emission may result from chemical reactions between atmospheric species previously photodissociated or from charged-particle bombardment.

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Notes

1. Preparations for the experiment were begun in early 1963. The instruments were built by Labko Scientific, Inc., Stillwater, Oklahoma, under the direction of L. C. Labarthe. The integration of the instruments onto the spacecraft was conducted by G. McNutt and E. F. Mackey of Packard Bell Electronics, Newbury Park, California; and E. McMillan, H. Canvel, A. Lane, and R. Carlson of the Jet Propulsion Laboratory. The data reduction was carried out by Mrs. C. Leyner, Mrs. S. Schaffner, and D. E. Anderson of the University of Colorado, with the help of the University Computing Center. During the early stages of the formulation of the experiment, J. W. Chamberlain and J. C. Brandt of Kitt Peak National Observatory, Tucson, Arizona, contributed useful ideas.
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Venus: Ionosphere and Atmosphere as Measured by Dual-Frequency Radio Occultation of Mariner V

Abstract. *Venus has daytime and nighttime ionospheres at the positions probed by radio occultation. The main layers are thin by terrestrial standards, with the nighttime peak concentration of electrons being about two orders of magnitude below that of the daytime peak. Above the nighttime peak were several scale-height regimes extending to a radius of at least 7500, and probably to 9700, kilometers from the center of Venus. Helium and hydrogen at plasma temperatures of 600° to 1100°K seem indicated in the regimes from 6300 to 7500 kilometers, with cooler molecular ions in lower regions. Above the daytime peak a sharp plasmapause was discovered, marking a sudden transition from appreciable ionization concentrations near Venus to the tenuous conditions of the solar wind. This may be indicative of a kind of interaction of the magnetized solar wind with a planetary body that differs from the two different kinds of interaction characterized by Earth and by Moon. For Venus and probably for Mars, the magnetic field of the solar wind may pile up in front of the conducting ionosphere, form an induced magnetosphere that ends at the plasmapause, above which any ionosphere that tends to form is swept away by the shocked solar wind that flows between the stand-off bow-shock and the magnetopause. The neutral atmosphere was also probed and a surface reflection may have been detected, but the data have not yet been studied in detail. Results are consistent with a super-refractive atmosphere, as expected from Soviet measurements near the surface. Thus, two unusual features of Venus can be described in terms of a light trap in the lower atmosphere, and a magnetic trap in the conducting ionosphere.*

As Mariner V passed behind Venus on 19 October 1967, dual-frequency radio transmissions from Earth reached the spacecraft after passing through Venus's ionosphere and atmosphere. Signal characteristics were measured and stored on magnetic tape for later transmission to Earth on the telemetry channel. From these characteristics, preliminary profiles of electron concentration as a function of radius have been derived, by techniques described previously (*1*), for both the nighttime and daytime ionospheres probed by the signals. Effects of the dense neutral atmosphere were measured over the same two regions on Venus, but very little analysis has been attempted thus far since the principal effects of the lower atmosphere were more accurately determined in the S-band experiment (*2*). During the cruise portion of the mission, the dual-frequency experiment measured characteristics of the interplanetary plasma, but these results will be reported elsewhere.

This is primarily a report on the planetary data obtained from the dual-frequency experiment, including some very preliminary discussion and interpretation relative to physical and chemical properties of the upper atmosphere. In addition, we discuss briefly how the results may help define a third type of interaction of a planetary body with the solar wind, where that of Earth and Moon represent the other two types.

Harmonic, continuous-wave signals at 49.8 and 423.3 Mhz were transmitted from a 150-foot (46-m) steerable, parabolic antenna at Stanford. Transmitter powers were about 350 kw at the lower, and 30 kw at the higher, frequency. The signals were received by fixed, low-gain antennas on the spacecraft provided by feeding two of the solar panels for the lower frequency, and by adding a dipole with reflectors at the end of one of the panels for the higher frequency. The design of a phase-locked, dual-frequency receiver for interplanetary plasma measurements on Pioneer spacecraft was modified for the Mariner instrument.

At the spacecraft, the 2/17th subharmonic of the higher frequency was compared with the lower frequency to provide a beat note whose frequency was measured by counting positive and negative zero crossings. These counts provided a dispersive Doppler measurement of the change in the amount of plasma along the path, with one count representing a change of about 2×10^{14} electrons m^{-2}. The sign of the change could also be determined since the two frequencies actually differed from the 2/17 ratio by a precisely determined bias of 50 hz. Thus the count was 60 in the 0.6-second sampling period if no change of ionization occurred along the changing path in that interval of time, and values larger or smaller than 60 indicate the amount and sign of the change.

The amplitudes of each of the two signals were measured every 0.6 second during encounter. Changes in amplitude caused by Venus were expected due to: (i) focusing and defocusing in its ionosphere; (ii) defocusing in its neutral atmosphere; (iii) possible absorption in its ionosphere or atmosphere; and (iv) the possible diffractive cutoff of signals by the limb of the solid planet. It appears that (i) and (ii) were seen and (iv) was not seen, while it has not yet been determined whether or not there was any measurable absorption.

The dispersive Doppler and two sets of amplitude measurements constitute the results of the experiment to be discussed further. While the frequencies of the two signals were also measured, and several differential group-path measurements were made near encounter, they are not sufficiently precise to aid in the preliminary analysis. The frequency measurements were included in the original receiver design for engineering and operational use, while the group-path measurement is of particular value for the interplanetary studies.

A figure in the introductory paper (*3*, Fig. 3) illustrates the regions probed at Venus by the radio signals. During entry the ionosphere and atmosphere at about 35°N were measured. The solar zenith angle was 140°, and this area had been out of direct sunlight for about 16 Earth days. At exit, the latitude was 35°S, the solar zenith angle 40°, and the region studied had been in sunlight for about 42 Earth days. Assuming that the solar wind arrives at about 5° from the Sun-Venus line due to aberration, the angle between the subsolar-wind point and the daytime region of the atmosphere probed by the radio waves was about 45°.

Figure 1 illustrates the amplitude measurements. In the absence of the planet, all amplitude curves of Fig. 1 would ideally stay at the level indicated as *0 dB*. The most obvious effect of Venus is the general reduction of signal strength on entry, and the rise on exit, which show the defocusing effects of the neutral atmosphere. However, for this report, the ionospheric effects indicated by numbers *1* to *5* are of prime interest.

The feature indicated by *1* in Fig. 1 is the focusing and defocusing at 423.3 Mhz due to the dense part of the nighttime ionosphere. These effects should be magnified at the lower frequency since the angle of ray bending is proportional to f^{-2}, where f is the radio frequency (*1*). At 49.8 Mhz the feature at *2* shows 16 db of signal loss due to ionospheric defocusing.

At exit over the daytime side of the planet, the main ionospheric effect at 423.3 Mhz is indicated by *3*. This feature is rather similar to *2* for the nighttime ionosphere measured at 49.8 Mhz. If they were the same, it would follow that the shapes of the two layers near their peaks would be approximately the same, but the peak electron concentration would be related as

$$(N_{max})_{day}/(N_{max})_{night} = (17/2)^2\, z_{night}/z_{day}$$

where z_{night} and z_{day} are the distances from the limb of the planet to the spacecraft at entry and exit occultation, respectively, and N_{max} is the peak electron concentration (*1*). Thus, to the extent that *2* and *3* are similar, $(N_{max})_{day} \cong 50(N_{max})_{night}$.

The more detailed amplitude features of *2* and *3*, in particular the cusps on the right side of *2* and left side of *3*, are similar to what would be expected if caustics were formed before the rays reached the spacecraft. That is, it appears that certain of the adjacent rays that were parallel (having come from Earth) as they entered the ionosphere were refracted differentially to the extent that they crossed over (formed caustics) in the region between the planetary limb and the spacecraft. This results from high values of the second derivative of electron concentration with altitude (*1*). Because of the caustics, special precautions and procedures are required in the analysis.

It appears from feature *5* that the effects of the daytime ionosphere were so intense that they may have prevented reliable measurement of the 49.8-Mhz signal for most of the time up until the raypaths were passing several hundreds of kilometers above the peak of the layer. Indicated signal strength between $E + 22^{m}\ 0^{s}$ and $E + 23^{m}\ 30^{s}$ is so low that the receiver may actually have been out of lock at this time. However, such ionospheric interference would be quite incompatible with the low densities and gradients that would be expected at these altitudes if the main layer decays with altitude, as would be expected. It could be that *5* is due to the receiver not locking to a strong signal in the expected way,

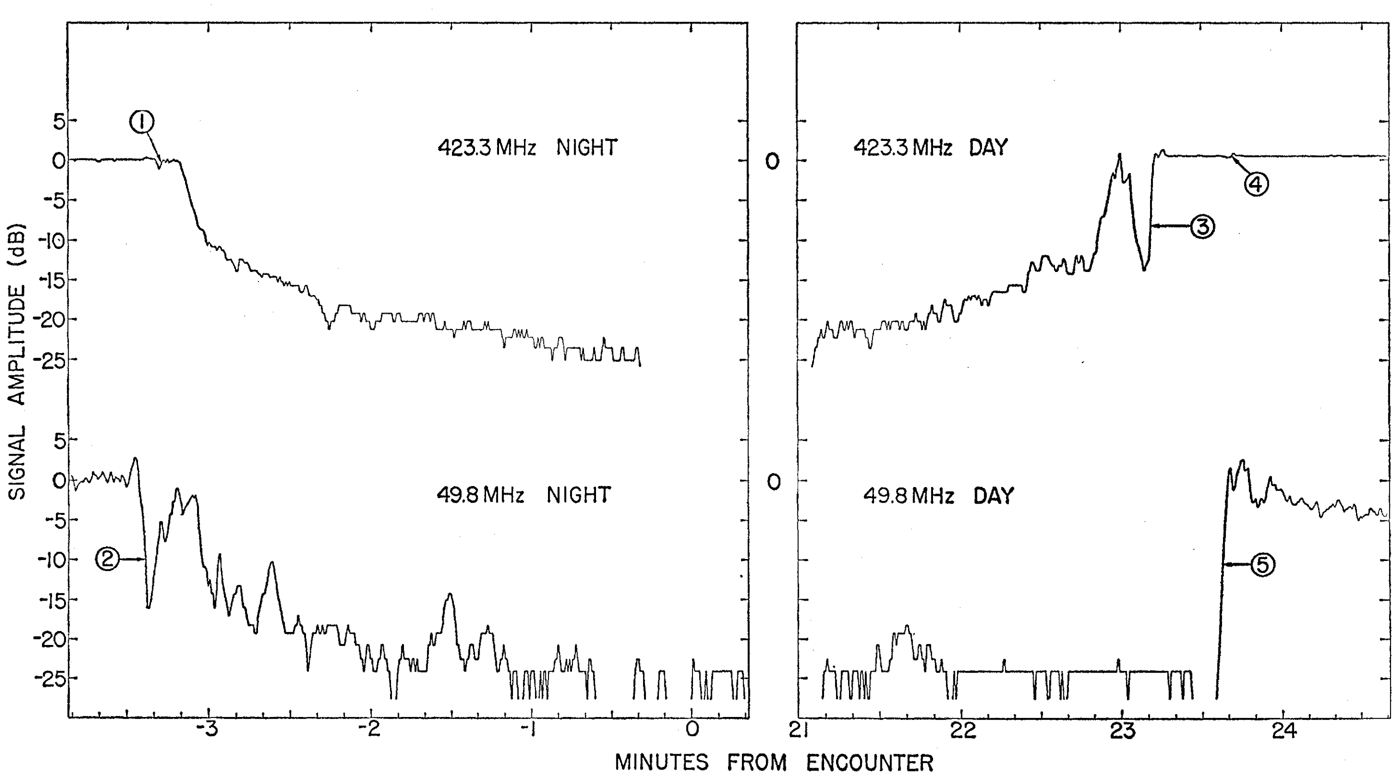

Fig. 1. Signal amplitudes at two frequencies during entry (nightside) and exit (dayside) occultation. Ionospheric effects are tagged *1* to *5*, while the dense neutral atmosphere caused the general slow decay at entry and rise at exit.

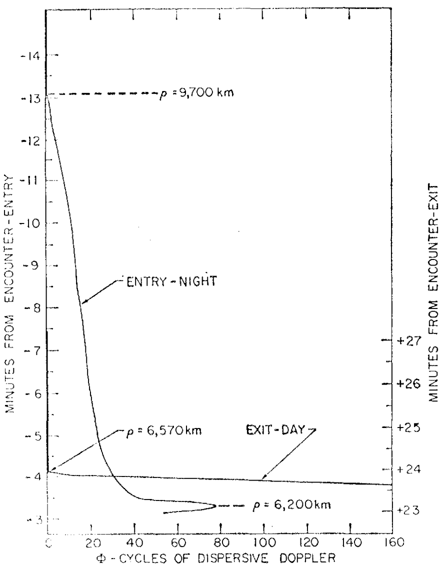

Fig. 2. Dispersive phase due to the ionosphere at entry and exit, plotted as a function of time and radius from the center of Venus.

but the alternate possibility that this high region of the atmosphere has unsuspected characteristics is strengthened by the small amplitude fluctuation noticed at *4* in the signal strength of the 423.3-Mhz signal.

Figure 2 illustrates the main results of the dispersive Doppler measurements. Curves of integrated Doppler frequency, or cycles of dispersive Doppler phase, are shown as a function of time relative to encounter, with the time scales for entry and exit positioned so that the two curves can be compared in terms of altitude. The distance scale is not quite linear with time, but several positions of interest are indicated for ρ, the distance from the center of the planet to the nearest point on a straight-line path between Earth and the spacecraft.

Before encounter the very sensitive Doppler system was measuring a dispersive frequency of about +0.06 hz, corresponding to an increase in the integrated electron content between Earth and Mariner of about 2.4×10^{13} electrons m^{-2} sec^{-1}. This is almost entirely due to changes with time of the content of Earth's ionosphere. In fact, measurements between the Stanford station and the Applications Technology Satellite (ATS) taken during the time of entry and exit showed effects due to Earth's ionosphere corresponding to a nearly constant frequency of about 0.07 hz when analyzed for the Mariner path. At about E -13^m, the Mariner Doppler frequency changed to about 0.11 hz and stayed near this value to about E -5^m, when it started to increase more dramatically. Since the Earth measurements remained about the same, the change starting at E -13^m must be due either to a changing interplanetary content or to ionization extending nearly 10,000 km from the center of Venus on the night side.

For both curves of Fig. 2, we have subtracted the measured effect of Earth's ionosphere and assumed that the remainder, in terms of changing electron content along the path, is due to the nighttime and daytime ionospheres of Venus. While it is possible that changes in interplanetary conditions could have caused the slow buildup of phase indicated between E -13^m and E -5^m, it does not seem likely since the Mariner and ATS measurements of changing content along their paths correspond very closely before E -13^m and after E $+24^m$. Also the interplanetary content appeared to remain relatively steady throughout the day, indicating an average electron concentration of about 4.3 cm^{-3} along the Earth-Mariner path.

After E -5^m, the dense part of the nighttime ionospheric layer caused the rapid changes in phase shown in Fig. 2.

The effect of the daytime ionosphere is dramatically different. There does not appear to be any effect of the planet above about ρ = 6570 km; that is, above an altitude of about 500 km. [An altitude scale can be approximated by using 6056 km for the planetary radius, as determined by radar (*4*).] Even more surprising is the very sudden transition from interplanetary conditions to the very sharp and large increase of dispersive phase with decreasing altitude. Apparently the dispersive Doppler was not accurately measured further down into the ionosphere because of the near or complete absence of signal at 49.8 Mhz, as indicated before the rise at *5* in Fig. 1.

A combination of the Doppler and amplitude results has been used to deduce preliminary profiles of electron concentration as a function of distance from the center of Venus. Integral inversion was used to derive profiles directly from the measured Doppler data (*1*), while very preliminary model-fitting computations have been used to obtain approximate characteristics of profiles

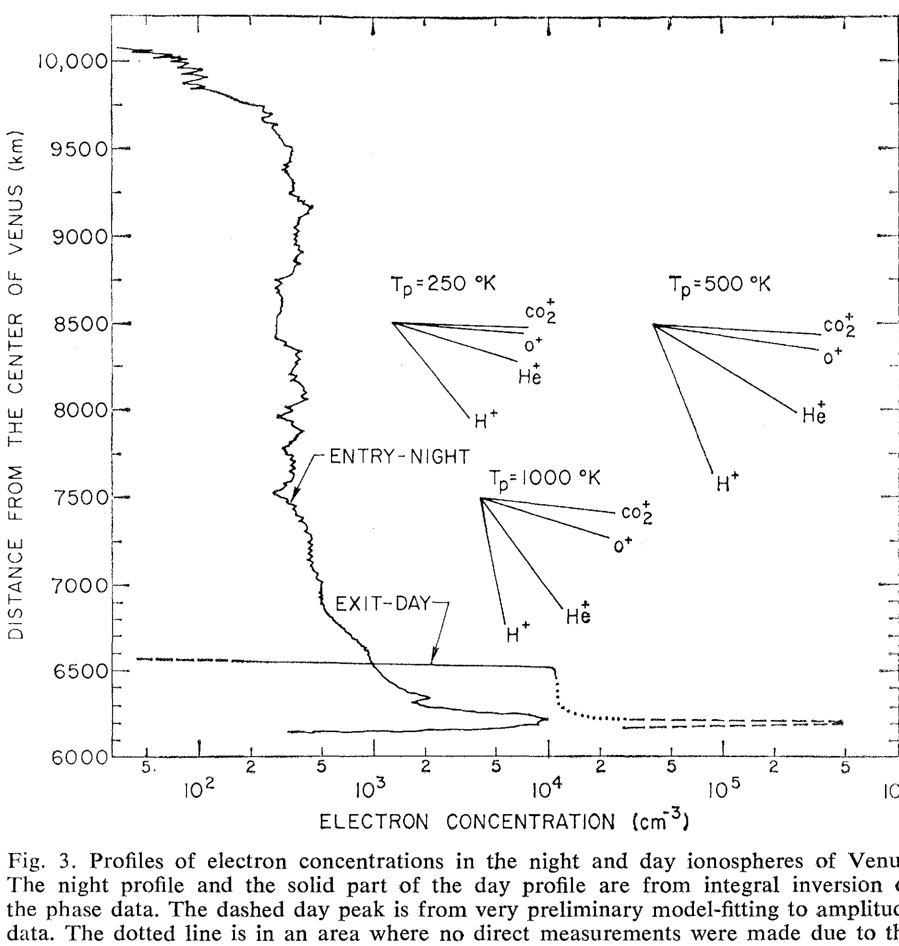

Fig. 3. Profiles of electron concentrations in the night and day ionospheres of Venus. The night profile and the solid part of the day profile are from integral inversion of the phase data. The dashed day peak is from very preliminary model-fitting to amplitude data. The dotted line is in an area where no direct measurements were made due to the formation of caustics.

from the measured amplitude data. The results are illustrated in Fig. 3. Because of the wide range of electron concentrations that were measured, a logarithmic scale is used. This also allows comparisons of slopes with plasma scale heights computed for various possible constituents and temperatures.

The total nighttime profile that is illustrated in Fig. 3 was obtained by inversion of the Doppler data if one assumes straight-line propagation. When ray-bending was included in the analysis, a profile was obtained with practically no change from Fig. 2 down to a radius of about 6250 km, but this analysis could not proceed further down because of cross-over of the computed raypaths. While this could be due either to noise in the data or to the formation of a real caustic, it is believed that a real caustic formed. Thus the profile shown below this altitude cannot be said to be a true representation of the layer. On the other hand, the error in peak concentration may not be very large since model-fitting, using a limited number of Chapman layers, shows reasonable agreement (including the cusp) with *2* of Fig. 1 for $N_{max} = 10^4$ cm^{-3} and a plasma scale height of 10 km near the peak.

Above 6250 km there appear to be several regimes on the nightside characterized by different scale heights. The almost constant density shelf with $N \cong 300$ cm^{-3} between radii of 7500 and 9500 is difficult to explain. If the constant Doppler bias used in setting the zero of the phase curve in Fig. 2 were changed, the magnitude of N in the shelf would change but not its near constancy with radius. From the shape of the phase curve, it appears to us that the electron concentration is probably fairly constant up to a relatively sudden plasmapause near 9700 km radius. However, it could well be that a very small, nonconstant frequency term due to the interplanetary medium or a lack of spherical symmetry could tilt this portion of the profile sufficiently to correspond to a diffusive equilibrium distribution of H^+ at a reasonable temperature on the order of 1000°K.

There is not much latitude in interpreting the slope between 6800 and 7500 km. Hydrogen ions and a plasma temperature (mean electron and ion temperature) between 625° and 1100°K seem to be the only likely explanation for this feature in the data. The region below 6800 km and down to 6300 km

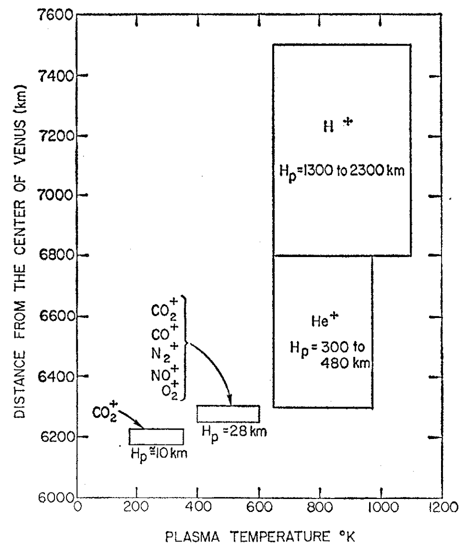

Fig. 4. Possible constituents and plasma temperatures for the nighttime upper atmosphere, derived from measured scale heights (upper three boxes) and preliminary model-fitting to the amplitude measurements (lower box).

is most likely composed of He^+ with a plasma temperature of 620° to 970°K. At lower altitudes there are a number of heavier ions that can explain the observed scale heights, as illustrated in Fig. 4.

The ionization peak observed on the nightside of Venus is probably analogous to the E and D regions found in the nighttime atmosphere of Earth. This would require a neutral density of from 10^{13} to 10^{15} molecules cm^{-3} at the ionization peak. Possible energy sources include galactic cosmic rays, solar Lyman radiation backscattered from hydrogen, and meteoric bombardment. It also seems possible that the peak may have been produced by horizontal transport of plasma from the dayside of the planet. In this case it may be located at a neutral density level which is several orders of magnitude lower. The dayside peak may be of the F_1, E, or D types. An F_2 layer with the principal ion O^+ can probably be ruled out since no oxygen was detected with the ultraviolet experiment (*5*).

It is not possible to limit the number of possibilities before the neutral density at the observed peaks can be determined by extrapolation from the lower atmosphere. It is expected that current systems are set up in the ionosphere, and these might have an effect on the distribution of ionization on both sides of the planet.

Integral inversion of the dispersive Doppler measurements near the daytime plasmapause provides the profile indicated by the solid curve in Fig. 3. As discussed previously with regard to scaling between *2* and *3* of Fig. 1 and the fit obtained for the nighttime peak, it follows that a Chapman layer of $N_{max} = 5 \times 10^5$ cm^{-3} and a plasma scale height of 10 km provides a first-order approximation to the features of *3*. These values were used to show the dashed-line daytime peak of Fig. 3. Neither the amplitude nor Doppler measurements provide direct information about the ionization lying between the main peak and the higher plasmapause. The dotted line shown in Fig. 3 is meant only to illustrate the transition.

Because of the unusual and unpredicted nature of the daytime plasmapause, we have tried to find a possible alternative explanation of the measurements. Suppose the indicated high values of N do not exist in these regions which are several hundred kilometers above the main ionization peak. This condition would seem to require both an unusual raypath geometry due to complex lower layers that focus refracted rays up toward the spacecraft, and unexpected behavior of the 49.8-Mhz receiver in not locking onto the strong direct signal, to explain both *5* and the measured Doppler. Even this combination of events would not be capable of explaining the amplitude ripple in the 423.3-Mhz signal at *4*. While this ripple is small, it represents a change of two data levels in a region where it stands out as being unusual, and its shape, position, and magnitude correspond approximately to the derived plasmapause features. Thus, our preliminary conclusions are that the indicated daytime plasmapause, ending at a 6570-km radius, is most likely real, and that the complete or very nearly complete absence of planetary plasma above this radius is real.

The daytime plasmapause plus other Mariner V measurements (*5a*) may be of great significance for understanding the interaction of the solar wind with Venus. In retrospect, this ionospheric feature is beginning to appear to be a natural extension of previous work on the interaction of the magnetized plasma of the solar wind with a planetary body having little or no intrinsic magnetic field, but having relatively high conductivity. The interplanetary magnetic field lines cannot pass rapidly through the conducting body, so a stagnation field builds up that deflects subsequent lines and particles, and a bow-shock forms.

The simplest case of a solid, nonmagnetic, conducting body in the solar wind has been treated by Gold (*6*). He discussed the problem in terms of Moon, where the concept is probably not applicable because the conductivity is not sufficiently high (*7*). The presence of an atmosphere complicates the problem, but can provide the needed high conductivity due to the formation of an ionosphere. Dessler (*8*) has treated this case in the context of nonmagnetic Mars, where the concept probably is applicable although no measurements have been made that relate directly to the predictions. Dessler considers the potential flow of the solar wind around Mars that would have a standing bow-shock wave at a radius of about 1.4 times the radius of Mars on the dayside. The shock in turn results from the pileup of interplanetary magnetic field against the nearly impervious (to motion of magnetic field lines) conducting ionosphere. [In the absence of both body magnetism and body (including the atmosphere and ionosphere) conductivity, the interplanetary magnetic field would pass through the body and the solar wind particles would be undeviated until they struck the atmosphere or surface.] In his treatment, Dessler was primarily concerned with the ionizing effect of the shocked solar plasma inside the bow-shock as it interacts with the upper atmosphere of Mars. This mechanism may be the cause of the high level of ionization seen in comets (*9*), and may help explain the relatively high plasma density just inside the plasmapause.

After the possible existence of a sharp plasmapause in the upper atmosphere of Venus was announced as a preliminary result of the Mariner V mission, Johnson (*10*) extended the concepts introduced by Dessler in a preliminary consideration of the transition region between where the currents flow (the main ionospheric layer) and the level where the shocked solar wind can flow past the planet without being impeded by the atmosphere. In his description the plasmapause would also be the magnetopause of an induced magnetosphere. Above this level any planetary atmosphere particle that is or becomes ionized is quickly carried away by the shocked solar wind that flows by the planet between the bow-shock and the magnetopause. The induced magnetosphere consists of compressed interplanetary magnetic field having sufficient magnetic pressure to deflect both particles and field of the solar wind. The pressure is transferred to that level of the ionosphere where currents sufficient to nearly terminate the magnetic field can flow, and where the pressure can in turn be transferred from the ionospheric plasma to the neutral atmosphere through collisions.

While we have not made a detailed analysis of the dual-frequency measurements of the neutral atmosphere, a few points of interest are apparent from Fig. 1. There is no evidence of a diffractive cutoff of the signal due to the limb of the solid planet, as would be expected from the results of the Soviet probe which indicate that the atmosphere should be superrefractive (*11*). Thus, horizontal radio and light rays at the critical level are bent completely around the planet. From the duration of the 423.3-Mhz signals on entry, for example, it follows that the atmosphere was probed down to within a few kilometers of the level of critical refraction.

The 423.3-Mhz signal shows more fluctuation in amplitude when it is going through the atmosphere ($E\ -3^{m}\ 10^{s}$ to $E\ -0^{m}\ 20^{s}$ and $E\ +21^{m}\ 10^{s}$ to $E\ +23^{m}\ 0^{s}$) than when there are no planetary effects. This has implications with regard to atmospheric irregularities and possible layering. The average values of defocusing at the higher frequency could be used to find average refractivity as a function of height, and from this temperature and number density profiles could be derived if one assumes CO_2 as the principal constituent, and assumes no absorption. While the principal atmospheric properties are better defined from the S-band frequency measurements (*2*), it remains important to conduct a detailed analysis of the dual-frequency results as a check, in a search for possible differential absorption with frequency, and for study of the fluctuations.

At 49.8 Mhz the amplitude fluctuations are much larger, so the differential effect relative to the higher frequency may help determine characteristics of ionospheric irregularities. The up-fades between $E\ -1^{m}\ 40^{s}$ and $E\ -1^{m}\ 10^{s}$ reach a strength that is about 7 db greater than the relative strength of the signal at 423.3 Mhz. This would have been attributed to the generally irregular atmospheric-ionospheric effects, except for a similar up-fade in the 49.8-Mhz signal at $E\ +21^{m}\ 30^{s}$ to $E\ +21^{m}\ 50^{s}$. It appears possible that these are reflections from the solid surface of Venus.

We had previously studied the expected signal characteristics for surface reflections from a planetary body having a superrefractive atmosphere. We concluded that atmospheric defocusing on the direct signal could, under certain conditions, be markedly greater than for a near-grazing reflection path that would be bent around the planet by the same amount. This effect can more than compensate for the loss at reflection, and it was predicted, for example, that the reflected signal would become stronger than the direct signal in the vicinity of these up-fades. If they do represent reflections, the dispersive Doppler should show differences due to the different paths for the direct ray at 423.3 Mhz and the bounce ray at 49.8 Mhz. While dispersive Doppler measurements in this region are not completely reliable, they do show effects at both entry and exit that are of the right sign, and are reasonably close to the predicted magnitude, to correspond to surface reflections. The ability of the phase-locked systems to respond to such reflections is critically dependent upon their spectral width, and only at the lower frequency would the predicted bandwidth of reflected signals be small enough for most of the energy to lie within the receiver bandwidth. Raypaths can of course reach the surface through a superrefractive atmosphere since they pass through the critical level at angles of incidence less than 90°, while direct occultation rays would be at 90° when they reach the critical refraction level.

Considerably more work needs to be done in the analysis and study of the dual-frequency measurements, particularly in regard to the amplitude measurements and the neutral atmosphere, model-fitting to the daytime ionization peak, constituents, number densities, and temperatures above the nighttime ionization peak, characteristics and theories of both peaks, characteristics of the daytime plasmapause, and comparisons with the results of the S-band and other Mariner V experiments. This preliminary report was prepared before such analysis and comparisons could be accomplished, and is offered with these limitations only because of the balancing urgency on the reporting of principal results.

The dynamic range of the dual-frequency experiment in terms of electron concentration at Venus is seen from Fig. 3 to be more than three orders of magnitude. The precision is variable, depending on whether dispersive Doppler or amplitude measurements are used in the analysis. Caustics cause particularly difficult problems and were certainly encountered on the day side and probably on the night side near the main ionization peak. In a future flight it would be valuable to have a second dispersive Doppler comparison (between 423.3 Mhz and S-band, for example) so that all of the levels of ionization could be measured with the high precision of this type of measurement.

Perhaps the most important single result of the dual-frequency experiment was the discovery of the dayside plasmapause inside which interplanetary magnetic field lines are expected to be entrapped. The Venus magnetic trap, and the light and radiowave trap in the superrefractive atmosphere, are features of special interest for further study and analysis. It seems very likely that Mars also has an induced magnetosphere, magnetopause, and plasmapause due to the solar wind. Mars appears to be without appreciable self-magnetism, and it has a conducting daytime ionosphere comparable to that of Venus (*12*). The sensitivity of a dispersive Doppler experiment may be required for its detection (*1*). There appear to be three different types of interaction of planetary bodies with the magnetoplasma of the solar wind, with Earth representing one, Moon a second, and Venus and Mars a third class. These differ because of planetary magnetism (Earth), high ionospheric conductivity and an atmosphere but no magnetism (Venus and Mars), and no magnetism, no atmosphere, and low conductivity (Moon).

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11 December 1967

Atmosphere and Ionosphere of Venus from the Mariner V S-Band Radio Occultation Measurement

Abstract. *Measurements of the frequency, phase, and amplitude of the S-band radio signal of Mariner V as it passed behind Venus were used to obtain the effects of refraction in its atmosphere and ionosphere. Profiles of refractivity, temperature, pressure, and density in the neutral atmosphere, as well as electron density in the daytime ionosphere, are presented. A constant scale height was observed above the tropopause, and the temperature increased with an approximately linear lapse rate below the tropopause to the level at which signal was lost, presumably because heavy defocusing attenuation occurred as critical refraction was approached. An ionosphere having at least two maxima was observed at only 85 kilometers above the tropopause.*

On 19 October 1967, the Mariner V space probe passed within about 4100 km of the surface of Venus. Its trajectory had been designed so that the craft as observed from Earth appeared to pass almost diametrically behind the planet. About 3 minutes before the closest approach time, the S-band radio beam emanating from the paraboloidal high-gain antenna of the probe began to enter the sensible neutral atmosphere on the dark side of Venus with a relative velocity of about 7.3 km/sec, at a radial distance of about 6145 km from the center. At the point of tangency, the latitude was about 37°N, and the solar zenith angle was 142.3°. As the beam penetrated the atmosphere, refraction caused the path of propagation to deviate from a straight line, and the velocity of propagation to vary from the speed of light in free space. In addition, the lenslike effect of the gradient of refractivity caused defocusing, which spread the power in the beam over a greater angular width, and caused the signal power received at Earth to decrease. These effects were observed as changes in the frequency, phase, and signal strength received during this period at the tracking stations on Earth.

As the beam penetrated deeper into the dense atmosphere of Venus these effects became more pronounced, until at about 2 minutes and 40 seconds past the closest approach time the received signal strength gradually descended below the threshold of the receiver apparatus. This indicated that, rather than being physically interrupted by the limb of the planet, the signal was gradually extinguished by rapidly increasing refractive defocusing as the critical refraction level was approached.

Approximately 15 minutes later, the signal again began to be discernible as the radio beam emerged from behind the sunlit side of the planet and