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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} *times 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

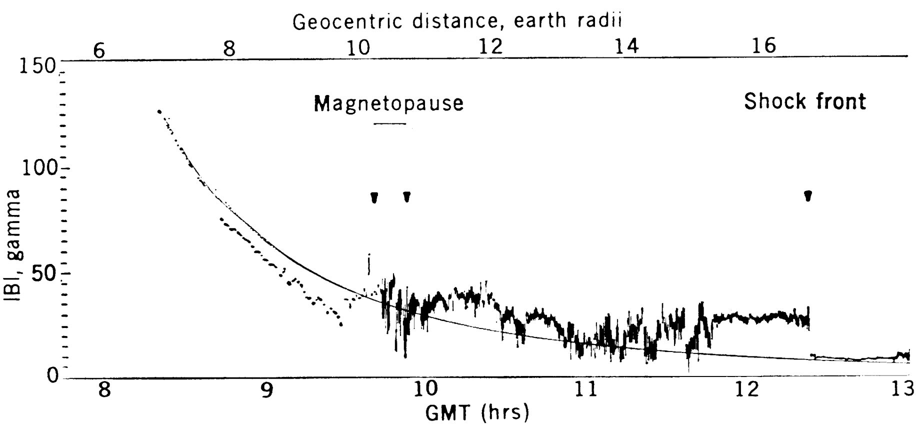


Fig. 1. Mariner V magnetic field data near Earth. Ambient field magnitude is plotted as a function of time (bottom) and geocentric distance (top). Three triaxial samples were telemetered every 12.6 seconds, and the corresponding computed field magnitude for all the data without any averaging is shown. 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°.

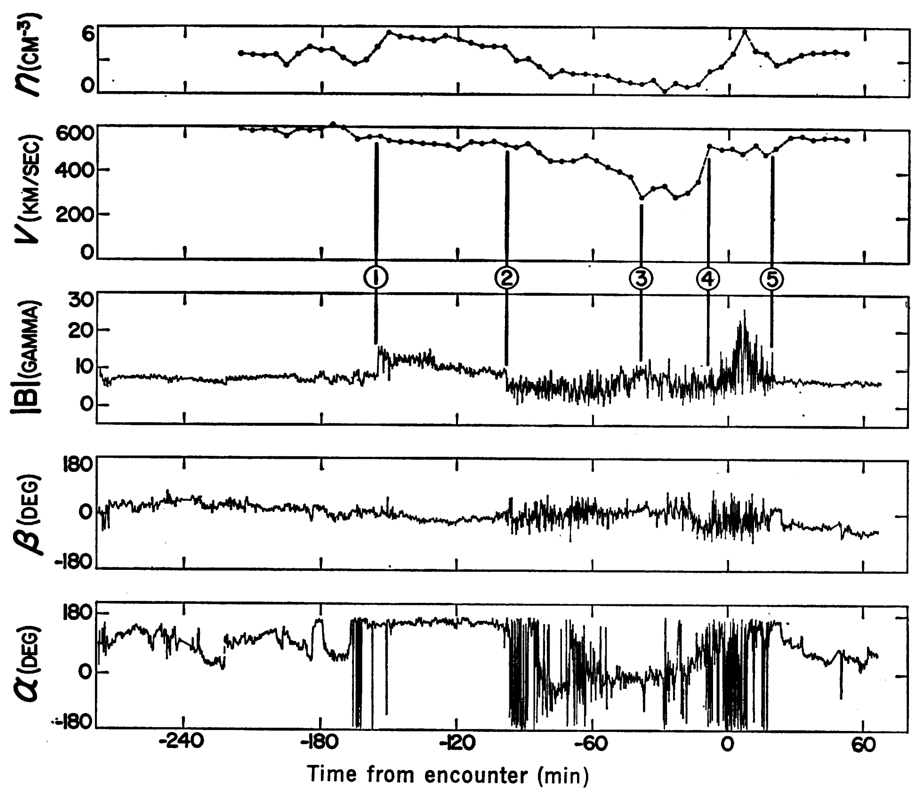


Fig. 2 (left). Plasma and magnetic field data near Venus. Time indicated at zero corresponds to closest approach. Vertical lines and circled numbers denote the features of special significance discussed in the text.

or more regimes in the magnetosheath characterized by different amplitudes of fluctuations and different values of average field strength is a common occurrence, probably the effect of the convection into the magnetosheath of filamentary structures in the solar wind, which often shows abrupt changes in properties.

The plasma and magnetic-field data near Venus are shown in Fig. 2. The two uppermost curves, the positive ion number density (*n*) and the bulk velocity (*V*), are plasma parameters computed from the observed energy spectra. The middle trace is the ambient field magnitude ($|B|$) computed from the three measured components after subtracting the spacecraft field. The two bottom curves give the field direction in spherical coordinates. The angle α is the longitude or azimuth measured in the **RT** plane, where **R** is a unit vector in the antisolar direction and **T** is an orthogonal vector which is parallel to Sun's equatorial plane and points in the direction of the planet's orbital motion. For most purposes, the **RT** plane may be regarded as parallel to the ecliptic plane with which it makes an angle of only 7°. The angle β is the latitude measured from the **RT** plane; positive values indicate that the field has a northward component. The direction toward Sun corresponds to $\alpha = \pm 180°$, and the ideal spiral field direction near the orbit of Venus to $\alpha = 145°$ when the sense of **B** is toward Sun.

The data are plotted as a function of time (in minutes), zero being taken at the instant of periapsis. Five features in the plasma and field data are identified by circled numbers. The positions of these features on the Mariner orbit are indicated in Figs. 3 and 4.

Figure 3 is a polar plot with the planet-spacecraft separation and the Sun-planet-spacecraft angle as coordinates. It is equivalent to tracing the path of the spacecraft in a plane that rotates about the Venus-Sun line with the spacecraft. To the extent that the phenomena have cylindrical symmetry about this line, these are the pertinent parameters.

The three parts of Fig. 4 show the usual orthographic projections of both teh Mariner trajectory and the measured fields. The aphrodiocentric-solar-ecliptic (ASE) coordinates are defined by a plane parallel to the ecliptic passing through the center of Venus and by X_{ASE}, the projection in this plane of the direction to Sun. The axis Z_{ASE} points toward the north ecliptic pole, and Y_{ASE} completes the orthogonal, right-handed set. The field vectors are

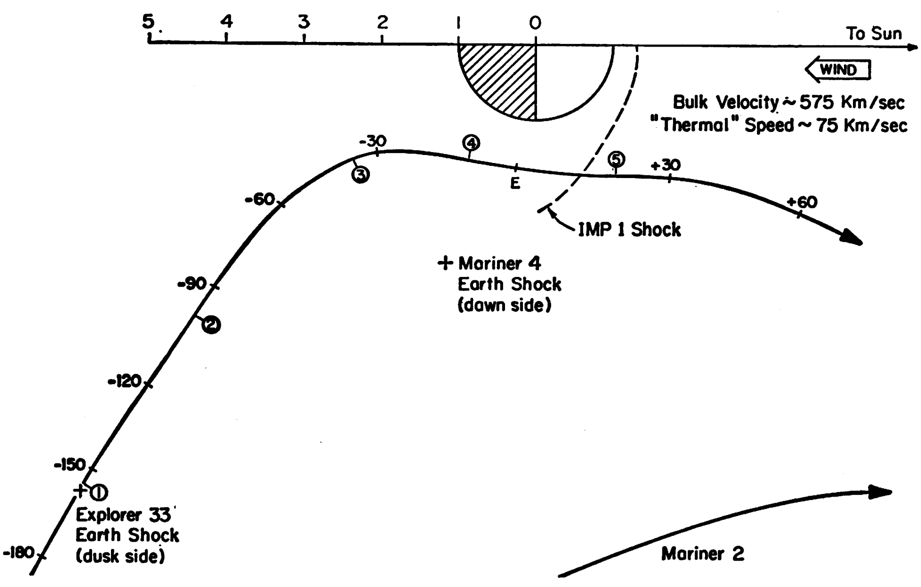


Fig. 3 (left). Mariner orbit relative to Sun-Venus axis. Trajectories of Mariner V and Mariner II near Venus, rotated into a plane which contains the Venus-Sun line, are shown. Times in minutes relative to encounter (*E*) are indicated on the trajectory. Circled numbers refer to events described in the text. The bow shock is taken from IMP-1 data scaled down so that the magnetopause passes through the observed boundary of the ionosphere (*7*). The scaled-down shock crossings of Mariner IV on the dawn side of Earth and of Explorer XXXIII indicate the shape of the shock boundary at large Sun-Venus-spacecraft angles. Because point 1 actually occurred on the dusk side of Venus, the dusk-side shock crossing of Explorer XXXIII was used for comparison (*12*).

not shown at equally spaced intervals but at times that best illustrate the character of the average magnetic field within the various regions.

The observations are most easily described in terms of a proposed specific model, which should be regarded only as phenomenological; its dynamical validity has not yet been substantiated.

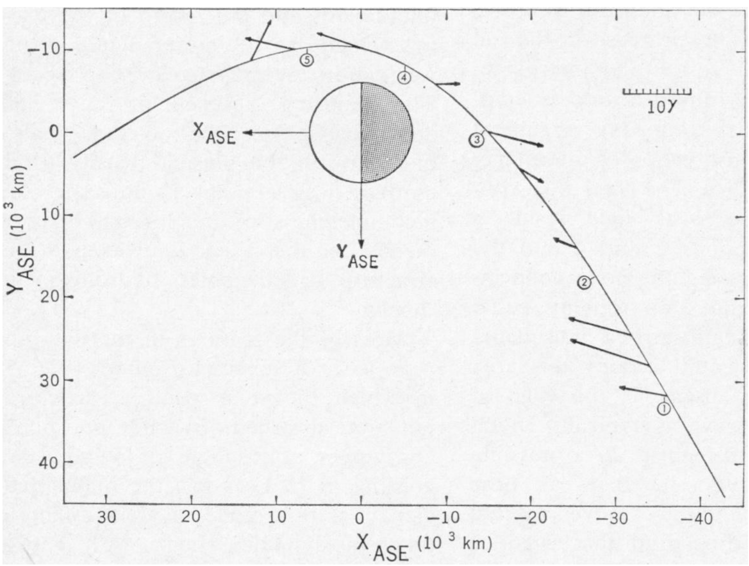
The interplanetary conditions before and after encounter were only moderately disturbed. The plasma properties were quite steady, but the velocity ($\sim$590 km sec^{-1}) and "temperature" [$\sim 3 \times 10^5$(°K)] were unusually high. The direction of the magnetic field showed substantial fluctuations, but its magnitude was nearly constant at $\sim$8 gamma, a value close to that expected at the orbit of Venus. Apparently, a series of solar wind structures, perhaps filaments, were convected past the spacecraft, with transitions at intervals of a few to 30 minutes. Such a transition will sweep over the region between 1 and 5 in 1.3 minutes.

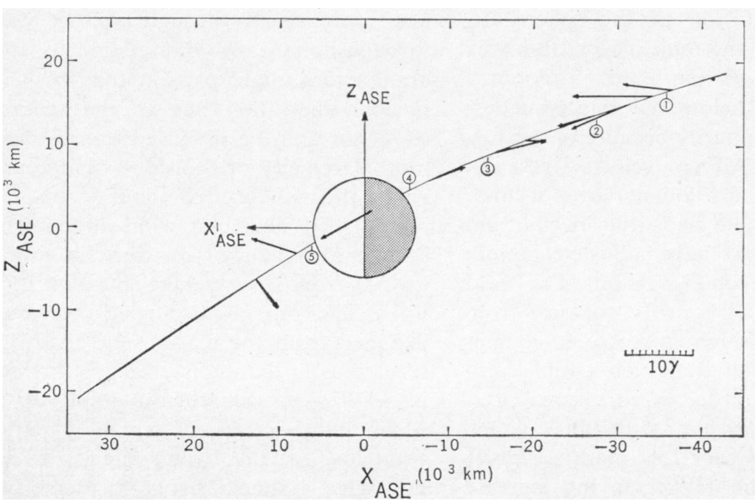
The influence of Venus on the solar wind flow first became apparent at point 1 of the figure. The magnetic field strength increased abruptly from 8 to 15 gamma, and the fluctuations increased markedly, although the average direction remained nearly along the Venus-Sun line. The plasma velocity dropped slightly ($\sim$10 percent), and the density increased markedly ($\sim$40 percent). Such changes are commonly seen across a shock; together with the subsequent observations, they make the identification of point 1 as a bow shock almost inescapable.

For a few minutes just before 1 and again just after 5 (which we shall identify below as a shock crossing), the field had a characteristic direction and strength. It would be possible to identify these regions as part of the shock structure and to ascribe a previous occurrence at -180 minutes to a motion of the shock front of the kind often seen near Earth. However, in the absence of a corresponding magnitude change, we reject this identification and treat the field at these times as interplanetary in origin.

During the hour after event 1, the plasma velocity and density dropped slightly, and there was a marked broadening of the velocity distribution. The field characteristics were unchanged except for one abrupt decrease in magnitude and in the amplitude of the fluctuations. Because similar changes are often observed in Earth's magnetosheath (Fig. 1), we interpret this decrease as a response to changes in the interplanetary medium.

At event 2, there was a second abrupt change; the field strength dropped from 9 to 6 gamma (less than the average magnitude in interplanetary space) with little change in average direction, and the fluctuations increased substantially. The plasma density and velocity began steady decreases, reached their minimum values near event 3,





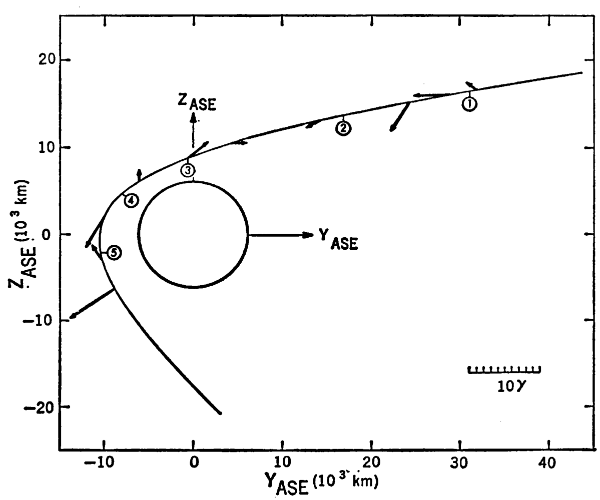


Fig. 4. Mariner trajectory and magnetic-field vectors. The three panels contain aphrodiocentric-solar-ecliptic projections of the Mariner trajectory and of the measured field at specific points.

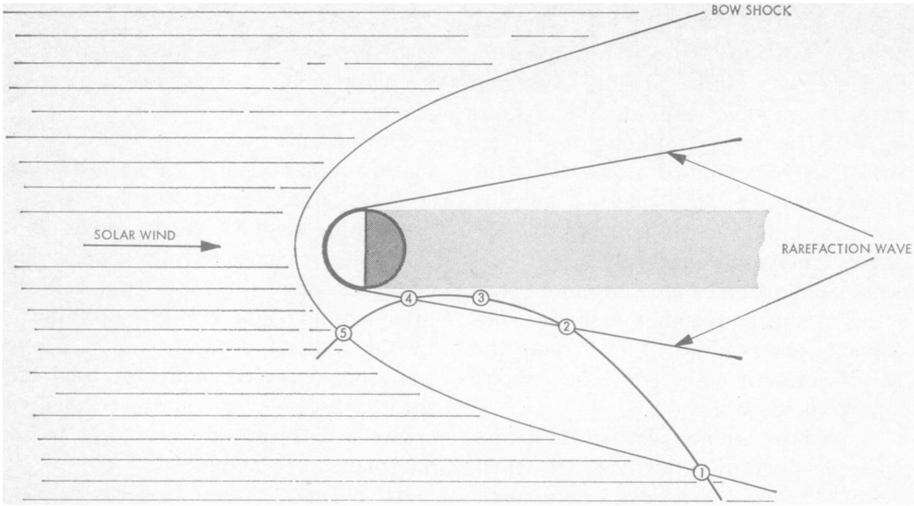


Fig. 5. Schematic representation of the solar-wind interaction with Venus. The heavy circle around Venus represents the atmosphere. The rarefaction wave, where the shocked solar wind is expanding into the plasma shadow cast by Venus, occupies an extended region near the indicated cone. The cavity is shown as a shaded cylinder; although structure might be expected there, the inner edge of the wave, Mariner V made no measurements in that region. The anemopause is at the top of the atmosphere on the front side and bounds the cavity to the rear. A rough approximation to the Mariner V trajectory containing the five features observed by the plasma and field experiments is shown.

and returned to high values by point 4. Fifteen minutes after event 2, the direction of the field made the first of three reversals that are not associated with other significant changes; presumably the field direction in the undisturbed solar wind was reversing much as it did during the 2 hours before event 1. The change at event 2 does not appear to be a magnetopause crossing because of these reversals and because the plasma characteristics resemble those of a magnetosheath, not of a magnetosphere or magnetospheric tail.

The most natural interpretation of these results is that the electrically conducting ionosphere of Venus cannot be penetrated quickly by the solar-wind field and that most of the plasma is therefore prevented from reaching the atmosphere. Thus, a standing shock is formed ahead of the planet. The compressed solar plasma behind the shock flows around the sides of the planet, becomes supersonic, and tends to leave a cavity behind the planet. The magnetic and gas-kinetic pressures should produce an expansion into the partially empty cavity; the edge of the expansion wave may approximate a cone running through point 2, near point 4, and about 500 km above the surface of the planet. Within 45° of the subsolar point, the interface between the atmosphere and the solar wind (the anemopause) (*6*) appears to be at about this level, where the Stanford group (*7*) observed an abrupt decrease in the ion density from 10^4 cm^{-3} to an interplanetary value. This interpretation is compatible with the following argument based on the conservation of interplanetary magnetic flux. The total flux contributed by the weak field inside a cone through points 2 and 4 and the strong field crossing the cone connecting points 1 and 2 is roughly equal to the flux of undisturbed interplanetary field that would occupy this area if Venus were absent. If the edge of an expansion wave is typically much less sharp than feature 2, a possible explanation would be that, as near Earth, all boundaries move rapidly from time to time, and that event 2 is a rapid shift of the expansion region across the position of the spacecraft.

At point 3, the total plasma flux was reduced to $\sim 10^7$ cm^{-2} sec^{-1} (about a factor of 20 below the interplanetary value) and, primarily because of the low density, the Alfvén velocity rose to several hundred kilometers per second. Thus, the plasma had little inertia, and the field should have adjusted rapidly to a vacuum configuration. The field direction, nearly radially outward from Sun, and the slight increase in magnitude near point 3, which could compensate for the decreased plasma pressure, are consistent with this model. However, the very low plasma density near 3 and the accompanying increase in $|B|$ cannot both be explained as due to an expansion wave. Perhaps the plasma flow along these tubes of flux, which must pass very close to the planet, was partially obstructed by an interaction with the atmosphere. Any comments on whether the unobserved region in the shadow of Venus was occupied by interplanetary field that passed through the planet, by magnetosheath field carried in by the expansion wave, or by an intrinsic planetary field would be pure speculation at this preliminary stage in the analysis of the data.

Conditions in the region between events 4 and 5 were comparable to those observed in the magnetosheath of Earth at about the same local time. The high values of $|B|$ may have been caused by the compression of the plasma as it passed through the shock or, in part, by the very irregular structure of the magnetic field generated at the shock. No feature characteristic of a magnetopause was present. Because of the abrupt decrease in the magnetic fluctuations and the return of the plasma velocity to its interplanetary value, we identify event 5 as the bow shock. The puzzling absence of any sudden change in the average value of $|B|$ or in the plasma density (such as there was at point 1) illustrates the incompleteness of our present experimental and theoretical knowledge of the structure of collisionless hydromagnetic shocks.

Most of the features in the data appear to fit a schematic model (Fig. 5) in which the solar wind is deflected, but not absorbed, by the ionosphere and upper atmosphere of Venus. According to L. Lees (*8*), the major deficiency of this model is that a laboratory gas-dynamic shock with appropriate scaling would be expected to pass more nearly through point 2 than through point 1. A combination of several factors might explain this. (i) The normal aberration due to the motion of Venus and the observed average azimuthal velocity of the solar wind could rotate the axis through about 5° toward point 1. (ii) The solar wind direction is known to fluctuate—at times, as much as 5° from its average position (*9*). (iii) The magnetoacoustic velocity deduced from the plasma and field observations in the undisturbed solar wind is ~120 km/sec, corresponding to a Mach number of ~5, which is somewhat low for the hypersonic limit and may give a shock that is farther from the axis. (iv) The highly irregular magnetic field in the magnetosheath region contributes an additional pressure that is not included in the usual gas-dynamic analysis. Until further analysis, and perhaps further observations, have been made, these suggestions must be regarded as speculative, and the dynamic soundness of our model must be regarded as uncertain.

Other models are possible but unattractive. Most of the features seen near Venus could be regarded individually as features of the interplanetary medium even though some of them are very unusual. However, it seems extremely unlikely that all these features would have been observed during the short period in which Mariner was near the planet and that they would have been organized purely by coincidence into the observed pattern.

The magnetopause and bow shock observed around Earth can be scaled so that the shock passes through point 1 and very near to point 5. The scaled magnetopause is then in the upper atmosphere at the subsolar point, and the trajectory would be inside the magnetosphere between points 2 and 4. The corresponding scaling of the dipole moment gives a value for Venus about 1/700 that of Earth. Although the presence and position of the shock is an attractive feature of this model, the presence of solar wind inside the scaled magnetopause and the very low value of $|B|$ near event 3 seem to rule out the model completely.

An upper bound can be placed on the magnetic moment of Venus, but it depends for its precise value on the details of the model used. The unsuitability of the scaled geomagnetic analogue summarized above requires that the actual ratio of dipole moments be significantly smaller than that derived from the model. We estimate a reasonable limit to be within a factor of two of 10^{-3} times that of Earth. Obviously, there is no way to tell from such analyses whether or not Venus has an intrinsic field smaller than the upper bound. Nothing that we report here is inconsistent with the available information on the recent Russian observations which appear to give an even lower limit.

The interaction of the solar wind with Venus differs from its interaction with either Earth or Moon. In the case of Moon, the plasma ions are absorbed by the lunar surface, and no shock develops (*10*). Moreover, Moon appears to be a sufficiently good insulator to allow the interplanetary field to be convected nearly unchanged through it (*11*). Except for a region close to or inside the lunar shadow, the plasma flow near Moon is unaffected by its presence. In contrast, the plasma flow near Venus is bounded by an anemopause. The shock around Venus resembles that around Earth except in scale, but conditions inside are quite different because the anemopause around Venus is probably supported by the ionosphere, whereas that around Earth is supported by the geomagnetic field. The plasma appears to expand into the cavity on the downwind side of Venus, whereas, behind Earth, inward expansion is prevented by the magnetic field in the geomagnetic tail.

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Venus: An Upper Limit on Intrinsic Magnetic Dipole Moment Based on Absence of a Radiation Belt

Abstract. *On the basis of the absence of energetic electrons* ($E_e > 45$ *kiloelectron volts) and protons* ($E_p > 320$ *kiloelectron volts) associated with Venus to within a radial distance of 10,150 kilometers from the center of the planet and using a physical similitude argument and the observational and theoretical knowledge of the magnetosphere of Earth, we conclude that the intrinsic magnetic dipole moment of Venus is almost certainly less than 0.01 and probably less than 0.001 of that of Earth. Corresponding upper limits on the magnetic field at the equatorial surface of Venus are about 350 and* 35×10^{-5} *gauss, respectively.*

The University of Iowa apparatus on Mariner V comprises three Geiger tubes and a 32-μm thick, totally depleted, surface-barrier silicon detector with four electronic discrimination levels. The data obtained during Mariner V's encounter with Venus on 19 October 1967 establish a complete, or nearly complete, absence of energetic electrons and protons associated with the planet, in to the minimum radial distance of approach of 10,150 km (*1*). These results are consistent with earlier ones from the 41,000-km approach of Mariner II to Venus in 1962 (*2*), but they are much more definitive by virtue of the closer approach.

Specific upper limits on the average