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Solar Wind Influences on the Induced Magnetic Field of Mars: MAVEN Observations

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Abstract: Since ancient times, human beings have never stopped exploring outer space. As one of the eight planets, Mars has naturally become one of our key research objects. This paper mainly studies the characteristics and influencing factors of the Martian space environment. By using MAVEN's observation data for many years, we found that the intensity of the induced magnetic field is enhanced under the condition of high solar wind pressure, and this phenomenon is explained by the analysis method based on MHD equation.

1. Introduction

As is known to all, Mars is a special exist in solar system, it's a terrestrial planet, but unlike Earth, it lacks a thick atmosphere like Earth's and a water source. According to long-term studies by scientists, Mars is in this condition because it lacks a strong magnetic field like the Earth.

Mars has a much cooler and less active core than Earth, which makes it unable to generate a strong magnetic field through the dynamo effect. Mars also lacks the plate tectonics that are present on Earth, which can help to maintain a magnetic field over geological time scales. Although Mars does have some areas of localized magnetic fields[1], they are not strong enough to create a global dipole field. This shows that a little radiation from the solar wind and other charged particles will also have a relatively great impact on Mars, which can lead to the erosion of its atmosphere and the loss of water over time[2].

Solar wind is a stream of charged particles, mostly protons and electrons, which are constantly emitted from the Sun's corona into space. The solar wind is the primary driver of space weather in the Solar System, and its interaction with planetary space environment (primarily magnetosphere) is a key factor in shaping their atmospheres and ionospheres [3][4].

Solar wind flows along with the "frozen-in" interplanetary magnetic field (IMF). The IMF is created by the magnetic field carried by the solar wind that is embedded in the plasma. The solar X-rays and extreme ultraviolet radiation emitted by the sun ionizes Mars' upper atmosphere, so Mars' space environment becomes like a highly conductive obstacle with the presence of the ionosphere to the magnetized solar wind. Electric currents are thus induced in the ionosphere, the magnetic pressure becomes slow and the solar wind gets deflected. The IMF gets draped around the planet and the induced magnetosphere is formed. The induced magnetosphere acts as a shield against the solar wind, deflecting charged particles around the planet and protecting its atmosphere from erosion. However, the Martian induced magnetosphere is not strong enough to completely protect the planet, and the solar wind can still have a significant impact on the erosion of Martian atmosphere[3][4][5].

Ionospheric erosion has a great influence on the atmosphere of Mars.When charged particles from the solar wind collide with the Martian atmosphere, they can ionize its molecules, creating a layer of charged particles called the ionosphere. The ionosphere is a key part of the Martian atmosphere, as it helps to protect the planet from harmful solar radiation. However, the ionosphere can also be eroded by the solar wind, leading to a loss of atmospheric gases and a decrease in atmospheric density.

High-energy particles from solar wind can produce an effect on Martian atmosphere, causing the escape of atmospheric particles into space. This loss of atmosphere can lead to a decrease in atmospheric pressure and temperature, which can have significant impacts on the planet's climate and habitability.

These impacts are critical factors that will be considered for future human exploration of Mars. A detailed research about the connection between Mars and solar wind can make it easier for us to get to know the interaction among solar system, solar wind and planets. Although measurement by previous spacecraft missions such as Phobos-2, Mars Global Surveyor and so on, all have helped us better understand the environment Of Mars, in view of the measurement technology and orbital coverage we have so far, we can't get the complete structure of Mars induced magnetic field. However, a recent mission by NASA, Mars Atmosphere and Volatile EvolutioN (MAVEN) spacecraft enables us to study the global average induced magnetic field configuration around Mars.

By observing and analyzing the data accumulated by ion analyzer (SWIA) and magnetometer (MAG) for 6 years, as well as different parameters of the solar wind recorded by plasma instruments, we are able to find out how the MF and solar wind dynamic pressure have a hold on the induced magnetic field of Mars.

2. Instrument and Data

2.1 Instrument

The MAVEN data that we used for the research is from the measurements of the Solar Wind Ion Analyzer (SWIA) and the Magnetometer (MAG).

The SWIA instrument on the MAVEN mission is designed to survey the flow of solar wind ions around Mars, both upstream and in regions within the bow shock. These measurements are meaningful for us to the atmospheric escape from the Martian system and the structure of the dynamic magnetosphere. SWIA is equipped with a ring energy analyzer which has electrostatic deflectors ,can provide a wide field of view for 3-axis spacecraft and a mechanical attenuator that allows high dynamic range.SWIA enables high-resolution measurements of ion velocity distributions with the energy ranging from 5 eV to 25 keV. Fundamental properties of the solar wind at a frequency of 0.25 Hz can be measured by on-board calculations of volume moments and energy spectra. The full three-dimensional distribution takes only 8 seconds by SWIA, which greatly improves the efficiency.

The magnetic field instrumentation consists of two independent tri-axial fluxgate magnetometer sensors and each magnetometer can measure the ambient vector magnetic field over a wide dynamic range (to 65,536 nT per axis) with a resolution of 0.008 nT. Its accuracy can be better than 0.05%. MAG can measure magnetic field vectors at rate of 32 vector samples per second.

The data collected by various plasma instruments and the magnetometer contributes to the overall objectives of the MAVEN mission in characterizing the upper atmosphere, at the same time, estimating the total loss of atmospheric gases throughout Mars' history.

2.2 Data

There are two datasets for this research. The first dataset which includes the magnetic field data of the entire Martian space environment is derived from the MAG and the second dataset which includes the data of upstream solar wind parameters of the solar wind particles (mainly protons) is derived from the (SWIA).

We examined the data from the MAG and SWIA, spanning from 2014 to 2019. We also use the continuous solar wind data to examine the change of the solar wind from2014 – 2021 and examine the effect of the solar wind on Martian magnetic field. Through these data, we used the data recorded by the magnetometer map the magnetic field distribution around the Martian space environment and use the upstream Solar wind parameter dataset utilized to each orbit to calculate the solar wind's dynamic pressure respectively.

We checked the IMF and solar wind distribution used in our data. We can see it clearly from Figures 1a–1c histograms of the upstream average IMF and solar wind parameters for each orbit to avoid possible statistical basis. The magnitude of the IMF is mostly smaller than 5 nT and peaks near 2 nT. The upstream solar wind velocity is mostly distributed around 400 km/s.

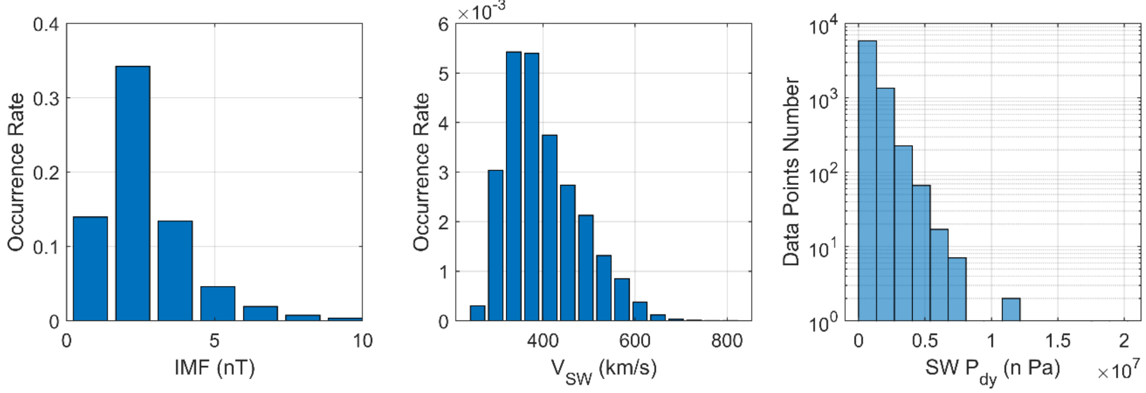

Figure 1: Histograms of (a) the interplanetary magnetic field (IMF) strength, (b) the solar wind velocity, and (c) the solar wind dynamic pressure respectively.

2.3 Method

The magnetic field data provided by MAG, we can directly calculate the data of a certain location of Mars by calculating the magnetic field of three different vectors, and based on the orbital position of the spacecraft provided by the data in Mars-Sun-Orbital (MSO) coordinates, we can map the distribution of the induced magnetosphere around Mars as Figure 1 shows.

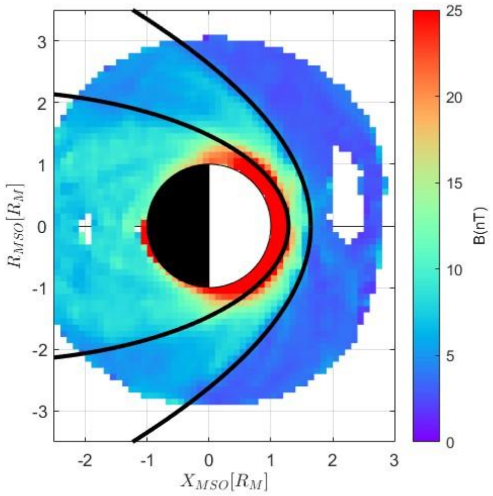

Figure 2: Distribution of the induced magnetic field by the magnetic field observation of MAVEN from 2014 to 2019.

In order to calculate the solar wind's dynamic pressure and study the effect the solar wind on the Martian induced magnetic field, we first calculated the upstream solar wind dynamic pressure for each single orbit using the utilized solar wind dataset by using the equation

$$P_{sw} = n_p m_p v_p^2,$$

Where n_p is the proton density, m_p is the proton mass, and $v_p$is the speed of solar wind. Then, in order to determine a comparative value, we calculate the median which is the whole solar wind dynamic pressure data and designate the value larger than the median as high dynamic pressure and vice versa as low dynamic pressure. After we classify the data the median of solar wind dynamic pressure, we select the data in the magnetic field data by the orbiting time with high dynamic pressure and relatively when the dynamic pressure is low respectively, and finally we can map the Induced magnetic field distribution around Mars under different conditions when the solar wind dynamic pressure change for comparison.

2.4 Results

After we sifted the data and mapped the induced magnetic field distribution around Mars under different solar wind dynamic pressure conditions with MAVEN survey during 2014 to 2019 (Figure 2) , we can see the differences in Figure 3, and the comparison shows that the magnetic field intensity around Mars changes as expected with the magnitude of solar wind dynamic pressure, the high solar wind dynamic pressure in the left-hand plot makes the magnetic field magnetic induction intensity of Mars stronger, while low solar wind dynamic pressure in the right-hand plot makes the magnetic field magnetic induction intensity of Mars weaker. (The distribution of the induced magnetic field strength demonstrates that the strength of the field from magnetosheath to the induced magnetosphere boundary are stronger under high solar wind dynamic pressure conditions compared with the low dynamic pressure ones)

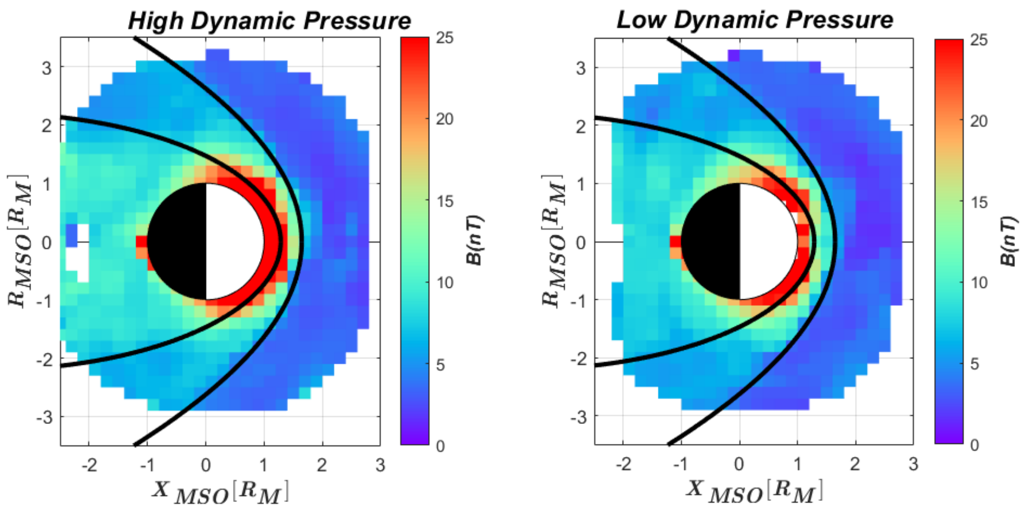

Figure 3: The induced magnetic field distribution of Mars under high (left) and low (right) solar wind dynamic pressure conditions.

3. Conclusion

In this study, based on the magnetic field and upstream solar wind observations by MAG and SWIA onboard MAVEN spacecraft from 2014 to 2019, we mapped Martian environment and its induced magnetic field, meanwhile, systematically studied the influences from the solar wind dynamic pressure. We discovered that the global induced magnetic field's intensity around Mars become enhanced (from the magnetosheath to the induced magnetosphere boundary) due to the compression of higher solar wind dynamic pressure in such conditions.

The physical mechanism behind the compression of what happens to Martian induced magnetosphere can be described by through magnetohydrodynamic (MHD) momentum theory:

$$\rho\left(\frac{\partial}{\partial t}+\mathbf{v}\cdot\nabla\right)\mathbf{v}=-\nabla p+\mathbf{J}\times\mathbf{B} \tag{1}$$

ρ represents plasma density while ∇p is the thermal pressure gradient and J × B is the Hall force generated by the current density J and the magnetic field B. The displacement current term comes from Maxwell-Ampére equation can be neglected while supposing a low-frequency interaction, we can set J = (∇×B)/μ0. When the conditons are stable enough, i.e. ∂/∂t = 0, then the momentum equation weill become

$$\rho(\mathbf{v}\cdot\nabla)\mathbf{v}+\nabla p-\frac{1}{\mu_0}(\nabla\times\mathbf{B})\times\mathbf{B}=0 \tag{2}$$

i.e. the magnetic pressure gradient and the magnetic tension force. Assuming that B varies only in the direction of B, so that (B · ∇) B = 0, the gradient of the magnetic pressure is the one left in the equation. Therefore eq (3) can be written as:

$$\rho(\mathbf{v}\cdot\nabla)\mathbf{v}+\nabla p+\nabla\left(\frac{B^2}{2\mu_0}\right)=0 \tag{3}$$

For the solar wind, the density $\rho=\rho_{\mathrm{sw}}$ and $\mathbf{v}=-v_{\mathrm{sw}}\cos(\theta)\hat{x}$ can be taken into account, tθ is the angle between the solar wind flow and the boundary normal vector $\hat{x}$. At the interface between the solar wind and ionosphere only the1D pressure balance equation is left, it is assumed to be incompressible flow,

$$\frac{\partial}{\partial x}\left(\frac{1}{2}\rho_{\mathrm{sw}}v_{\mathrm{sw}}^2\cos^2\theta+p_{\mathrm{th}}+\frac{B^2}{2\mu_0}\right)=0 \tag{4}$$

solar wind dynamic pressure is expressed as $\rho_{\mathrm{sw}}v_{\mathrm{sw}}^2/2$, p_{th} represents thermal pressure and $\frac{B^2}{2\mu_0}$ is magnetic pressure. relatively small thermal pressure term can be neglected under balanced conditions, so the formula will turn into the following

$$\frac{1}{2}\rho_{\mathrm{sw}}v_{\mathrm{sw}}^2\cos^2\theta+\frac{B^2}{2\mu_0}=\text{ constant} \tag{5}$$

Thus, the solar wind dynamic pressure got balanced because of the induced magnetic pressure, which to help halted and deflect the solar wind , the most important is the location that called Induced Magnetosphere Boundary (IMB) .

The upstream solar wind from the Sun can systematically influence the Martian induced magnetosphere from global distribution to magnetic topology near the surface (Weber et al., 2019), it also serves as primary energy input for the atmospheric charged particles to influence the atmospheric escape rate and ultimately climate evolution[5].

Finally, simultaneous multipoint observations for the upstream solar wind and the Martian space environment in future missions are highly desired, as they can help us better understand how the induced magnetosphere of Mars responds to the sudden change of the upstream solar wind.

According to previous studies, the dynamic pressure of the solar wind will be maintained in a state of equilibrium with the magnetic field pressure of Mars by itself. In present study, when the solar wind strength increases or decreases, the external magnetosphere of Mars will change accordingly with the solar wind, which can make a difference to magnetic field pressure of Mars, and thus the difference in the distribution of magnetic induction intensity of the magnetosphere of Mars will be like the results of the present study.

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