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P2_7 Magnetic Mayhem

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Abstract
This study calculates the increase in solar wind pressure required to compress the nose of the magnetopause of the Earth, down to its surface. It is found that the solar wind pressure would have to increase by at least a factor of 3.06×10^5 to do this.

Introduction

The magnetic field of the Earth acts as a shield against the solar wind, which is a stream of highly energetic plasma released from the solar corona [1]. The highly energetic particles within the solar wind are deflected by the Lorentz force associated with the Earth's magnetic field, preventing them from interacting with the planet's atmosphere or surface. In some cases, the solar wind pressure is strong enough to compress magnetospheres; the magnetosphere of Mercury can be compressed down to the surface of the planet, allowing the solar wind to interact with the surface [1]. Other planets without a magnetosphere, such as Venus, have their atmospheres continuously stripped away by the incoming solar wind [1]. This study calculates the solar wind pressure needed to compress the Earth's magnetosphere down to the surface of the planet, allowing the solar wind to interact with the atmosphere and surface.

Theory

The magnetopause is the boundary between the Earth's magnetic field and the solar wind. At this boundary, the solar wind momentum flux, or dynamic pressure, is balanced with the magnetic pressure associated with the Earth's magnetic field. This implies

$$\rho_{SW} V_{SW}^2 = \frac{B_{MP}}{2\mu_0}, \quad (1)$$

where ρ_{SW} is the mass density in the solar wind, V_{SW} is the velocity of the solar wind, B_{MP} is the Earth's magnetic field at the magnetopause, and μ_0 is the permeability of free space [2]. The pressure associated with the Interplanetary Magnetic Field (IMF) and the dynamic pressure associated with the plasma within the magnetosphere are considered negligible [2].

Since there is a gradient between the magnetic fields of the IMF and the Earth's magnetosphere at the magnetopause, Ampère's law implies that there must be a current sheet existing at this boundary. In turn, this current has a magnetic field associated with it which acts to enhance the Earth's dipolar magnetic field strength at the magnetopause such that

$$B_{MP} = 2B_{dipole} \quad (2)$$

where B_{dipole} is the magnetic field strength of the Earth's dipolar field [3]. In the equatorial plane of the Earth, the dipolar magnetic field strength drops off as $1/r^3$ where r is the distance from the Earth's surface. The magnetic field strength of the Earth at the nose of the magnetopause in the equatorial plane is given by

$$B_{dipole} = B_{eq}\left(\frac{R_P}{R_{MP}}\right)^3, \quad (3)$$

where B_{eq} is the equatorial magnetic field strength at the Earth's surface, R_P is the radius of the Earth, and R_{MP} is the distance from the centre of the Earth to the magnetopause, known as the magnetopause stand-off distance [3].

Now, substituting equation (3) into equation (2) and then equation (2) into equation (1) gives

$$\rho_{SW} V_{SW}^2 = \frac{2B_{eq}^2}{\mu_0}\left(\frac{R_P}{R_{MP}}\right)^6, \qquad (4)$$

where the left hand side of equation (4) is the solar wind dynamic pressure.

Results and Conclusions

Setting $R_{MP} = R_P$ in equation (4) will give the solar wind dynamic pressure needed to compress the nose of the magnetopause to the surface of the planet. The equatorial field strength of the Earth B_{eq} is typically $0.305 \times 10^{-4} T$ [4]. Therefore, using these numbers in equation (4) gives a solar wind pressure to compress the magnetopause to the surface of the Earth of $1.53 \times 10^{-3} Pa$. The number density of particles in the solar wind is typically in the range of $3 - 6\ particles/cm^3$ and the bulk velocity of the solar wind ranges from $350 - 700\, km/s$ [5]. Using the fact that $\rho_{SW} = nm_p$ where n is the number density in the solar wind and m_p is the mass of a proton, we can use the upper limits of the solar wind particle number density and velocity in the left hand side of equation (4) to calculate the maximum solar wind pressure. This gives a pressure of $\sim 5 \times 10^{-9} Pa$. It can therefore be seen that the solar wind pressure would need to increase by at least a factor of 3.06×10^5 to compress the nose of the magnetosphere down to the surface of the Earth. For comparison the magnetopause of Mercury can be compressed down to its surface [6]. However, the typical magnetopause stand-off distance of Mercury is 1.5 planetary radii compared to the 10 planetary radii for the Earth [7]. This is due to Mercury's closer proximity to the Sun and its weaker magnetic field. It can therefore be seen that a smaller increase in the solar wind dynamic pressure is required to compress the Hermean magnetopause down to the planetary surface than for the Earth.

Geomagnetic storms are disturbances in the magnetosphere due to increased solar wind pressure from events such as a solar coronal mass ejections or a co-rotating interaction regions [8]. These interactions will cause an increase in the movement of plasma throughout the magnetosphere and an increase in the current sheet at the magnetopause boundary. This can effect satellite instruments and other electronic equipment on the surface, if there was a geomagnetic storm strong enough to compress the magnetopause to the surface of the planet. The largest recorded geomagnetic storm, known as the Carrington event, occurred in 1859 and caused telegraph lines to be become electrified and auroral activity as low as Hawaii and Cuba to be witnessed [9].

An event which causes the magnetopause to be compressed to the surface of the Earth would result in severe problems for all electronic equipment due to the increased electric currents. Fortunately, it is unlikely that the solar wind pressure will increase by a factor of 3.06×10^5. It has however been seen that large geomagnetic storms can cause electrical problems at the surface of Earth and it has been predicted that another large magnetic storm could occur between 2012 and 2022 [10]. Therefore, studies into predicting and protecting against such events are important.

References

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