IN SITU MEASUREMENTS OF THE PHOBOS MAGNETIC FIELD DURING THE PHOBOS-2 MISSION

V.G. Mordovskaya and V.N. Oraevsky

1Institute of Terrestrial Magnetism, Ionosphere, and Radiowave Propagation (IZMIRAN), Troitsk, Moscow region, 142190 Russia, mail: valen@izmiran.rssi.ru

ABSTRACT

In this communication, we examine in situ observations of the magnetic field in the vicinity of Phobos on the Phobos-2 mission and give some analysis of the data during a unique experiment “Celestial Mechanics,” which leads to the support of evidence of the Phobos magnetic field. In particular, it is suggested that the peculiarity of the solar wind interaction with Phobos and rotating direction of the magnetic field obtained on the circular orbits around Mars are the evidence for the existence of an intrinsic planetary field of Phobos.

INTRODUCTION

The principal objective of the Phobos mission was to investigate Phobos, its substance, and the solar wind interaction with Phobos. With this aim the project had an experiment “Celestial Mechanics” (Kolyuka et al., 1991). Unfortunately, the spacecrafts were lost. However, Phobos 2 spacecraft was lost when it was in the vicinity of Phobos. Therefore, some part of the experiment was carried out in the Phobos vicinity but the data obtained were not studied, moreover, most of the data are unpublished. In the present paper, we study the measurements of the magnetic field in the vicinity of Phobos. The disturbances was observed on the circular orbits near Phobos at distances of 180–250 km from its center when Phobos was in a solar wind. During these events, a sharp rise in the regular part of the magnetic field was observed. Analyzing the interaction of the obstacle with the solar wind plasma, Mordovskaya et al. (2001) came to the conclusion, that Phobos has its own magnetic field. Using the equation of pressure balance for the solar wind and the magnetic field of Phobos at the magnetopause, in the dipole approximation the estimate of the magnetic moment of Phobos \( M' \) was obtained, \( M' \approx 10^{15} \text{ A-m}^2 \).

According to the measurements performed in the solar wind, the projection of the Phobos magnetic moment onto the Mars ecliptic plane points in the direction of the trailing side of Phobos, i.e., to the opposite direction of its motion along the orbit around Mars. Phobos represents itself as a magnetized body. Phobos rotates around Mars, turning it by the same side. It always presents the same face to a hypothetical observer on Mars. This peculiarity of the rotation of the magnetized Phobos results in the magnetic field signatures, which, specifically the direction, are phase locked with Phobos rotation rate. The direction of the magnetic field observed should correspond to the direction given by the rotation. To resolve this issue completely, in situ measurements in the Phobos vicinity are required. Unambiguous evidence of the Phobos magnetic field will only be obtained from the direct observations. This problem will be explored in the present paper.

THE NAVIGATION ASPECTS OF THE PHOBOS MISSION

The Phobos space project had a very complicated scheme of flight relative to Phobos and the organization of a unique experiment named “Celestial Mechanics.” A description of the spacecraft flight profile is given by Kolyuka et al. (1991). The spacecraft was transferred onto such an orbit around Mars on March 22, 1989 and it remained permanently within a vicinity of Phobos until March 27. The semi-major axis and plane of the spacecraft orbit coincided with those of Phobos and there is a small difference in the orbital eccentricities.
Then, the motion of the spacecraft relative to Phobos takes the form of ellipses around Phobos, hence, the name quasi-synchronous orbit.

![Image of Phobos orbit](image-url)

**Fig. 1.** The sketch of the measurements during the “Celestial Mechanics” experiment on March 22–26, 1989 and a schematic model of the Phobos magnetic field with its rotation around Mars are presented in the projection onto the Mars ecliptic plane \(XOY\).

THE MAGNETIC FIELD MEASUREMENTS NEAR PHOBOS ON THE QUASI-SYNCHRONOUS ORBIT

Onboard the spacecraft, the two three-axes fluxgate sensors of the FGMM and MAGMA instruments carried out the magnetic field measurements. A detailed description of the magnetometers and the first results can be found in (Auster et al. (1990), Aydogar et al. (1989), Möhlmann et al. (1990), Riedler et al. (1989)). We will examine 45-s resolution magnetic field measurements on circular orbits from March 22 until March 26, 1989 to present the experimental evidences of the Phobos magnetic field.

The Solar Wind Interaction with Phobos

The main argument of the evidence of an intrinsic magnetic field of Phobos is peculiarities of the solar wind interaction with Phobos. First, the effective scale of the Phobos obstacle for the solar wind was observed. Phobos, due to its intrinsic magnetic field forms a large obstacle, which makes the solar wind be shielded from the surface, leading a region of about 170 km from dayside surface (the sizes of Phobos are \(18 \times 21 \times 27\) km). Second, the subsolar stand-off distance of the deflection depends on the solar wind parameters. The morphology of magnetic field signatures due to the interaction of the Phobos with the solar wind plasma during the time interval of March 22–26, 1989 was studied by Mordovskaya et al. (2002). Here we consider the evidence of the existence of the Phobos magnetic field using data obtained from 18:00 to 20:00 on 24 March, 1989 when we can see the pure planetary magnetic field. The magnetic field signature is displayed during this encounter with a planetary magnetic field of Phobos in Fig. 2a. In the middle panel of the Fig. 2 the plasma parameters are given. During this period when the spacecraft approached to Phobos at a distance of 170–180 km from its dayside the magnetic field signature has a sharp rise with a characteristic “shock-like” behavior, which is marked by the arrows. The velocity \(V\) and density \(n\) obtained demonstrate a lack of the solar wind plasma. This fact gives a strong argument in favour of the existence of the Phobos magnetic field and its magnetosphere.
Fig. 2. a) The plot of the magnitude of the observed magnetic field (B) versus the time. b) The plot of the velocity V and the density n of the plasma; c) The amplitudes, the direction of the vectors of the magnetic field Bx/By and the satellite (S/C) trajectory are given in the Phobos centric coordinate system for 18:00–20:00 on 24 March, 1989.

The value of the magnetic moment $M'$, which has been calculated with the use of the equation of pressure balance for the solar wind and dipole field of the planet on the magnetopause, is $M' \approx 10^{15}$ A·m².

The Phobos-2 encounter with a planetary magnetic field of Phobos described by help of magnetic field lines is shown in Fig. 2c). The amplitudes, the direction of vectors of the magnetic field Bx/By, and the satellite trajectory (S/C) are given in the Phobos centric coordinate system. The field observed along the trajectory at 45-s intervals is represented by a scaled vector projection of B originating from the position of the spacecraft at the corresponding times. Analyzing the magnetic field direction near Phobos we can determine with a great precision the boundary between completely open field lines of the solar wind and those with at least one end in Phobos. A dramatic change in field line topology from 18:43 to 19:41 on March 24, 1989 is an evidence indicating a transition from field lines with no connection to Phobos to field lines with at least one end in Phobos.

The Corotating Part in the Measured Magnetic Fields

Other evidence for an intrinsic magnetic field is the existence of the corotating part in the measured magnetic fields near Phobos. To demonstrate the rotation of the direction of the magnetic fields we will employ the method describing the magnetic events with help of the magnetic force lines.

According to the peculiarity of the rotation of Phobos around Mars, the magnetic moment is directed in opposite sides in the Mars wake and solar wind. Figure 1 depicts the rotation of the magnetized Phobos around Mars in the projection onto the Mars ecliptic plane. Comparing the data, which were obtained and predicted from the peculiarity of the rotation of Phobos around Mars, it is necessary to remind the spacecraft was located permanently in the vicinity of Phobos at this time and the magnetic field data obtained should indicate the rotation of the direction of the Phobos magnetic field. In addition, one should take into consideration that, depending on mutual position of the S/C and Phobos, there exist different situations like S2, S4, S6, and S8. The magnetometers acquired the vector measurements of the Phobos magnetic field beginning at various part of the Phobos vicinity. There exist the following four situations: the S/C moves from Phobos (S2); Phobos approaches the S/C (S4); Phobos moves from the S/C (S6); the S/C approaches Phobos (S8).

Three typical examples of the data measured continuously are represented in Fig. 3. The field observed along the trajectory at 45-s intervals is represented by a scaled vector projection of B originating from the position of the spacecraft at such times. In this view, the Mars shadow is marked by the dark line. The spacecraft trajectory is marked by encounter times of year 1989, hour:minute day.month UT. The corresponding locations of Phobos at these moments can be found in the scheme shown in Fig. 1.
Fig. 3. Top parts show the orientation and the magnitude of the magnetic field projection onto the Mars ecliptic plane. The magnitudes of the observed magnetic field versus the time are shown in the bottom parts. The expected directions of the Phobos magnetic field are depicted by the schematic sketch of Phobos magnetosphere. a) The data from 20:00 on March 22, 1989 to 04:00 on March 23, 1989. b) The data from 17:45 to 22:45 on March 24, 1989. c) The data from 17:00 on March 25, 1989 to 00:45 on March 26, 1989.

The magnitude of the observed magnetic field versus the time is represented in the bottom panels of Fig. 3. The velocity $V_s$ and density $n_s$ of the solar wind are also given (the units for velocity and density are km/s and cm$^{-3}$, respectively). To compare the model data with the measurements, we have chosen the appropriate orientation of the Phobos magnetic moment and depicted the schematic models of Phobos magnetosphere in Fig. 3. The corresponding positions of the spacecraft are indicated by the dotted lines. The big grey arrows going from the schemes indicate the corresponding place of the measurements. It is easily seen that the directions of the model magnetic field coincide with that of the measured one. When comparing the fields, one should take into consideration that there exist the differences between the measurements of the magnetic field of the Phobos vicinity in the Mars wake and that in the solar wind.
Figure 3b shows a unique case, when the dynamic pressure of the solar wind seems dropped and the manifestation of the Phobos magnetic field can be detected over the entire orbit. At least, the rotation of the magnetic field direction is clearly observed. This fact gives the additional evidence that the magnetic field observed during 18:43–19:41 on March 24, 1989 can be associated with an intrinsic magnetic field of Phobos.

**About the Measurements in the Martian Wake**

It is more easy to distinguish the Phobos magnetic field signature in the Martian wake rather than in the solar wind. The Martian wake is the most appropriate region for testing the presence of the Phobos magnetic field and the most disputable one. The rotation of the field direction in agreement with the manifestation of the Phobos magnetic field in the Martian wake is demonstrated in Fig. 3.

To compare the magnetic signature obtained near corotating region of Phobos (Fig. 3) with one obtained in the “pure” wake of Mars, in Fig. 4 we present the magnetic field measurements, which were acquired by the spacecraft when its orbit did not coincide with that of Phobos.

The orientation of the field in the Martian wake is governed by the direction of the solar wind magnetic field (Russell et al., 1995). Figure 4a shows a typical example of the magnetic signatures when the magnetic field of the solar wind points away from the Sun. The data shown in Fig. 3 are entirely different from that in Fig. 4a. Another example illustrating the magnetic signatures, when the magnetic field of the solar wind points toward the Sun, is shown in Fig. 4b. The change in polarity of magnetic field components in the Martian wake can be similar in Fig. 3 and 4b. In Figure 3, however, in the vicinity of terminator the magnetic field features, which are caused by the corotating region near Phobos, and the absence of filamentation of the magnetic field are typical manifestations of the Phobos magnetic field in the Mars wake.

Under the favorable conditions depending on the relative position of Phobos and spacecraft, the manifestation of the Phobos magnetic field was observed and the expected directions of the magnetic field is always similar to those depicted in Fig. 3 when the spacecraft was in the vicinity of Phobos within the Mars wake.

![Fig. 4. The same as in Fig. 3, but a) - the data from 00:00 to 06:45 on March 17, 1989; b) - the data from 22:00 on March 8 to 05:45 on March 9, 1989.](image-url)
Conclusion

The trajectory of Phobos-2 provided the collection of data in the regions that are relevant for the investigation of Phobos vicinity and have not been explored before. In this study we considered the evidences of the existence of Phobos magnetic field from the Phobos-2 data acquired on 22–24 March, 1989. We could directly probe regions to observe the pure planetary magnetic field of Phobos during the closest approaches of the spacecraft to the Phobos surface at the distance of 170–180 km.

Source with an equivalent magnetic moment \( \simeq 10^{15} \text{ A} \cdot \text{m}^2 \) within Phobos leads to the development of an obstacle for solar wind flow around Phobos with the subsolar stand-off distance of the deflection about 16–17 Phobos radii. In the plane coinciding with the projection onto the ecliptic plane of Mars the magnetic moment of Phobos points to the trailing side. In the projection onto the Z-axis of the coordinate system used, the magnetic moment of Phobos points out in the negative direction of Z-axis. In the present paper, the direction of the Phobos magnetic moment is determined at a qualitative level. To obtain its direction more precisely, special care should be taken when calculating the orbits. The magnetization of the Phobos substance is 0.15 CGS. It should be noted that there are some meteorites with a magnetization of 3 CGS (Gus’kova, 1972).

Our results confirm the existence of a corotating part of the measured magnetic fields. Such a rotation of the magnetic field direction near Phobos gives an additional evidence that an intrinsic magnetic field of Phobos does exist.

In conclusion, it is necessary to point out that solving the problems mentioned in this paper, in the context of the “Celestial Mechanics” experiment, is only at the very beginning.

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