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

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Abstract By use of the global PPMLR Magnetohydrodynamics (MHD) model, a serial of quasi-steady-state numerical simulations were conducted to examine the modulation property of the interplanetary magnetic field 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°, 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 with varying other solar wind conditions. The function form of such an invariant modulation is found to be $\sin(\theta/2)^{2.70} + 0.25$.

Key words MHD simulation, Clock angle, Energy input, Energy coupling function

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0 Introduction

The energy input into the magnetosphere from the solar wind is regarded as the ultimate source of dynamics of the Magnetosphere-Ionosphere (M-I) system, which drives many space weather phenomena, such as magnetic storms, substorms, aurora and other magnetospheric activities[1]. The Solar Wind-Magnetosphere (SW-M) system energy coupling has been the frontier and hot issue in space physics. However, quantitatively direct measurement of determining such energy input in the global context is still a key challenge until today. Therefore, a large number of theoretical or empirical methods have to be developed to assess the power input relying on activity proxies instead. For example, some previous works[2−6] suggested that the solar wind conditions, Interplanetary Magnetic Field (IMF) and the clock angle of the IMF controlled the energy input from the solar wind into the magnetosphere. Perreault and Akasofu[2] developed the widely-used parameter

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$$\varepsilon = \left(\frac{4\pi}{\mu_0}\right) v B^2 l_0^2 \sin^4\left(\frac{\theta}{2}\right)$$

to represent the energy input power empirically, where l_0^2 is an empirical scaling factor, v is the solar wind velocity, B is the IMF magnitude, θ is the IMF clock angle with $\tan\theta = B_y/B_z$. From the aspect of theoretical dimensional analysis, Vasyliunas *et al.*[6] developed a physically-based general expression of the energy coupling function. However, some parameters are not determined. Besides, other coupling functions have been proposed[7−10].

Recently, global 3-D MHD simulations provide an effective approach to investigate the energy coupling processes in the Solar Wind-Magnetosphere-Ionosphere (SW-M-I) system[11−14]. Palmroth *et al.*[14] developed a new method to characterize the solar wind power input at the magnetopause using the global MHD simulation GUMICS-4. The magnetopause is identified with solar wind streamlines (see details in Ref. [14]). The energy input can be calculated based on the magnetopause with the follow equation:

$$E_{\rm in} = \int {\rm d}A \boldsymbol{K}\cdot\hat{\boldsymbol{n}}, \tag{1}$$

where dA is the area of the surface element and $\hat{\boldsymbol{n}}$ is the unit normal vector. $\boldsymbol{K}$ is the total energy flux density including thermal, kinetic and electromagnetic terms. Lu *et al.*[12] and Jing *et al.*[11] studies the energy input distribution on the magnetopause of quasi-steady state for northward and southward interplanetary magnetic fields and during sudden changes of the IMF orientation respectively based on the MHD simulation and streamline method.

Basing on the Piecewise Parabolic Method with a Lagrangian Remap (PPMLR) MHD simulation, we determined the specific form of the general expression given by Vasyliunas *et al.*[6] in our previous work[15]. The energy coupling function is given as:

$$E_{\rm in} = 3.78\times10^7 n^{0.24} v^{1.47} B_{\rm t}^{0.86}\cdot \left[\sin\left(\frac{\theta}{2}\right)^{2.70} + 0.25\right]({\rm W}), \tag{2}$$

where n is the solar wind number density, v is the solar wind velocity, $B_{\rm t}$ is the transverse magnetic field, and θ is the IMF clock angle. The modulation of IMF clock angle on the energy input is $G(\theta) = \sin(\theta/2)^{2.70} + 0.25$, which is obtained using one group data with solar wind parameters and IMF magnitude unchanged. In Ref. [15], the situation that such modulation of IMF clock angle is independent on the IMF magnitude is used to validate the fitting process and to prove that the solar wind parameters and IMF do not change the form of $G(\theta)$, but do not give more details and the explanation. Wang *et al.*[15] mainly focused on the energy input affected by solar wind conditions and IMF and the energy coupling function fitting. In this paper, we will study the situation that the modulation of IMF clock angle is independent on the IMF magnitude and solar wind parameters (such as velocity and density) in detail and give an explanation using the PPMLR MHD simulation to validate the conclusion of the invariance of IMF clock angle control effect on the energy input. This paper is a supplement and further study of Wang *et al.*[15] and meanwhile a complete research with Wang *et al.*[15].

1 Simulation Model and Data Sets

As there are as yet no global measurements that would continuously provide direct estimates of the solar wind energy input into the magnetosphere, we apply the global 3D PPMLR MHD simulation model developed by Hu *et al.*[16−17] to simulate the SW-M-I coupling system and calculate the energy input. The ideal MHD equations are solved in the SW-M system, and the model is coupled to the electrostatic ionosphere with third-order spatial precision, second-order temporal precision, and very small numerical dissipation. Many scientific problems, such as the energy coupling function fitting, the polar cap open magnetic flux, large-scale current systems, the shape of magnetopause, the energetic characteristics of the super magnetic storm and Kelvin-Helmholtz instabilities at the magnetopause[15,18−23] have been successfully studied based on this model. The solution domain of the code is taken to be $-300\,R_{\rm e} \leqslant x \leqslant 30\,R_{\rm e}$ and $-150\,R_{\rm e} \leqslant y,\ z \leqslant 150\,R_{\rm e}$ in GSM coordinate system and it includes $160 \times 162 \times 162$ grid points in total with a uniform mesh grid $0.4\,R_{\rm e}$ in the near-Earth domain of $0 < |x, y, z| < 10\,R_{\rm e}$, and the grid spacing outside increases according to a geometrical series of common ratio 1.05 along each axis. The inner boundary is taken at $3\,R_{\rm e}$ centered on the Earth to avoid the complexity associated with the plasma sphere and the strong magnetic field. A spherical surface with $R_{\rm ion} = 1.017\,R_{\rm e}$ is taken as the ionosphere boundary with a uniform Pedersen conductance of 5 S and zero Hall conductance for simplicity. The computations continue for more than 5 h in physical time when the SW-M-I system reaches a quasi-steady state. The relative changes of key parameters such as the magnetic field, density, velocity *etc.* are less than 5% for the time interval of about half an hour. The MHD equations are solved in fully conservative form in the SW-M system and the electrostatic equations are solved in the ionosphere. In M-I system, we map the field-aligned currents near the inner boundary into the ionosphere by magnetic field lines and remap the electric field obtained from a Poisson equation to the inner boundary in the opposite direction to obtain the convective velocity. More details of the model and the numerical algorithm see Ref. [17].

To investigate the effect invariance of the IMF clock angle control effect on the energy input process, seven groups of simulation data cases have been conducted with the unchanged solar wind parameters and IMF magnitude and the IMF clock angle rotating from 0° to 360° with 10° interval. Every group of data set includes 37 quasi-steady cases. The IMF x component is set to zero to ensure the non-divergence of magnetic field. Table 1 summarizes the solar wind conditions of each group of data set. No.1~3 data set are to study the IMF magnitude effect on the IMF clock angle control effect on the energy input. No.1, No.4, and No.5 are to study the density effect. No.1, No.6, and No.7 are to study the velocity effect.

Table 1 Solar wind conditions of seven groups of data sets (IMF clock angle is 0°~360°)

No.	density/cm^{-3}	velocity/(km·s^{-1})	IMF $B_{\rm t}$/nT
1	5	400	5
2	5	400	10
3	5	400	20
4	10	400	5
5	15	400	5
6	5	600	5
7	5	800	5

2 Methodology

In this paper, the streamline method developed by Palmroth *et al.*[14] is used to identify the magnetopause by finding approximately the inner edge of the void encompassed by the solar wind streamlines with some minor improvements[15,18]. Firstly, we create a set of streamlines beyond the bow shock, about at $x = +25\,R_{\rm e}$. In the yz plane, streamlines grid is set in a circle with a radius of $25\,R_{\rm e}$ centered on the x axis. The circle is divided with $0.5\,R_{\rm e}$ between neighboring streamlines in the radial direction and 1° in the angular direction, giving 18 000 stream lines in total. Secondly, the 18 000 streamlines are tracked in steps of $0.5\,R_{\rm e}$ in the x direction from $x = 25\,R_{\rm e}$ until to $x = -60\,R_{\rm e}$. And the inner boundary of each yz plane is sought for each step by excluding three closest streamlines. The test results indicated that the magnetopause obtained by streamline method matched with the plasma density contours very well at $x > -20\,R_{\rm e}$. However, the density gradients especially in the magnetotail are not sufficiently sharp.

After the magnetopause surface is identified, we can calculate the energy flow across the magnetopause surface[14]. The energy input into the magnetosphere can be calculated by Eq.(1). In Eq.(1), $\boldsymbol{K}$ is the total energy flux density including thermal, kinetic and electromagnetic terms.

$$\boldsymbol{K} = \left(U + P - \frac{B^2}{2\mu_0}\right)\boldsymbol{v} + \frac{1}{\mu_0}\boldsymbol{E}\times\boldsymbol{B}, \tag{3}$$

where $U = \dfrac{P}{\gamma-1} + \dfrac{1}{2}\rho v^2 + \dfrac{B^2}{2\mu_0}$ is the total energy density, including the thermal energy density, kinetic energy density, and magnetic energy density; $\gamma = \dfrac{5}{3}$ is the polytropic exponent; P is the thermal pressure; B is the magnetic field; v is the velocity and $\boldsymbol{E} = -\boldsymbol{v}\times\boldsymbol{B}$ is the convection electric field. More details about the energy input calculation methodology are given by Palmroth *et al.*[14] and Wang *et al.*[15].

3 Results

The function of IMF clock angle $G(\theta)$ was fitted with the No.1 data set. Fig. 1 is the normalized energy input of different IMF magnitude data sets and $G(\theta)$. The hot pink, sea green and dodger blue lines are the normalized energy input results with the average energy of the group cases for No.1, No.2 and No.3 data set, respectively. Different IMF magnitudes will result in different energy input, but the IMF magnitude does not affect the form of the IMF clock angle function and does not change the control effect of IMF clock angle on the energy input process. The prediction efficiency ($\eta_{\rm PE}$) for 5 nT, 10 nT, and 20 nT are 0.98, 0.97, 0.95, respectively.

Fig. 2 and 3 are the same results but for different solar wind densities and solar wind velocities. In Fig. 2, the hot pink solid line is the normalized energy input of $N = 5\,{\rm cm}^{-3}$ data set, the sea green line is for $N = 10\,{\rm cm}^{-3}$, and the dodger blue line is for $N = 15\,{\rm cm}^{-3}$. Fig. 2 indicates that the variation trends of the normalized energy input of different solar wind density cases have little difference and are very similar with the variation trend of $G(\theta)$. The $\eta_{\rm PE}$ is 0.98, 0.95, and 0.94, respectively for $N = 5$, 10, 15. In Fig. 3, the hot pink, sea green and dodger blue lines are the normalized energy input of $v = 400$, 600, 800 km·s^{-1} respectively. The results of velocity are similar with the results of density data sets with $\eta_{\rm PE} = 0.98$, 0.99, 0.97. The solar wind parameters such as density, velocity and IMF magnitude contribute to the energy input into the magnetosphere.

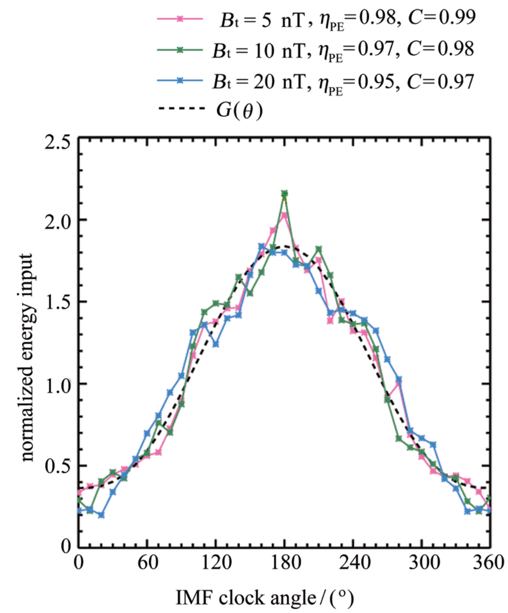

Fig. 1 Normalized energy input of different IMF magnitude versus the IMF clock angle. The hot pink asterisk solid line is the normalized energy input for $B_{\rm t} = 5$ nT, the sea green asterisk solid line is for 10 nT, the dodger blue asterisk solid line is for 20 nT, and the black dashed line is the normalized $G(\theta)$ fitted from the energy input for 5 nT

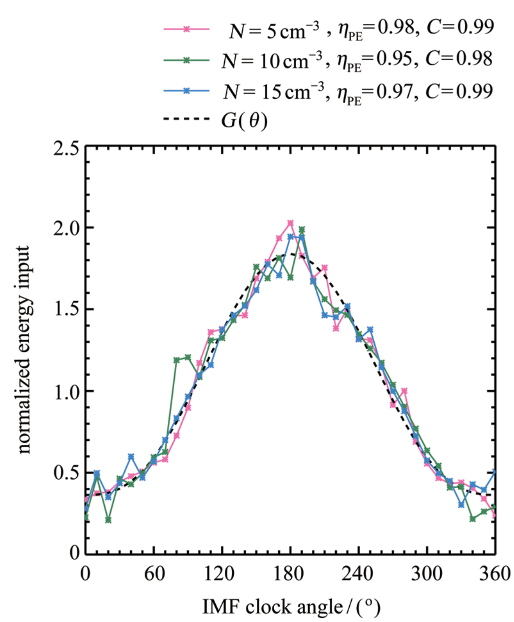

Fig. 2 The same as Fig. 1 but for different density

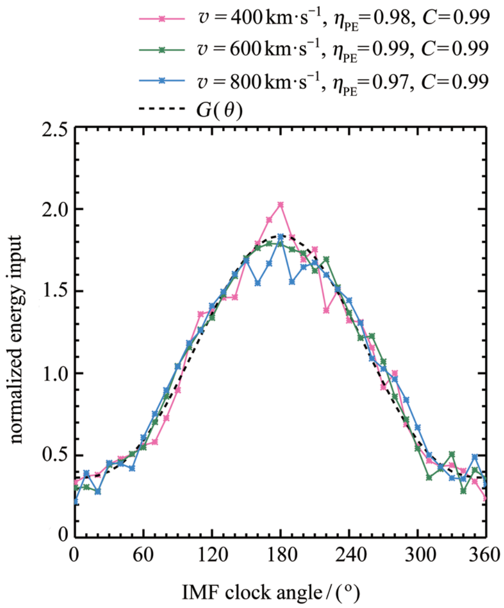

Fig. 3 The same as Fig. 1 but for different velocity

In addition, from Eq. (2) we can conclude that the larger the solar wind parameters with the same IMF clock angle are, the more contribution to the energy input is. However, the increase of energy input does not result from the variation of $G(\theta)$ and the variation of solar wind parameters does not change the form of $G(\theta)$.

4 Discussion and Conclusion

Seven groups of data sets with the solar wind parameters and IMF magnitude keeping constant and the IMF clock angle varying from 0° to 360° with 10° interval are conducted with PPMLR MHD simulation. Each group data set includes 37 quasi-steady state cases. The transfer energy of these cases is calculated with the method of Wang *et al*[15] and the energy of each group of data set is normalized with the average energy of the group cases. The simulation results indicate that the solar wind parameters, such as velocity and density, and IMF magnitude do not affect the control effect of IMF clock angle on the energy input. The previous studies[12] and our simulation results have indicated that the energy input process mainly occurs in the dayside of the magnetopause and the near magnetotail by magnetic reconnection process. In addition, we have conducted some testing simulations and the simulation results also indicated that the solar wind parameters and IMF magnitude can affect the energy input process and the magnetopause configuration of far magnetotail, but do not change the magnetopause configuration significantly in near magnetotail and dayside region (not shown). Furthermore, the dayside magnetopause configuration and the near magnetotail magnetopause configuration determine the mode of the solar wind energy input into the magnetosphere process. Therefore, this can explain why the solar wind parameters and IMF magnitude do not change the form of $G(\theta)$. The variation of solar wind parameters and IMF magnitude can result in the energy input variation but do not change the pattern of the energy input variation with the IMF clock angle.

$G(\theta)$ can be regarded as a sluice gate of the dam. The specific form of $G(\theta)$ is like the width and height of the sluice gate. The specific form is the intrinsic attribute of the magnetosphere and changeless. The IMF clock angle is like the sluice gate opening size. If the IMF is more southward then the opening size of the gate is larger. The solar wind parameters, such as velocity and density, are like the velocity and density of water flow in the dam. The velocity and density of water flow do not change the width and height of the sluice gate. And the solar wind parameters do not change the specific form of $G(\theta)$.

We conducted a series of simulation and the results indicated that the solar wind parameters and IMF magnitude do not change the pattern of the energy input variation with the IMF clock angle. The specific form of $G(\theta)$ is the intrinsic attribute of the magnetosphere. The results are consistent with Vasyliunas *et al.*[6].

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