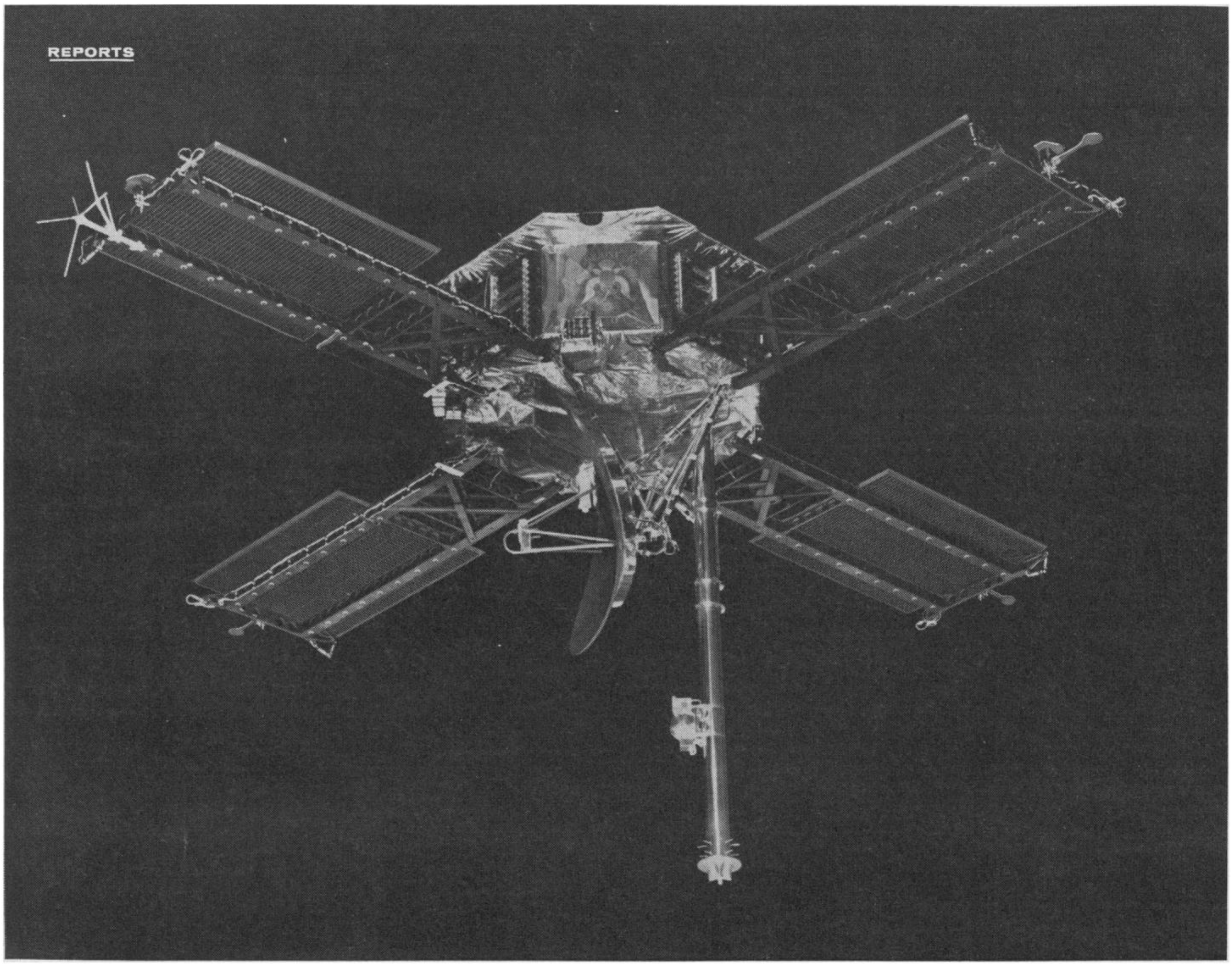

Fig. 1. The Mariner V spacecraft as it would have appeared if visible from Earth about 60 days after launch. Its top side, facing Sun, is almost flat except for the plasma sensor and solar attitude sensors. The bottom side carries several of the scientific instruments as well as the parabolic directional antenna and the mast-like "omnidirectional" antenna, on which the magnetometer is mounted. The receiving antenna for the 423-Mhz signal extends from the tip of the solar panel at the upper left.

Mariner V Flight Past Venus

Abstract. *On 19 October 1967 the Mariner V spacecraft passed by Venus 10,151 kilometers from the center of the planet; the gravitational field, atmosphere, ionosphere, hydrogen corona, and interaction with the solar wind were observed.*

The Mariner Venus 1967 mission was authorized by the National Aeronautics and Space Administration in December 1965. The Jet Propulsion Laboratory, California Institute of Technology, converted the spare spacecraft from the Mariner Mars 1964 mission for achieving a close flyby of Venus during 1967 (*1*). The primary scientific objective of the mission was to obtain information about the atmosphere, the ionosphere, and the plasma environment of the planet. The following papers present detailed and technical (although in all cases preliminary) accounts of the results.

Seven scientific experiments were planned and all were conducted successfully. Included here is a brief summary of the findings. The seven experiments can be classified into four groups:

1) The plasma probe, the magnetometer (*2*), and the energetic particle detectors (*3*) were designed to measure the interrelated phenomena concerned with the interaction between the planet and the interplanetary medium—the environment of Venus.

2) The ultraviolet photometer (*4*) was designed to measure the properties of the topmost layers of the atmosphere.

3) In the two occultation experiments (*5*, *6*), radio waves were sent through the atmosphere to probe its properties, from the highest level where it has any perceptible effect on the propagation of a radio wave all the way down (it was hoped) to the surface.

4) The very precise measurement of the mass of Venus and the shape of its gravitational field was the planet-related objective of the celestial mechanics experiment (*7*).

The interplanetary medium is a very hot, tenuous, ionized gas—a plasma—

which is an extension of the atmosphere of Sun. It is called the "solar wind." It flows outward from Sun at a velocity averaging near 500 km/sec essentially because one layer in Sun's atmosphere (the corona) is so hot, so energetic, that the gravitational field cannot confine it. This plasma carries with it a magnetic field that originates in Sun.

The 1962 Venus mission, Mariner II, which first established the presence and the properties of the solar wind, also included a study of its interaction with Venus; but the encounter orbit, chosen to optimize the overall scientific mission, did not pass through the region where this interaction occurs. Thus the plasma environment of Venus has been completely unknown until now.

The interaction with Earth has been studied extensively by satellites for almost a decade, and it has been found that the plasma is deflected by the geomagnetic field and flows around Earth, never approaching it closer than about 50,000 km. Upstream from the cavity (the magnetosphere) that the solar wind does not penetrate, there is a detached bow shock in the plasma because the solar wind is, in a sense, "supersonic."

In recent months the lunar satellite Explorer XXXV (*8*) has explored the environment of Moon and found a completely different kind of interaction. The plasma appears to strike the surface of Moon (and be absorbed), and the magnetic field passes through the moon with little, if any, interference.

Mariner V spent 2 hours within the interaction region around Venus, observing an interface which is similar to the bow shock near Earth and some additional structure inside of the interface. Two very significant inferences can be made: (i) The magnetic dipole moment of Venus is much smaller than that of Earth (roughly at least a thousand times smaller), as proved by the small extent of the interaction region. (ii) The solar wind flows around the planet without striking it, in contrast to the case of Moon. The obstacle that deflects it appears to be the dense ionosphere on the sunlit side of Venus. Its high electrical conductivity prevents the passage of the incoming magnetic field (essentially an eddy-current effect), and the "pile-up" of the field alters the flow of the plasma. The most persuasive evidence supporting this conclusion is the observation by the Stanford occultation experiment (*5*) that the upper boundary of the daylight ionosphere is exceedingly sharp and is pushed down very close to the planet (about 500 km altitude) by the momentum of the solar wind. No such phenomenon has previously been observed in space.

At the shock, and elsewhere in the interaction region near Earth, energetic particles accelerated by electric fields are observed. None were observed near Venus (*3*), probably because the region is too small.

The identification of rare species in the atmosphere by observing the ultraviolet sunlight scattered from them has been successfully employed on Earth and is planned for future planetary probes. The photometer on Mariner V sought to detect atomic hydrogen and atomic oxygen, which have strong lines in the far-ultraviolet region of the spectrum, at 1216 and 1304 Å, respectively. In the upper atmosphere of a planet, a gravitational fractionation process separates the constituents according to molecular weight, with hydrogen on top, helium below it, and atomic oxygen coming next. By designing the photometer so that the scattered light was observed only in a very narrow cone and causing the spacecraft motion to sweep the cone across the planet, a record of light intensity as a function of altitude was obtained; this record can be interpreted as a density versus altitude profile for each species. The spatial rate of change of density is a measure of temperature.

Precise quantitative results are not yet available because the analysis of the ultraviolet data is a very complex problem in radiative transfer. However, three very significant and mutually consistent observations were made. (i) The light scattered from hydrogen on the sunlit side was intense, indicating a total quantity of hydrogen comparable to or greater than that in the upper atmosphere of Earth. (ii) The scale height, and hence the temperature, of the hydrogen is much lower than in Earth's exosphere; hence the escape rate of neutral hydrogen, determined by this temperature, is very much lower. (iii) The quantity of oxygen in the upper atmosphere of Venus is so small that it was not detected, probably because the temperature is so low.

To probe the atmosphere, radio signals of three frequencies were sent through it as the spacecraft passed behind Venus. The Stanford University transmitter sent two signals, at 49.8 and 423.3 Mhz, which were received and analyzed on the spacecraft. Slightly more than half the data storage was allotted to these data. The spacecraft telemetry signal at S-band (near 2298 Mhz), traveling in the opposite direction, was received on Earth, where vastly more data could be recorded. In both cases, the measured effects on the radio waves were reduction of signal strength because of absorption and defocusing, and shift in frequency because of the refraction effect. Both experiments obtained data on the neutral atmosphere and on the ionized atmosphere. The use of two harmonically related frequences in the Stanford ex-

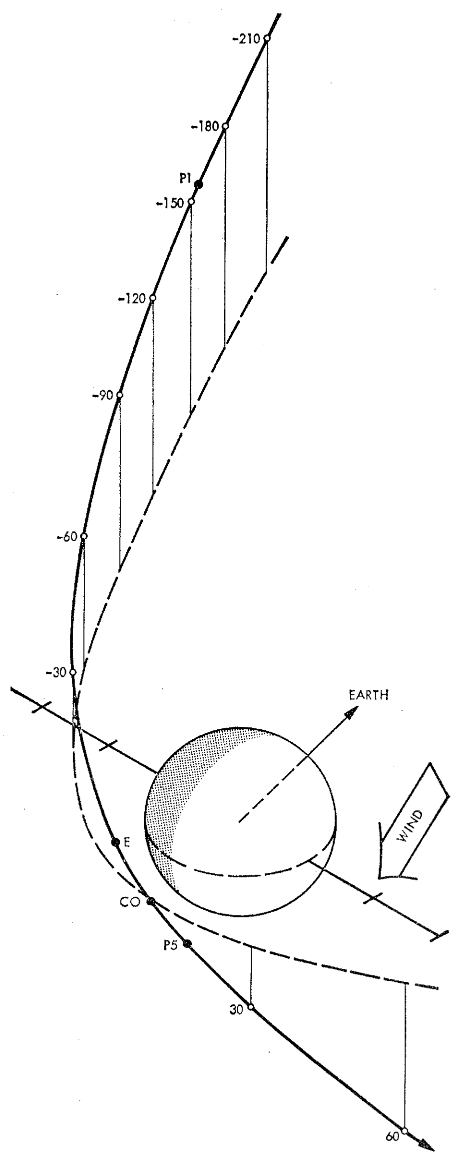

Fig. 2. Isometric projection of the Venus encounter orbit. Time (in minutes) from encounter (periapsis) are indicated. In this and subsequent figures, events marked on the orbit are identified by codes listed in Table 1.

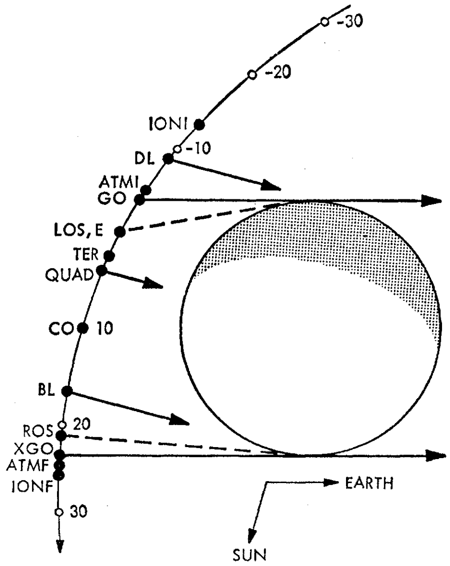

Fig. 3. Venus encounter orbit shown in the orbit plane. Short arrows show line of sight of ultraviolet photometer as it observed the crossings of the dark limb, the terminator, and the bright limb. Long arrows indicate paths of radio signal, at boundaries of occultation period, which would have been observed with very little atmosphere. Dashed lines indicate (schematically only) the actual radio rays at loss and reacquisition of the telemetry signal. Sun was 31.7° above the orbit plane in the direction shown.

periment provided extremely high sensitivity for the ionized component. Consequently the weak nighttime ionosphere was clearly observed in this experiment, whereas both experiments obtained altitude profiles of the strong daytime ionosphere. The S-band experiment, because of its enormous quantity of data, provided more precise information on the neutral atmosphere.

The altitude in the atmosphere at which data is obtained at any given time is calculated from the spacecraft orbit, which is very precisely known (better than 1 km relative to Venus) from the measurements of range and range rate relative to Earth. Thus spacecraft position is determined relative to the gravitational center of Venus. To convert this distance to altitude requires a knowledge of the local Venus radius. The currently accepted value of the mean radius near the equator is 6056 km (*9*), but how accurately this represents the radius at the point of interest is not known. This uncertainty becomes troublesome as soon as one attempts to relate the Mariner measurements to those of Venera-4, where the data were related to the local planet surface by means of a radioaltimeter (*10*).

The nighttime ionosphere was first observable several thousand kilometers from the surface of Venus. A fairly complex layered structure was observed with a peak in density near 200 km altitude. On the daylight side, a peak density about 50 times greater was observed near an altitude of 130 km, with a decline in density with altitude, terminating suddenly near 500 km as already discussed.

The neutral atmosphere first became observable in the S-band signal by a change in frequency at 6145-km range or 90-km altitude, where the pressure is about 1 mbar (0.001 atm). (For the convenience of the reader, altitudes relative to the assumed 6056-km radius are quoted, although their validity is uncertain.) As the spacecraft moved behind Venus, the shift in the signal frequency increased steadily to a maximum value of 16,000 hz at the moment of occulation. In the Mariner IV occultation of Mars, the total shift had been only 5 hz. Thus the very great density of the Venus atmosphere is immediately apparent.

The signal frequency shift is related directly to the refractivity of the atmosphere. The derivation of more interesting atmospheric properties (composition, temperature, density, pressure) requires the comparison of the refractivity data with other information, out of which a consistent model of the atmosphere can eventually be derived. For the details of the preliminary model generated from the Mariner V data and the assumptions involved in it, the reader is referred to the S-band paper (*6*), but in rough summary the findings were as follows.

The spatial rate of change of density is a measure of temperature, since

$$-d\rho/\rho \, dz \equiv h = kT/gM$$

where ρ is density, T is temperature, M is molecular weight, k the Boltzmann constant, and g the local gravitational acceleration. The parameter h is defined as the scale height of the atmosphere at altitude z.

The scale height of the atmosphere at 60 to 70 km altitude is about 5.4 km, from which a value near 5.7 for the ratio of temperature to mean molecular weight (T/M) is derived. This number is consistent with a temperature near 230°K (inferred from astronomical observations) and a mean molecular weight near 40. Thus the atmosphere at this level is composed chiefly of CO_2 (molecular weight = 44) as is the lower atmosphere where it was

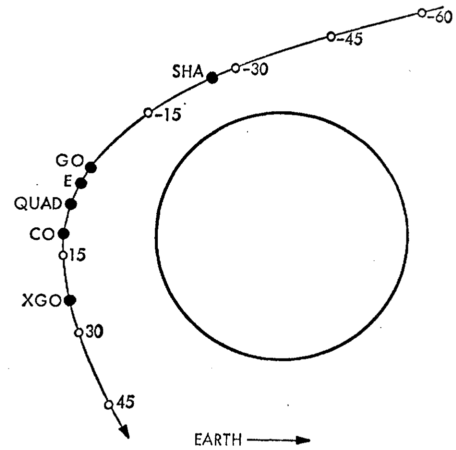

Fig. 4. Venus encounter orbit projected on the terminator plane.

measured by Venera-4 (near 25 km altitude) on the day before our encounter. The exact percentage of CO_2 in the atmosphere cannot be calculated without knowing the identity of the second most abundant constituent. Thus the preliminary Mariner V value (69 to 87 percent if nitrogen is the second constituent) may or may not agree with the Soviet measurement (first quoted as 90 to 95 percent).

The S-band paper contains graphs of pressure, temperature, and density as functions of range, corresponding to model atmospheres having proportions 3:1 and 9:1 for the $CO_2:N_2$ abundances. Roughly speaking, the temperature is constant at 210° to 240°K above the tropopause at about 70 km and rises approximately linearly to 390° to 450° at 40 km. The pressure (in either model) rises from 0.02 (Earth) atm at 75 km to 5 atm at 40 km.

Further analysis will extend the information, but the properties of the bottom of the atmosphere cannot be probed by the occultation technique. At some limiting altitude (estimated to be near 10 km) the refractivity gradient of the dense CO_2 atmosphere is so high that a light ray or radio ray entering tangentially is bent into an inward spiral and cannot escape. This phenomenon of critical refraction was not unexpected. It was in fact assumed to be present once the Soviet Union had revealed the CO_2 content of the atmosphere. The nature of the signal fadeouts on both occultation experiments is also consistent with critical refraction.

Since the preliminary Venera-4 data indicate pressures from 1 to 20 atmospheres and temperatures from 313° to 543°K, it seems clear that the results of the two sets of experiments

Table 1.

P1	E − 156 min	Initial passage through a boundary in the solar plasma
SHA	E − 22 min	Closest approach to shadow of Venus
IONI	E − 13.1 min	Initial detection of ionosphere by dual-frequency receiver
DL	E − 7.9 min	Dark limb of planet observed by ultraviolet photometer
ATMI	E − 3.18 min	Initial detection of atmosphere by S-band occultation experiment
GO	E − 2.0 min	"Geometrical occultation"—Earth-spacecraft line of sight intersects dark limb of planet
LOS	E − 14 sec	Loss of spacecraft radio signal resulting from occultation
E	E	Periapsis
TER	E + 3.4 min	Terminator crossing observed by ultraviolet photometer
QUAD	E + 3.55 min	Quadrature; Sun-Venus-Mariner angle 90°
CO	E + 10.0 min	Center of geometrical occultation
BL	E + 16.7 min	Bright limb crossing observed by ultraviolet photometer
P5	E + 18 min	Final passage through a boundary in the solar plasma
ROS	E + 20.6 min	Reacquisition of signal by Goldstone tracking station
XGO	E + 22.8 min	Exit from geometrical occultation at bright limb
ATMF	E + 23.0 min	Final observation of atmospheric effect on S-band signal
IONF	E + 24.0 min	Final detection of ionosphere by dual-frequency receiver

are overlapping and complementary. However a puzzling inconsistency appears. The minimum altitude quoted for Mariner data (40 km) and the maximum quoted for Venera data (26 km) do not indicate overlap, although the atmospheric data clearly do. Stated in another way, the atmosphere at 26 km from Venera (0.7 atm, 313°K) is observed by Mariner at 6114-km range, corresponding to an altitude of 58 km. It will be of great interest to see how this discrepancy can be reconciled. Until both sets of data have been studied in greater depth, it would be premature to speculate on the cause of the disagreement.

However it should be noted that the two American experiments were made on opposite sides of the planet, with the Russian experiment about halfway between, and that the shape of Venus (which determines the conversion from range to altitude) is completely unknown. The mysteries about Venus have by no means all been dispelled by the two highly successful and complementary Venus missions in October 1967.

The Mariner V spacecraft (Fig. 1) was launched from Cape Kennedy at 06 : 01 : 00 U.T. on 14 June 1967. That day had been selected in advance to optimize the value of the scientific data at the planet. An orbit correction maneuver was performed late on 19 June, and the spacecraft passed by Venus on 19 October at 17 : 34 : 55.3 U.T. 10,151.0 km from the center. It passed out of telemetry range early in December, and proceeded toward the perihelion of its solar orbit. Like all Mariners, this spacecraft was oriented with respect to Sun and Canopus by an attitude control system to within one-half degree about each axis. An abbreviated chronology of significant events during the Venus encounter is given in Table 1, which also lists the codes used to represent the events on the orbit plots.

Approximately 850 hours of telemetry data at 33.33 bits per second were received by the Deep Space Net during the first 40 days. Subsequently, at a data rate of 8.33 bits per second, an additional 1670 hours of data were received prior to Venus encounter and about 600 hours were received after encounter. Near the planet 937,000 information bits (of which 648,000 were scientific data) were stored by the spacecraft tape recorder. These were transmitted to Earth twice during the following week.

Of the specifically scientific instruments aboard, four were slightly modified versions of instruments originally built for the 1964 Mars mission—the magnetometer, the plasma probe, the charged-particle detectors, and the ultraviolet photometers. The fifth scientific instrument was the dual frequency radio receiver. The spacecraft science data subsystem provided the sequencing command pulses to operate all these instruments, and transferred their data outputs to the telemetry subsystem. The dual frequency receiver provided scientific data whenever it was receiving signals from the Stanford University transmitter. The other instruments produced data continuously throughout the flight. The spacecraft transponder received commands from Earth and transmitted data to Earth. In addition, it provided the capability for the range data and the Doppler range-rate data required for the celestial mechanics experiment and the radio signal required for the S-band occultation experiment.

The output of the science data subsystem was in binary digital form, arranged into a frame 420 bits in length, repeated every 50.4 seconds during the latter portion of the flight. During the Venus encounter this "real time data format" was recorded on the magnetic tape and simultaneously sent to the telemetry transmitter. In addition the data from certain experiments (the dual-frequency receiver, the ultraviolet photometers, and one of the charged-particle detectors) were sampled more frequently and recorded on the tape, the data storage rate being 133.33 bits per second.

At the time that Mariner flew by Venus, it was 79,764,370 km from Earth, so that the transit time for radio signals was 266 seconds. To avoid confusion between spacecraft time and Earth time, it is convenient to specify the times of all encounter events relative to the time of closest approach (conventionally called "encounter" and denoted by E).

Figure 2 presents an isometric view of the orbit from E −210 minutes to E +30 minutes, a time period which includes all planet-related observations except that of the outermost edges of the hydrogen corona. The spacecraft approached the dark side of Venus from north of the planet's orbit, crossed the plane of the terminator shortly after passing periapsis, and was deflected sharply (101.5°) in toward Sun by the gravitational field.

The motion of the spacecraft in its actual orbital plane is shown in Fig. 3. This view is the appropriate one for most purposes, as the center of Earth lies only 1.5° off this plane, and the line of sight for the ultraviolet photometers makes an angle of only 3.2° with it. Events pertinent to the ultraviolet experiment and the two occultation experiments are shown on the figure.

A projection onto the plane of the terminator (Fig. 4) depicts the orbit as seen from Sun. This view demonstrates that the spacecraft never passed into the optical shadow of the planet. To have done so would have caused loss of orientation control. The minimum distance to the shadow was more than 2400 km, at E −22 minutes. An additional representation of the orbit, particularly suited to illustrating the plasma interaction, is contained in the following paper (*2*).

CONWAY W. SNYDER
Jet Propulsion Laboratory, California Institute of Technology, Pasadena

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1. This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract No. NAS7-100, sponsored by the National Aeronautics and Space Administration.
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11 December 1967

Mariner V: Plasma and Magnetic Fields Observed near Venus

Abstract. *Abrupt changes in the amplitude of the magnetic fluctuations, in the field strength, and in the plasma properties, were observed with Mariner V near Venus. They provide clear evidence for the presence of a bow shock around the planet, similar to, but much smaller than, that observed at Earth. The observations appear consistent with an interaction of the solar wind with the ionosphere of Venus. No planetary field could be detected, but a steady radial field and very low plasma density were found 10,000 to 20,000 kilometers behind Venus and 8,000 to 12,000 kilometers from the Sun-Venus line. These observations may be interpreted as relating to an expansion wave tending to fill the cavity produced by Venus in the solar wind. The upper limit to the magnetic dipole moment of Venus is estimated to be within a factor of 2 of 10^{-3} items that of Earth.*

The first attempt to observe a disturbance in the interplanetary medium caused by the planet Venus was made with Mariner II on 14 December 1962. No effect was observed (*1*), partly because the spacecraft passed on the sunward side of the planet and came no closer than 40,000 km or 6.6 Venus radii (r_V). Thus, it was shown that an upper limit to the magnetic dipole moment of Venus is approximately 20 times less than that of Earth.

The trajectory of Mariner V was more favorable for this type of observation because the spacecraft approached to within 0.4 r_V of the optical shadow of the planet and to within 0.7 r_V of the surface. The data from the magnetometer and plasma probe show unmistakable evidence for the existence of a bow shock around Venus similar to, but much smaller than, that near Earth, as well as additional structure inside the shock.

The low-field vector helium magnetometer was first flown on Mariner IV (*2*). The instrument has an intrinsic noise level of 0.1 gamma (RMS) and a digitization uncertainty of 0.2 gamma (1 gamma equals 10^{-5} gauss). Five triaxial field samples were obtained every 50.4 seconds.

The magnetometer sensor was located about 2 m from the main body of the spacecraft. To minimize the spacecraft field, magnetic constraints were imposed on the spacecraft, which was also demagnetized prior to launch. With the following techniques, the magnitude of the spacecraft field at the sensor was determined in-flight to be 10 gamma. First, the rolling of the spacecraft about the Sun direction for 17 hours immediately after launch and for several hours after the mid-course orbit correction established the values of the two components perpendicular to the axis of rotation. Second, all three components were computed by a new technique (*3*) based on the frequently occurring changes in the interplanetary field that conserve the field magnitude. Such changes are associated with contact surfaces traveling outward in the solar wind (*4*). This procedure allows continual checking of the spacecraft fields in flight, an important consideration in that Mariner V was attitude-stabilized. We estimate that the components of the spacecraft field were determined to within 0.5 gamma.

The plasma detector, a modulated-grid Faraday cup (*5*), was essentially identical to that on Mariner IV. Positive-ion currents are measured in 32 energy intervals covering the range from 40 to 9400 ev. The detector points at Sun. Its sensitivity is fairly constant up to 30° off the Sun-spacecraft line and then decreases rapidly to zero at 65°. A current measurement at one energy level has an integration time of ~5 msec, and the sampling rate is such that a plasma energy spectrum is determined every 5 minutes. However, all the significant measurements in a spectrum were completed in 3.8 minutes or less.

For comparison with the near-Venus data, Fig. 1 shows $|B|$, the total field magnitude, as observed by Mariner V in the vicinity of Earth. These data show the characteristic field changes at the magnetopause (the surface separating magnetic lines of force connected to Earth from the heated, compressed, and semiturbulent region called the magnetosheath) and the bow shock (the usually sharp boundary outside of which lies the free-streaming interplanetary medium). The presence of two

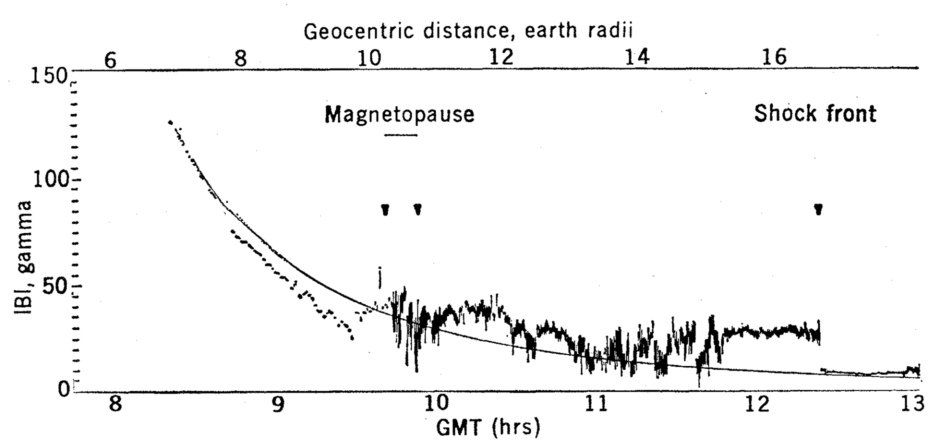

Fig. 1. Mariner V magnetic field data near Earth. Ambient field magnitude is plotted as a function of time (bottom) and geocentric distance (top). Three triaxial samples were telemetered every 12.6 seconds, and the corresponding computed field magnitude for all the data without any averaging is shown. The smooth curve is the magnitude of the extrapolated surface geomagnetic field. Multiple crossings of the magnetopause (caused by boundary motion) are indicated by the double arrow. The observations were made at ~ 1500 hours local time and at a geomagnetic latitude of ~ −25°.