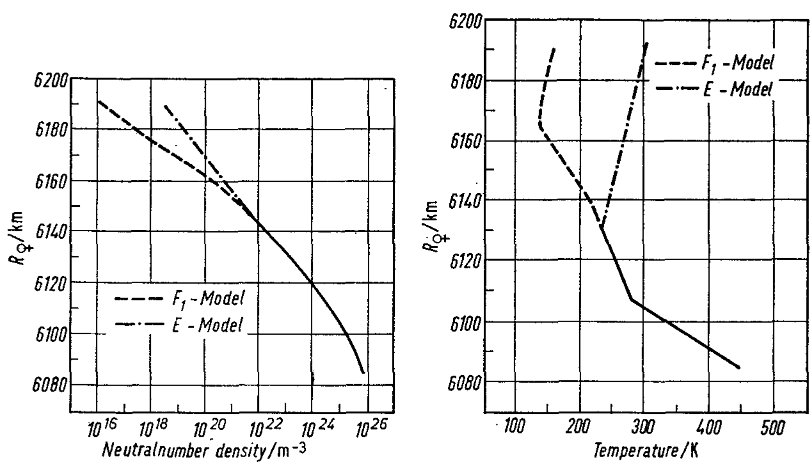

Fig. 19. Models of the daytime neutral atmosphere of Venus calculated from experimental data obtained by Mariner 5, corresponding to ionospheric models of the type of the terrestrial F1 and E layers.[7] Ordinate: radius from center of Venus. Left: number densities, right: temperatures, for two different models.

β) A detailed analysis of the characteristic features of the neutral atmosphere of *Venus*, obtained by indirect and *in-situ* methods can be found in a review paper.[11]

As for the composition of the Venusian lower atmosphere, data obtained in Venera 5 and 6 experiments showed that the CO_2 content in the atmosphere of

* G. FJELDBO and V. R. ESHLEMAN: Planet. Space Sci. **16**, No. 8, 1035 (1968).

[11] V. I. MOROZ: Uspehi Fisičeskih Nauk **104**, No. 2, 255 (1971).

Venus is as high as 93 to 100%; nitrogen and other inert gases contribute some 2 to 5%, while the oxygen, O_2 content[12,13] does not exceed 0.1%.

So oxygen is practically absent in the upper atmospheres of both planets. For this reason the ionospheric models obtained by analogy with the terrestrial ionospheric layer F2 need to be abandoned.

The F1-type model, for the Venusian ionosphere where a pure CO_2 atmosphere and hence CO_2^+ ions alone are assumed, seems to be the model most consistent with the observations. The Martian ionosphere electron density profiles can also most closely be matched with the F1-type models.

The following ions are thought to be the main components of the Martian ionosphere[14]: CO_2^+ due to photoionization of CO_2; O_2^+ due to the charge-exchange reaction $CO_2^+ + O \rightarrow O_2^+ + CO$; possibly O^+ at greater heights due to photoionization of an atomic oxygen O.

γ) There is, however, another difficulty since *dissociation* of CO_2 should take place under the influence of the Schumann-Runge bands in the solar spectrum:

$$CO_2 + h\nu \rightarrow CO + O. \tag{11.1}$$

This raises the question as to how the products of dissociation, namely atomic oxygen and CO, could disappear from the upper atmospheres so rapidly that no F2 layer appears above the F1 peak.

Molecular recombination of CO and O is slower[15] than recombination of O with O. Hence one should ask what mechanism could prevent the rapid formation of molecular oxygen, O_2. This species should be identifiable rather easily by spectroscopic measurements. Anyway, some effective mechanism of CO and O_2 interaction must be removing CO from the upper atmospheres of Mars and Venus.

So far attempts have been made to solve this problem by considering local photochemical processes. McElroy and Hunten[9] postulated that most of the oxygen in the upper atmospheres was formed in the (^{1}D) state. This would react with CO_2 to produce CO_3, and this activated complex might easily be deactivated down to the ground state by emission of photons. This de-activated CO_3 may then react with CO to produce 2 CO_2 so that the overall result of the process would be a very rapid recombination of CO and O. However, as shown by Shimizu and other authors[16-18] and recently acknowledged by McElroy,[14] the above reaction chain with CO_3 is not acceptable, since O (^{1}D) would rapidly revert to O (^{3}P) because of inelastic collisions with CO_2.

Since local reactions do not seem to give satisfaction, American and Japanese authors are now considering columnar equilibrium with vertical interchange by mixing and vertical transport of dissociation products down into the lower regions of the planetary atmosphere where reactions with triple collisions could be operative and play the main role.

From their calculations these authors conclude that the eddy-diffusion coefficient K_{turb} for the Martian atmosphere must be of the order of $10^3\ m^2\ s^{-1}$ [18,19] which is an order of magnitude higher than for the Earth's atmosphere. All the CO and O (^{3}P) which may be produced in the upper atmosphere should be trans-

[12] A. P. Vinogradov, Ju. A. Surkov, B. M. Andreyčikov, O. M. Kalinin, and I. M. Grečiševa: Kosmič. Issled. **8**, 4, 578 (1970).

[13] V. S. Avdujevskij, M. Ja. Marov, and M. K. Rojdestvenskij: Kosmič. Issled. **7**, 2, 233 (1969).

[14] M. B. McElroy: Upper Atmospheres of the Planets. Preprint of paper given at the Symposium of IAGA, Moscow, August 1971.

[15] I. D. Clark and J. F. Noxon: J. Geophys. Res. **75**, 7311 (1970).

[16] M. Shimizu: Icarus **9**, 593 (1968).

[17] M. Shimizu: Icarus **10**, 11 (1969).

[18] T. Shimazaki and M. Shimizu: Rep. of Ionosph. and Space Research in Japan **24**, 80–98 (1970).

[19] M. Shimizu: J. Geophys. Res. **78**, 6780 (1973).

ported downwards to the level where recombination to CO_2 under the influence of catalytic reactions[20] with HO_2 or H_2O will be almost complete. In the Martian stratosphere the effect of turbulence may well exceed that of Earth's[6] because of the absence of an ozone layer in the atmosphere of Mars. In the terrestrial atmosphere this particular layer provokes a temperature inversion that prevents the penetration of energy from the lower towards the upper regions of the atmosphere.

The eddy-diffusion coefficient K_{turb} for the Venusian atmosphere[19] must be of the order of: 10^2 to 10^3 $m^2 s^{-1}$.

α) The failure of the theory involving the CO_3 complex proposed to explaining the photochemistry of the Martian and Venusian atmospheres created new problems concerning the *structure of the Venusian upper atmosphere*. As will be shown below, a hydrogen-deuterium model of the upper atmosphere has been proposed to account for observations of the scattering of solar Lyman-alpha radiation by the atmosphere.[21] From these observations it was concluded[22] that K_{turb} could not exceed 10 $m^2 s^{-1}$ otherwise the H density necessary to explain the Lyman-alpha observations would not be afforded. It is quite possible that turbulent mixing is less important in the Venusian atmosphere than in the Martian one, since tidal motions are absent on Venus because of the slow rotation of the planet. The atmosphere of Venus is extremely dense and a temperature maximum seems to exist since waves propagating from the lower to the upper regions of the Venusian atmosphere appear to be reflected. But if the eddy-diffusion coefficient is $K_{turb} \sim 10$ $m^2 s^{-1}$, the problem of CO_2 photochemistry in the lower Venusian atmosphere remains unexplained.

12. The upper ionosphere of Venus.

α) A most peculiar feature of the upper ionosphere of Venus is a sharp decrease in the electron density at a height of about 500 km in the daytime, but of about 3000 km in the night-time. This feature is similar to the Earth's plasmapause, which is usually observed at a distance of about 20000 km from the Earth. Venus, unlike Earth, has no strong internal magnetic field and hence there is no magnetosphere which could act as an obstacle to stop the solar wind. The role of obstacle may be filled by the Venusian ionosphere[1,2] which may cause a shock wave at a short distance from the planet. If this is so, electric currents must be induced in the ionosphere as a result of interaction with the (rather weak) interplanetary magnetic field. This process may create an induced magnetosphere or *pseudo-magnetosphere*. The boundary of the disturbed interplanetary magnetic field and this kind of magnetosphere may indeed correspond[1,3] to the observed *plasma-pause* (or *anemopause* as it is sometimes called). On the night-time side of the planet the plasmapause is adjacent to the zone of disturbed solar plasma flux, which is therefore farther from the planet on the night-side.

β) Above the ionization maxima of the Venusian ionosphere a noticeable increase in the scale height is observed. By day this is above 200 km, by night above 300 km of altitude. This observation indicates the presence of light ions. For example, in the vicinity of the peak of the daytime profile the plasma scale

[20] R. R. REEVES *et al.*: J. Phys. Chem. **70**, 1637 (1966).
[21] C. A. BARTH: J. Atmos. Sci. **25**, 564 (1968).
[22] M. B. MCELROY and D. M. HUNTEN: J. Geophys. Res. **74**, 1720 (1969).
[1] H. S. BRIDGE, A. J. LAZARUS, C. W. SNYDER, E. J. SMITH, L. DAVIS, JR., P. J. COLEMAN, JR., and D. E. JONES: Science **158**, 1669 (1967).
[2] F. S. JOHNSON and J. E. MIDGLEY in: K. S. CHAMPION, P. A. SMITH and R. L. SMITH-ROSE (eds.): Space Research **IX**. Amsterdam: North-Holland Publ. Co. 1969, 760.
[3] Mariner Stanford Group: Science **158**, 1678, 1683 (1967).

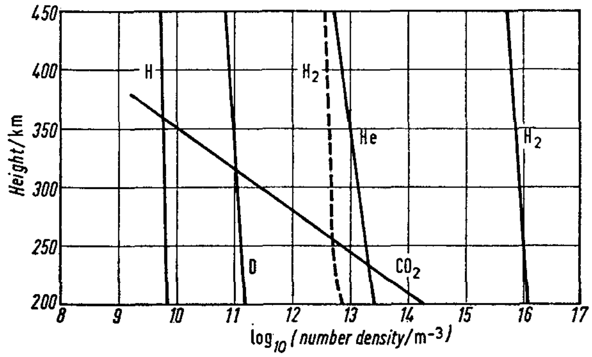

Fig. 20. Distribution of the neutral constituents in the upper atmosphere of Venus after BARTH's results computed by McELROY and HUNTEN.[8] These authors give, however, reasons in favor of the broken line for H_2.

height H_p is (13 to 15) km, corresponding to a temperature $T_p = (300 \text{ to } 400)$ K if the main component is taken to be CO_2. However, above the 300 km level H_p is as large as 30 km.

From measurements of the intensity distribution of the Lyman-alpha radiation in the upper atmosphere it is concluded that the upper neutral atmosphere of Venus consists of two components whose scale heights differ by a factor of two.[4,5] If one supposes the emission to be due to fluorescent scattering of the solar Lyman-alpha radiation in the atmosphere and that one of its components is atomic hydrogen, H, then the second component would be molecular hydrogen or deuterium. The author of the Lyman-alpha experiment, BARTH[4], assumed that the second component was H_2. According to his estimates the H and H_2 densities in the upper atmosphere should have the distributions depicted in Fig. 20. However, McELROY and HUNTEN[6] and DONAHUE[7] have critisized this H—H_2 model of the outer Venusian atmosphere. They argue that photodissociation of H_2 would produce so much atomic hydrogen H that its density would greatly exceed the density necessary to explain the observed intensity of Lyman-alpha radiation. According to McELROY and HUNTEN's estimates,[8] the H_2 density in the Venusian upper atmosphere cannot exceed the limit indicated by a broken line in Fig. 20.

As mentioned above, a hydrogen-deuterium model could also explain the observed facts. In that case the concentration of *deuterium*, D, would have to be one order of magnitude higher than the H density near the base of the exosphere. This is rather astonishing since the D/H ratio in the Earth's oceans is of the order of 10^{-4}. McELROY and HUNTEN[8] then DONAHUE[9] and WALLAS[10] proposed that the enrichment of deuterium in the Venusian atmosphere would be due to different rates of thermodissociation. Allowing for this effect, one finds that with a ratio D/H of only 0.1 in the lower Venusian atmosphere this ratio in the upper atmosphere would be of the order of 10. Since the magnitude of the D/H ratio

[4] C. A. BARTH: J. Atmos. Sci. 25, 564 (1968).
[5] C. A. BARTH, L. WALLACE, and J. B. PEARCE: J. Geophys. Res. 73, 7, 2541 (1968).
[6] M. B. McELROY and D. M. HUNTEN: J. Geophys. Res. 74, 1720 (1969).
[7] T. M. DONAHUE: J. Atmos. Sci. 25, 568 (1968).
[8] M. B. McELROY and D. M. HUNTEN: J. Geophys. Res. 75, No. 7, 1188 (1970).
[9] T. M. DONAHUE: J. Geophys. Res. 74, 1128 (1969).
[10] L. WALLACE: J. Geophys. Res. 74, 115 (1969).

is strongly dependent on the eddy-diffusion coefficient K_{turb}, this theory requires an eddy-diffusion coefficient of the order of 10 $m^2 s^{-1}$ which seems far too small in view of the CO_2 chemistry of the Venusian atmosphere (see Sect. 11).

Helium may also be one of the components of the neutral upper atmosphere of Venus.[11,12] The curve in Fig. 20 that represents the atomic He density[8] has been computed from an electron density profile for the night-time Venusian ionosphere under the assumption that the night-time ionization maximum was due to charge exchange of CO_2 with helium ions arriving from the daytime ionosphere.[11]

γ) Among the proposed *models of the Venusian ionosphere* the most detailed are those of BANKS and AXFORD[13] and of BAUER and his coauthors [*3*].[14–16] These are all based on the model of the upper neutral atmosphere presented in Fig. 20.

In both models, the main ionization peak of the daytime ionosphere is attributed to photoionization of CO_2 by ultraviolet solar radiation, whereas the outer regions of the ionospheres differ in their composition. H and D are the main components in the model of BANKS and AXFORD[13] while H (or D) and He are the main components in the model of BAUER *et al.*[14] Another difference is that BAUER and his coauthors[14] consider a static model (i.e. one in static equilibrium) while BANKS and AXFORD[13] insist on the need for a dynamic model (i.e. one in dynamical equilibrium).

In both models the position of the anemopause is determined by the condition that the dynamical solar wind pressure equals the pressure in the ionosphere. In the BANKS and AXFORD[13] model the directional fluxes of the ionospheric ions H^+ and D^+ participate in the pressure balance at the anemopause height. Under the influence of the solar wind, at heights of about (400 to 500) km where the ion diffusion coefficient in the neutral gas is high enough, the ions may travel around the planet and so reach the nightside up to a height of 3000 km.

In the model of BAUER and his coauthors a horizontal magnetic field of about 10 γ (as has been measured by the magnetometer aboard of Venera 4 at a height of about 200 km[17]) is included in the pressure balance. They found a self-consistent solution including density and temperature distributions in the daytime Venusian ionosphere, see Fig. 21. According to their calculations, the directional ion fluxes sweep up the transverse magnetic field from the ionosphere and hence increase its thermal conductivity. The increased thermal conductivity leads to a reduction of plasma temperature, thus provoking a disturbance of the pressure balance at the anemopause. Very large H^+ and D^+ ion fluxes would be needed to maintain the balance. These cannot be provided from ionosphere sources like photoionization of H and D or by a hypothetical charge-exchange reaction between H and CO_2^+ as proposed by BANKS and AXFORD. Therefore BAUER *et al.* suppose that the magnetic field participates in the pressure balance and that helium ions rather than H^+ and D^+ ions play the main role in determining the upper daytime ionosphere of Venus. According to their model the eddy-diffusion coefficient in the Venusian atmosphere must be of the order of 100 $m^2 s^{-1}$ in order to provide a He density of $5 \cdot 10^{13}$ m^{-3} at 100 km (see Fig. 20). It appears that the origin of the

[11] M. B. McELROY and D. F. STROBEL: J. Geophys. Res. **74**, No. 5, 1118 (1969).
[12] R. C. WHITTEN: J. Geophys. Res. **75**, 19 (1970).
[13] P. A. BANKS and W. I. AXFORD: Nature **225**, 924 (1970).
[14] S. J. BAUER, R. E. HARTLE, and J. R. HERMAN: Nature **225**, No. 5232, 533 (1970).
[15] S. J. BAUER, R. E. HARTLE, and J. R. HERMAN: Nature (London) **225**, No. 5232, 533 (1970).
[16] J. R. HERMAN, R. E. HARTLE, and S. J. BAUER: The Dayside Ionosphere of Venus, Goddard Space Flight Center, Greenbelt, Maryland, 620—272, June 1970 (Preprint), (1970b).
[17] Š. Š. DOLGINOV, E. G. JEROŠENKO, and L. N. ŽUZGOV: Kosmič. Issled. **6**, 561 (1968).

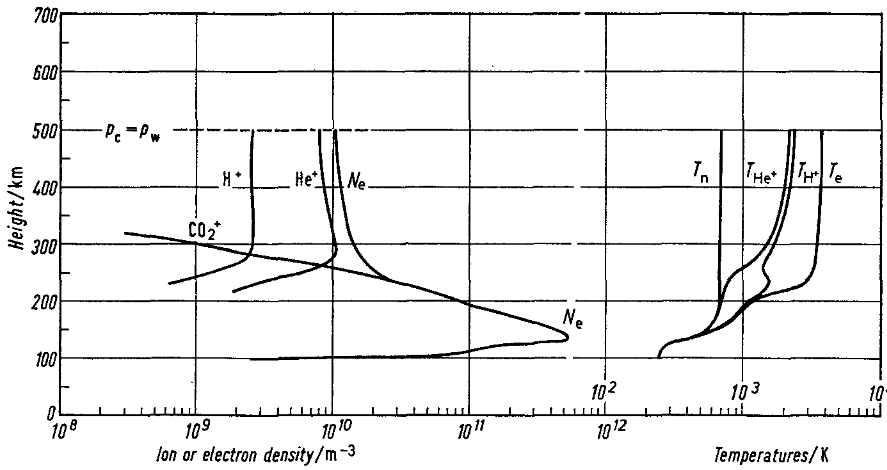

Fig. 21. Model of charged-particle density (electrons and ions CO_2^+, He^+, H^+) and temperature (neutrals, He^+ ions, H^+ ions, electrons) distributions of the Venus ionosphere consistent with pressure balance between solar wind and the ionosphere (balance pressure $p_c = p_w$ about $8.65 \cdot 10^{-10}$ N m^{-2}).[15]

night-time ionization maximum is connected with the assumption of an abundance of He^+ ions in the upper Venusian atmosphere.

δ) It is difficult to explain the high ion densities near the night-time ionization peak of Venus. The time constant of recombination in the vicinity of the maximum is (100 to 200) sec. Such ionization sources as cosmic rays, meteors and scattered Lyman-alpha radiation cannot produce a peak of ionization at the observed heights, and it is hard to imagine that the solar wind would penetrate down to these levels of the night-time ionosphere.

McElroy and Strobel[11] suggested that the night-time ionization maximum was sustained by *transfer of charged particles* from the daytime side of the planet.

Developing this idea, Bauer *et al.*[15,16] suppose that helium ions are transferred to the nightside ionosphere and that charge exchange occurs with CO_2. The CO_2^+ ions formed in this way diffuse downward into the dense atmosphere where they recombine. The ionization maximum then occurs at the height where the rate of dissociative recombination becomes comparable with the rate of CO_2^+ influx due to diffusion.

Banks and Axford[13] note that the inverse charge-exchange reaction of H^+ appearing in the night-time Venusian atmosphere with CO_2 is not sufficiently effective to explain the high ion densities in the night-time maximum. Therefore they also incline to the idea that H_2^+ ions which come from the daytime ionosphere exchange their charge with CO_2 molecules. Numerical calculations have not been presented for either model of the night-time ionosphere.

The altitude distribution of electrons in the Venusian ionosphere in 1974 as obtained by the Mariner-10 S- and X-band measurements is shown in Fig. 22.[18]

One can see that the electron density vs. height profile has two "ledges", one near 180 km, another near 250 km altitude. The plasmapause was located near 300 km. The electron density at the plasmapause is by an order of magnitude smaller than that obtained with the Mariner-5 experiments, but the rampressure

[18] H. T. Howard and C. L. Taylor *et al.*: Science **183**, No. 4131 (1974).

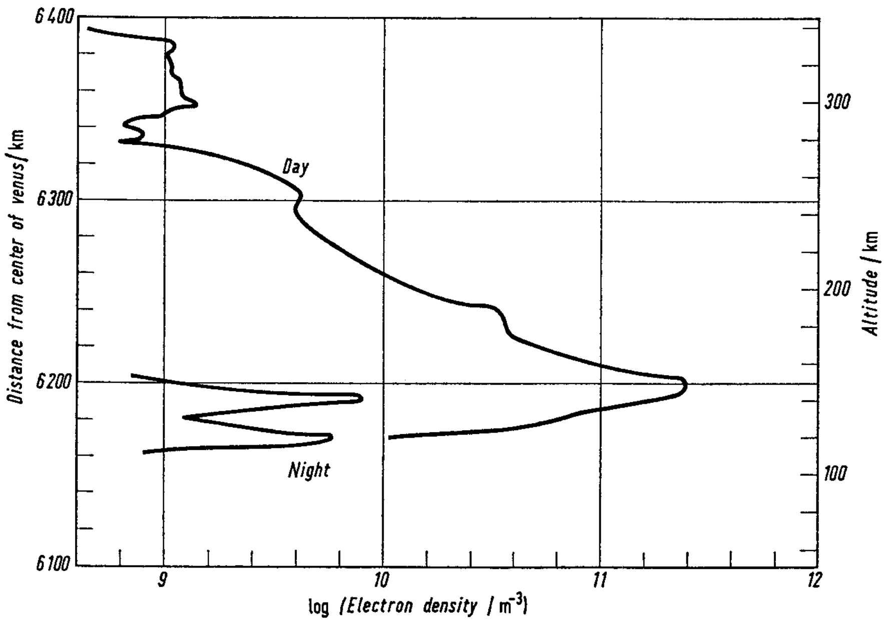

Fig. 22. Dayside and nightside electron number density obtained by differential Doppler S- and X-band observations of Mariner 10.[19]

of the Solar wind during the Mariner-10 encounter was by about a factor of 1.5 greater than during the Mariner-5 encounter.[20]

The Mariner-10 experiments detected a considerable amount of atomic oxygen and neutral helium in the upper atmosphere of Venus.[21]

BAUER and HARTLE[22] have suggested a new model of the day-side ionosphere of Venus, based on the Mariner-10 data. The "ledge" of the electron density profile at 180 km is treated in this model as an F2-layer consisting of O^+, deformed by the direct influence of the solar wind pressure. The assumption that He^+ is the dominant ion in the upper atmosphere of Venus has now been experimentally confirmed and the upper ledge of the density profile is explained as consisting of He^+.

Unfortunately, the pressure balance problem at the plasmapause is even more difficult after the Mariner-10 experiment. The same can be said about the explanations of the height structure of the venusian ionosphere; apart from the previous difficulties one must now explain a new and strange form of the Ne(h)-profile at night. May be that electron fluxes as revealed by Venera 9 and 10 in the planet's optical umbra[23] might produce the Venusian night-time ionosphere.[24]

[19] H. T. HOWARD, G. L. TYLER, and G. FJELDBO *et al.*: Science **183**, 1297–1301 (1974).

[20] H. S. BRIDGE, A. J. LAZARUS, and J. D. SCUDDER *et al.*: Science **183**, 1293–1296 (1974).

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[24] JU. N. ALEXANDROV, M. B. VASILIEV, A. S. VIŠLOV *et al.*: Venus ionosphere as measured by dual-frequensy radis occultation of Venera 9 and 10. Preprint P_2-278, Space Research Institute, Akademika Nauk SSSR, 1976.

13. The upper ionosphere of Mars. According to the results of magnetic field measurements onboard Mars-2 and 3[1] Mars may possess an intrinsic magnetic field corresponding to a magnetic moment of $2 \cdot 4 \cdot 10^{12}$ T m^3 ($= 2.4 \cdot 10^{16}$ Gs m^3). This field stops the solar wind at a distance of about 1000 ... 1500 km from the planet's surface.[2-5]

The shock front due to interaction of the solar wind and Mars' magnetosphere is apparently removed to 2500 km from the surface ($\approx 0.7\ R_M$)[2].

Plasma distribution in the martian magnetosphere may resemble the corresponding distribution in the Earth magnetosphere with a plasmapause at some distance from the surface.

However, the existence of a plasmapause apparently can not be detected from electron density profiles (Fig. 6), due to strong fluctuations of electron density found by means of the radio-occultation method.

Conclusions.

From our short description of experimental data obtained in the Martian and Venusian ionospheres, the methods of measurement, and the models constructed to explain these data, it appears that there are still many problems which demand further experiments.

First of all, it is necessary to obtain more accurate electron density profiles, especially for the night-time ionosphere of Venus, and better neutral densities too. Other vital data are direct measurements of plasma composition and density above the main ionization peak, neutral particle temperatures, ratios of upper atmosphere neutral composition, and neutral density profiles. Measurements of variations in space and time of ionospheric parameters, and of relevant horizontal gradients would advance our understanding, in particular of a possible particle transfer from the daytime side of the planet. The launching of artificial planetary satellites with appropriate orbits and equipment and also *in-situ* measurements by means of space vehicles descending into the planetary atmospheres would be of enormeous value in solving these problems.

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[*2*] Gringauz, K. I., and T. K. Breus: Comparative charateristics of the ionospheres of the planets of the terrestrial group: Mars, Venus and the Earth. Space Sci. Rev. **10**, 743–769 (1970).

[*3*] Bauer, S. J.: Physics of planetary ionospheres. In: Physics and Chemistry in Space, Vol. 6. Berlin-Heidelberg-New York: Springer 1973.

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