Solar wind and magnetospheric ion impact on Mercury’s surface

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1. Introduction

[2] Mercury has a weak intrinsic magnetic field and tenuous atmosphere that makes the surface of the planet a target for solar wind particles. The weak intrinsic magnetic field results to a miniature magnetosphere in which the subsolar distance of the bow shock and magnetopause have been estimated to be only ~1.8 \( R_M \) and ~1.4 \( R_M \) (\( R_M = 2440 \) km), respectively [Ogilvie et al., 1977]. The solar wind particles near the surface can freely hit the surface of the planet because the planet has an exosphere without an atmosphere [Killen and Ip, 1999].

[3] Ion impact at Mercury has been a subject of several analyses motivated by Mariner 10 (M10) magnetic field and electron measurements made in 1974–1975. Unfortunately, there are no direct ion measurements available from M10 flybys. The Hermean magnetosphere is commonly regarded as a scaled down version of the Earth’s magnetosphere. The knowledge of the Hermean ion environment soon after M10 flybys relied therefore strongly on the measurements made in the Earth’s magnetosphere [Ogilvie et al., 1977; Slavin and Holzer, 1979; Goldstein et al., 1981]. Quantitative models about the solar wind-Mercuryinteraction studies have focused to analyzing the role of the interplanetary magnetic field [Luhmann et al., 1998; Kabin et al., 2000; Killen et al., 2001; Sarantos et al., 2001; Ip and Kopp, 2002; Kallio and Janhunen, 2003b], the motion of ions in the Hermean magnetosphere produced from the Hermean exosphere and emitted the surface [Ip, 1987; Delcourt et al., 2002, 2003; Killen and Sarantos, 2003], and the motion of the solar wind protons injected from the tail [Lukyanov et al., 2001] and during SEP (Solar Energetic Particle) event [Leblanc et al., 2003]. The role of the impact of the solar wind protons has received recently a noticeable interest because the ion sputtering was proposed as a potential candidate to explain the rapid temporal variations in the Hermean sodium exosphere observed in Earth-based remote sensing measurements [Potter et al., 1999].

[4] In this paper the impact of the solar wind protons is studied for a first time by a self-consistent quasi-neutral hybrid model. The hybrid model takes into account ions finite gyroradius effects and it provides a powerful approach to study Hermean, or Martian, size magnetospheres [Kallio and Janhunen, 2003a]. The paper is organized as follows. Macroscopic parameters and the morphology of the magnetic field are illustrated after a brief description of the used hybrid model. Then the flux of the solar wind protons at four different upstream parameters is studied and the three high impact flux regions on the surface are presented.

2. Model Description

[5] The quasi-neutral hybrid model is described in detail elsewhere [Kallio and Janhunen, 2003a] and here only the properties that are most important for the present study are briefly listed. In the model the ions are treated as particles and they are accelerated by the Lorentz force. The model thus includes automatically finite ion gyroradius effects. The velocity distribution of the ions is fully three-dimensional. Ions can hit the surface of the planet and if they do so they are taken away from the simulation. Electrons form a charge neutralizing (quasi-neutrality is assumed) massless fluid. In this paper H⁺ ion impact in four runs is shown. The upstream parameters of the analyzed stationary cases are shown in Table 1. It should be noted that while the used solar wind density of 76 cm⁻³ represents a typical solar wind density value at Mercury at the pericenter the used total IMF is smaller than its typical pericenter value of about 46 nT [Slavin and Holzer, 1981]. Also, the used velocity value of 860 km/s does not represent any specific solar wind event and it was chosen only to represent an artificial high solar wind speed case. The coordinate system is the following: The solar wind flows in the -X direction, \( U_{SW} = (-|U_{SW}|, 0, 0) \), the Hermean intrinsic magnetic field is modeled by a magnetic dipole moment that points the -Z direction, and the Y coordinate completes the right hand coordinate system. The value of the magnetic dipole moment was chosen to give [300, 0, 0] nT magnetic field.
on the surface of the planet in the magnetic equator. The used grid size is 305 km (=0.125 \(R_M\)).

### 3. Solar Wind Protons Near Mercury: An Overview

Figure 1 shows the density of the solar wind protons and the magnetic field lines in the analyzed four cases. The black solid lines give the position and shape for the bow shock and the magnetopause in the North IMF case (see Kallio and Janhunen, 2003b, for the details of the used analytical functions for these two boundaries). Figure 1 illustrates several characteristic features about the solar wind-Mercury-interaction. First, the smallness of the Hermean magnetosphere compared with the Earth’s magnetosphere which implies that the high proton density region is close to the planet. Second, how the IMF \(B_x\) component in the Parker spiral angle case results in a North-South asymmetry, the other hemisphere being magnetically connected to the solar wind. Third, how the bow shock and the magnetopause can be located very close to the surface of the planet at high solar wind dynamic pressure.

<table>
<thead>
<tr>
<th>Name of the run</th>
<th>IMF ([nT])</th>
<th>(U_{SW}) ([\text{km s}^{-1}])</th>
<th>(q_{tot}) ([10^{25} \text{cm}^{-3}])</th>
<th>(q_{N}^a) ([%])</th>
<th>(q_{D}^b) ([%])</th>
</tr>
</thead>
<tbody>
<tr>
<td>North IMF ([0, 0, 10])</td>
<td>430</td>
<td>3.9</td>
<td>6</td>
<td>53</td>
<td>53</td>
</tr>
<tr>
<td>South IMF ([0, 0, -10])</td>
<td>430</td>
<td>3.4</td>
<td>6</td>
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</tr>
<tr>
<td>Parker IMF ([32,10, 0])</td>
<td>430</td>
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<td>36</td>
<td>59</td>
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<td>High (U_{SW}) ([0, 0, 10])</td>
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In all cases the density of the solar wind, \(n_{SW}\), was 76 \(\text{cm}^{-3}\) and the sonic Mach number 7.7. The values of \(q_{tot}\), \(q_{N}\), and \(q_{D}\) show the total flux of impacting \(H^+\) ions, how many percent of the total \(H^+\) flux goes to the Northern hemisphere \((z > 0)\) and to the dawn hemisphere \((y < 0)\), respectively.

\(^a\) \(q_{N}^a = \frac{q_{tot}(R_{SW} \times R_M)}{R_M} \), \(R_M = 2440 \text{ km}\).

\(^b\) \(q_{D}^b = \frac{q_{tot}(z > 0)}{q_{tot}} \), \(q_{D}^b = \frac{q_{tot}(y < 0)}{q_{tot}}\).

4. Impacting Solar Wind Protons

Figure 2 gives a three-dimensional view of the particle flux of the solar wind protons at the surface and the open/closed field lines in the pure north IMF and in the high \(U_{SW}\) cases. Figure 2 shows how the particle flux is low near the magnetic poles on the nightside and that the highest particle fluxes can be found on the dayside in the noon midnight meridian plane between the magnetic poles and the magnetic equator. Note also how the magnetic poles are surrounded by a high particle flux region. These flux pattern is analyzed in more detail later. Finally, Figure 2b depicts how the compression of the Hermean magnetosphere in a high \(U_{SW}\) case increases the impact of the solar wind protons, especially around the subsolar point.

A more detailed view to the high particle flux regions is shown in Figure 3. In all four analyzed cases, high particle flux bands can be found at latitudes about 20–60 deg. in both the Northern and Southern latitudes. These bands are near, but slightly equatorward, from the open/closed field line boundary. The proton impact at these two high flux bands is referred to as the auroral impact in this paper in analogy with the Earth’s auroral ovals around the Earth’s magnetic poles.

**Table 1.** The Total Particle Fluxes of the Impacting Solar Wind Protons in the Four Analyzed Cases

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The magnetic field lines are shown by red lines. The solid black lines show the position of the bow shock and the magnetopause in the pure northward IMF case.

Figure 1. The density of the solar wind protons \((\text{cm}^{-3})\) and the magnetic field lines in the (a) pure northward IMF, (b) pure southward IMF, (c) in the Parker spiral angle IMF, and (d) in the high solar wind speed \((U_{SW} = 860 \text{ km s}^{-1})\) cases. The magnetic field lines are shown by red lines. The solid black lines show the position of the bow shock and the magnetopause in the pure northward IMF case.
magnetic poles. The highest fluxes on these auroral ovals can be found on LT/C24 12:00 (longitude/C24 0 deg.) resembling the particle impact at the Earth’s magnetic cusps, or cusp entry layers. Figure 3c, instead, represents a third kind of high impact region, namely a high particle flux region near the subsolar point. This ion impact region, referred to as the nose impact region, occurs when the solar wind speed and, consequently, its dynamic pressure is high and it does not have a clear analogy with the ion impact at the Earth. It is also noteworthy that increasing the solar wind velocity is also expected to increase the gyroradius of the ions. For a reference, an H\(^+\) ion moving at speed 430 km s\(^{-1}\) and 860 km s\(^{-1}\) perpendicular to a 10 nT magnetic field has a gyroradius of 0.18 R\(_{\text{M}}\), and 0.37 R\(_{\text{M}}\), respectively.

[9] The total particle fluxes in the analyzed cases are summarized in Table 1. When U\(_{\text{SW}}\) was 430 km s\(^{-1}\), the total impact rate of the solar wind protons is \~5\% of the impact rate that would take place without the shield of the magnetosphere. It should be noted that the total H\(^+\) flux seems to be slightly larger in the north IMF than in the south IMF cases, that is, in the “closed” magnetosphere than in the “open” magnetosphere. An explanation for that could be that in the “closed” (the north IMF case) magnetosphere the closed field lines occupy a larger fraction in the magnetosphere and, consequently, the H\(^+\) ions can easily be trapped into the closed field lines and finally hit the surface. Table 1 also shows that when U\(_{\text{SW}}\) increases from 430 km s\(^{-1}\) to 860 km s\(^{-1}\) the absorption increases from \~5\% to \~25\%. The orientation of the IMF contributes also to the distribution of the solar wind protons negative IMF B\(_x\), resulting in higher total particle flux in the Southern hemisphere than in the Northern hemisphere.

5. Discussion

[10] In this paper the impact of the solar wind protons at Mercury was studied for the first time with a quasi-neutral hybrid model. Although a detailed quantitative comparison of the presented results and the previous studies is beyond the scope of this paper, it is worthwhile to note the following qualitative similarities.

[11] The impact of the solar wind protons was found to be intense in the auroral region (Figure 3), much in agreement with the former analysis based on an analogy with the Earth’s magnetosphere [Ogilvie et al., 1977]. When the formation of the auroral impact formed in the simulation were studied by a test particle simulation (figure not shown) those ions which
penetrated into the closed field lines were found to move along the magnetic field line and finally hit the surface of the planet. Such an ion loss is consistent with the fact that the ions at Mercury have a large loss cone angle [Ogilvie et al., 1977; Delcourt et al., 2003] due to which particle can easily hit the surface. The motion of ions in the Hermean magnetosphere is different from the motion in the terrestrial magnetosphere also because the gradient drift plays a larger role at Mercury that at the Earth [Ogilvie et al., 1977; Delcourt et al., 2002] Furthermore, increasing solar wind dynamic pressure was found to push the magnetopause toward the planet (Figure 1), in agreement with an MHD model runs [Kabin et al., 2000]. In such a case an intense H\(^+\) ions impact was found also near the subsolar point.

Furthermore, the orientation of the IMF was found to affect the morphology of the Hermean magnetosphere and to the H\(^+\) ion impact. The magnetic cusps were found to be sited closer to the magnetic equator in IMF B\(_z\) < 0 case than in IMF B\(_z\) > 0 case (compare Figures 3a and 3b). Consequently, the south IMF case resulted a larger open field line region on the surface than the north IMF case (compare Figures 3a and 3b) which is qualitatively in agreement with an MHD model [Ip and Kopp, 2002]. The North-South asymmetry in the Hermean magnetic field caused by the IMF B\(_z\) component [Sarantos et al., 2001; Kallio and Janhunen, 2003b] resulted in a North-South asymmetry also in the impact of the solar wind protons: The total H\(^+\) ion particle flux is higher on the hemisphere that is magnetically connected to the solar wind (Figure 1c) than in the opposite hemisphere. The impacting H\(^+\) emit neutral atoms and ions (see, for example, Killen and Ip, 1999) and, therefore, the non-uniform H\(^+\) impact shown in this paper forms a non-uniform neutral source for the Hermean exosphere and a non-uniform ion source for its magnetosphere.

It should finally be worth noting that the present study leaves room for more comprehensive studies in the future. In addition to the numerical issues (see discussion in Kallio and Janhunen, 2003a, for details) there are many physical issues to be studied such as how the Hermean exospheric ions affect the impact, the role of the resistivity (which in the presented runs is zero both above and within the planet), the magnetospheric dynamics associated with time dependent upstream parameters, and the role of ions gyroradius. The model should also be made more self-consistent by taking into account the emission of neutrals and ions resulted from the H\(^+\) impact.

6. Summary

In this paper the particle flux of the solar wind protons was calculated self-consistently with a hybrid model. The impact was found to be high near the rings around the magnetic poles, in analogy with the ion impact at the Earth’s auroral ovals. The impact within these rings was most intense in the dayside near the noon-midnight plane resembling ion impact at the Earth’s cusps. A substantially different impact that has no analogy with Earth-like case was found when the solar wind dynamic pressure is high. In such a case a high particle flux was found around the subsolar point as well. Hemispherically asymmetric particle impact controlled by the orientation of the interplanetary magnetic field was also found. Overall, the study illustrates that the solar wind ions are impacting non-uniformly on the surface and that the site where the high particle impact is high depends on the upstream parameters.

References


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