Invariant Modulation of Solar Wind Energy Input into the Magnetosphere by IMF Clock Angle (Postprint)

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Abstract

By use of the global PPMLR Magnetohydrodynamics (MHD) model, a series of quasi-steady-state numerical simulations were conducted to examine the modulation property of the interplanetary magnetic field (IMF) clock angle θ on the solar wind energy input into the magnetosphere. All the simulations can be divided into seven groups according to different criteria of solar wind conditions. For each group, 37 numerical examples are analyzed, with the clock angle varying from 0° to 360° with an interval of 10° while keeping the other solar wind parameters (such as the solar wind number density, velocity, and the magnetic field magnitude) unchanged. As expected, the solar wind energy input into the magnetosphere is modulated by the IMF clock angle. The axisymmetrical bell-shaped curve peaks at the clock angle of 180°. However, the modulation effect remains invariant under varying solar wind conditions. The functional form of such an invariant modulation is found to be $\sin^{2.70}(\theta/2) + 0.25$.

Full Text

Invariant Modulation of IMF Clock Angle on Solar Wind Energy Input into the Magnetosphere

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Abstract

Using the global PPMLR magnetohydrodynamics (MHD) model, we conduct a series of quasi-steady-state numerical simulations to examine the modulation properties of the interplanetary magnetic field (IMF) clock angle ( ) on solar wind energy input into the magnetosphere. All simulations are divided into seven groups according to different solar wind conditions. For each group, we analyze 37 numerical examples with the clock angle varying from 0° to 360° at 10° intervals, while keeping other solar wind parameters (such as solar wind number density, velocity, and magnetic field magnitude) unchanged. As expected, the solar wind energy input into the magnetosphere is modulated by the IMF clock angle, exhibiting an axisymmetrical bell-shaped curve that peaks at a clock angle of 180°. However, this modulation effect remains invariant across varying solar wind conditions. The functional form of this invariant modulation is found to be $\sin^2 \cdot$ (/2) + 0.25.

Keywords: MHD simulation, clock angle, energy input, energy coupling function

1 Introduction

The energy input from the solar wind into the magnetosphere is regarded as the ultimate source of dynamics for the magnetosphere-ionosphere (M-I) system, driving numerous space weather phenomena such as magnetic storms, substorms, aurora, and other magnetospheric activities [?]. However, quantitative direct measurement of this energy input in a global context remains a major challenge even today, necessitating the development of numerous theoretical and empirical methods that rely on activity proxies instead. For example, previous studies [?, ?, ?, ?, ?] have suggested that solar wind conditions, the interplanetary magnetic field (IMF), and the IMF clock angle control the energy input from the solar wind into the magnetosphere. Perreault and Akasofu (1978) developed a widely-used empirical parameter to represent the energy input power, where [MATH_FORMULA] is an empirical scaling factor, [MATH_FORMULA] is the solar wind velocity, [MATH_FORMULA] is the IMF magnitude, and [MATH_FORMULA] is the IMF clock angle with [MATH_FORMULA]. From the perspective of theoretical dimensional analysis, Vasyliunas et al. (1982) developed a physically-based general expression for the energy coupling function, though some parameters remained undetermined. Additionally, other coupling functions have been proposed [?, ?, ?, ?].

Recently, global 3-D MHD simulations have provided an effective approach for investigating energy coupling processes in the solar wind-magnetosphere-ionosphere (SW-M-I) system [?, ?]. Palmroth et al. (2003) developed a new method to characterize solar wind power input at the magnetopause using the global MHD simulation GUMICS-4. The magnetopause was determined using solar wind streamlines (see details in Palmroth et al., 2003), and the energy input could be calculated based on the magnetopause using the following equation: [MATH_FORMULA], where [MATH_FORMULA] is the area of the surface element and [MATH_FORMULA] is the unit normal vector. The term [MATH_FORMULA] represents the total energy flux density (including thermal, kinetic, and electromagnetic terms).

Building upon the PPMLR MHD simulation, Wang et al. (2014) determined the specific form of the general expression given by Vasyliunas et al. (1982). The energy coupling function is expressed as follows: [MATH_FORMULA], where [MATH_FORMULA] is the solar wind number density, [MATH_FORMULA] is the solar wind velocity, [MATH_FORMULA] is the transverse magnetic field, and [MATH_FORMULA] is the IMF clock angle. The modulation of the IMF clock angle on energy input is [MATH_FORMULA]. They suggested that this modulation of the IMF clock angle is independent of the IMF magnitude. While Wang et al. (2014) focused primarily on how energy input is affected by solar wind conditions and IMF, they used dimensional analysis and global MHD simulation to determine the specific form of the solar wind-magnetosphere energy coupling function. From this energy coupling function, we can conclude that the manner in which the IMF clock angle affects the energy input process is independent of solar wind parameters and IMF magnitude. In this paper, we use the PPMLR MHD simulation to study the effects of other solar wind parameters on the form of [MATH_FORMULA] to validate the conclusion regarding the invariance of the IMF clock angle control effect on energy input.

2 Simulation Model and Data Sets

This study employs the global 3D Piecewise Parabolic Method with a Lagrangian Remap (PPMLR) MHD simulation model developed by Hu et al. (2005) and Hu et al. (2007) to simulate the SW-M-I coupling system. The ideal MHD equations are solved in the solar wind and magnetosphere, and the model is coupled to an electrostatic ionosphere with third-order spatial precision, second-order temporal precision, and very small numerical dissipation. Many scientific problems, such as the interaction of interplanetary shocks with the magnetosphere, large-scale current systems, and Kelvin-Helmholtz instabilities at the magnetopause [**?**, **?**, **?**], have been successfully investigated using this model. The solution domain of the code extends from -300 RE to 30 RE in the X direction and from -150 RE to 150 RE in the Y and Z directions in the GSM coordinate system, comprising 160×162×162 grid points in total. A uniform mesh with grid spacing of 0.4 RE is applied in the near-Earth domain of 0 RE $<$ |X, Y, Z| $<$ 10 RE, while the grid spacing outside this region increases according to a geometric series with a common ratio of 1.05 along each axis. We set the inner boundary at 3 RE to avoid complexities associated with the plasmasphere and strong magnetic fields. For simplicity, a uniform Pedersen conductance of 5 S is prescribed in the ionosphere, and the Hall conductance is assumed to be zero. The code solves the MHD equations in fully conservative form in the SW-M system, while electrostatic equations are solved in the ionosphere. The coupling between the magnetosphere and ionosphere consists of mapping field-aligned currents from the inner boundary of the magnetosphere to the ionosphere and mapping the electric potential in the opposite direction, with both mappings occurring along Earth' s dipole field lines.

To investigate the invariance of the IMF clock angle control effect on the energy input process, we conducted seven groups of simulation data cases with fixed solar wind parameters and IMF magnitude, while rotating the IMF clock angle from 0° to 360° at 10° intervals. Each group dataset includes 37 quasi-steady cases. The IMF x-component is set to zero to ensure magnetic field non-divergence. Table 1 summarizes the solar wind conditions for each group dataset. Datasets NO.1-3 are designed to study the effect of IMF magnitude on the IMF clock angle control effect on energy input. Datasets NO.1, NO.4, and NO.5 examine the density effect, while datasets NO.1, NO.6, and NO.7 investigate the velocity effect.

3 Methodology

In this study, we use the streamline method developed by Palmroth et al. (2003) to identify the magnetopause by approximately locating the inner edge of the void encompassed by solar wind streamlines, with some minor improvements [**?**, **?**]. First, we create a set of streamlines at X = +25 RE, well beyond the bow shock. In the YZ plane, a circle with a radius of 25 RE is established to divide the streamline grid, with its center located on the X axis. The radial distance between neighboring streamlines is 0.5 RE and the angular separation is 1°, yielding 18,000 streamlines in total. Second, the inner boundary of each YZ plane is sought from X = 25 RE to X = -60 RE by excluding the three closest streamlines. Test results indicate that the magnetopause obtained by this streamline method matches plasma density contours very well.

After the magnetopause surface is identified, we can calculate the energy flow across the magnetopause surface [**?**]. The energy input into the magnetosphere can be calculated using equation (1). In equation (1), [MATH_FORMULA] is the total energy flux density (including thermal, kinetic, and electromagnetic terms), where [MATH_FORMULA] is the total energy density (including thermal energy density, kinetic energy density, and magnetic energy density), [MATH_FORMULA] is the polytropic exponent, [MATH_FORMULA] is the thermal pressure, [MATH_FORMULA] is the magnetic field, [MATH_FORMULA] is the velocity, and [MATH_FORMULA] is the convection electric field.

4 Results

The function of the IMF clock angle, [MATH_FORMULA], was fitted using dataset NO.1. Figure 1 [Figure 1: see original paper] shows the normalized energy input for different IMF magnitude datasets and [MATH_FORMULA]. The red, green, and blue lines represent the normalized energy input results averaged over each group for datasets NO.1, NO.2, and NO.3, respectively. While different IMF magnitudes result in different energy inputs, the IMF magnitude does not affect the functional form of the IMF clock angle function nor alter the control effect of the IMF clock angle on the energy input process. The prediction efficiency (PE) for BT = 5 nT, 10 nT, and 20 nT is 0.98, 0.97, and 0.95, respectively.

Figures 2 [Figure 2: see original paper] and 3 [Figure 3: see original paper] present the same type of results but for different solar wind densities and velocities. In Figure 2, the red solid line shows the normalized energy input for the N = 5 cm ^{3} dataset, the green line for N = 10 cm ^{3}, and the blue line for N = 15 cm ^{3}. The figure indicates that the variation trends of normalized energy input across different solar wind density cases show little difference and are very similar to the variation trend of [MATH_FORMULA]. The PEs are 0.98, 0.95, and 0.94 for N = 5, 10, and 15, respectively. In Figure 3 [Figure 3: see original paper], the red, green, and blue lines represent the normalized energy input for V = 400, 600, and 800 km/s. The velocity results are similar to those of the density datasets, with PE = 0.98, 0.99, and 0.97. Solar wind parameters such as density, velocity, and IMF magnitude all contribute to the energy input into the magnetosphere. Furthermore, from equation 2 we can conclude that larger solar wind parameters with the same IMF clock angle contribute more to the energy input. However, the increase in energy input does not result from variation of [MATH_FORMULA], and variation of solar wind parameters does not change the functional form of [MATH_FORMULA].

5 Discussion and Conclusion

Seven groups of datasets with constant solar wind parameters and IMF magnitude, but with IMF clock angle varying from 0° to 360° at 10° intervals, were conducted using PPMLR MHD simulation. Each group dataset includes 37 quasi-steady-state cases. The transferred energy of these cases is calculated using the method from Wang et al. (2014), and the energy of each group dataset is normalized by the average energy of the group cases. The simulation results indicate that solar wind parameters such as velocity and density, as well as IMF magnitude, do not affect the control effect of the IMF clock angle on energy input. Previous studies [**?**] and our simulation results have shown that the energy input process occurs mainly on the dayside magnetopause and in the near magnetotail through magnetic reconnection. Additionally, the simulation results indicate that while solar wind parameters and IMF magnitude can affect the energy input process and the magnetopause configuration of the far magnetotail, they do not significantly change the magnetopause configuration in the near magnetotail and dayside region. The dayside magnetopause configuration and the near magnetotail magnetopause configuration determine the mode of solar wind energy input into the magnetosphere. Therefore, this explains why solar wind parameters and IMF magnitude do not change the functional form of [MATH_FORMULA]. Variation of solar wind parameters and IMF magnitude can result in energy input variation but does not change the pattern of energy input variation with IMF clock angle.

The function [MATH_FORMULA] can be regarded as a sluice gate of a dam. Its specific form is like the width and height of the sluice gate—an intrinsic attribute of the magnetosphere that remains unchanged. The IMF clock angle is like the opening size of the sluice gate: if the IMF is more southward, the opening size is larger. Solar wind parameters such as velocity and density are like the velocity and density of water flow in the dam. Just as water flow velocity and density do not change the width and height of the sluice gate, solar wind parameters do not change the specific form of [MATH_FORMULA]. We conducted a series of simulations, and the results indicate that solar wind parameters and IMF magnitude do not change the pattern of energy input variation with IMF clock angle. The specific form of [MATH_FORMULA] is an intrinsic attribute of the magnetosphere. These results are consistent with Vasyliunas et al. (1982).

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