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A simple test of the induced nature of the Martian tail

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Abstract. The cross tail component of the magnetic field in the Mars wake allows a simple test of the contribution of the intrinsic planetary magnetic field to the observed magnetic field. If the magnetic tail is entirely induced, then the direction of this cross tail component should be highly correlated with the direction of the interplanetary magnetic field. It is found that the direction of the cross tail magnetic field is so highly correlated with the direction of the cross flow interplanetary magnetic field that there can be little intrinsic contribution to the Martian magnetotail. This in turn implies that the upper limit to the Martian magnetic moment is about 4×10^{11} Tm^3.

Introduction

The intrinsic magnetic field of Mars is clearly very small. Just how small is very controversial. Limits were first placed on the magnetic moment of Mars through the inferred size of an obstacle to the solar wind flow that would give the size of the bow shock detected by *Mariner* 4 (Dryer and Heckman, 1967; Smith, 1969). The upper limit thus obtained was 2×10^{12} Tm^3. Later, initial interpretations of the *Mars* 2 and 3 magnetic field data suggested that an intrinsic magnetic moment had been directly detected (Dolginov *et al.*, 1972; Gringauz *et al.*, 1974). The magnetic moment consistent with the purported detection was 2.4×10^{12} Tm^3 (Dolginov, 1978). This intrinsic field interpretation met with some controversy and alternate interpretations of the observations were presented (Wallis, 1975; Russell, 1978a). Later, it was shown that the behavior of the magnetic field could be replicated with a gas dynamic numerical simulation (Russell *et al.*, 1984). The lowest upper limit to the intrinsic moment came as a result of a reanalysis of the *Mars* 5 data by Russell (1978b) who proposed that all the *Mars* 5 magnetic field measurements were consistent with a draped induced magnetic field and thus the moment need be no larger than 10^{11} Tm^3.

It was hoped that the *Phobos* magnetic field data would settle this question. During its first four orbits it approached twice as close to the surface as had the *Mars* spacecraft, i.e. within 800 km of the surface. Later, it provided over a month of data in an 8 h circular orbit that passed through the center of the tail three times a day. There was no unambiguous evidence that any of the field lines crossed by the *Phobos* spacecraft, either in the elliptic orbit phase or the circular orbit phase, were associated with current systems inside the planet, i.e. a planetary magnetic field (Riedler *et al.*, 1989). Later papers attempted to infer the presence or absence of an intrinsic field with various, sometimes indirect, tests.

Yeroshenko *et al.* (1990) reported that the direction of the tail lobe field was ordered by the interplanetary magnetic field as one would expect for an induced magnetotail, i.e. that the tail current sheet was a plane passing through the planet whose normal was along the projection of the upstream interplanetary magnetic field in the dawn–dusk plane. Dolginov and Zhuzgov (1991) simply inverted the data close to the planet assuming it was solely intrinsic to the planet to get a moment of 1.4×10^{12} Tm^3 without justifying this assumption. Mohlmann *et al.* (1991) claimed that spectral peaks at 8, 12 and 24 h periods in Fourier analysis of the data were due to the rotation of an intrinsic field. However, in a test of artificial time series, Russell *et al.* (1992) showed that such spectral peaks could arise from the nature of the orbit through an induced magnetosphere. Slavin *et al.* (1991) pointed out that distant bow shock crossings occasionally occurred and suggested that this might be due to the expansion of an intrinsic magnetosphere at times of low solar wind pressure. In an alternative explanation of these same data, Russell *et al.* (1993) showed that distant bow shock crossings occurred at times of low Mach number and low solar wind dynamic pressure, even for an unmagnetized planet. Verigin *et al.* (1991) found a pressure dependence for the radius of the Martian tail which was similar to that expected

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for the nose of an intrinsic magnetosphere, and offered this as evidence for the intrinsic nature of the Martian magnetosphere. However, Lui (1986) and Petrinec and Russell (1993) showed that the pressure dependence of the radius of the Earth's tail behaved differently than that of the nose. Moreover, Gringauz *et al.* (1993) showed that the radius of the Martian and Venus tails were similar at similar solar wind dynamic pressures, implying that the greater width of the Martian tail was due to the lower solar wind dynamic pressure at Mars. In short every inference of a possible intrinsic magnetic field had a counter argument presented, and the issue is not yet settled.

A new test of the nature of the Martian tail

The most sensitive region in which to test for the presence of any weak intrinsic field at Mars is in the wake or tail where the planetary magnetic field would be swept by its interaction with the solar wind. This field would be quite distorted by its interaction with the solar wind but its direction should be principally controlled by the planet and not by the IMF. An induced magnetotail on the other hand is intimately controlled by the IMF. The locations of its two lobes, the field in one generally pointing toward the sun and in the other generally pointing away, are on either side of a current sheet that passes through the planet, the normal to which is along the projection of the IMF on the plane perpendicular to the solar wind. Yeroshenko *et al.* (1990) showed that the lobes are about where they are expected to be, but there is marginally enough data for such a test to be convincing. Another test would be to use the component of the field perpendicular to the solar wind flow in both the solar wind and in the tail. These should be parallel in an induced tail but would not necessarily be parallel in an intrinsic magnetosphere in which field lines linking two regions on the planet would determine the cross tail component of the field as in the Earth's tail where the field is predominantly from south to north (Tsyganenko, 1989).

We can easily test if the cross tail field direction is controlled by the solar wind with the existing *Phobos* data obtained during the circular orbit phase during which the spacecraft spent about 4 h in the solar wind followed by about 4 h in the tail. We first divide the orbit up into 16 half-hour sectors, as shown in Fig. 1. Sector 1 is just outside the shock; sector 2 is further into the solar wind; and sector 8 is the last sector in the solar wind. Sector 9 is the sector just behind inbound shock crossing; sectors 12 and 13 are directly behind the planet; and sector 16 is the last sector in the magnetosheath just before the outbound shock crossing. Figure 2 shows where these divisions occur on a plot of 8 h of magnetic field data. We note that due to the variability of the interaction with the solar wind the bow shock occurs only close to and not precisely at the boundaries between sectors 1 and 16, and 8 and 9.

Ideally we would like to measure the orientation of the field in the tail simultaneously with a measurement of the orientation in the solar wind. If the correlation time of the IMF field direction with itself were sufficiently long, we would not have to worry about the lack of simultaneous data and could directly compare solar wind directions with tail measurements. Fortunately with 4 h of IMF data for each orbit we can test our assumption of the approximate stationarity of the cross flow IMF direction, which we will call the clock angle direction.

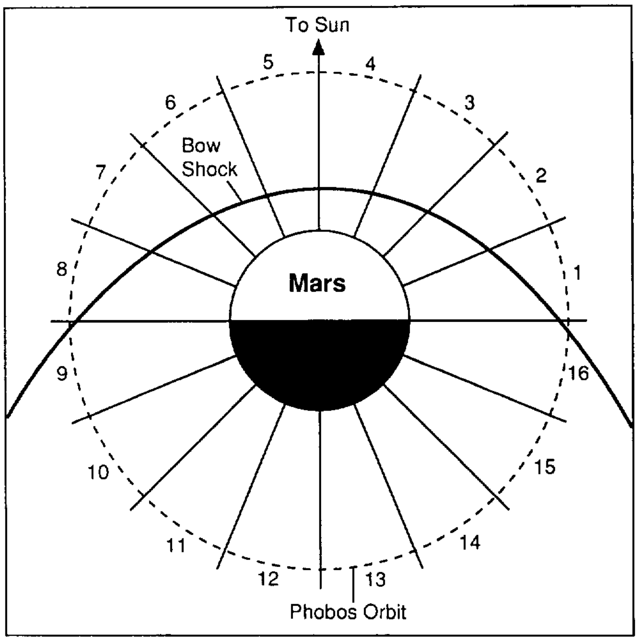

Fig. 1. Sectors used for averaging the *Phobos* magnetic measurements during the circular orbit phase of the mission. Sector 1 is the half-hour period just sunward of the dawn terminator (and the average dawn bow shock)

Our simple test of the intrinsic versus induced nature of the tail will be as follows. For each orbit we will construct pairs of values of the clock angle of the magnetic field (cross flow or cross tail) and then determine if these pairs of angles are strongly or weakly correlated. We will do this first for the IMF to determine how well the technique works in a region where there is no influence of the planet. If the tail and wake regions correlate with the IMF just as well as does the IMF with itself then the influence of any intrinsic magnetic field must be very small. We note that in this study we use almost exclusively

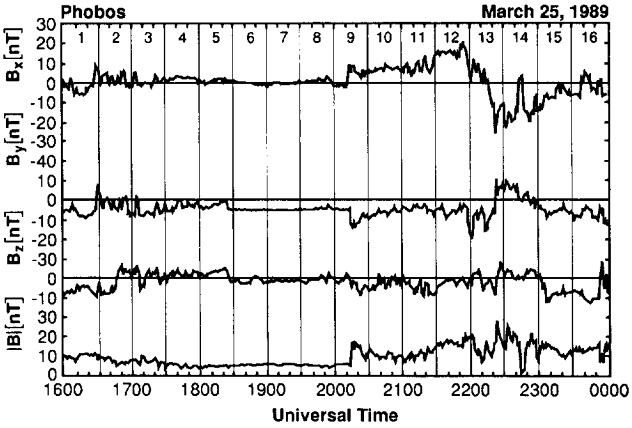

Fig. 2. Magnetic measurements in Mars solar orbital coordinates divided into the sectors illustrated in Fig. 1

Table 1. Correlation of IMF clock angle with other IMF clock angles: reference time preceding

Time separation (h)	Number of points	Correlation coefficient	Slope
0.75	20	0.904	1.11
1.25	20	0.907	1.13
1.75	21	0.936	1.09
2.25	21	0.932	1.19
2.75	19	0.917	1.36
3.25	20	0.911	1.47

data from sessions in which the spacecraft was rotating. These data have some errors caused by inaccurate spin periods but over the short periods used in this study ~2 h, these errors are not significant.

The IMF clock angle correlation

To reach the center of the tail which lies between sectors 12 and 13 from the middle of either sector 8 (going forward in time) or sector 1 (going backward in time) is 2.25 h. The equivalent correlations in the IMF are that of sector 1 with sectors 5 and 6 and sector 8 with sectors 3 and 4 (the lags of 2 and 2.5 h respectively average to 2.25 h). Figure 3 shows the correlation between half-hour average clock angles for these sectors, 2.25 h forward and back from the reference point. We have chosen every pair of points in the *Phobos* data set for which a sector 5 or 6 point occurred on the same orbit as a valid sector 1 data point. Similarly we examined every valid pair of sector 8 and sectors 3 and 4. There is some scatter but the correlation coefficient is quite significant 0.78 and 0.93. Tables 1 and 2 give the correlation coefficients for all sector pairs. We have clustered our correlation intervals in pairs (2,3), (4,5), (5,6), etc. to increase our statistical accuracy. Tables 1 and 2 show that the correlations seen in Fig. 3 are typical. We attribute the lack of perfect agreement possibly to noise sources rather than the natural variability of the IMF because the correlation coefficient seems to be independent of separation time. With natural fluctuations in the direction of the IMF one would expect a gradual fall in the correlation coefficient with increasing separation. The noise could be due to spacecraft sources or to natural sources. A natural source that could have the same effect as spacecraft noise is the bow shock. Since we are using sectors 1 and 8 which are adjacent to the average location of the bow shock and sometimes include it, bow shock associated noise might affect our correlation coefficients.

Table 2. Correlation of IMF clock angle with other IMF clock angles: reference time following

Time separation (h)	Number of points	Correlation coefficient	Slope
0.75	16	0.982	0.923
1.25	16	0.911	0.834
1.75	16	0.778	0.758
2.25	16	0.784	0.801
2.75	16	0.820	0.905
3.25	15	0.811	0.969

Table 3. Correlation of IMF clock angle with sheath and wake clock angles: reference time preceding

Time separation (h)	Number of points	Correlation coefficient	Slope
0.75	12	0.977	1.15
1.25	12	0.979	1.29
1.75	10	0.918	1.42
2.25	9	0.876	1.29
2.75	11	0.926	1.64
3.25	12	0.868	1.56
3.75	11	0.710	1.09

The tail clock angle correlation

The sectors in the center of the tail are sectors 12 and 13 whose mid point occurs 2.25 h after sector 8 or 2.25 h before sector 1 (in the preceding orbit). Figure 4 shows these two correlations, 0.87 and 0.94. The former correlation is very close to the average corresponding IMF correlations and the latter more but each are within one standard deviation of the mean correlation of IMF data with itself. If there were a planetary contribution, uncorrelated with the IMF, then the correlation coefficient should have dropped, not increased. However, if the uncorrelated variance seen in the IMF were due to spacecraft noise, then we might expect a smaller influence of this noise in the tail because the ambient field in the tail is larger, hence minimizing the effect of spacecraft sources. In any event, the coefficients in question are all within one standard deviation of the mean. Tables 3 and 4 give the correlations for all the sectors. We note that we have fewer pairs of points here than in Tables 1 and 2 because there were fewer data recorded in the center of the tail than in the solar wind.

Discussion and conclusions

The direction of the field in the center of the Martian tail is just as correlated with the direction of the IMF immediately outside the bow shock as the magnetic field in the solar wind is correlated with itself at similar lags. It

Table 4. Correlation of IMF clock angle with sheath and wake clock angles: reference time following

Time separation (h)	Number of points	Correlation coefficient	Slope
0.75	24	0.953	1.04
1.25	19	0.957	1.19
1.75	11	0.956	1.40
2.25	10	0.942	1.44
2.75	11	0.825	1.77
3.25	12	0.731	0.965
3.75	13	0.873	1.80

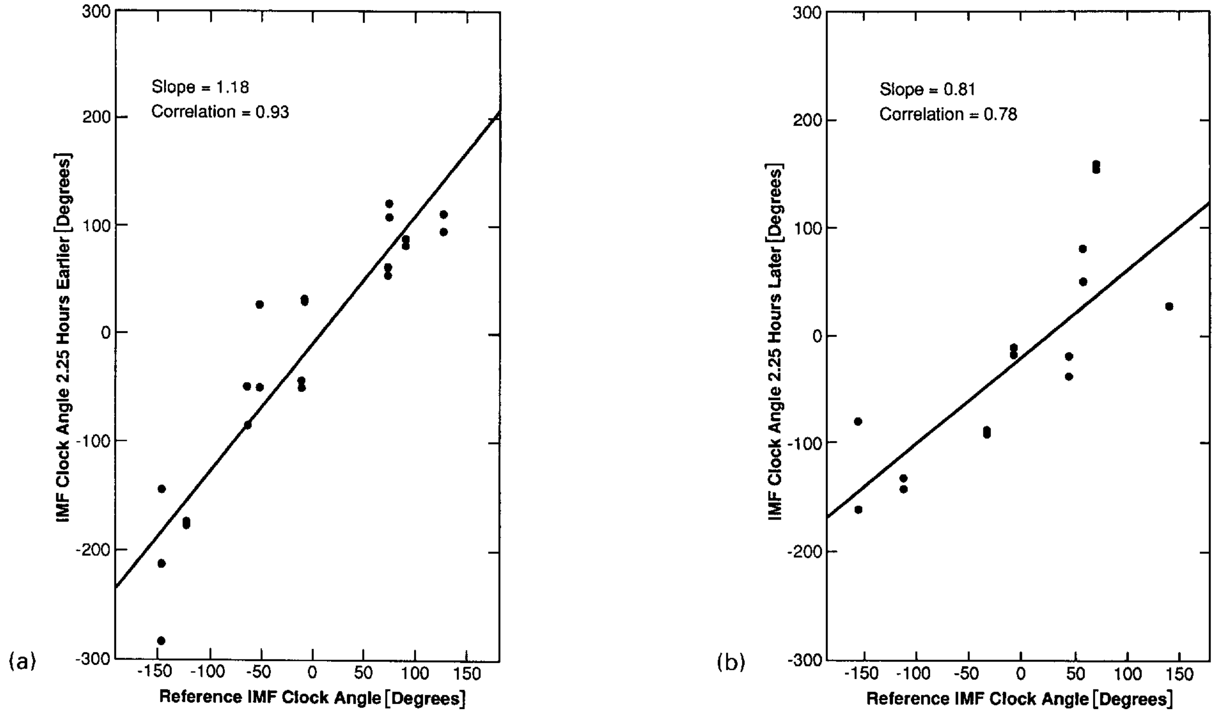

Fig. 3. IMF clock angle compared with earlier and later IMF clock angles. Clock angle is defined as the angle around the direction from the sun. Zero degrees is northward; 90° points opposite planetary motion. (a) Correlation with earlier times. (b) Correlation with later times

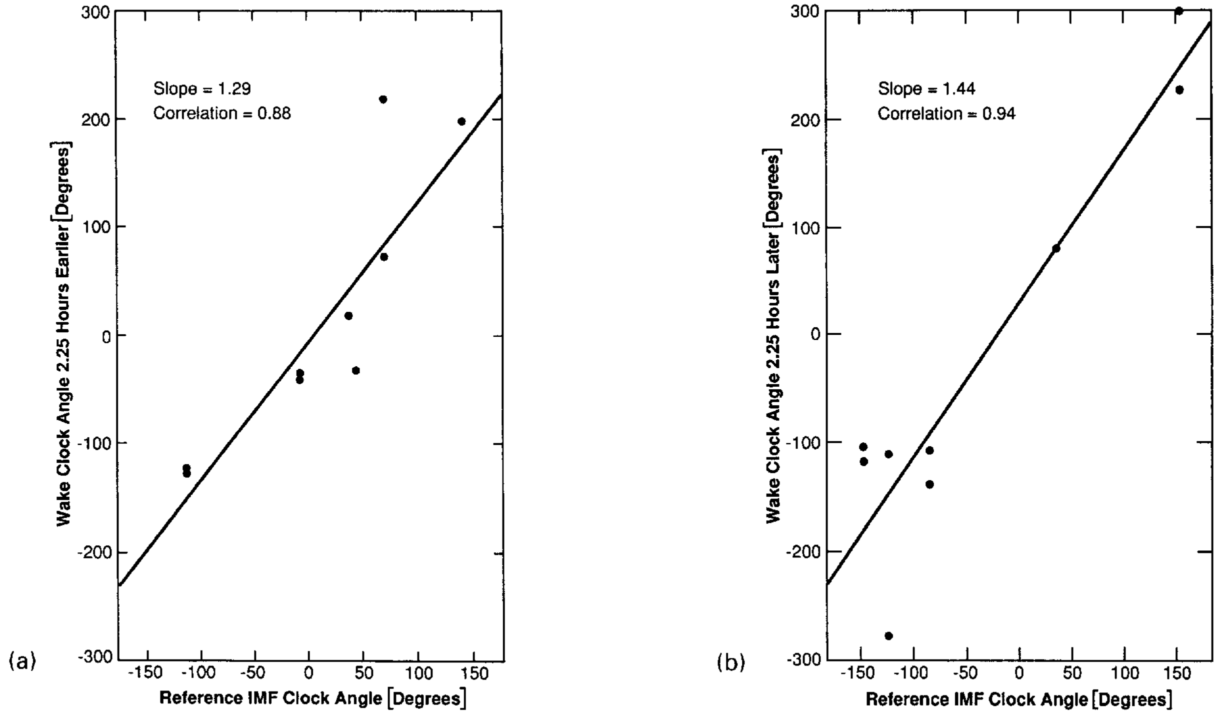

Fig. 4. Wake clock angle (sectors 12 and 13) compared with earlier and later IMF clock angles. (a) Correlation with earlier times. (b) Correlation with later times

is clear that any intrinsic magnetic field of the planet is having little effect on the cross tail component of the tail magnetic field. If we took a model of the tail in which there was an intrinsic portion and an induced portion of the tail, in one of which we were located at any one time, the amount of uncorrelated variance in our study allows us to be in the intrinsic portion less than about 10% of the time. Thus the planetary field must contribute less than about 10% to the force balance with the solar wind. Since a moment of 1.4×10^{12} Tm^3 (Dolginov and Zhuzgov,

1991) is just barely sufficient to stand off the solar wind, and since pressure is proportional to the square of the magnetic field strength we might naively expect that the upper limit to the intrinsic magnetic field to be about 4×10^{11} Tm^3.

Alternatively, if one were to assume that the uncorrelated variance was due to an intrinsic component of about 10% of the induced field strength added to the tail field, then the strength of this component could only be about 0.6 nT since the average cross tail field at the *Phobos* spacecraft is about 6 nT (Yeroshenko *et al.*, 1990; Luhmann *et al.*, 1991). To use this to estimate what the intrinsic moment might be we argue from models of the Earth's magnetic field. In the Tsyganenko (1989) model of the Earth's magnetic field the field at an equivalent distance down tail is about one-sixtieth that at the nose. Peredo *et al.* (1993) have argued that this model predicts too small a cross tail field by a factor of perhaps 2. If so then the ratio of the cross tail field and the current sheet to the intrinsic field contribution to the magnetopause region field is about 12. Multiplying this by our Martian intrinsic contribution to the cross tail field we obtain a nose contribution of about 7 nT or a planetary moment of about 3×10^{11} Tm^3. These estimates of the upper limit to the intrinsic magnetic moment of course are quite uncertain. The only conclusion about which we can be certain is that any magnetic field intrinsic to the planet plays at most a minor role in the dynamics of the solar wind interaction with Mars.

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