Reprinted from

COSPAR COLLOQUIA VOLUME 4

PLASMA ENVIRONMENTS OF NON-MAGNETIC PLANETS

Edited by

T. I. GOMBOSI

PERGAMON PRESS

OXFORD · NEW YORK · SEOUL · TOKYO

1993

THE SOLAR WIND INTERACTION WITH MARS: PHOBOS-2 BOW SHOCK OBSERVATIONS ON 24 MARCH 1989

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ABSTRACT

On 24 March 1989 Phobos-2 observed a series of weak, quasi-perpendicular bow shock crossings in the subsolar region at X = 2.8 R_m which is nearly twice the mean shock distance. The solar wind Mach numbers and dynamic pressure determined by the TAUS and MAGMA instruments just upstream of these unusually distant bow shock encounters were M_s = 10, M_a = 1.8, and 1 x 10^{-9} dynes/cm^2. These Alfvenic Mach number and dynamic pressure values are lower than the expected means at 1.5 AU by factors of approximately 5 and 10, respectively. A Rankine-Hugoniot analysis of the bow shock on this occasion indicated close agreement between the observed magnetic field jump conditions and those predicted for a fast mode shock standing in the solar wind. Application of gasdynamic modeling to this unusual event indicates that the width of the magnetosheath increases significantly in response to low Mach number conditions. However, the March 24th Phobos-2 events are so distant from the planet that they also require that the subsolar obstacle be at the unusually high altitude of 2000 km in order to reproduce the observed bow shock encounters. If the gasdynamic model calculations are accurate in this low M_a regime, then a magnetopause formed by the interaction of a 1 x 10^{22} G-cm^3 Mars dipole magnetic field with a 1 x 10^{-9} dynes/cm^2 solar wind dynamic pressure is suggested as the most probable mechanism for producing such a high altitude obstacle.

INTRODUCTION

Previous investigations of planetary bow shocks have established that their position, shape and jump conditions are functions of the upstream flow parameters and the nature of the solar wind interaction producing them /1,2/. In the case of Mars, the exact nature of its solar wind interaction has yet to be determined due to a lack of low altitude in situ measurements /3,4/.

The Phobos-2 bow shock encounters on 24 March 1989 considered in this study are important in these regards because they occurred at unusually large distances from the planet. Previous observations of very distant bow shock encounters at Mars, for example, have been cited as evidence for a small, order 10^{22} G-cm^3 intrinsic magnetic field /5/. However, the earlier shock measurements were generally quite limited in scope and accuracy /e.g., 6/. Toward this end, we analyze in some detail the bow shock measurements returned by the modern instruments on Phobos-2. The implications of the results for the nature of the solar wind interaction with Mars and low M_a flow about planets are discussed.

AVERAGE AND UNUSUAL BOW SHOCK LOCATIONS

The location of the Martian bow shock has now been well studied by the Mariner-IV, Mars-2, Mars-3, Mars-5 and Phobos-2 missions. Figure 1 presents a compilation of bow shock crossings from these

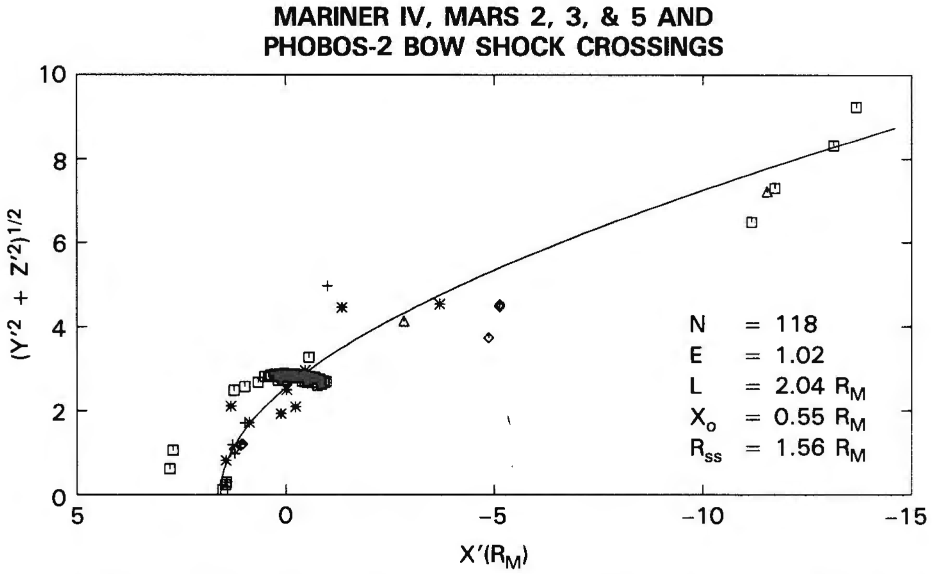

Figure 1. Bow shock crossings recorded by the Mariner IV (triangles), Mars 2 (plus signs), Mars 3 (stars), Mars 5 (diamonds) and Phobos-2 (boxes) missions along with a best fit shock surface /7/.

missions along with a second order model surface with a subsolar distance of 1.56 R_m /7/. Studies of the bow shock by the Phobos 2 investigators /8, 9, 10/ have produced good agreement with an average subsolar shock distance from the center of the Mars of about 1.5 R_m. However, a pair of unusually distant bow shocks encounters in the subsolar region are apparent in Figure 1. These shock encounters took place on 24 March 1989 while Phobos-2 was in its 2.8 R_m circular orbit phase.

Phobos-2 measurements of magnetic field intensity on 24 March 1989 are displayed in Figure 2. The interval begins with the spacecraft in the magnetosheath near the dawn terminator. A series of bow shock crossings at somewhat smaller Sun-Mars-spacecraft (SMS) angles than usual, marked with vertical dashed lines, were observed as the spacecraft moved outward into the upstream solar wind. Under normal conditions, no additional bow shock crossings would be observed until the spacecraft reached the dusk terminator about 4 hours later. This orbit appears unique, however, in that a set of clear bow shock encounters take place as Phobos 2 approached the Sun-Mars line. Although somewhat weaker than the bow shock observed at the flanks, these distant shock crossings are very distinct with little upstream wave activity or overshoots in the magnetic field data. The observations strongly suggest that the Martian bow shock moved outward from its typical subsolar location at 1.5 R_m to near or just beyond the 2.8 R_m circular orbit of Phobos-2 for an interval of about an hour.

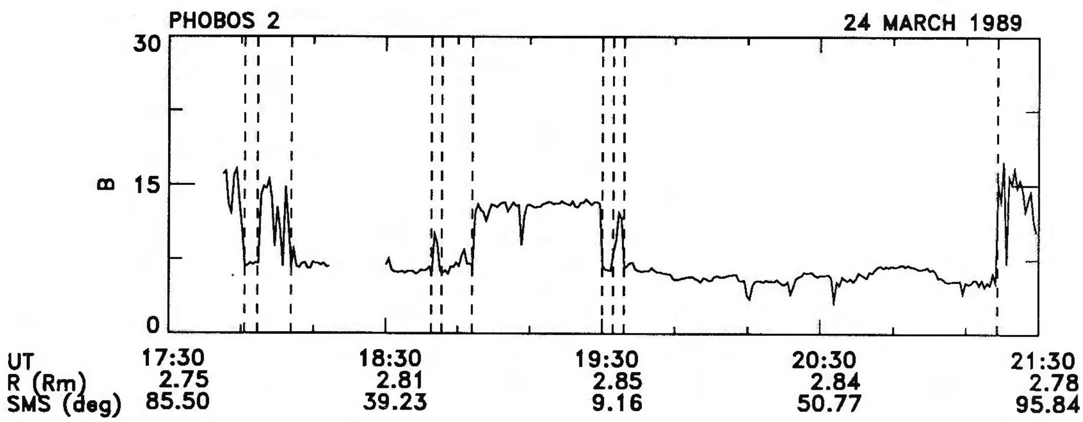

Figure 2. Phobos-2 measurements of magnetic field strength are displayed. The sample rate of the MAGMA instrument was 45 sec during this interval. The location of the spacecraft is given in terms of radial distance from the center of the planet (R) and the Sun-Mars-spacecraft (SMS) angle.

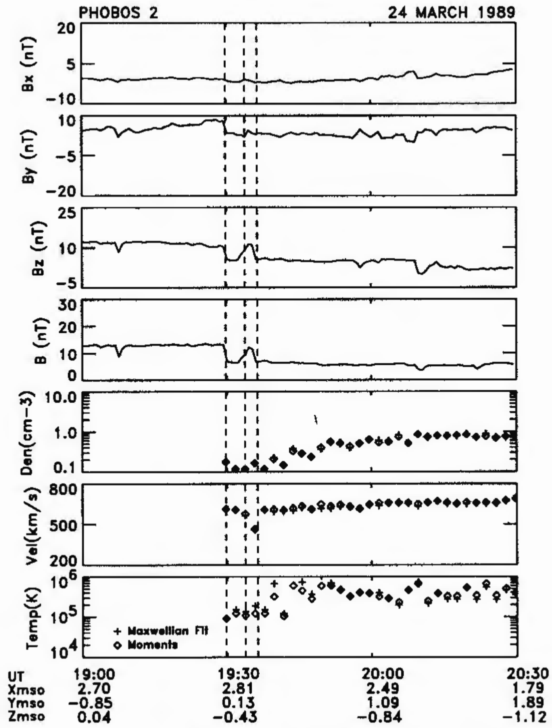

Figure 3. Phobos-2 MAGMA and TAUS measurements of the magnetic field and plasma parameters during distant bow shock encounters on March 24th are displayed above.

PLASMA AND MAGNETIC FIELD MEASUREMENTS

The only other relevant measurements taken during this interval are those from the TAUS plasma analyzer. They are available beginning just in front of the shock after 19:30 UT with ion distributions being returned at a temporal resolution of approximately 2 min. A summary of the Phobos-2 plasma and magnetic field measurements for the March 24th distant bow shock crossings are displayed in Figure 3. The solar wind density was extremely low near the time of the shock crossing, 0.1 - 0.2 cm^{-3}, and was observed to increase to about 1 cm^{-3} half an hour later. The solar wind speed also increased from about 600 km/s at the shock to 700 km/s an hour later. The ion temperature values have a large scatter and are not very reliable in the vicinity of the bow shock where the count rates were low. The proton temperature a half an hour after the shock crossing was 3 x 10^5 ^oK. The corresponding sonic Mach number just upstream of the bow shock was slightly elevated at a value of 10. The Alfven Mach number just upstream of these distant bow shock crossings, however, was extremely low with a value of only 1.8. This is approximately a factor of 5 below the average for this distance from the Sun. The corresponding solar wind dynamic pressure was also very low at 1 x 10^{-9} dynes-cm^{-2} or nearly an order of magnitude lower than the average expected at 1.5 AU. Taken together, these measurements suggest that Mars encountered a short duration interval of fast, hot, but very low density solar wind.

BOW SHOCK JUMP CONDITIONS

The MAGMA and TAUS measurements displayed above have been used to analyze the distant Phobos 2 shock encounters. Normal vectors to the main outbound bow shock ramp at approximately 19:30 UT (i.e., R = 2.8 R_m, SMS = 8^o) have been determined using a model shock surface /7/ and magnetic coplanarity /11/. Both methods yielded normals essentially parallel to the Sun-Mars axis as expected for crossings near the nose of the Martian bow shock. The angle between the shock normal and the upstream IMF, θ_{BN}, was approximately 70^o consistent with the quasi-perpendicular appearance of the shock. The total intensity of the magnetic field behind the shock was predicted to be 12.5 nT on the basis of the Rankine-Hugoniot equations /12/ and the Mach numbers just upstream of the last of the distant shock encounters. This prediction is in good agreement with the measured downstream field strength of 13.3 nT. These findings are significant because they 1) confirm that the discontinuities in the magnetic field in Figure 2 are indeed fast mode bow shocks, 2) demonstrate that calculated sonic and Alfvenic Mach numbers are appropriate for modeling of solar wind flow about Mars on this occasion, and 3) indicate that the TAUS and MAGMA measurements are internally self-consistent.

BOW SHOCK POSITION UNDER LOW M_a AND LOW P_{sw} CONDITIONS

The most commonly used method of calculating solar flow patterns about the planets is the gasdynamic model of Spreiter and co-workers /e.g., 1/. While the ability of this approach to accurately model bow shock shape and location and magnetosheath conditions for typical solar wind Mach numbers has been well demonstrated /2/, little attention has been given to low, trans-super-magnetosonic conditions such as those encountered by Phobos-2 on March 24th. Since the gasdynamic equations represent an approximation to the more general MHD equations in which the Alfven Mach number is set equal to infinity (i.e., the magnetic terms are neglected), these models are expected to gradually lose validity as M_a approaches unity.

While a separate modeling study is planned to compare the March 24th observations with the output of a full MHD simulation /e.g., 13/, it is instructive none-the-less to examine the predictions of gasdynamic theory for this unusual event. For this purpose the gasdynamic model of Spreiter and Stahara /1/ has been run for an upstream magnetosonic Mach number of 1.8, an adiabatic exponent of 2 and a magnetopause shaped obstacle with a subsolar radius of 1.15 R_m. The subsolar bow shock radius predicted by the gasdynamic model is 2.0 R_m as compared with the 2.8 R_m indicated by the Phobos-2 observations at 19:30 UT on March 24th. The corresponding ratio of subsolar magnetosheath width to obstacle radius of 0.7 is significantly greater than the average value of about 0.4 expected for typical solar wind conditions /2/. Still, the predicted shock radius is only 70% of that observed by Phobos-2 for this event. If the gasdynamic model is accurately representing the low M_a flow pattern, then the subsolar obstacle altitude necessary to produce these distant shocks is 2000 km as compared with a typical value of only 500 km /2/.

SUMMARY

This study has analyzed in some detail the unusually distant Mars bow shock crossings reported earlier /7/ on the basis of Phobos-2 magnetic field observations. A Rankine-Hugoniot analysis using both the plasma and magnetic field measurements has confirmed that these discontinuities in the magnetic field are indeed consistent with a fast mode bow shock standing in the solar wind. This result is important because Phobos-2 was less than 1000 km upstream of the moon Phobos at the time of these bow shock measurements and the possibility existed that these discontinuities in the magnetic field might not be shocks, but some other type of current layer associated with a cometary-type interaction between the solar wind and neutral gas or dust originating from Phobos /14, 15/. While such an interaction may exist, it appears very doubtful that it could create the non-turbulent, thin, M_{ms} = 1.8 bow shock observed by Phobos-2.

Further examination of the MAGMA and TAUS measurements has shown that these distant shock encounters took place during an interval of low Alfvenic Mach number and low dynamic pressure solar wind. Although further comparisons with MHD flow calculations are planned, we have modeled this low M_a interval using gasdynamics /1/. If the gasdynamic modeling is accurate for these low M_a conditions, then the results indicate that the subsolar obstacle altitude is approximately 2000 km at the time of the Phobos-2 distant bow shock encounters. Such a large inflation of the dayside obstacle in response to very low solar wind pressure appears to be possible only if Mars possesses a small, but dynamically significant intrinsic magnetic field. For the observed upstream dynamic pressure of 1 x 10^{-9} dynes/cm^2, the corresponding dipole Martian magnetic moment is approximately 1 x 10^{22} G-cm^3. Similar moments have been suggested previously based upon Mars 2 and 3 observations during intervals of low solar wind dynamic pressure /see 4,5/.

ACKNOWLEDGMENTS

One of the authors (JAS) acknowledges useful discussions with T. Breus, E. Dubinin and Ye. Yeroshenko. Assistance with computational aspects of this work at GSFC was provided by E. Mazur.

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