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What Density of Magnetosheath Sodium Ions Can Provide the Observed Decrease in the Magnetic Field of the "Double Magnetopause" during the First MESSENGER Flyby?

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Abstract: On 14 January 2008, the MESSENGER spacecraft, during its first flyby around Mercury, recorded the magnetic field structure, which was later called the "double magnetopause". The role of sodium ions penetrating into the Hermean magnetosphere from the magnetosheath in generation of this structure has been discussed since then. The violation of the symmetry of the plasma parameters at the magnetopause is the cause of the magnetizing current generation. Here, we consider whether the change in the density of sodium ions on both sides of the Hermean magnetopause could be the cause of a wide diamagnetic current in the magnetosphere at its dawn-side boundary observed during the first MESSENGER flyby. In the present paper, we propose an analytical approach that made it possible to determine the magnetosheath Na^+ density excess providing the best agreement between the calculation results and the observed magnetic field in the double magnetopause.

Keywords: Mercury; double magnetopause; sodium ions; Na^+

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1. Introduction

Sodium Fraunhofer lines at 5890 and 5896 angstroms were found by the on-ground telescope during investigation of Mercury in 1985 (e.g., [1], and references therein). Later it occurred that the sodium exosphere is time-dependent and controlled, in particular, by the solar wind. During two first MESSENGER flights the so-called "double magnetopause" was found at the dawn-side magnetospheric boundary [2,3]. For the first flyby (M1) the interplanetary magnetic field (IMF) was northward when the spacecraft exited into the dawn-side magnetosheath, while for the second one (M2) it was southward. In the both cases the magnetic field decrease between two narrow current sheets was observed and called "dayside boundary layer (D-BL)". From this fact Müller et al. [3] concluded that the D-BL and two current sheets at its boundaries do not depend on IMF direction. Belenkaya [4] showed for the terrestrial magnetosphere that the magnetopause currents generated by the magnetosheath ions and caused by the violation of the symmetry of the plasma parameters are directed from dawn to dusk regardless of the north–south IMF orientation. Thus, the magnetosheath ions of different sorts can be responsible, in principle, for these qualitatively similar magnetic field and plasma structures.

Slavin et al. [2] mentioned that at ~19:10:35 and at 19:14:15 on 14 January 2008, current sheets with similar small thicknesses and orientations were observed when MESSENGER exited magnetosphere at the dawn-side during M1. At 19:14:15, the MESSENGER spacecraft intersected the magnetopause, and the outer current sheet was interpreted by the authors as the "real" magnetopause, while the inner current sheet was supposed to be created by the pick-up ions of the planetary origin (predominantly Na^+), which entered the magnetosphere from the solar wind side. It was emphasized by Slavin et al. [2] that the outer current is twice as strong than the inner one. The authors mentioned that both current layers were separated by the wide D-BL region~1000 km. This length is almost a half of the Mercury radius (R_M = 2440 km (e.g., [5]). However, it should be noted that the inner current sheet (at ~19:10:35) was as narrow as the outer one, and if it were generated by sodium ions, then it should have been much wider.

Figure 1 illustrates a rough diagram of the Hermean magnetosphere. The magnetopause bounds the cavity filled with a magnetic field (solid lines with arrows). Parts of the Larmor circles of sodium pick-up ions from the magnetosheath located out of the magnetosphere are marked with dashed curves, and parts placed in the magnetosphere that create the boundary current are shown by solid curves. Trajectory M1 is shown.

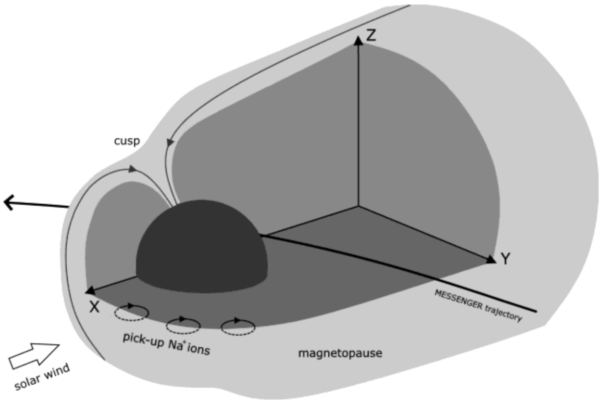

Figure 1. Scheme of the Mercury's magnetosphere (following Figure 1 in [2]).

Möller et al. [3] showed that the thin inner current sheet of a double magnetopause can be created by proton pressure gradients. The authors used 3D hybrid numerical simulations for investigation of such double magnetopause observed during first MESSENGER flyby. The planet's magnetic field was taken from the Alexeev et al. [6] model, but some simplifications were used later by the authors. Möller et al. [3] concluded that although the inner current sheet can be explained without sodium ions, their influence should nevertheless be taken into account. They noted that for working of the mechanism suggested by Slavin et al. [2], most of the sodium ions should be produced out of the Mercury's magnetosphere, but not inside it. Sodium pickup ions density in the magnetosheath during M1 was estimated by Sarantos et al. [7] as 0.1–3 cm^{-3}. Here, we consider what can be expected if the situation suggested by Slavin et al. [2] was implemented.

2. Magnetopause Current Generated by Sodium Ions Penetrated from the Magnetosheath. Methods of Investigation

The magnetizing current arises if at least one plasma parameter (for example, density) or magnetic field changes at the boundary between two media. If sodium ions are present in the magnetosheath with a density higher than their density in the magnetosphere, they participate in the creation of an additional magnitizing current at the magnetopause. Sodium ions and neutrals are of planetary origin. Since the Mercury's atmosphere is very weak, energetic ions, neutrals, meteors, and the thermal or photon stimulated desorption produce the sodium exosphere around Mercury. Besides sodium, other substances are formed from the planet's surface, but sodium probably predominates ([8,9], and references therein). Ionisation is produced by UV radiation and the solar wind charge particles precipitation. Sometimes this process is more intense outside the magnetosphere, where Na$^+$ ions are picked-up and accelerated, while solar wind charged particles are slowed down.

Slavin et al. [2] showed the MESSENGER magnetic field data, including its exit from the dawn magnetosphere in the first flyby. The interplanetary magnetic field was northward. This situation is similar with the northward IMF for the Earth, since the dipole magnetic axes for both planets are directed southward. Belenkaya [10] considered the structure of the terrestrial magnetopause current for the northward IMF. It was shown how solar wind protons create a dawn-dusk magnetizing current at the equatorial dayside magnetospheric boundary. A kinetic approach was applied. Using the obtained distribution function, we derived an equation for the current density of the magnetosheath ions [10] as a function of the distance from the magnetopause x (x positive sunward). Here, we rewrite it for the sodium ions as Equation (1):

$$j_{\mathrm{mshy}} = \frac{e}{\pi} n_{\mathrm{msh0}} \sqrt{\frac{2kT_{\mathrm{msh}}}{m_{\mathrm{msh}}}} \sqrt{1 - \left(1 + \frac{x}{\rho_{\mathrm{msh}}}\right)^2} \tag{1}$$

where n_{msh0} and T_{msh} are the Na$^+$ ion's magnetosheath density excess relative to the magnetospheric density, and temperature in the magnetosheath, respectively; m_{msh} and ρ_{msh} are the mass and gyro-radius of the magnetosheath sodium ions penetrating the magnetosphere, respectively. Larmor radius of the sodium ion penetrating from the magnetosheath is:

$$\rho_{\mathrm{msh}} = \frac{m_{\mathrm{msh}} V_{\mathrm{Na}^+}}{z_{\mathrm{Na}^+} e B_{\mathrm{msph}}} \tag{2}$$

where $m_{\mathrm{msh}} = 3.8 \times 10^{-26}$ kg, $z_{\mathrm{Na+}} = 1$, e is the electron charge, and B_{msph} is the average field in the magnetosphere near the dawn magnetopause (which should be in the absence of Na$^+$). If we assume, following Belenkaya [10], that the width of the magnetosheath sodium ions' current sheet inside the magnetosphere is $L \approx 2\rho_{\mathrm{msh}}$, then from the observed D-BL thickness we can find ρ_{msh}. From the Slavin et al. [2] data it follows that L~1032 km (Möller et al. [3] estimated L as 1000–1100 km), and consequently ρ_{msh} = 516 km. Sarantos et al. [7] mentioned that the slow-down of the magnetosheath flow may be due to the loading by the sodium ions.

In Figure 2, one can see that the current sheet arises at the Mercury's magnetopause inside the magnetosphere, if the density of Na$^+$ ions outside the magnetosphere at the time under consideration was higher than inside it. Solar wind protons have much smaller gyroradii than sodium ions. For this reason, the diamagnetic current sheet created by Na$^+$ penetrating the Hermean magnetosphere is much thicker than the current carried by protons. All these currents are directed from dawn to dusk independent of the IMF B_{mshz} direction [10].

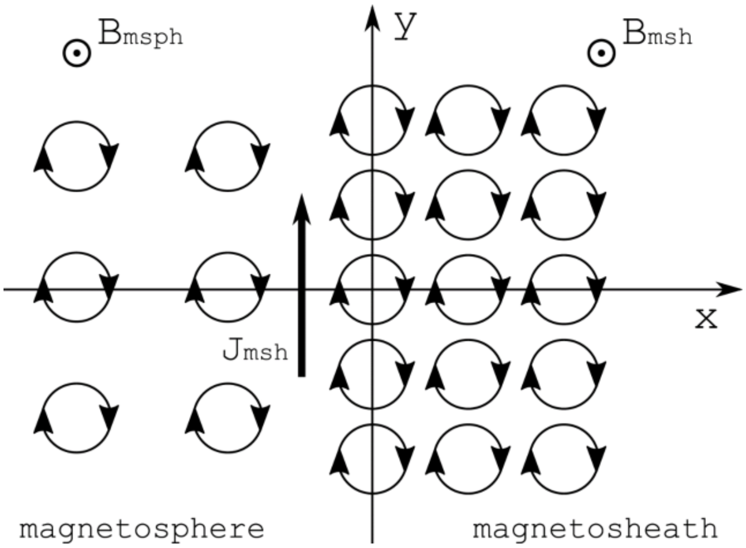

Figure 2. For northward IMF ($B_{\mathrm{mshz}} > 0$), the Larmor circles of sodium ions are shown in the equatorial plane near the magnetopause (Y axis) dividing magnetosphere (on the left side) and magnetosheath (on the right side). J_{msh} is the magnetizing current carried by sodium ions due to their different densities on both sides of the magnetopause. The X axis is sunward, the Y—towards dusk.

Linear integral current density carried by the magnetosheath sodium ions is [10]:

$$J_{\text{mshy}} = \int_{-2\rho_{\text{msh}}}^{0} j_{\text{mshy}} dx = \frac{e}{2} n_{\text{msh0}} \sqrt{\frac{2kT_{\text{msh}}}{m_{\text{msh}}}} \rho_{\text{msh}} \tag{3}$$

The magnetic field generated by the sodium ion current density j_{mshy} (Equation (1)) is determined by the equation: curl $(B_z(x)/\mu_0) = j_{\text{mshy.}}$

$B_z(x)$ for $-2\rho_{\text{msh}} < x < 0$ generated by this current sheet according to [10] is:

$$B_z(x) = -B_0 - \frac{\mu_0 e}{2\pi} n_{\text{msh0}} \sqrt{\frac{2kT_{\text{msh}}}{m_{\text{msh}}}} \rho_{\text{msh}} \left[\left(1 + \frac{x}{\rho_{\text{msh}}}\right) \sqrt{1 - \left(1 + \frac{x}{\rho_{\text{msh}}}\right)^2} + arcsin\left(1 + \frac{x}{\rho_{\text{msh}}}\right) \right] \tag{4}$$

where

$$B_0 = -\frac{B_{\text{msh0}} + B_{\text{msh0}}}{2} \tag{5}$$

is the background magnetic field strength. Here, B_{msh0} and B_{msph0} are magnetic fields in the magnetosheath and magnetosphere, respectively, outside the considered current sheet of Na^+ ions. From the magnetic field data presented by Slavin et al. [2], rough estimations give B_{msh0}~30 nT and B_{msph0}~90 nT, thus, $B_0 = -60$ nT.

3. Results

For the sodium ion density outside the magnetosphere and inside it, close to the magnetopause, Exner et al. [11] give a modeled result of 1–100 cm^{-3}. Mȕller et al. [3], considering the possibility that Na^+ ions play a significant role in creation of a double boundary layer, noted that the density of these ions can reach ~10 cm^{-3} in the inner dawn magnetosphere. Thus, the estimated value of n_{msh0} varies considerably. Moreover, this value is time dependent and therefore subject to change.

In Figure 3 we present calculations by Equation (4), which show that $n_{\text{msh0}} = 2\ \text{cm}^{-3}$ provides the best coincidence with observations.

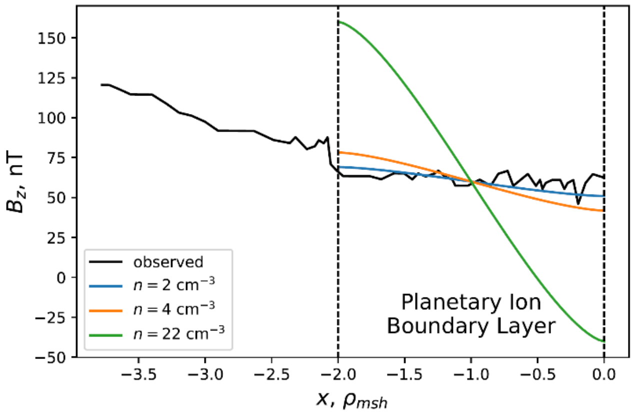

Figure 3. Magnetic field of the current of Na^+ ions in the magnetospheric boundary layer. The black curve marks the observed magnetic field during M1 flight [2]; colored curves indicate calculation results by Equation (4) for $n_{\text{msh0}} = 2\ \text{cm}^{-3}$ (blue), $n_{\text{msh0}} = 4\ \text{cm}^{-3}$ (orange), and $n_{\text{msh0}} = 22\ \text{cm}^{-3}$ (green). The right vertical dashed line marks the magnetopause. The left dashed vertical line is the inner sodium ion current boundary at $-2\rho_{\text{msh}}$.

Figure 3 shows that in the considered case, under the assumption that the sodium magnetosheath pick-up ions penetrate into the Mercury's magnetosphere, creating the observed boundary layer, and in the approach used by Belenkaya [4,10], the density excess of these Na^+ magnetosheath ions relative to the magnetospheric density of sodium ions should be n_{msh0} ~2 cm^{-3}.

4. Discussion and Conclusions

Möller et al. [3] stated that the phenomena leading to the formation of a double magnetopause observed at the dawn magnetospheric boundary during the M1 and M2 flybys are not well understood. The authors used the hybrid simulation code A.I.K.E.F. (Adaptive Ion-Kinetic Electron-Fluid) [12]. The asymmetry of the plasma and magnetic field parameters leads to special processes that can be described using the kinetic approach. The A.I.K.E.F. code was used, in particular, for investigation of the interaction of the solar wind with Mercury [12]. The hibrid approach includes kinetic analysis of ions, since their Larmor radii are comparabel to the scale of the obstacle, and electrons are considered to be neutralizing liquid. This code was also used, for example in [13], to study the interaction of the Kronian magnetosphere with Dione.

For the M1 flight around Mercury, Möller et al. [3] received good agreement with observations even in the absence of sodium ions in the solar wind and in the Hermean exosphere. They found that the inner narrow current sheet can be generated by proton pressure gradients caused by trapped protons. However, Möller et al. [3] noted that, nevertheless, heavy ions may be important for the Hermean magnetospheric current systems generation.

Here, we estimate the sodium ions density excess in the magnetosheath required to generate a wide boundary layer in the Hermean dawn magnetosphere during the M1 flyby, under the assumptions that the inner narrow current sheet is caused by proton pressure gradients [3], and the outer current sheet is a typical magnetopause shielding current created by solar wind protons [2].

In order to do this, we used the analytical expressions obtained by Belenkaya [10] for the magnetopause diamagnetic currents carried by the magnetosheath ions. Comparison with the observed magnetic field data in the D-BL region [2] during the M1 flyby shows that the magnetosheath Na^+ density excess should be n_{msh0} ~2 cm^{-3}. In this case, the violation of the symmetry of the plasma parameters at the magnetopause could explain the observations.

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