

REVISED UPPER LIMIT ON THE INTERNAL MAGNETIC MOMENT OF VENUS

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ABSTRACT

Over four Venus years of low altitude nightside PVO magnetometer observations are used to establish a new upper limit for the magnetic moment of Venus. Improvements over previous studies include data coverage and new instrument calibration information. The upper limit on an internal dipole moment is determined to be $8.4 \times 10^{10} \text{ T m}^3$.

INTRODUCTION

The planetary magnetic field of Venus has proven elusive since the arrival of the first spacecraft missions. No unambiguous evidence for a dynamo-driven internal field or for surface magnetism has been found. However, analyses of spacecraft data /e.g., 1,2,3/ have steadily lowered the upper limit on a possible planetary dipole moment, with the most recent estimate being $3 \times 10^{11} \text{ T m}^3$, corresponding to an equatorial surface field of 1.35 nT. This limit is far below the predictions of planetary scaling laws /e.g., 4/, suggesting either that the processes used to justify these laws are inadequately understood, or that Venus lacks the internal energy source necessary to drive a magnetic dynamo (see for example /5/). As in /3/, this study involves analysis of Pioneer Venus Orbiter (PVO) magnetometer data. Improvements featured here include expansion of planetary coverage, greater volume and accessibility of data, and new instrument background information. There is little possibility that PVO will return additional low altitude data; we consider this data set complete.

In order to explain clearly the constraints placed on a magnetic field search, it is first necessary to describe the magnetic environment of Venus. The planetary obstacle consists of a highly conducting ionosphere which is able to electrically shield out the solar wind about 80% of the time; mass addition by newly ionized exospheric particles also influences the interaction. The solar wind, with an imbedded magnetic field of typically 10 nT, passes through a standing bow shock. The enhancement of the magnetic field at the shock and in the magnetosheath results in a predominantly horizontal field, often exceeding 100 nT, overlying the ionosphere. The dayside ionosphere is generally free of large scale magnetism, but usually contains small scale flux ropes and under certain circumstances can become substantially magnetized by diffusion and downward convection of field from the magnetosheath. On the nightside, the ionosphere-magnetosheath boundary is poorly defined and often irregular. The nightside sheath field is generally horizontal and of the order of 10-20 nT, with occasional large regions of radially-oriented field and accompanying plasma depletions, called "holes" /6/. These holes have been shown to respond to the IMF orientation and thus can be considered anomalous background rather than manifestations of a planetary field /7,8/.

THE DATA

The data used in this study are 12-second averaged low altitude magnetometer observations in the Venus Solar Orbital (VSO) system. PVO has a highly eccentric, nearly polar orbit with periapsis near 150 km for the first 600 orbits and then steadily rising. The retrograde rotation of Venus about its axis and its revolution about the sun cause periapsis to move eastward at roughly 1.5° of longitude per day while remaining nearly fixed in latitude at 15° N . During each Venus year observations of a particular longitude region are associated with a specific range of local time; thus, planetary coverage is determined by choice of solar zenith angle (SZA) or local time and altitude.

Since this study involves identifying a signal of probably less than 1 nT in a much larger background field, it was necessary to check carefully the zero levels of the magnetometer. This determination was based on the observed characteristic of the IMF that directional changes often occur with little or no magnitude change. IMF rotations of greater than 30° occurring within two hours were used to determine the zero levels required to minimize the change in field magnitude. Monthly averages of the zero levels were calculated after discarding values greater than one standard deviation from the mean. The zero levels of the Z component, roughly parallel to the spacecraft spin axis, exhibit linear behavior with time. The monthly averages and best fit function are shown in Figure 1; this function was added to data used in this study. In the X and Y components, lying in the spin plane, any field fixed in the main body of the spacecraft would not contribute to the measured field because the external field is a sinusoidal wave in the body fixed frame. However, a background field in the "inertial" frame could be caused by the high gain antenna, which always points toward earth and moves slowly with respect to the solar direction, which is the reference direction for our "inertial" coordinate system. Accordingly, the X and Y offset monthly averages were fit to combinations of the sine and cosine of the Sun-Venus-Earth angle, which varies nonlinearly with time. Figure 2 shows the best fit functions, which were used to determine the contribution of the high gain antenna.

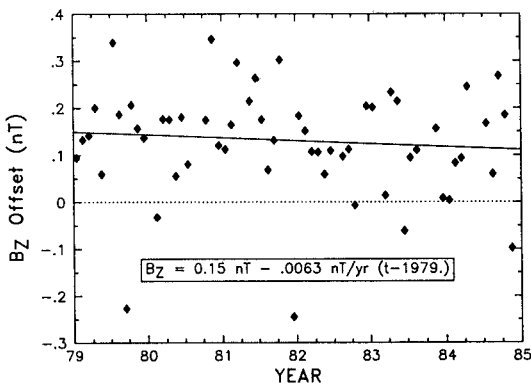


Fig. 1. Monthly averaged magnetometer Z component zero levels for 1979-1985. Solid line and equation in box describe best linear least squares fit; this function was added to data.

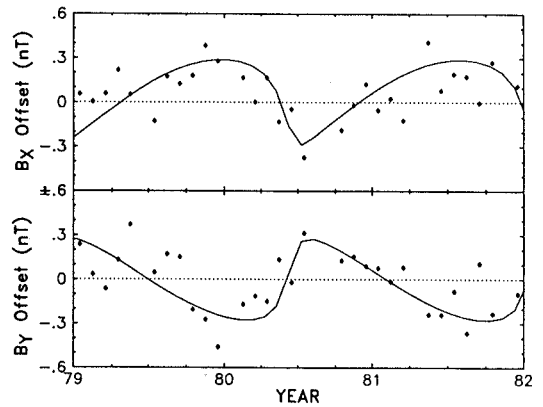


Fig. 2. Monthly averaged magnetometer X and Y component zero levels for 1979-1982. Solid lines represent best least squares fits to combinations of the sine and cosine of the Sun-Venus-Earth angle; these functions were added to data. Offsets show no obvious periodicity after 1982.

The next decision to be made concerned the position and altitude ranges to be surveyed in order to maximize the signal to noise ratio. Due to the dominance of solar wind flow effects in the interaction, flow zenith angle (FZA), similar to SZA but incorporating a 5° aberration to compensate for planetary motion, was chosen as the appropriate position parameter. The data, after addition of the background functions described above, were binned into 10° square bins of longitude and latitude. For each spacecraft pass through a particular bin, the vector mean magnetic field was calculated in a planetary cartesian system in which X points toward the 0° meridian, Y toward the 90° meridian, and Z toward orbital north. The calculations were carried out for each orbit with periapsis below 1200 km. Vector means of all the measurements for each bin were calculated, and a mean FZA was assigned to each bin. The data were then inverted into equivalent planet-centered dipole moments. The magnitudes of the moments were binned by FZA; Figure 3 shows the median moment as a function of FZA. Based on this result, 105° was chosen as the minimum FZA for subsequent calculations. A similar process was carried out to determine the median moment as a function of altitude for FZA $> 105^\circ$. The results are shown in Figure 3; 750 km was chosen as the maximum altitude for subsequent calculations.

The final data set contains just over four orbital seasons of low altitude nightside observations: orbits 26-125, 287-350 (this second wake passage was shortened by a superior conjunction), 475-574, 701-798 and 927-942 (truncated by rising periapsis altitude). A total of over 18,000 12-second averages of the magnetic field and the corresponding positional data were used. For comparison, Russell et al. /3/ used two orbital seasons, restricted to below 600 km and above 120° SZA. Figure 4 shows the planetary coverage of this and the previous study /3/.

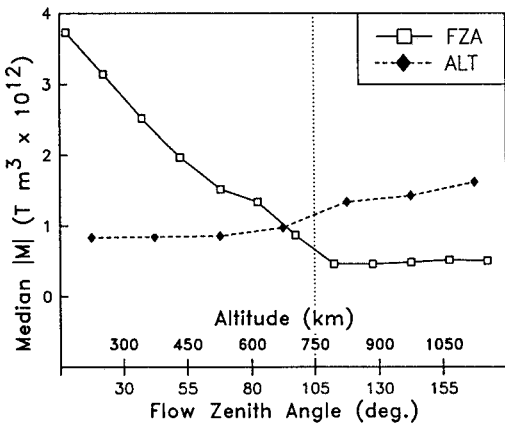


Fig. 3. Medians of the magnitude of the planet-centered dipole moment for 10° latitude-longitude bins as functions of FZA and altitude. 1050 and 750 km were chosen as the limits for data use in calculating the moment.

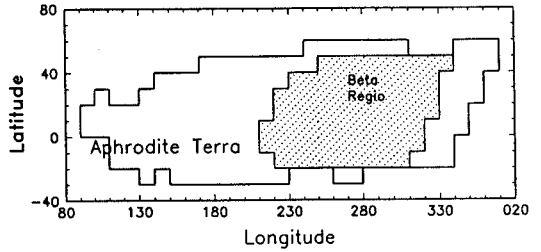


Fig. 4. Mercator projection of planetary coverage of the final data set (outer perimeter) and the subset used by Russell et al. /3/ (shaded area). Data set is restricted on the north and south by altitude, on the east by FZA, and on the west by both altitude and FZA. The general locations of Beta Regio and Aphrodite Terra are indicated.

THE MAGNETIC MOMENT

As a final calculation, the data set was binned again into 10° latitude-longitude bins. Additionally, the "hole" measurements, somewhat arbitrarily considered to be those for which the radial magnetic field exceeded 10 nT and for which the field was inclined more than 45° from local horizontal, were discarded. As in the previous section, an equivalent vector dipole moment was determined for each bin. The mean moment for each component and the resulting magnitude, which corresponds to an equatorial surface field of 0.33 nT, are as follows:

$$\begin{aligned}
 M_x &= 3.32 \times 10^{10} \text{ T m}^3 \\
 M_y &= -2.34 \times 10^{10} \text{ T m}^3 \\
 M_z &= -6.01 \times 10^{10} \text{ T m}^3 \\
 M &= 7.21 \times 10^{10} \text{ T m}^3
 \end{aligned}$$

In a study of this sort, the probable error of the estimate is as important as the estimate itself. The major factor in determining this probable error is the independence of the contributing measurements. Solar wind and IMF conditions normally change relatively little during the low altitude portion of a particular orbit, which is a roughly meridional transit. Therefore, all 181 individual moment estimates cannot be considered independent. However, during the 6-7 orbits which span each 10° longitudinal bin conditions typically change greatly, and of course change even more from one orbital season to the next. Accordingly, a better approximation to the number of independent estimates is the sum of the longitudinal bins covered during each of the five orbital seasons, a total of 73. The probable error of the mean for each moment component is the standard deviation of the individual estimates for that component, divided by the square root of the number of independent estimates:

$$\begin{aligned}
 E_x &= 4.66 \times 10^{10} \text{ T m}^3 \\
 E_y &= 3.22 \times 10^{10} \text{ T m}^3 \\
 E_z &= 6.23 \times 10^{10} \text{ T m}^3 \\
 E &= 8.42 \times 10^{10} \text{ T m}^3
 \end{aligned}$$

Note that the above estimates and probable errors are not inconsistent with zero planetary moment. We have used a conservative determination for the number of independent observations contributing to the above results; it could be argued on the basis of changing orbit and solar wind conditions that each of the 378 orbits used represents an independent estimate. Even so, our estimate of the probable error of the mean would drop only by a factor of two and we would not consider our estimates to be statistically significantly different from zero. Furthermore, we have no indication either direct or indirect that Venus has an intrinsic magnetic field. Thus, we consider our estimate of the probable error of the mean to give the most probable upper limit to the planetary moment, and the obtained mean moment to be a random value consistent with that error. Accordingly, our estimate of the upper limit of the internal magnetic moment is $8.4 \times 10^{10} \text{ T m}^3$, equivalent to a surface equatorial field of 0.4 nT.

CONCLUSIONS

The calculations described above have reduced the previous upper limit for the Venus internal moment by a factor of three. It appears increasingly likely that Venus has no measurable intrinsic field. The data set used here can be considered a "mission best" in the sense that no new low altitude nightside magnetometer data will be available until the arrival at Venus of the next suitably equipped spacecraft. However, some improvements can be made in the treatment of the data. First, improved understanding of the solar wind interaction with Venus and particularly of the nightside "holes" is necessary to properly treat solar-wind driven magnetic effects. Second, the increased longitudinal coverage available in this data set makes possible more sophisticated fitting of the data to an internal moment. Finally, this greater planetary extent and the data overlap between seasons enables a more extensive search for surface magnetism.

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