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Magnetic field overshoots in the Martian bow shock

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Abstract. In 1989 the Phobos 2 spacecraft provided sufficient plasma and magnetic field data for statistical investigations of the Martian bow shock structure. Significant magnetic field overshoots were observed in more than 70% of the bow shock crossings detected in the terminator region. According to our studies based on the available low-resolution data set, the features of the Martian overshoots are very similar to those observed in the terrestrial and Venusian bow shock: the magnitude increases with increasing Mach number and the thickness scales as the proton gyroradius computed from the upstream solar wind speed and magnetic field strength. Our investigations seem to support the idea of *Mellott and Livesey* [1987] suggesting that overshoots may develop not only in supercritical shocks but also when the Mach number is below or around the critical value.

Introduction

Spacecraft observations proved that collisionless bow shock waves exist in front of the planets of the solar system. Since interplanetary magnetic field, solar wind plasma density, and proton and electron temperature gradually decrease with increasing heliocentric distances [*Slavin and Holzer*, 1981], the observations performed aboard the different planetary space probes provide a wide range of plasma parameters for studying the structure of planetary bow shocks.

First, *Heppner et al.* [1967] noted that an unusual "bump" could often be observed in the magnetic field profiles just downstream of the terrestrial bow shock. On the basis of the initial ISEE magnetometer results, *Russell and Greenstadt* [1979] suggested that the overshoot region must play an important role in the physics of collisionless shocks. According to their investigations, the magnetic field structure in the transition layer of a quasi-perpendicular high Mach number bow shock typically exhibits an upstream foot, a sharp shock ramp, and a cyclic overshooting and undershooting of the final downstream average value. The thickness scales of the few selected shocks were of the order of the upstream proton inertial length c/ω_{pi1} (where c is the light velocity and ω_{pi1} is the upstream ion plasma frequency) or a small multiple of c/ω_{pi1}.

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Later, magnetic field overshoots were also discovered in the bow shocks of Venus, Jupiter, and Saturn by *Russell et al.* [1982]. When comparing the individual cases observed at the bow shocks of these planets and the Earth, they suggested that the magnitude of the overshoots is increasing with increasing plasma β and increasing magnetosonic Mach number. Observations at the outer planets provided very large overshoot magnitudes as a consequence of the high Mach numbers.

Numerical hybrid simulations (taking particle ions and fluid electrons) of *Leroy et al.* [1981, 1982] confirmed the suggestion of *Russell et al.* [1982] that the structure of a perpendicular high Mach number shock is associated with ion reflection. They found that gyrating ions play a crucial role in building up and maintaining overshoots in the potential, density, and magnetic field. Both the number of reflected ions and the field overshoot are increasing with increasing Alfvenic Mach number for $M_A > 3$. The thickness of the magnetic field overshoot (including foot, ramp, and the first overshoot downstream of the shock) scales as $\sim 3V_1/\omega_{ci2}$ where V_1 is the upstream bulk speed and ω_{ci2} is the downstream gyrofrequency. According to the results of the model calculations of *Leroy et al.* [1981, 1982], ion reflection was absent in the low Alfvenic Mach number regime, and the perpendicular shocks were characterized by a smooth transition layer scaling with the resistive length c/ω_{pe}, where ω_{pe} is the upstream electron plasma frequency.

These numerical simulation results were in good agreement with theory. The change in the shock dissipation mechanism and in the shock structure can be expected at the first critical Mach number M_c for which the downstream plasma flow speed V_2 equals the downstream sound speed. While "classical" fluid theory satisfactorily describes subcritical shocks [e.g., *Tidman and Krall*, 1971], the jump in the field parameters cannot be determined by the Rankine-Hugoniot conditions at supercritical shocks. For typical solar wind parameters, M_c is between about 1 and 2 [*Edmiston* *and Kennel,* 1984], which is lower than the theoretical value of $M_c = 2.64$ found by *Marshall* [1955] for perpendicular shocks.

The results of the first statistical investigation of magnetic field overshoots were in good agreement with the above described numerical simulations and theoretical expectations. *Livesey et al.* [1982] studied 110 quasi-perpendicular bow shock crossings observed aboard the ISEE 1 and ISEE 2 spacecraft and found that the amplitude of the overshoot increased with M_f/M_c (where M_f is the fast Mach number) and, to a lesser degree, with solar wind ion β. The thickness of the overshoots was found to be a few ion gyroradii ($r_L = V_1/\omega_{ci1}$) computed from the upstream solar wind speed and magnetic field strength. Only supercritical shocks exhibited an overshoot.

On the basis of a statistical study of Pioneer Venus Orbiter (PVO) data, *Tatrallyay et al.* [1984b] reported that the characteristic features of magnetic field overshoots in the Venusian bow shock are very similar to those of the terrestrial shock. However, the increase of the overshoot magnitude was moderate with increasing Mach number relative to the results of *Livesey et al.* [1982], since no really large overshoots were found in the analyzed low-resolution PVO data set.

In 1989, Phobos 2 was the first spacecraft which provided sufficient magnetic field and plasma data for performing a statistical study of the structure of the Martian bow shock. In this paper, we will investigate the characteristics of the transition layer at the Martian bow shock in the terminator region. Our results on the behavior of magnetic field overshoots will be compared to earlier investigations including observations of other planets and theoretical works. Also, the three-dimensional hybrid simulations of *Brecht and Ferrante* [1991] and *Brecht et al.* [1993], which suggested that the Martian bow shock is different from other planetary bow shocks, will be discussed.

Observations

On January 29, 1989, Phobos 2 reached Mars, and after completing four highly elliptical orbits around the planet, it was transferred to a circular orbit with a period of 8 hours and a radius of 2.86 R_M (measured in Mars radii), quasi-syncronous with the orbit of the Phobos moon [*Zakharov,* 1992]. During more than 100 orbits, Phobos 2 collected more plasma and magnetic field data around Mars than all earlier space probes together.

For our investigations, we used low-resolution magnetic field data measured by the triaxial fluxgate magnetometer of the MAGMA experiment during the circular orbits. Since most of the available data were collected with a resolution of 45 s [*Riedler et al.,* 1989], measurements of higher resolution were averaged by 45 s in order to work with a uniform data set. The spacecraft often lost three-axis stabilization therefore despun magnetic field components had to be used in many cases.

Plasma parameters at the shock were determined from data measured by the ion spectrometer of the TAUS instrument. Upstream velocity V, density n, and temperature T_p of solar wind protons were basically those used by *Verigin et al.* [1993] when investigating the dependence of the Martian bow shock and magnetopause location on solar wind ram pressure. Since electron temperature was not measured by TAUS, the $T_e = 2T_p$ approximation was applied. Also, control calculations were performed by using a constant upstream electron temperature of $T_e = 120,000\ K$ for the whole period of time on the basis of Ulysses measurements around 1.5 AU [*Hoang et al.,* 1992; *Phillips et al.,* 1995].

In the circular orbits of Phobos 2, we found only 82 bow shock crossings when both magnetic field and plasma data were available. These crossings occurred in the terminator region, mostly in the solar zenith angle (SZA) range of 80°< SZA < 110°[*Gévai,* 1991]. The angle between the bow shock normal (determined from model calculations) and the direction of orbital motion of the spacecraft (approximately parallel to the solar wind direction in the terminator region) was around 40°–50°. In 56 cases, overshoots were reliably detected in the magnetic field profiles just downstream of the bow shock. In about 10 more bow shock crossings, indications of an overshoot were observed, but some of the necessary parameters could not be reliably determined. In several cases, the magnetic field was very disturbed at the time of the bow shock crossings as a result of interplanetary activity. There was no selection according to the angle between the upstream magnetic field and the shock normal Θ_{Bn}. Twelve bow shock crossings were found to be quasi-parallel (Θ_{Bn}<45°) out of the 56 cases when overshoots were identified at the shock.

Figure 1 shows three examples of magnetic field overshoots observed at the Martian bow shock during the Phobos 2 circular orbit phase. In order to illustrate the deviations between the measurements and theoretical downstream field values predicted by the fluid theory, Spreiter's magnetogasdynamic model [*Stahara et al.,* 1977; *Spreiter and Stahara,* 1980] was applied. The actually measured upstream field values were used for the simulation. The value of the sonic Mach number applied for the simulation was $M_s = 6$, while the corresponding measured Mach numbers (the magnetosonic Mach number $M_{ms}^{-2} = M_s^{-2} + M_A^{-2}$ corresponds to the sonic Mach number used in gasdynamic models [*Tatrallyay et al.,* 1984a]) were lower, $M_{ms} = 3.5$, 4.9, and 3.6 for March 5, 18, and 22, respectively. Since Spreiter's simple model did not provide the correct location of the bow shock for each individual case, the calculated location was adjusted to the measured location. As can be seen in Figure 1, the maximum field value B_M at the overshoot is well above the calculated value B_2 which corresponds approximately to the average downstream value.

In agreement with earlier investigations [*Livesey et al.,* 1982; *Tatrallyay et al.,* 1984b], we determined the magnitude of the overshoots as $A = (B_M - B_2)/B_2$. The thickness of the overshoot was taken as the distance (along the shock normal) between the beginning of the shock foot and the minimum of the first undershoot. The apparent overshoot thickness is larger by about ~40% since the spacecraft passed

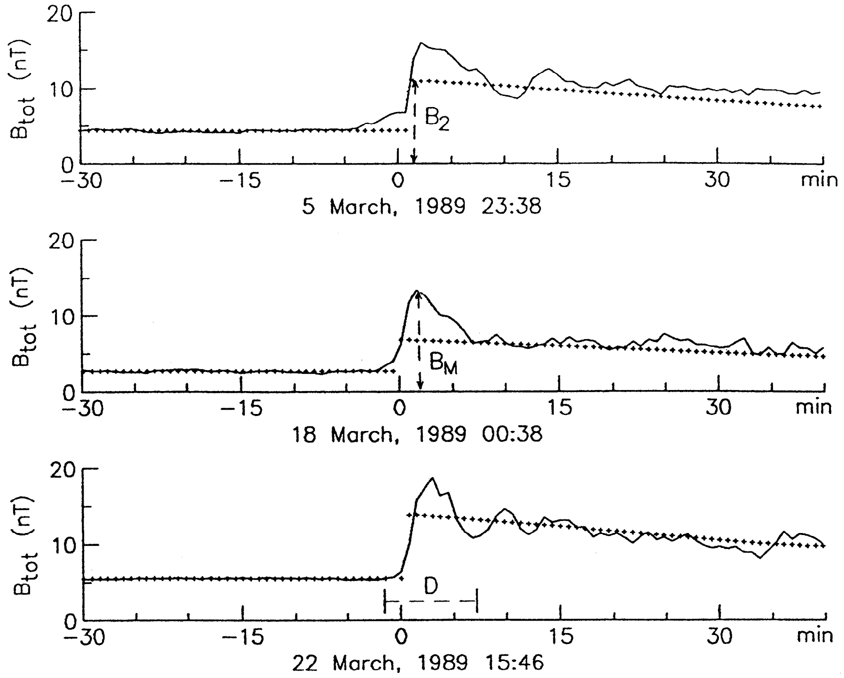

Figure 1. Magnetic field profiles along three circular orbits of Phobos 2 for 30 min before and after the bow shock crossing. Continuous line, measured total field; dotted line, simulated values using Spreiter's magnetogasdynamic model. B_M is the maximum field value at the overshoot, B_2 is the calculated downstream field at the shock, and D is the apparent thickness of the overshoot along the spacecraft trajectory.

through the shock at an angle of about 40°−50°. For illustration, the actual apparent thickness D is shown in Figure 1 for one of the exhibited bow shock crossing cases. Phobos 2 had no twin spacecraft therefore the changes in the location of the bow shock could not be controlled. When determining the thickness of the overshoot, we had to suppose that the bow shock was not moving relative to Mars while the spacecraft was passing through the overshoot. For weakly magnetized planets, like Venus and Mars, this is an acceptable simplification for such a short time when there is no sudden change in the interplanetary parameters. Double crossings indicating the displacement of the shock were likely observed only in a few cases in the whole data set when the interplanetary field was very disturbed and an overshoot could not be identified.

The relations between the overshoot magnitude and the different plasma parameters measured upstream of the shock were investigated. The local Mach numbers were determined as the ratio of the upstream solar wind speed (component perpendicular to the shock) to the velocity of the actual wave mode. According to our study, the best correlation was found with the ratio of the fast Mach number to the critical Mach number M_f/M_c. The fast Mach number is based on the speed of the fast-mode MHD wave [*Kennel et al.*, 1985]

$$M_f^{-2} = [M_{ms}^{-2} + \sqrt{(M_{ms}^{-2})^2 - (2cos\Theta_{Bn}/M_A M_s)^2}]/2.$$

$M_f = M_{ms}$ for perpendicular shocks, while $M_f > M_{ms}$ when $\theta_{Bn} < 90°$.

Figure 2 presents the relation between the overshoot amplitude and M_f/M_c when the electron temperature was approximated as $T_e = 2T_p$. Quasi-parallel shocks, shown by circles, seem to fit in with the general trend of the data determined for quasi-perpendicular shocks shown by triangles. For quasi-parallel shocks, error bars of both parameters are presented supposing that the error in the direction of the magnetic field calculated from the despun magnetic field components is less than ~10°. For quasi-perpendicular shocks, only the maximum and minimum values of the estimated errors are presented.

In Figure 3 two histograms illustrate the thickness of the Martian bow shock overshoots which were in most of the cases between 0.5 and 2.5 r_L (r_L denotes the proton gyroradius calculated from the upstream solar wind speed and magnetic field strength). In ion inertial length, the typical thickness was in the range of $2 < c/\omega_{pi} < 8$. As mentioned above, the apparent overshoot thicknesses observed along the Phobos 2 orbit are larger by ~40% than the values presented in Figure 3.

Discussion

The structure and location of the terrestrial bow shock were carefully examined on the basis of the large data set measured aboard the twin spacecraft ISEE 1 and ISEE 2 which provided some possibility to select temporal and spatial variations. The Pioneer Venus Orbiter was a single spacecraft mission, but it also provided a great amount of data during its lifetime of 14 years in order to study the Venusian bow shock. In comparison with these data sets, the amount of plasma data available for the investigation of the solar

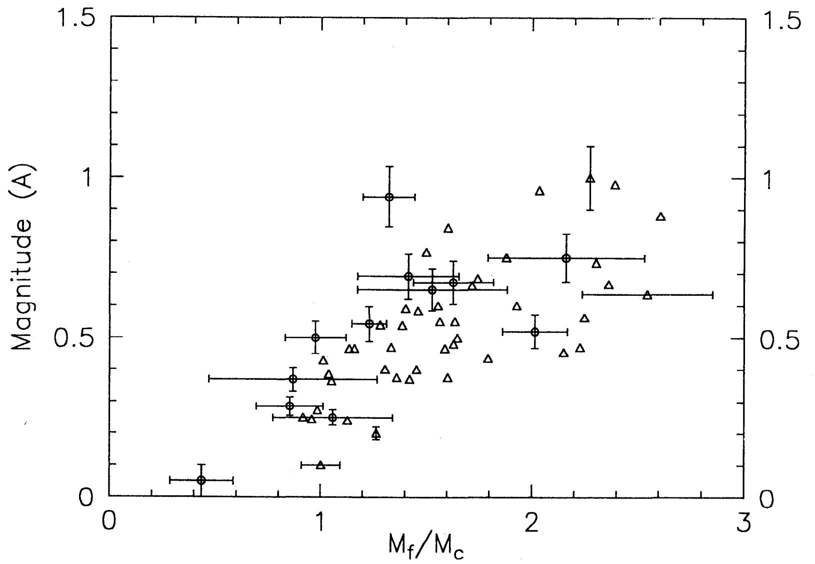

Figure 2. The overshoot magnitude versus the ratio of the fast Mach number to the critical Mach number when $T_e = 2T_p$ is taken for the electron temperature. Circles with both error bars mark quasi-parallel shocks; triangles with sample error bars show quasi-perpendicular shocks.

wind interaction with Mars is very limited. In spite of that, the average location of the Martian bow shock was separately determined from different observations: from the magnetic field [*Schwingenschuh et al.*, 1990; *Zhang et al.*, 1991], from plasma parameters [*Verigin et al.*, 1993], and from plasma wave data [*Trotignon et al.*, 1991, 1993] measured aboard Phobos 2 in a period of high solar activity. According to the applied different methods of optimization, the subsolar standoff distance was found to be 1.5–1.6 R_M, while the distance to the best fit shock profile was 2.5–2.7 R_M at the terminator. These values are somewhat larger than the Venusian ones during solar cycle maximum (1.35 R_V and 2.35 R_V, respectively [*Zhang et al.*, 1990]).

The aim of this paper is to compare the structure of the Martian bow shock with that of the other planets. As discussed earlier in this paper, the typical thickness of the transition layer of the Earth and Venus bow shocks (including foot, ramp, and overshoot) is around 1–3 r_L. At Earth, the proton gyroradius r_L is negligible compared to the bow shock size. At Venus, r_L is typically around 0.06 R_V [*Brecht et al.*, 1993], while the average thickness of the sheath can be estimated as $\sim$0.34 R_V at the nose and $\sim$1.34 R_V at the terminator [cf. *Kliore*, 1992; *Zhang et al.*, 1990]. At Mars, the typical proton gyroradius is much larger, and it exceeds the thickness of the magnetosheath in the subsolar region where $r_L \approx 0.4\ R_M$. In the Martian terminator region, the thickness of the magnetosheath is $\geq 1.2\ R_M$ [*Verigin et al.*, 1993] and r_L is smaller than at the nose of the bow shock.

In order to investigate the transition layer at the Martian bow shock and the thickness of the magnetosheath, *Brecht and Ferrante* [1991] developed a time-dependent three-dimensional hybrid model which permitted study of finite gyroradius effects in the solar wind interaction with Mars compared to the case of Venus. On the basis of their simplified model (the planet was taken as a conducting sphere, no ionosphere was included, and only the subsolar region was considered), solar wind interactions with Venus and Mars seemed to be substantially different from each other. While the interaction with Venus could be generally viewed as a "magnetized interaction", the Mars interaction was "very kinetic in nature", and no collisionless shock was obtained in the conventional sense. According to these model calculations, no overshoot region was found at low solar zenith angles (SZA < 30°), and the ions were reflected not at the shock but rather at the magnetic barrier. The simulated magnetic field components showed the presence of strong fluctuations in agreement with in situ measurements taken in the Phobos 2 elliptical orbits at low solar zenith angles [*Brecht et al.*, 1993].

One of the motivations of this study is to prove, on the basis of observed data, that the structure of the Martian bow shock is not so very different from the Venusian (and also from the terrestrial) bow shock as predicted by the numerical approach of *Brecht and Ferrante* [1991] when they investigated only the subsolar region of Mars and found that this planet appeared not to have a shock in the classical sense. It has to be mentioned here that this numerical model was later extended to the terminator [*Brecht et al.*, 1993] and tail [*Brecht*, 1995] regions, and a "shocklike" structure was also found to exist at higher solar zenith angles. Since the Phobos 2 space probe provided only three bow shock crossings at low solar zenith angles when both MAGMA and TAUS measurements are available, the transition layer at the bow shock could statistically be studied only in the terminator region based on the data collected in the circular orbits.

As mentioned in the introduction, *Livesey et al.* [1982] reported that the overshoot amplitudes observed in the terrestrial bow shock increased with M_f/M_c and to a lesser degree with solar wind ion β. No overshoots

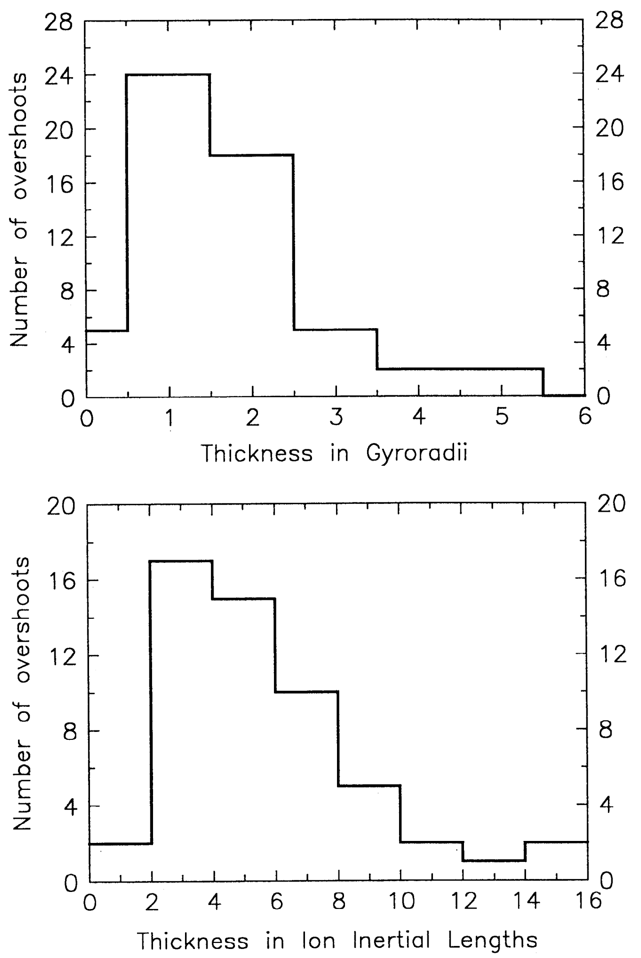

Figure 3. Overshoot thickness normalized to the gyroradius r_L (calculated from the upstream solar wind speed and magnetic field strength) and to the ion inertial length c/ω_{pi} (ω_{pi} is the upstream ion plasma frequency).

were found at subcritical shocks ($M_f < M_c$). This study based on high-resolution ISEE 1 and ISEE 2 magnetic field data was later revisited by *Mellott and Livesey* [1987]. They used 0.25 s high-resolution data (but not exactly the same data set which was used earlier by *Livesey et al.* [1982]) and also 2.5 s-averaged data. When comparing the two data sets, *Mellott and Livesey* [1987] found that overshoots calculated from the averaged data were lower while they confirmed the general trend of the high-resolution data. The results based on the averaged data showed two specific differences from the work by *Livesey et al.* [1982]: (1) the increase in overshoot magnitude at high Mach number and large plasma β was less dramatic, and (2) there was little evidence for the presence of a first critical Mach number, that is, measurable overshoots were observed also in subcritical shocks. On the basis of this latter result, *Mellott and Livesey* [1987] suggested that a small but measurable number of reflected ions may be present also at subcritical shocks.

The second aim of this paper is to find evidence in the Phobos 2 plasma and magnetic field data that either overshoots are associated only with supercritical shocks or that they can be recognized also at subcritical or marginally critical shocks. Our investigation was similar to the study of *Mellott and Livesey* [1987] in the sense that low-resolution data (one averaged magnetic field vector in every 45 s) were used. Since the Phobos 2 spacecraft had an orbital velocity of about 2.1 km/s, the distance between two subsequent magnetic field vectors was ~95 km. This value is about 10 times smaller than the typical upstream proton gyroradius at the Martian bow shock in the terminator region. This sampling rate is slightly worse than the spatial resolution of the averaged magnetic field data set used by *Mellott and Livesey* [1987].

Mellott and Livesey [1987] obtained high correlation factors (>0.7) between the overshoot magnitude and upstream plasma parameters like M_A, M_{ms}, and electron β, while the correlation was lower for ion β. The correlation factors between the overshoot magnitude and the different upstream plasma parameters determined from the Phobos 2 data are lower in general. According to our investigations, M_f/M_c has the largest effect on the overshoot magnitude. When $T_e = 2T_p$ is taken for the electron temperature, the correlation factor is ~0.7. When the $T_e = 120,000\ K$ approximation is used, the correlation is smaller (~0.5).

Alfvenic Mach number and M_A/M_c have a lesser effect on the overshoot magnitude according to our statistical investigations, but the study of individual cases definitely suggests that larger overshoots develop at larger Mach numbers (fast, magnetosonic, and Alfvenic). In the case of small ion plasma β, small overshoot magnitudes were found. For larger β values, however, no general increasing can be observed therefore the correlation between the ion plasma β and the overshoot magnitude is very small. Electron β values were not available for our study.

While the magnitude of the overshoots observed at the Martian bow shock seems to be less influenced by the upstream plasma parameters than in the terrestrial case, the two histograms in Figure 3 illustrate that the thickness of the overshoots is in good agreement with those observed at Earth and Venus. *Livesey et al.* [1982] reported that the typical thickness of the overshoots at the terrestrial shock was around 1–3 r_L (gyroradius calculated from the upstream solar wind speed and magnetic field strength) corresponding to the range of $4 < c/\omega_{pi} < 8$ in ion inertial length. *Tatrallyay et al.* [1984b] found similar values for the thickness of the overshoots observed in the Venusian bow shock. In the case of Mars, the most typical thickness values were in the same range (slightly smaller) as shown by Figure 3.

In summary, it can be stated that the transition layer at the Martian bow shock in the terminator region seems to be comparable to the transition layer of other planetary bow shocks. Shock foot, shock ramp, and overshoot-undershoot oscillations were found in many cases. Upstream solar wind parameters seem to control the magnitude of the overshoot in a similar way as they do in the case of the terrestrial and Venusian shock. The lower values of the obtained correlation factors (compared to the study by *Mellott and Livesey* [1987]) may be explained by several reasons. (1) The interplanetary field was very disturbed in March 1989. Sometimes, irregular fluctuations occurred at the shock which influenced the determination of the overshoot magnitude. (2) The observed range of Mach numbers and ion β was not wide enough ($M_f/M_c < 2.8$ in Figure 2). Compared to the observed upstream parameters available for *Livesey et al.* [1982] and *Mellott and Livesey* [1987] (e.g., M_f/M_c up to 5–6), higher values are absent in our data set which would favor the development of larger magnitudes. (3) The error of the determined upstream parameters may be larger than estimated. In more than half of the cases, despun magnetic field components were used for determining the magnetic field direction. Also, there was an uncertainty in the calculation of the solar wind proton density [cf. *Verigin et al., this issue*]. (4) The Martian data set is smaller. We selected 56 overshoots (including 12 quasi-parallel cases), while *Livesey et al.* [1982] analyzed 110 overshoots at quasi-perpendicular shocks, and *Mellott and Livesey* [1987] studied 65 cases. (5) Finally, the transition layer at the bow shock of Mars may be slightly different from that of Earth owing to the difference in specific scale factors and environments.

Figure 2 presents some indication that small overshoots may occur at lower Mach numbers when M_f is close or below the critical value M_c. When the estimated errors are taken into account, the M_f/M_c values show some uncertainty, either the shocks are subcritical or marginally critical in at least eight cases. On the other hand, with the approximation of $T_e = 120,000\ K$ for the upstream electron temperature, five bow shock crossings were found for which the difference between the fast Mach number and the critical value was within 2%–3% ($M_f \approx M_c$), and $M_f \ll M_c$ was obtained in one case.

Recently, we have revisited the Venusian data set analyzed earlier by *Tatrallyay et al.* [1984b] and have found that for a few shock crossings presented in their Figure 3 (overshoot magnitude vs. fast Mach number), M_f was very close to the critical value. Among the approximate 110 observed overshoots, the shock was found to be subcritical in three cases and marginally critical in another two cases.

Farris et al. [1993] examined the structure of low-beta quasi-perpendicular shocks observed by ISEE 1 and ISEE 2. They also found subcritical bow shock crossings which had nonnegligible overshoots. Therefore they concluded that the ion reflection process begins below the first critical Mach number. However, when M_f was much smaller than the critical value, the shock crossings exhibited no overshoot. *Scopke et al.* [1990] also analyzed low Mach number, low β shocks from plasma, and magnetic field data taken by the AMPTE/IRM (Ion Release Module) spacecraft. They found that reflected-gyrating ions were contributing to the downstream ion temperature at marginally critical shocks.

In agreement with the results of *Mellott and Livesey* [1987] and *Farris et al.* [1993] for the terrestrial shock, we think that some Venusian and the Martian observations favor the idea that overshoots may be observed at the bow shock of these planets, too, even when the fast Mach number is below or around the critical value showing that some ion reflection occurs in these cases.

According to our investigations, bumps were found just downstream of the Martian shock also in the case of a few quasi-parallel bow shock crossings. In spite of the fact that ion reflection at the shock is different when Θ_{Bn} is close to 90° from the case when Θ_{Bn} is small, these overshoot-like bumps had very similar characteristics to the overshoots observed at quasi-perpendicular shocks (in agreement with the results of *Tatrallyay et al.* [1984b] for the Venusian bow shock). On the basis of our relatively poor Phobos 2 data set, it is impossible to analyze the real differences between the nature of the bumps found at quasi-parallel shocks and the characteristic features of the real overshoots observed at quasi-perpendicular shocks.

Conclusions

Before this study of the Martian bow shock, magnetic field overshoots had been observed in the bow shock of several other planets. Detailed statistical investigations, however, were performed only in the case of the Earth and Venus where the amount of available data permitted such an approach. In 1989 the Phobos 2 space probe provided sufficient magnetic field and plasma data for performing the first statistical study of the structure of the Martian bow shock.

The investigation of low-resolution data collected aboard the Phobos 2 spacecraft showed that magnetic field overshoots were clearly observed at the Martian bow shock in the terminator region in more than 70% of the cases. On the basis of a statistical study, the characteristic features of these overshoots were found to be very similar to those observed in the terrestrial and Venusian bow shock. The magnitude of the overshoots increased with increasing M_f/M_c (the ratio of the fast Mach number to the critical Mach number): the correlation coefficient was found to be ~0.7 when $T_e = 2T_p$ was taken, and it was ~0.5 when the upstream electron temperature was approximated by the constant value of $T_e = 120,000\ K$. The thickness of the overshoots was typically 0.5–2.5 proton gyroradii calculated from the upstream solar wind speed and magnetic field.

Our results seem to favor the idea of *Mellott and Livesey* [1987] and *Farris et al.* [1993], who found overshoots at the terrestrial bow shock not only in supercritical shocks but also when the Mach number was below or around the critical value. We think that M_c is not a strict mathematical limit; the transition between subcritical and supercritical shocks must be gradual. Ions may be reflected also at low Mach number shocks, but only a smaller fraction of the ions is involved in this process.

Unfortunately, the first larger data set available for studying the plasma environment of Mars is still very limited (mainly owing to the short active lifetime of the mission, low time resolution of the data, uncontrolled spinning of the spacecraft in more than half of the orbits, etc.). Also, the interplanetary field was very disturbed during the 2 months when Phobos 2 was orbiting Mars; the solar cycle reached its maximum activity in February-March 1989.

We hope future missions to Mars will soon provide more data for further statistical studies including many bow shock crossings at lower solar zenith angles. We also expect that a wider range of plasma parameters will be available and higher Mach numbers will be observed when overshoots with large magnitude develop as expected.

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