THE MAGNETIC MOMENT OF VENUS: VENERA-4 MEASUREMENTS REINTERPRETED

Christopher T. Russell
Institute of Geophysics and Planetary Physics
University of California, Los Angeles, California 90024

Abstract. Re-examination of the Venera-4 magnetic field measurements at Venus encounter suggests that Venus may have an intrinsic magnetic dipole moment of about 6.5x10^22 Gauss-cm^3 which corresponds to a surface field of 30 gammas (1y=10^-9 Tesla).

Introduction

Direct observations over the last several years of the magnetic fields surrounding the terrestrial planets, Jupiter and the moon have stimulated much present interest in planetary magnetism and the geodynamo mechanism. The strongest of these planetary fields is that of Jupiter whose magnetic moment is 1.4x10^30 Gauss-cm^3 with a surface field strength of 4 Gauss (Smith et al., 1974) compared with the terrestrial moment of 8x10^25 Gauss-cm^3 and a surface field of 0.31 Gauss. The next most intense field is Mercury's with a moment of 5x10^22 Gauss-cm^3 and a surface field of 350 y (Ness et al., 1975) followed by Mars with a moment of 2.5x10^22 Gauss-cm^3 and a surface field of 64 gammas (Dolginov, 1976). For Venus and the moon only upper limits have been reported, 5 to 8x10^21 Gauss-cm^3 corresponding to a surface field of 2-4y for Venus (Dolginov et al., 1969), and 1019 Gauss-cm^3 corresponding to a surface field of 0.2y (Russell et al., 1975).

The lack of a present day lunar planetary field is not surprising. The lunar rotation rate is slow and its iron or iron sulfide core is small, ~400 km, (Kaula et al., 1974; Nakamura et al., 1974; Goldstein et al., 1975). However, the lack of a measurable magnetic field on Venus is surprising. The core of Venus should be similar in size to that of the earth and therefore larger than Mercury's and its rotation rate is only a factor of 4 less than that of Mercury. In fact, one of the most recent predictions of the moment of Venus gives a moment of 1.9x10^23 Gauss-cm^3 and a surface field of 80y (Busse, 1975).

In view of this apparent divergence between observation and theory it is important to re-examine the evidence for the lack of a planetary field on Venus. In the next section we will review this evidence and in the following section examine one of these sets of data, the Venera-4 entry data, in detail. In this examination we find that the data do not rule out a planetary field, but rather they suggest the presence of a planetary field of sizeable magnitude. In fact, the magnetic moment of Venus may exceed both that of Mars and Mercury.

Early Observations

The first attempt to measure the planetary field of Venus was made in 1962 with the Mariner 2 spacecraft (Smith et al., 1963, 1965). Mariner 2, approaching within 6.6 planetary radii of Venus detected no planetary field, not even a disturbance of the solar wind by the planet. This absence led these authors to estimate an upper limit of 4x10^24 T-cm^3 for the planetary magnetic moment. In 1967, both the USA and the USSR sent probes to Venus: Mariner 5 on a flyby trajectory, and Venera 4 on an impact trajectory. An estimate of the upper limit to the planetary moment from the Mariner 5 data was derived from the observed position of the bow shock (Bridge et al., 1967). This upper limit was 8x10^22 Gauss-cm^3 corresponding to a surface field of 36y.

The Venera-4 data, in principle, required no such inferences in order to deduce the planetary field since the spacecraft entered the Venus atmosphere, providing data down to an altitude of 200 km (Dolginov et al., 1969). Using these data together with simultaneous Mariner 5 data in the solar wind only 80 planetary radii away at the time of the Venera-4 entry, Dolginov et al. quote a limit of 5 to 8x10^23 Gauss-cm^3 or a surface field of 2 to 4y. Since these latter data place the most stringent constraints on the intrinsic field of Venus, we will examine them in detail.

The Venera-4 Entry Data

The last 80 minutes of magnetic field data from the Venera-4 spacecraft are shown in Figure 1, together with simultaneous observations of the interplanetary magnetic field by Mariner 5 only 80 planetary radii distant. In the coordinate system in which these data are displayed, N is directed perpendicular to the solar equator northward, R is in
the anti-solar direction, and T completes the orthogonal set roughly in the direction of planetary motion. The Mariner data have been offset in time by 14 minutes to account for the propagation of solar wind features from Venera-4 to Mariner 5 (Dolginov et al., 1969). The near coincidence of a tangential discontinuity at Mariner 5 and the Venera-4 shock crossing suggest that this time shift is approximately correct. Although the magnitudes of the two measured fields agree, examination of the vector field reveals differences of the order of 5 to 10 gamma in each component which may be due to spacecraft fields (Dolginov et al., 1969). Thus, we feel the agreement of the magnitudes is fortuitous and we will make no conclusions based on the magnitude of the field plotted in this figure. In the far left of the figure, Venera-4 was in the solar wind, then it crossed the bow shock into the magnetosheath, and 40 minutes later entered the Venus atmosphere passing through two possibly quasi-static current layers along the way at about 2.35 and 1.4 planetary radii. All distances have been scaled from figure 4 of Gringauz et al. (1968). The three dimensional trajectory has not been published.

From the point labelled current layer 1 to the end of transmission we observe a gradual and continuous change in the direction of the field with some superimposed level of fluctuation. This gradual evolution of the vector field is not observed in the total field. We note that it was the constancy of this total field which led Dolginov et al. to place their 2-4y limit on the strength of the surface field. Our firmest constraint on the Venus magnetic field, independent of these data, is the Mariner 5 encounter which gives an upper limit to the magnitude of the surface field of 35y. If we restrict our attention to the portion of the trajectory for which a 35y surface field would have an effect of 5y or greater we are left with the data on the right hand side of the dashed line, i.e., the last 10 minutes of data (altitudes less than 5000 km).

**Interpretation**

The problem, at hand, then is to determine whether the variation in the three components of the magnetic field is consistent with an intrinsic planetary dipole. The only trajectory data at our disposal is the distance of the spacecraft from the center of the planet as a function of time. Thus, our only available test is to examine the altitude dependence of the magnitude of the "planetary contribution" to the observed field, and our task reduces to the problem of determining the planetary contribution. To do this we must make assumptions about the nature of the solar wind Venus interaction. We will examine three different models, each increasing in sophistication and determine an altitude dependence for each one. This will allow some assessment of the stability of the resultant estimates to perturbations of the assumptions.

Our first model assumes there are just two fields, that of the interplanetary medium and that of the planet and that these fields simply add. This assumption would be true in a vacuum and could be true if the solar wind were able to interact directly with the atmosphere of Venus, but would be a poor assumption if Venus had a well developed magnetosphere which shielded the planet from the solar wind. Since the Mariner 5 data indicate a moderately steady interplanetary field, we use the preshock Venera-4 measurements to draw baselines for the entry data (labelled 1 in Figure 1). This procedure also removes the steady spacecraft field. We then take 10 samples (one per minute) of each component, calculate the magnitude of this residual field and assign the sample a planetocentric distance using Figure 4 of Gringauz et al. (1968). These residual fields are plotted in Figure 2, panel A, as a function of distance. The line shown is a least square fit to the logarithms of the quantities. Its slope is -1.60 and it intersects the planetary surface at 18y. Alternatively extrapolating each of the individual samples to the surface with an inverse cube law gives a magnitude of 30.5×2.6y.

Our second model admits the presence of the magnetosheath and a current layer at the bow shock but assumes that the magnetosheath field is spatially uniform between the shock and the planet and that the observed fluctuations are due only to temporal changes in the interplanetary field or due to the planetary field. Here the baseline, number 2 in Figure 1, is chosen to be the value of the magnetosheath field when the Mariner 5 data indicate the interplanetary field is ori-
The strong altitude dependence seen in all three panels of Figure 2, its closeness to an inverse cube law in two of them and the stability of the inverse-cube extrapolation at near 30° leave little doubt that the upper limit of 2-4 γ quoted by Dolginov is much too low. Rather it is possible that Venus has an intrinsic moment of the order of 6.5 × 10^{22} \text{ Gauss-cm}^3. We note that near the planet the field is principally along the N-direction which is approximately along the ecliptic north pole. This component of the field is negative, as would arise from a northward pointing magnetic moment, similar to that of Mars and Jupiter and opposite that of the earth and Mercury. Without detailed trajectory data we can say nothing about the inclination of the moment, its offset from the center of the planet, etc.

An alternate interpretation of these data is that observed "planetary" field is not intrinsic to the planet but rather is induced in the ionosphere. Two modes of induction are theoretically possible: the transverse magnetic mode driven by the motional electric field of the solar wind, also called unipolar induction; and the transverse electric mode driven by the time-varying magnetic field, also called Cowling induction (cf. Sonett et al., 1971). The transverse magnetic mode generates a current in the ionosphere corresponding to field lines draped over the planet. One would expect that in this case the induced planetary field would be a parallel to and larger than the component of the external field in the N-T plane far from the planet. However, the field clearly rotates in this plane.

The transverse electric mode is strictly a time-dependent phenomenon, corresponding in the low frequency limit to the diffusion of field lines into the ionosphere. To visualize the effects of this mode, assume that Venus is surrounded by a uniform magnetic field for a period of time long enough for the field to diffuse into the ionosphere. Then let the external field reverse direction, as might occur at a sector boundary. Initially, ionospheric currents would be set up to retain the old field in the ionosphere and exclude the new. Since this mode depends on the past history of the external magnetic field we cannot use simple directional arguments to rule it out.

One would hope the altitude dependence shown in Figure 2 would aid in distinguishing between induced and intrinsic fields. Since the induced currents flow in the ionosphere through which the spacecraft is passing on its impact trajectory, one might expect a change in slope in
this effect. We do note that the field at the lowest altitude is slightly below the trend at higher altitudes. However, the difference is no greater than that expected from the observed scatter in the data.

If the fields are indeed intrinsic to the planet, the present estimate of the moment should be encouraging for those working on the geodynamo problem. Since surface fields of 80n such as those proposed by Busse (1975) do not appear to be present, disagreements by factors of only 2 or 3 are encouraging rather than discouraging in this field. Moreover, the present estimate agrees much better with a recent dynamo scaling law proposed by Dolginev (1975) than Dolginov's original estimate of the moment.

The existence of a weak planetary field allows implications in the solar wind interaction with the planet. While the field does not appear to be strong enough to stand off the solar wind, it could prevent the solar wind from directly interacting with the ionosphere over a significant fraction of the planet in much the same way the weak localized lunar magnetic fields are believed to deflect the solar wind in the terminator regions causing limb compressions (Russell and Lichtenstein, 1975) but on a much grander scale. We note, however, that there is very little evidence for deflection of the solar wind in these records. There is no evidence for shielding of one field from the other at current layer 2, which is close to but outside of the Mariner 5 "rarefaction" boundary. However, the interplanetary field was directed northward, opposite the planetary field, and if the terrestrial analog were followed, we would expect a merging of the magnetosheath and planetary fields. Finally, we note that the current layer 2 occurs closer to the extrapolated Mariner 5 position of the bow shock than the magnetopause, that the field increase is reminiscent of the increase at this boundary in a similar manner as at the bow shock (see figure 2 of Gringauz et al., 1968). However, if it is a bow shock crossing, the prior exit from the magnetosheath is not evident. One possible solution of this dilemma is that this current represents a second standing shock.

In conclusion, the existence of an intrinsic planetary moment of 6.5x10^22 Gauss-cm^3 is one possible and plausible, interpretation of the Venera-4 measurements. However, the present analysis is neither conclusive nor complete. A proper measurement of the planetary moment awaits the repeated measurement of a Venus orbiter.

Acknowledgments. This work was supported by the National Aeronautics and Space Administration under contract NAS 2-8808.

References


Dolginov, Sh. Sh., On the magnetic dynamo mechanism of the planets, preprint N9a(124), IZMIRAN, Moscow, 1975.


(Received November 13, 1975; revised January 5, 1976; accepted January 24, 1976.)