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THE INTERACTION OF THE SHOCKED SOLAR WIND AND THE PLANETARY IONS AT MARS

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ABSTRACT

In this study we investigate that region of the dayside magnetosphere of Mars where we may expect that the shocked solar wind comes into direct contact with the planetary ions, and where energy and momentum transfer from the solar wind to planetary plasma may take place. It is our intention to analyse whether the dominant microphysical processes are similar to those observed in the equivalent regions of the magnetosphere of Venus, that is in the dayside mantle of Venus. In this study we present results obtained along the first elliptic orbit of the Phobos 2 spacecraft. Our first conclusion is that around Mars it is the magnetic barrier region that corresponds to the dayside mantle of Venus. In this region at Mars wave excitations are observed, dominantly in the 5 to 50 Hz region; accelerated heavy ions and electrons were also detected. The major conclusion of this study is that despite several observed differences in the way that Venus and Mars interact with the solar wind, the dominant plasma features in the magnetic barrier region of Mars and the dayside mantle of Venus are very similar, indicating that probably the underlying physics is also similar.

INTRODUCTION

Our objective is to study the physical processes that characterise the interaction of the shocked solar wind with ions of planetary origin at Mars, with an emphasis on those mechanisms that lead to momentum and energy transfer from the solar wind to the planetary plasma and to the Martian environment. Our previous investigations of these processes at Venus showed that the dayside mantle is an important region in this respect, and that these transfer processes are dominated by wave particle interactions. In this paper we examine the dayside region above the Martian ionosphere where both plasma populations, the shocked solar wind and ions of planetary origin are present. This study is confined to the plasma measurements carried out along the dayside portion of the first elliptic orbit of the Phobos 2 spacecraft, on 1 February 1989. Further measurements will be analysed in subsequent publications.

The interaction of the solar wind with the plasma environment of Mars shows many similarities to that of Venus, even though some observations and models indicate the presence of a small intrinsic magnetic dipole field (Axford, 1991, Verigin et al., 1993). However, simple fluid MHD description is generally inadequate, and hybrid models are needed to study the Mars - solar wind interaction (Brecht et al., 1993). The use of simple scaling laws, together with observations at Venus, does not lead to what has been observed at Mars. The subsolar location of the bow shock is farther upstream from the planet than it would follow from an appropriately scaled Venus-type interaction; the flare angle of the shock is larger at Mars than at Venus (Verigin et al., 1993). In the foreshock region of Mars the solar wind is decelerated (Verigin et al., 1996, Kotova et al., 1996), but no effect of similar scale was reported at Venus.

These differences might be connected with the fact that at Mars the neutral corona is more dense and extended than at Venus (Verigin et al., 1991, 1996). Kallio (1996) published recently an empirical model, based on the measured proton velocities by the ASPERA instrument (Kallio et al. 1994) that reasonably well reproduces the gross features of the Martian magnetosphere, including its magnetic barrier. A plasma depletion region associated with the magnetic barrier was identified by Pedersen et al., (1991). Kar et al. (1996) recently compared the in-situ O_2^+ profile as measured by the Viking landers to corresponding diffusive equilibrium profiles, and concluded that these profiles are depleted and a strong day to nightside ion flow is likely. In the light of this analysis, it seems to be an important question to investigate the microphysics of the interaction of the shocked solar wind and Martian ions, and to compare it with Venus.

At Venus, investigations revealed the existence of a broad and turbulent dayside interaction region, the dayside mantle, where the shocked solar wind and planetary ions interact. The characteristics of the electron energy spectra observed in the mantle were different from both those observed inside the ionosphere and those of the shocked solar wind (Spenner et al., 1980), and indicated the presence of a mixed plasma population. Investigation revealed that the obstacle of the solar wind is not the ionosphere but the magnetic barrier region, bounded from below by the ionosphere, and from above where the magnetic pressure is equal to half of the upstream solar wind dynamic pressure, corrected by the boundary normal angle (Zhang et al., 1991). A systematic investigation was launched earlier to study this interaction layer, especially to study the mechanism that leads to momentum and energy transfer there from the shocked solar wind to the planetary plasma (Nagy et al., 1990; Sagdeev et al., 1990; Szego et al., 1991, Shapiro et al., 1995, Quest et al., 1996), and to characterise what are the significant plasma features of the interaction region.

The following physical picture emerged from the above mentioned study: The dayside mantle is bounded from below by the ionosphere, defined as the boundary where the magnetic pressure of the shocked solar wind is balanced by the thermal pressure of the ionosphere. At this place the total magnetic field drops significantly. The upper boundary of the mantle is diffuse, this is where the shocked solar wind is deflected and depleted by the magnetic barrier. The width of this region is a few hundred kilometres along the Sun-Venus line. In the mantle the plasma includes both the shocked solar wind and plasma particles of planetary origin. To a very good approximation the latter consists of electrons and oxygen ions, whereas the shocked solar wind can be described as a warm, drifting Maxwellian distribution. The presence of these two populations is unstable to wave excitation. In the planetary frame of reference the source of the free energy is in the solar wind protons.

At Venus, inside the mantle, above the peak value of the magnetic field of the magnetic barrier, waves were observed in the 100-Hz frequency channel of the Orbiter Electric Field Detector (OEFD) carried onboard of the PVO. The peak of the wave electric field correlates well with the altitude where the number density of the O^+ ions is close to the density of the shocked solar wind. It was shown (Shapiro et al., 1995) that the excitation mechanism is a modified two-stream interaction (MTSI), and two branches of waves are excited. The frequency of the first branch is below the local lower hybrid frequency f_{LH}, the frequency of the second branch is a few times f_{LH}; the wave growth changes slowly as a function of the wave frequency, therefore the waves are excited in a broad frequency range between 4 to 8 times the f_{LH}. The frequency value of the peak intensity of the wave depends on the actual plasma parameters.

These waves interact with the resonant part of the electron and ion populations, heating and accelerating them. A part of the wave energy (about 10%, but the exact ratio needs further analysis) is transferred into the ionosphere. The available and relevant retarding potential analyser (ORPA) data from PVO were reviewed by Szego et al., (1996) in order to find evidence of accelerated electrons. Direct measurements are not available, because the ORPA had an upper energy limit of 60 eV. It was concluded, using indirect indicators, that this energetic electron population is very likely to be present in the dayside mantle of Venus. Field rotations were observed to occur in conjunction with the dayside ionopause (Law and Cloutier, 1995), and it was concluded that these rotations are a result of the velocity shear at the ionopause, and indicate the alignment of the magnetic field with the day to night ionospheric plasma flow. Shears in the magnetic field and the corresponding currents were also observed in association with the wave activity (Szego et al., 1996). Accelerated and tailward moving ions at Venus were identified both by the ion mass spectrometer and the neutral mass spectrometer carried onboard of the PVO (Taylor et al., 1981, Grebowsky et al., 1993). However, due to instrument limitations, these ions could be investigated only in the 40 eV-100 eV energy range.

In what follows, we shall refer to the model of Shapiro et al. (1995) as the "MTSI scenario". Other models were also suggested to explain the wave excitation in the mantle. Strangeway and Crawford (1993) suggested an ion acoustic-like instability; this idea was further developed by Huba (1993). It was argued, however by Shapiro et al. (1995) that cold planetary electrons may quench this instability. Crawford et al. (1993) also suggested that the waves might be generated by field aligned currents, but this idea was not worked out in depth. These authors also criticised the MTSI scenario, not so much concerning the wave excitation mechanism, but for other suggested consequences not discussed here. These debates were very useful for the development of the MTSI scenario.

An excellent paper was published recently by Strangeway and Russell (1996) reviewing the plasma waves and magnetic field data above the dayside ionosphere of Venus, with the objective of providing constraints for the various hypotheses put forward for wave excitation. The authors performed both case studies and statistical analyses of more than hundreds orbits. Whereas there is no disagreement concerning the characteristics and importance of major wave and magnetic features in the region (particle acceleration was not investigated), many new and important details were identified. It remains the task of future work to contrast these findings with models.

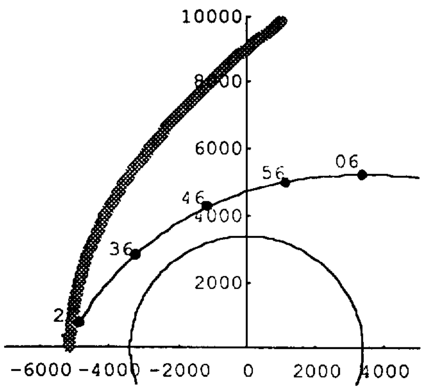

Figure 1. The spacecraft orbit around Mars on 1 February 1989. The vertical and horizontal axes are distances in km in the orbital plane (i.e. the horizontal axis is the Sun-Mars line, the vertical axis is the spacecraft distance from this line). The circles on the orbit mark time, 18:26, 18:36, 18:46, 18:56, and 19:06 UT, respectively.

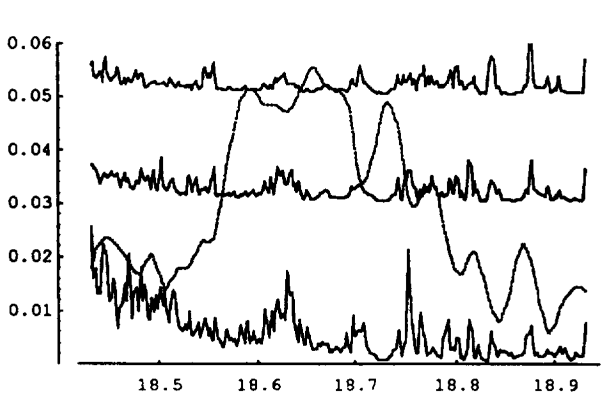

Figure 2. The total magnetic field, the spacecraft altitude and the electric fields in the 5-50 Hz (bottom), 50-100 Hz (middle), 100-150 Hz (top) channels are shown in arbitrary linear units. The horizontal axis shows time in UT. The bow shock was crossed at 18.4 (18:24) UT, the magnetic barrier was crossed slightly before 18.6 (18:36) UT.

A different possibility to validate or refute the different models is also available, namely an investigation of their applicability for the case of Mars. The objective of the current study is actually this; here we investigate whether the basic plasma signatures found in the Venus mantle are present in the appropriate region at Mars. The detailed investigation of the models will be carried out in other publications. We intend to reanalyse simultaneously all the existing experimental data about the interaction region of the shocked solar wind and the plasma of planetary origin at Mars. In this respect the data of the Russian Phobos 2 spacecraft (launched in 1898) is the most important set of measurements, because the earlier Mars missions did not approach the planet close enough, except for the Viking landers that carried only limited instrumentation to study Martian plasma. However, even the Phobos 2 spacecraft did not penetrate into the Martian ionosphere. The Mars 2 spacecraft on 8 January 1972 probably was also very close to this interaction region (Breus and Verigin, 1976), and its data might be considered as well for a complete study.

The Phobos 2 spacecraft visited Mars in 1989, and explored its magnetosphere for two months. It carried on board several plasma instruments, magnetometers, wave analysers, and charged particle detectors. A comprehensive, comparative analysis of all data collected by the plasma instrument on board of the Phobos 2 spacecraft at Mars has not yet been fully accomplished. We attempt to remedy this as well, at least for the first elliptic orbit. Specifically, we intend to use data both from the magnetometer MAGMA (Riedler et al., 1989), and from the plasma wave detector system PWS (Grard et al., 1989) that measured waves in 25 channels in the frequency range 0.2 Hz - 150 kHz. The charged particle analysers of interest are the differential Hyperbolic Retarding Potential Analyser (HARP), and TAUS. We shall also refer to published ASPERA data. The HARP instrument (Shutte et al., 1989) measured electron and ion spectra in a fan of eight coplanar view directions, symmetrically arranged with respect to the antisolar axis. The field of view of each angular sector was 10x20 degrees; the sensor head was mounted on the backside of the solar panels. The ion energy range, 0.3-500 eV, was covered in 42 steps, the integration time of one step was one second. The TAUS instrument (Rosenbauer et al., 1989) measured protons and ions in the 30 eV to 6 keV range, covering a 40x40 degrees sunward looking field of view, centred on the nominal aberrated solar wind direction, almost perpendicular to the solar panels. The field of view was divided into 8x8 separate channels both in elevation and azimuth. The few upper energy channels of HARP overlap with some of the lower energy channels of TAUS. This way, the field of view of these spectrometers are complementary to each other.

DATA ANALYSIS

In this paper we review the observational data of several plasma instruments collected along the first elliptic orbit of Phobos 2. The elliptic orbits are especially suitable for the analysis of the interaction region of the shocked solar wind and planetary plasma at Mars, because the spacecraft spent a long time flying inside or in the close vicinity of the magnetic barrier. To characterise the location of the spacecraft relative to the different plasma regions, we follow the indications derived from the field and particle data. As the spacecraft was spinning about the axis pointing to the Sun (x-axis) during the first two elliptic orbits, we use only B_x, or rotationally invariant magnetic field quantities. Though the geometry of the first three elliptic orbits are very close, due to the varying solar wind conditions the plasma regions the spacecraft visited and the time spent in certain regions changed considerably from orbit to orbit. A detailed description of all elliptic orbits will be the subject of a further publication. The orbit characteristics for 1 February are shown in Figure 1. The solar wind velocity on that day was 790 km/s, quite high compared to the values measured on the next two orbits.

On 1 February, between 18:24:22 and 18:25:52, B_{tot} jumped from 5.28 nT to 13.25 nT; this is identified as the bow shock crossing at an altitude of about 1600 km. Between 18:33:22 and 18:35:37, while the spacecraft altitude dropped from 1000 km to 916 km, B_{tot} increased from 16.76 nT to 29.02 nT; this is what we identify as the outer edge of the magnetic barrier (see Figure 2). The pericenter was reached at 18:39:20, at an altitude of 866 km; the spacecraft left the magnetic barrier region at about 18:44 when its altitude was about 930 km; it returned into the barrier at 18:47:46, at 1040 km altitude. This means that during more than 10 min the spacecraft travelled inside the barrier, while its altitude varied only about 150 km. During this interval the magnitude of B_{tot} dropped at 18:37:52, which we believe was caused by the spacecraft leaving, or getting closer to the edge of the barrier for a brief period of time.

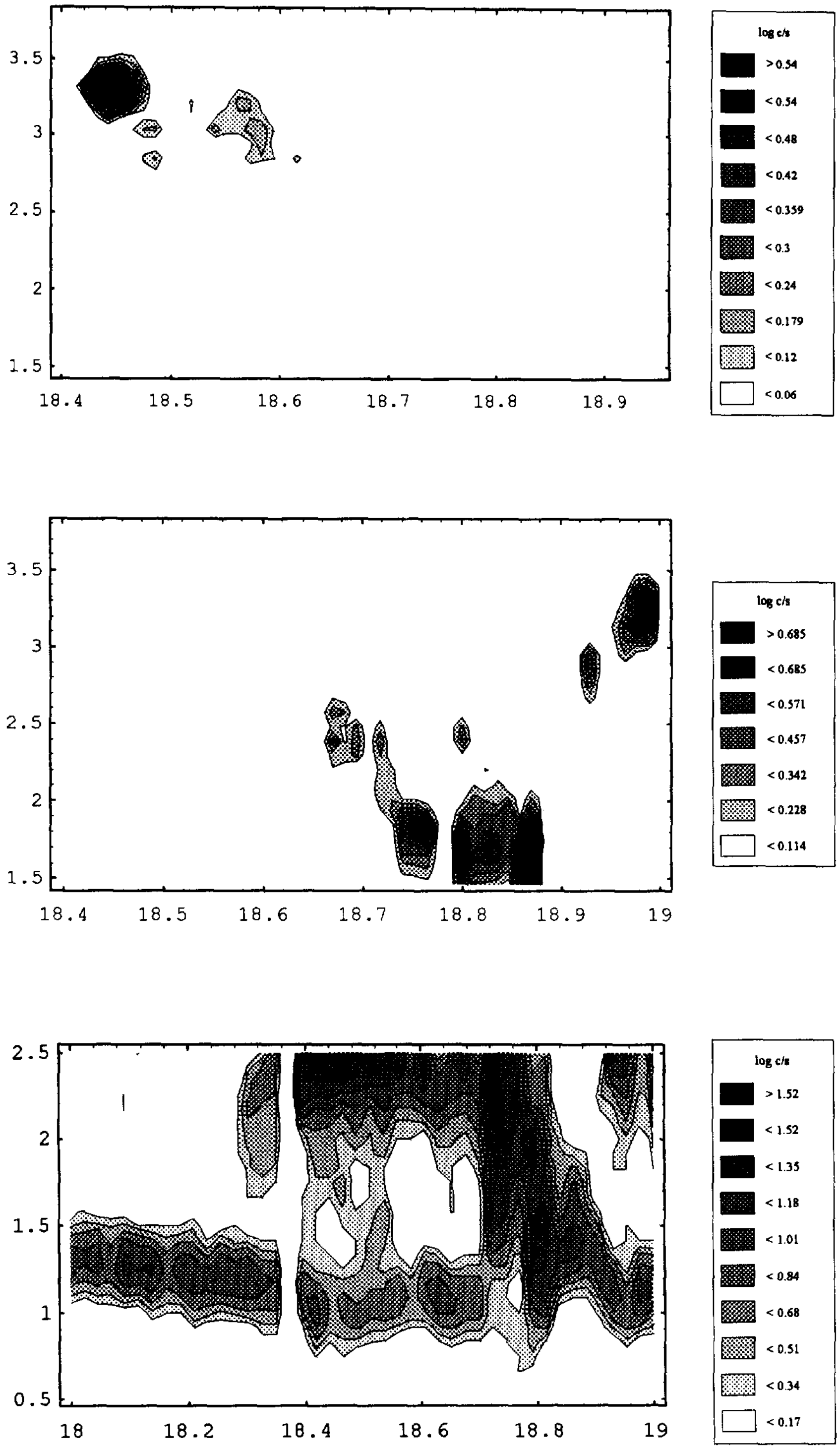

Figure 3. The TAUS proton (top), heavy ion (middle), and the HARP electron spectra (lower) are shown, as a function of time in UT, in log count/s units. The energy values are on the vertical axes, in log eV.

This interpretation correlates well with the fact that the proton flux disappeared from the field of view of TAUS at 18:34:55, with a one-time reappearance at 18:37:02, when the high resolution measurements of B_{tot} show a significant drop in magnitude of the magnetic field (Figure 2a). We note here that the nutation of the spacecraft reached 15 degrees time to time, making the view direction different from the expected. As there is no exact information on the time variation of the nutation angle, the data interpretation requires caution.

As it can be seen from Figure 2, just before the spacecraft entered into the barrier, and at those times when B_{tot} dropped, the electric field showed increased activities in the 5-50 Hz, 50-100 Hz, 100-150 Hz channels of the PWS. The signals were the strongest in the lowest frequency channel that covered the frequency range around the lower-hybrid frequency (20 Hz for B=30 nT). It is easy to interpret these signals qualitatively in the framework of the MTSI scenario. The density distribution of the ionospheric plasma, in a similar way as it was observed at Venus, very likely has a tail extending over the magnetic barrier, where it overlaps the shocked solar wind. This is an unstable situation leading to wave excitations. The observation of these waves supports both this model, and our picture about the plasma boundaries. The appearance of a shear in the magnetic field structure is a frequent phenomena accompanying the wave generation; some extent, this is also the case here. In Figure 4 we displayed the change of direction (the inclination angle) of the magnetic field, between any two consecutive magnetic field vectors in the sheath. As the vector product is rotationally invariant, this quantity is only slightly corrupted by spacecraft rotation, because the change in a theoretically static field direction is small between two consecutive measurements.

A further consequence of the MTSI scenario is particle acceleration. The electron spectra, as measured by the HARP analyser (see Fig. 2c), clearly show a high energy tail when the spacecraft is inside the magnetic barrier. It is interesting to note that a spectrum, characteristic of shocked solar wind electrons, is also observable inside the barrier.

Accelerated ions (Figure 2b) were detected by TAUS along the spacecraft trajectory inside the magnetic barrier, after 18:38:30. These ions have energies up to 300 eV. The energy distribution is rather flat, and the energy of the ions is more or less centred around 100 eV. These ions are moving tailward, similar to the observations at Venus. The ASPERA instrument also observed tailward moving ions (Lundin et al., 1989). The TAUS ion data also show bunches of accelerated ions around 19:00, in the 1 keV energy range. However, close to these events B_x changed sign at 18:49 and between 18:58 and 19:04, therefore we do not associate these events with the MTSI mechanism.

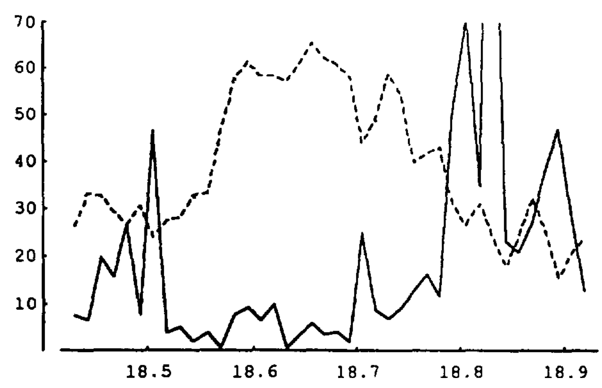

Figure 4. The total magnetic field value (dotted line) in arbitrary units, and the inclination angle of two consecutive magnetic field vectors (in degree) are shown as a function of time, along the first elliptic orbit, on 1 February.

DISCUSSION

As indicated earlier the objective of this paper is to investigate those processes that lead to momentum and energy transfer from the shocked solar wind to planetary ions; our starting point is a similar investigations for Venus. It was established by Zhang et al., (1991, 1993) that in the magnetic barrier region of Venus 83% of the kinetic pressure of the solar wind slowly changed to magnetic pressure, and the shocked solar wind gets depleted. Shapiro et al. (1995) showed, that in the Venus mantle the shocked solar wind transfers energy and momentum to planetary ions. This energy and momentum transfer is mediated by waves, excited in the vicinity of the lover hybrid frequency of the ambient plasma by a modified two-stream instability mechanism. We point out here that it is very likely that the magnetic barrier and the mantle are identical plasma regions, the different names arose because the regions were identified by different set of plasma measurements.

At Venus the waves were generated in a region where the ion density was about 100 particle/cm^3, a mixture of the two population. Therefore, at Mars we first looked for wave excitation in a similar region along the first elliptic orbit, in an approximately 30 min. interval after bow shock crossing. It was found that at Mars the waves are generated at/above the upper edge of the magnetic barrier, and the signal is the strongest in the 5 to 50 Hz channel of the PWS, in good agreement with the MTSI scenario. We do not have direct measurements of the ionospheric plasma. The HARP instrument in the ion mode could have detected these thermal ions, because its theoretical lowest energy limit was below 1 eV. However, the spacecraft potential was not under control; Pedersen et al. (1991) from the PWS data deduced the presence of a rapidly varying spacecraft potential of a few V. Due to the spacecraft motion the ions have a few km/s relative velocity with respect to the HARP sensor, but it is basically impossible to establish how these balance each other; it is conceivable that the planetary ions were effectively repelled from HARP.

Electron energy spectrum measurements are important indicators of the mantle region. At Venus Spenner et al. (1980) first detected this mantle by noting the changing characteristics of the electron population in the 10 to 40 eV energy range using the Retarding Potential Analyser carried onboard of the Pioneer Venus Orbiter. The HARP instrument operated in a broader energy range, from a few eV up to 400 eV. If we make energy cut-outs from the HARP data between 10 to 40 eV, the picture is similar to the PVO observations. The full picture is that the shocked solar wind electron component is present both in the sheath and inside the magnetic barrier. The electron component is very likely decoupled here from the protons. Almost immediately after the bow shock crossing a high energy tail is developing in the electron spectra, the energy peaks inside the barrier, very likely around the upper energy limit of HARP. From the point of view of the MTSI scenario the important thing here is the manifestation of electron acceleration, in the energy range predicted by Shapiro et al. (1995), because in the quasilinear approximation the electron acceleration can be treated reasonably well. We also note that in the region investigated the counts integrated over energy from HARP reach a maximum. However, this is due to the energetic electron component, and it does not indicate that the spacecraft got close or inside the ionosphere.

It is known that if B_x changes sign, the electric field associated with it by the Maxwell equations accelerate ions. We exclude these events in what follows. As it was described above, heavy ions were detected by TAUS along the spacecraft trajectory inside the magnetic barrier. These ions are not accelerated by some ExB mechanism, because ExB pick up mechanism is not compatible with either the narrow altitude region where the ions were observed, nor with the observational differences between TAUS and HARP.

The quantitative analysis of the ion acceleration is difficult, because it requires non-linear description. The reason is that though planetary ions interact with the waves, the excited MTSI modes are too fast to be in Cherenkov resonance with the slow planetary heavy ions. The coupling is the result of the non-linear Landau damping, the Cherenkov resonance becomes possible between the ions and low frequency beat waves which appear in the spectrum due to non-linear interaction. This interaction causes a kind of an anomalous friction between the shocked solar wind and the planetary ions; these ions are dragged away by the shocked solar wind. If the drag is effective and the interaction length is appropriate, the ions should reach the velocity of the shocked solar wind, that is we should see few keV ions. Such ions were sometimes seen along circular orbit by both ASPERA (Dubinin et al., 1996) and by TAUS (unpublished), but it requires further study to connect those observations with the MTSI model. Another possibility is that the bulk motion of the ions carries away the wave momentum, and the bulk moves in the direction of the group velocity of the waves. In this case the ion energies are lower.

The investigation of the heavy ion population along the elliptic orbits shows that the ions move inside the magnetic barrier, and the average ion energy is 100 to 200 eV. We are trying to find the footprints of these ions in the measurements made along the circular orbit ($R \sim 3\ R_M$), but those investigations are not yet finished.

These processes were also studied numerically using a one-dimensional hybrid code that retains the inertia of the electron species (Quest et al., 1996). It was shown that the lower hybrid waves propagating perpendicular to the magnetic field are destabilised and then saturated by electrostatic trapping of the proton species. The (simulated) saturation amplitudes are in reasonable agreement with observations. Further, oxygen pick-up and acceleration occurs as a consequence of the (relatively) low phase speed of the perpendicularly propagating waves, resulting in significant ion heating. This mechanism leads to a spatially turbulent ion population. However, due to some limitations inherent in the one-dimensional simulation, not discussed here, further work needs to be done before we can directly compare the results of this simulation with the data.

CONCLUSION

In this study we investigated that region of the dayside magnetosphere of Mars where we may expect that the shocked solar wind comes into direct contact with the planetary ions. The objective of the study was to analyse whether the measured physical characteristics are similar to those observed in the equivalent regions of the magnetosphere of Venus, that is in the dayside mantle of Venus. Our method was to compare the "MTSI scenario" (that is the predictions of our model developed to explain the physical processes operating in the mantle of Venus) with actual observations collected by the plasma instruments carried onboard of the Phobos 2 spacecraft.

The first conclusion is that around Mars it is the magnetic barrier region that corresponds to the dayside mantle of Venus. It is this region which contains the mixed plasma population made up of the shocked solar wind and planetary plasma, which is located around the upper edge of the magnetic barrier. We believe that in general the dayside mantle and the dayside magnetic barrier describe the same physical region; the only difference is associated with the location of their diffuse upper boundary is determined from the measurements of different plasma components (protons, electrons, ions, fields).

In the magnetic barrier region of Mars wave excitations are observed, dominantly in the 5 to 50 Hz region, in excellent correspondence with the MTSI scenario. The macroscopic consequences of the interaction of the excited waves with planetary plasma was also observed, in the form of both heavy ion and electron acceleration. Therefore the major conclusion of this study is that the MTSI scenario is very likely valid both at Venus and Mars.

The third conclusion is that whereas there are several observed differences in how Venus and Mars interact with the solar wind, at both planets the shocked solar wind comes into direct contact with the plasma of planetary origin, and the physical characteristics, the dominant physical processes taking place in this mixed plasma population, are very similar at Mars and Venus.

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