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PREDICTION OF THE IMF B_z USING A 3-D KINEMATIC CODE

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[**Abstract**] A scenario is introduced for predicting the perturbations of the south-north component B_Z of interplanetary magnetic field (IMF) ahead of fast Coronal Mass Ejection (CME). The three-dimensional (3-D) kinematic code of Hakamada-Akasofu-Fry (1986) is improved according to the scenario. Using the new code, we investigated the perturbation of IMF and plasma caused by the Halo CME at 06: 30UT, May 12, 1997 observed by SOHO in detail. Seventeen events of CME between 1978 and 1981 are examined. Of these 17 events the kinematic code correctly predicts the direction of perturbation of the south-north component of IMF for 14 events (82%). This shows that the direction predicted by the improved code agrees with observations very well.

[**Key words**] Coronal mass ejection, Space weather, Magnetic clouds, Interplanetary magnetic field, Kinematic code.

1 INTRODUCTION

One of the most important purposes of space weather research is to be able to predict geomagnetic disturbances for a specific solar event. In the past century, most of the prediction studies were statistical in nature. Such statistical results can give the qualitative relationship between the intensity of geomagnetic storms, the position and the explosive strength of the responsible solar events. However, it doesn't tell how long it takes for the solar disturbances to transit to the earth, and how the storm develops as a function of time for every special solar event.

In 1986, Akasofu and Fry[1] designed a first generation numerical geomagnetic storm prediction scheme, based on the three-dimensional (3-D) kinematic code developed by Hakamada and Akasofu[2] (referenced as HAF model in the following). Using the HAF model, one can simulate the propagation process of the disturbance in the interplanetary region, the solar wind speed, the plasma density, the three interplanetary magnetic field (IMF) components near the earth, the geomagnetic storm indices and the geometry of the auroral oval caused by a particular solar event. All of these values are as functions of time. Recently, Fry et al.[3] improved the HAF solar wind model to version 2, which can in real-time forecast, following the observed solar events, the solar wind conditions and interplanetary shock arriving time at earth.

Some authors investigated the relationship between different interplanetary disturbances and solar explosive events by the HAF model, which results show that the predictions agree with the observations in most cases. Chao et al.[4] reconstructed the solar wind disturbances during January 1–7, 1978. Two flares with their onset times on January 1, 07:17 UT at S17°E10° and 21:47 UT at S17°E32° respectively, were selected to generate two interplanetary transient shocks. The simulation results show that these two shocks interacted with the corotating shock in interplanetary space such that Helios 1 and Voyager 2 observed only one shock and Helios 1 and IMP 8 observed two shocks. Sun et al.[5] studied a series of events during the period between November 22 and December 6 1977 observed by a set of spacecraft, IMP 7, IMP 8, Helios 1, Helios 2 and Voyager 1. The simulation results also agree with the observation well. LIU et al.[6] investigated the connection between solar filament disappearance events (FD) and interplanetary disturbances using the 3-D HAF method. Good correlationship could be found between FD events and interplanetary disturbances, which indicates that FD events are important candidates as the source of interplanetary disturbance events.

The weakest part of the HAF scheme arises from the fact that causes of changes of the south-north component B_z of IMF are not well understood[1]. The direction of B_z predicted by the scheme is often different from the direction observed by spacecraft. It is well known that B_z plays an essential role on the energy coupling between magnetosphere and solar wind presumably through the process of magnetic reconnection. Intense southward IMF increasing in several hours are documented as causing the main phase of magnetosphere substorms and geomagnetic storms[7]. The origins of the interplanetary southward B_z events are quite varied, as pointed out by Tsurutani et al. from the analysis of the full component spacecraft ISEE3 plasma and field data[8]. Causes of IMF B_z are still one of the most important unsolved problems in solar-terrestrial physics, different reasons are supposed by different authors[9−11].

In this paper, a scenario is introduced for predicting the perturbations of B_z ahead of fast Coronal Mass Ejections (CMEs). The 3-D kinematic code is improved according to the scenario. Using the new code, we investigate the perturbations of IMF and plasma caused by several CMEs. In Section 2, the scenario is described in detail. In Section 3, several disturbance events are simulated using the improved model. Finally, some discussions are given in Section 4.

2 MODEL

2.1 The 3-D Kinematic Model

HAF model provides a first-order construction, temporally and spatially, following the solar observation, of background solar wind as well as shocks generated by solar events, which is very useful for the study of the solar wind macro-scale structure and the investigation of propagation of disturbance in the interplanetary space, and plays an important role for the geomagnetic storm prediction. Their basic assumption is that solar wind particles leave the so-called "source surface" (a spherical surface of radius of $2.5R_{\rm E}$) with only radial velocity, and bring the solar magnetic field into interplanetary region to form IMF through the magnetic frozen theory. The distribution of background solar wind initial speed at the source surface may be given due to the source surface magnetic field by different model[1−3]. The source surface magnetic field is explored from the photospheric magnetic field using the potential field conjecture, which is provided by the Wilcox Solar Observatory, Stanford University (In the second version of HAF model[3], it has been improved to utilize source surface maps from solar observatory data provided to the National Oceanic and Atmospheric Administration/Space Environment Center's (NOAA/SEC) Rapid Prototyping Center (RPC), which is updated daily).

Since the rotation of the sun, particles leaving the source surface with different speed will interact with each other such that particles with higher speed will be decelerated, while particles with lower speed will be accelerated. Basically, this interaction process should follow the Magnetohydrodynamic (MHD) equations. One can solve the MHD equation to decide the velocity of each particle, so to calculate the position R of each particle in the interplanetary region at time t (namely, the $R-t$ relationship). One of the crucial parts of the HAF model is that it uses an empirical $R-t$ relationship, which can reasonably produce the interplanetary forward and reverse shocks as well as other structures, and is comparable to the results obtained from MHD simulation and observation. In 1985, Sun et al.[5] calibrated the six parameters of the empirical $R-t$ relationship by approximating a one-dimensional MHD solution. When there is only the stable background solar wind, the trajectory of an IMF line is decided by the positions of particles leaving from the source surface with same latitude and longitude at different time. The strength of IMF can be calculated from the conservation of magnetic flux or the tightness of its nearby IMF lines.

Two influences on the corona may be produced by a coronal explosion event such as FD event, flare and CME. First, a high speed stream is introduced into the background solar wind stream, which propagates into the interplanetary region and causes the interplanetary shock. Second, the footpoints of coronal magnetic field lines are forced to move aside from center of the event explosion site. This will induce polar and azimuthal IMF vector components. As the disturbance moves outward past the source surface, the field lines gradually return to their original position on the source surface. The distortion of the field lines continues to propagate outward beyond the source surface, and causes the disturbance of IMF B_z, for the imbedding of field line in the outflowing plasma. This IMF B_z disturbance scenario has been considered in reference [1]. An assumed event is given as an example, in that case the background magnetic field configuration is that of a dipole field with a tilt of 20° with respect to the rotational axis. The field line location on the source surface is represented by its magnetic latitude which is disturbed by the explosion event. This kind of field line location model is reasonable for some special cases, but it can't self-adjust the movement of the field line footpoints due to events at different site on the source surface with different background magnetic field. Moreover, it doesn't keep the conservation of magnetic field flux on the source surface. In the following, we will improve the HAF model to overcome the above shortcomings.

2.2 The New Model

Consider a solar center sphere coordinate system, where the z axis is along the line connecting the solar center and the center of disturbance event site on the source surface, xoz plane is the solar longitude plane where the event exposes, θ is the polar angle between the radial direction and the z axis, φ is the azimuth angle between the x axis and the plane formed by the radial direction and the z axis. With this coordinate system, from the law of magnetic flux conservation, one can obtain

$$\frac{\partial B_{\mathrm{R}}}{\partial t}+\nabla\cdot(\boldsymbol{V}B_{\mathrm{R}})=0\,, \tag{1}$$

where $B_{\mathrm{R}}=B_{\mathrm{R}}(\theta,\varphi,t)$ is the radial magnetic field component strength, $\boldsymbol{V}=V_\theta(\theta,t)\hat{\boldsymbol{e}}_\theta$ is the plasma disturbance velocity on the source surface and $\hat{\boldsymbol{e}}_\theta$ is the unit vector in the θ direction. Eq.(1) can be written as

$$\frac{\partial(B_{\mathrm{R}}R_{\mathrm{S}}\sin\theta)}{\partial t}=-\frac{\partial(V_\theta B_{\mathrm{R}}\sin\theta)}{\partial\theta}\,, \tag{2}$$

where R_{S} represents the source surface radius. The variation of B_{R} satisfies $B_{\mathrm{R}}(t\to\infty)=B_{\mathrm{R}}(t=t_{\mathrm{F}})$, namely the disturbed magnetic field will finally self-recover to its original distribution before the starting time t_{F} of the explosion event in the corona. Since we have only one equation, V_θ should be previously given to decide the value of B_{R}. It is difficult to find a general function of V_θ that satisfies Eq.(2), because the initial distribution of B_{R} is complex and varies with different Carrington rotation. In the following, we will use the particle simulation method[12] in space physics to solve Eq.(2).

To calculate the variation of the magnetic field strength B_{R} and the plasma speed V_θ with time at the point $(R_{\mathrm{S}},\theta_0,\varphi_0)$, we divide the half-circle $\varphi=\varphi_0, 0<\theta<\pi$ with N evenly spaced meshes. The θ coordinate for each grid is noted by $(\theta_1,\theta_2,\cdots,\theta_i,\cdots,\theta_{N+1})=(0,\frac{\pi}{N},\frac{2\pi}{N},\cdots,\frac{i\pi}{N},\cdots,\pi)$. At the time $t=t_{\mathrm{F}}$, we evenly put M particles in every space mesh representing the total magnetic field flux nearby the corresponding mesh. Each particle in the same mesh carries with an equal part of the total flux in the mesh. For example, the magnetic flux carried by the particle j in the mesh i is

$$\phi_j=\frac{1}{M}B_{\mathrm{R}}(\theta_{i+1/2},\varphi_0,t_{\mathrm{F}})R_{\mathrm{S}}^2\sin(\theta_{i+1/2})\mathrm{d}\theta\mathrm{d}\varphi\,, \tag{3}$$

which does not change with time, where $j=M(i-1)+1,\cdots,Mi, \theta_{i+1/2}=(i+1/2)\pi/N$. Thus, there are totally NM particles, whose θ coordinate is given by $(\overline{\theta}_1(t), \overline{\theta}_2(t), \cdots, \overline{\theta}_j(t), \cdots, \overline{\theta}_{NM}(t))$, respectively, and $\overline{\theta}_j(t_{\mathrm{F}})=(j-1)\pi/NM$.

Due to the disturbance caused by the solar explosion event, the particles will move along the θ direction. Supposing each particle moves independently with each other, they first move outward from the center of the event, then they start to move backward gradually after time τ_{F} to their original location on the source surface. The speed function of the particle j is given by

$$\overline{V}_{\theta,j}(t)=2\frac{t-t_{\mathrm{F}}}{\tau_{\mathrm{F}}}\left(1-\frac{(t-t_{\mathrm{F}})^2}{\tau_{\mathrm{F}}^2}\right)\exp\left(1-\frac{(t-t_{\mathrm{F}})^2}{\tau_{\mathrm{F}}^2}\right)f(\overline{\theta}_j(t_{\mathrm{F}}))\,, \tag{4}$$

$$f(\overline{\theta}_j)=\frac{\overline{\theta}_j}{\sigma}\exp\left(1-\frac{\overline{\theta}_j^2}{\sigma^2}\right)\,, \tag{5}$$

where τ_{F} and σ are constants that describe the duration and area extent of the disturbance, whose values are chosen as same as values of the original HAF model. Integrating Eq.(4), one can obtain the following displacement function for the j particle

$$\Delta\overline{\theta}_j(t)=\frac{(t-t_{\mathrm{F}})^2}{\tau_{\mathrm{F}}^2}\exp\left(1-\frac{(t-t_{\mathrm{F}})^2}{\tau_{\mathrm{F}}^2}\right)f(\overline{\theta}_j(t_{\mathrm{F}}))\,, \tag{6}$$

when $t \to \infty, \Delta\overline{\theta}_j \to 0$, namely, all the particles remove to their original location, so the source surface magnetic field $B_{\rm R}$ recovers to its initial value before the event explosion.

The radial magnetic field strength $B_{{\rm R},i}$ and plasma disturbance velocity $V_{\theta,i}$ at grid i at time t is represented by the average value of magnetic flux and velocity, respectively, carried by all the particles in the region $[\theta_i - \pi/2N, \theta_i + \pi/2N]$.

$$B_{{\rm R},i}(t) = \frac{\sum\limits_j \phi_j}{R_{\rm S}^2 \sin(\theta_i){\rm d}\theta{\rm d}\varphi}\,, \quad \overline{\theta}_j(t) \in [\theta_i - \pi/2N, \theta_i + \pi/2N]\,, \tag{7}$$

$$V_{\theta,i}(t) = \sum_j \overline{V}_{\theta,j}(t)/n\,, \quad \overline{\theta}_j(t) \in [\theta_i - \pi/2N, \theta_i + \pi/2N]\,, \tag{8}$$

where n is the total number of particles in the above region. Then, the radial magnetic field strength $B_{\rm R}$ and plasma disturbance velocity V_θ at arbitrary position $(R_{\rm S}, \theta_0, \varphi_0)$ is obtained from its two neighboring grids by linearly interpolation. Due to the magnetic frozen effect, position of the magnetic field line footpoints at time $t + \Delta t$ is given by $\varphi(t+\Delta t) = \varphi(t) = \varphi_0, \theta(t+\Delta t) = \theta(t) + V_\theta \Delta t$. Finally, (θ, φ) should be transformed to the Heliospheric Equatorial (HEQ)[13] coordinate system for convention.

Using the model described above, the HAF code is improved. Of course, the main process using the code to simulate the interplanetary disturbance is not changed.

3 EXAMPLES

It is indicated from observation that CMEs are the crucial links between solar activities and transient interplanetary disturbances which cause large geomagnetic storms[14]. Interplanetary shock may be driven ahead fast CMEs, especially, when the magnetic field embodied in the CME or the IMF disturbed by the CME has large southward component, magnetospheric substorms as well as geomagnetic storms will developed[15]. The origins of southward B_z events may be different in different cases. In 1987, Gosling and McComas[10] have suggested that the ambient IMF draped about fast CMEs as they plow out through slower moving, quiescent solar wind, should cause systematic B_z perturbations. The direction of the B_z field perturbation in the "sheath" regions between interplanetary shocks and CMEs is based solely on the direction of the radial component of the upstream IMF, the relative location between the perturbation source and the spacecraft crossing the CMEs. The draping model is basically as same as the physical model described in Section 2, in which the distortion of the field lines on the source surface propagates outward into the interplanetary region to form the B_z perturbations, so one can forecast the direction of average B_z between the interplanetary shocks and fast CMEs using the improved HAF model.

3.1 Simulation of the Halo CME Event on May 12, 1997

To test the ability of the improved HAF model on predicting the B_z direction between fast CMEs and interplanetary shocks, the Halo CME event observed by SOHO (Solar and Heliospheric Observatory) on May 12, 1997 is simulated[16]. This CME was first observed by the SOHO/LASCO (Large Angle Spectrometric Coronagraph) C_2[17] telescope at 06:30 UT. It could be identified from the height-time profile of the CME leading edge that this CME

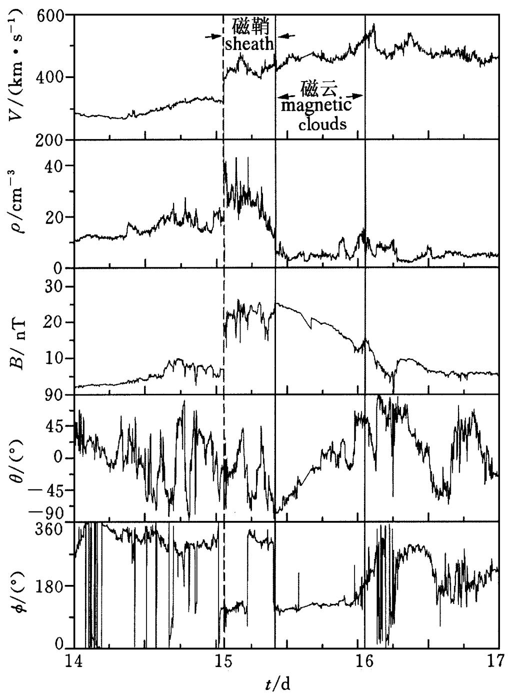

Fig. 1 Stackplot of IMF and plasma parameters from Wind for May 14–17, 1997

From top to bottom are plotted the plasma bulk velocity V, proton density ρ, the magneitc field amplitude B, polar angle θ, and azimuthal angle ϕ (GSE coordinates).

was associated the soft X-ray flare burst at 04:54 UT, N21°W08° in 8038 active region. At the same time, a global large amplitude waves propagating across the solar disk and a transient soft-X dimming region were observed by the SOHO/Extreme Ultraviolet Imaging Telescope (EIT) and the Soft X-ray Telescope (SXT) on Yohkoh[18], respectively. Fig. 1 shows the IMF and plasma profiles on this CME from Wind for May 14–17, 1997. The magnetic cloud is between the two solid lines, which is one of the main characters of CME in interplanetary region. The average B_Z between the fast shock (dashed line) and the magnetic cloud, namely the "sheath" reion, was southward (negative) with an average value of –7.578 nT. The average B_Z over the 12-hour interval immediately proceeding the shock was –0.377 nT, so the perturbation direction of B_z in the "sheath" region was southward with an average perturbation value of –7.201 nT due to the draping effects of CME.

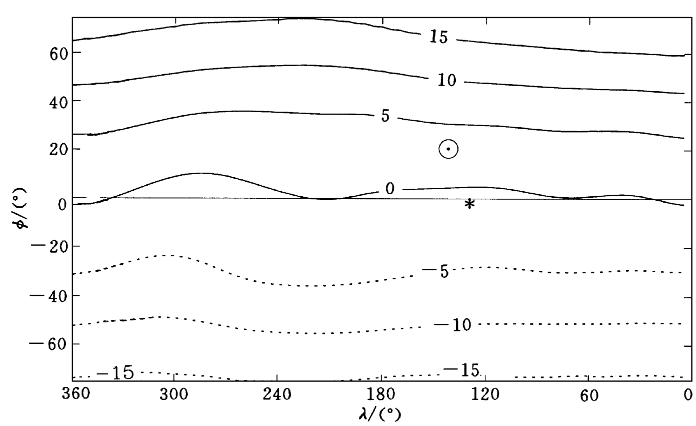

Fig. 2 Synoptic maps of the source magnetic field for CR 1922 in Carrington longitude-latitude coordinates

The source region of the flare or CME is represented by the symbol "⊙", and "∗" for the earth projection position on the sun when the CME is expelled from the sun. The unit of magnetic field strength is Micro-Tesla.

Moreover, the direction of the IMF was towards the sun, since the B_x component proceeding the shock was positive while B_y was negative. Fig. 2 shows the synoptic maps of the source magnetic field for Carrington rotation number 1922 in Carrington longitude-latitude coordinates. Giving the explosion time, location and strength of CME, we simulate the propagation process of the disturbance in the interplanetary region (Fig. 3) by the improved 3-D kinematic model. The perturbation of the solar wind speed, density, and the magnetic

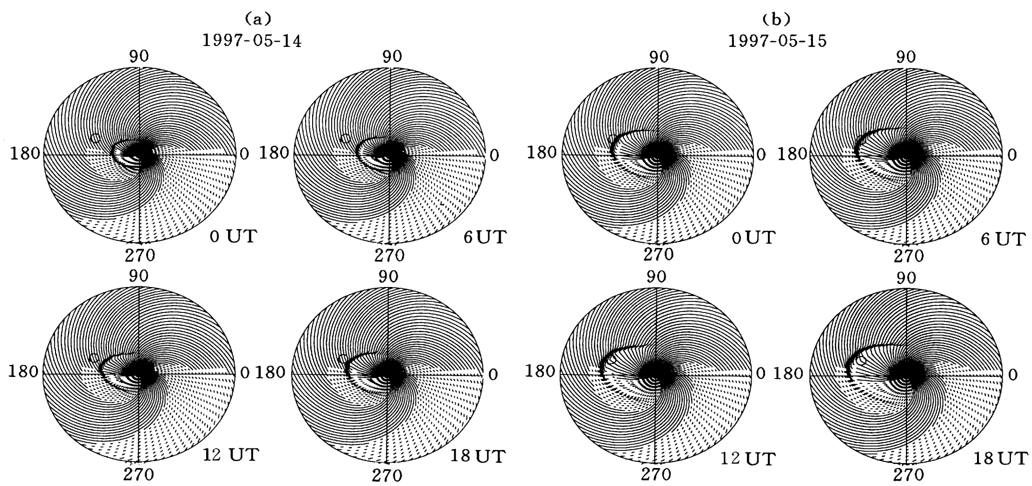

Fig. 3 Ecliptic plane plots of the disturbed IMF every 6 hours for May 14–15, 1997 in 2AU

The dashed and solid lines represent the fiel

(a) and (b) for May14 ;

field strength and direction at 1 AU are plotted in Fig. 4. One can see from Fig. 4 that the perturbation of B_θ component changes from negative to positive, which indicates that B_z is firstly disturbed southward then northward. Southward represents the direction of average B_z in the "sheath" region, which is as the same as the B_z direction observed by Wind, while northward represents the direction of IMF after the CME has crossed the spacecraft (we can not predict presently the magnetic field direction in CMEs). The improved kinematic model correctly predicts the B_z direction in the "sheath" region for this event. The basic values for the CME parameter used for simulation are given in Table 1.

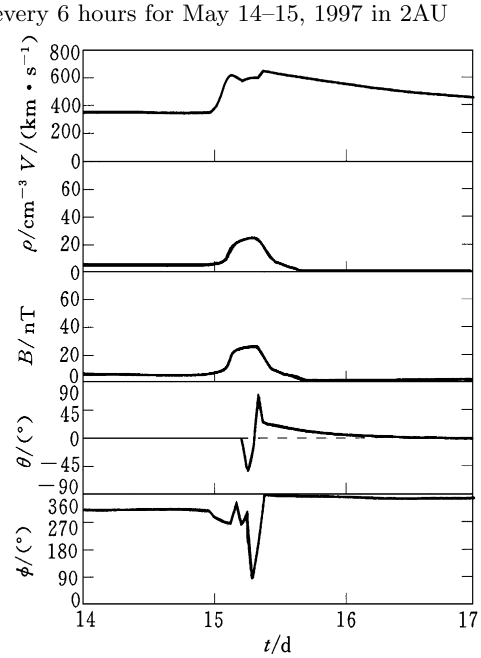

Fig. 4 Stackplot of IMF and plasma parameters near earth for May 14–16, 1997, obtained from the three-dimensional kinematic code simulation results

Table 1 Simulation parameters about the CME on May 12, 1997

Initial speed $V_{\mathrm{F}}/(\mathrm{km \cdot s^{-1}})$	Duration $\tau_{\mathrm{F}}/\mathrm{h}$	Area $\sigma/(°)$	Time Constant τ/h
600	7.2	40	750

3.2 Simulation of the 17 CMEs Between 1978 and 1981

CHEN et al.[19] simulated the 17 events of CME between 1978 and 1981, which have been studied by McComas et al.[20], to compare the B_z direction between simulation results by the improved kinemetic model and the observation results. Of these 17 events, 10 events correlated with double direction electron stream. Most of the rest events were accompanied with high-energy proton events occurring 2–3 days ago. The prediction results are shown in Table 2. The first column identifies each event. The second and third columns give the solar event explosion time and position on the source surface. The fourth column gives the date and time of interplanetary shock passage of the spacecraft. The sixth and seventh columns give the direction of B_z component in the upstream ahead shock from observation and the model, respectively. The eighth column gives the direction of the predicted B_z perturbation from simulation. It is shown that the kinematic code correctly predicts the direction of perturbation of the south-north component of IMF for 14 events (82%). This shows that the direction predicted by the improved code agrees with observations very well.

Table 2 Comparison between Observation and Prediction on CMEs between 1978 and 1981

Event	Solar Source			Shock		Upstream	Model	B_z Perturbation		
	Date	UT	Location	Date	UT	B_{x}	B_{x}	Predicted	Real (nT)	Score
A	1978-09-22	21:29	S23°W13°	1978-09-25	07:05	In	In	S	–1.6	1
B	1978-11-10	01:10	N17°E01°	1978-11-12	00:28	In	In	N	5.1	1
C	1979-02-16	01:50	N16°E59°	1979-02-18	02:20	Out	Out	N	3.3	1
D	1979-03-11	10:54	S24°W76°	1979-03-15	04:54	In	In	S	3.4	0
E	1979-04-03	01:11	S25°W14°	1979-04-05	01:21	In	In	S	2.3	0
F	1979-07-04	19:21	N11°E36°	1979-07-06	18:53	Out	Out	N	2.0	1
G	1979-08-17	22:21	S33°W35°	1979-08-20	05:52	In	In	N	11.9	1
I	1980-04-04	15:03	N27°W35°	1980-04-06	10:19	Out	Out	S	–1.5	1
J	1980-07-14	08:18	S17°E43°	1980-07-18	18:45	Out	Out	S	–13.2	1
K	1981-04-01	01:38	S43°W52°	1981-04-03	03:08	In	In	S	3.7	0
L	1981-04-24	13:55	N18°W50°	1981-04-26	07:50	In	In	S	–2.1	1
N	1981-05-13	03:57	N29°W10°	1981-05-14	18:27	Out	Out	N	1.5	1
O	1981-05-14	08:44	N20°E35°	1981-05-16	05:13	In	In	S	–1.4	1
Q	1981-08-21	08:32	S16°E02°	1981-08-23	12:17	Out	Out	S	–2.6	1
R	1981-10-07	22:59	S17°E83°	1981-10-10	13:54	Out	Out	S	–0.8	1
S	1981-10-12	06:27	S18°E31°	1981-10-13	22:17	In	In	N	1.0	1
U	1981-12-27	02:51	S13°E16°	1981-12-29	04:23	Out	Out	S	–4.6	1
Correction										14/17

Note: "S" and "N" represents the southward and northward direction of B_z, "In" and "Out" represents the direction of IMF is towards and far away from the sun, "1" and "0" represents the prediction is agree with observation or not, respectively.

4 CONCLUSION AND DISCUSSION

A scenario is introduced for predicting the perturbations of the south-north component B_z of IMF ahead of fast CMEs. The 3-D HAF kinematic code[1] is improved according to the scenario. Using the new code, we investigate the perturbation of IMF and plasma caused by the Halo CME at 06:30 UT, May 12, 1997 observed by SOHO in detail. Seventeen events of CME between 1978 and 1981[20] are also examined. The results show that the direction simulated from the improved kinematic code agrees with observation very well, so the improved code is basically suitable.

There are many reasons for the perturbation of south-north component of IMF. We only consider one possible reason in this paper, and can only predict the direction of B_z. To predict the concrete strength of the perturbation, some basic parameters should be previously decided from statistically studying a plenty of determinate events (namely, their start time, position on the solar disk, and their corresponding disturbance events in interplanetary region etc. are known). Some of the basic parameters in the HAF model are obtained from the observation data of flare, but it is believed now that CMEs are also one of the most important solar activities influencing the space environment near the earth.

The improved kinematic model doesn't correctly predict the B_z direction for three events, which may be due to several reason: (1) The position and start time of CMEs given in Table 1 are error for these three events; (2) Magnetic field of corona can not be observed directly, whose real direction at the source surface may be different from the Wilcox Solar Observation data explored from the photospheric magnetic field data with potential assumption; (3) There may be MHD waves and magnetic reconnection in the sheath region between CMEs and interplanetary shocks, which can change the direction of the draping magnetic field; (4) Perturbations of the B_z component may be due to other physical processes, which are quite different from the scenario considered in this paper. Finally, more halo CMEs observed by SOHO need to be investigated to test the reliability of the improved kinematic model. This will be considered in a future paper.

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