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CLASSIFICATION OF THE INTERPLANETARY SHOCKS BY SHOCK DRIVERS

SU YEON OH[1†], YU YI[1], JA-KYUNG NAH[1], AND KYUNG-SEOK CHO [2]
[1]Department of Astronomy & Space Science, Chungnam National University, Daejon 305-764, Korea
E-mail:osy1999@cnu.ac.kr
[2]Radio Research Laboratory, Space Environment Research, Ichon 467-880, Korea
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ABSTRACT

From the data of solar wind observation by ACE spacecraft orbiting the Earth-Sun Lagrangian point, we selected 48 forward interplanetary shocks(IPSs) occurred in 2000, maximum solar activity period. Examining the profiles of solar wind parameters, the IPSs are classified by their shock drivers. The significant shock drivers are the interplanetary coronal mass ejection(ICME) and the high speed stream(HSS). The IPSs driven by the ICMEs are classified into shocks driven by magnetic clouds and by ejectas based on the existence of magnetic flux rope structure and magnetic field strength. Some IPSs could be formed as the blast wave by the smaller energy and shorter duration of shock drivers such as type II radio burst. Out of selected 48 forward IPSs, 56.2% of the IPSs are driven by ICME, 16.7% by HSS, and 16.7% of the shocks are classified into blast-wave type shocks. However, the shock drivers of remaining 10% of the IPSs are unidentified. The classification of the IPSs by their driver is a first step toward investigating the critical magnitudes of the IPS drivers commencing the magnetic storms in each class.

Key words : solar wind, interplanetary shock, coronal mass ejection, magnetic cloud, high speed stream

I. INTRODUCTION

Importance of understanding the physics of the system composed of the Earth and space environments around the Earth is getting increased for space weather forecast to reduce the possibility of social and economic disasters in communications, navigational systems, operations of satellites, and so on. The interplanetary shocks(IPSs) driven by the eruptive solar activities are thought to be more effective on changes of space environments rather than the solar wind in steady state (Geiss et al. 1995, McComas et al. 1998). Currently many solar radio telescopes on the ground and coronagraphs in the space are watching solar activities related to the shock drivers around the clock. The eruptive appearances like coronal mass ejections(CMEs), flares, and radio bursts are suggested as the possible drivers of the IPSs. However, it is hard to find one-to-one connection between the solar eruptions observed by solar telescopes and the IPSs detected by spacecraft in front of the Earth's magnetosphere except some prominently extreme cases. Therefore, in this study, we try to find the IPS drivers purely by examining the profiles of the solar wind following the IPSs.

The IPSs driven by different shock drivers must have different physical properties. Thus the different kind of the IPS should take different effects on the Earth's magnetosphere. More precise space weather forecast about the effects of the IPSs directly from the different shock driving solar activities should be realized in the near future. In order to achieve such eventual purpose, the characteristics of the IPSs by different shock drivers and their typical effects on the Earth space environments should be investigated in the following researches. However, the classification of the IPSs by their drivers is a first step of the grand research road map.

Corresponding Author: S.-Y. Oh

II. DEFINITIONS OF KEY WORDS

(a) Forward Interplanetary Shock(IPS) and IPS Mach number

A class of sharp discontinuity, transverse to the flow direction, that is observed in solar wind speed, density, and temperature and lasts for a few minutes in the reference frame of the moving spacecraft. Such rapid upward jumps of solar wind parameters are defined as an IPS. The IPS is a disturbance propagating into the expanding solar wind. Shown in Figure 1, the IPS has a discontinuity plane between the slow downstream and the fast upstream. At the forward shock, all the parameters of plasma density, plasma pressure, plasma speed and magnetic field strength are increased after the discontinuity.

As an indicator quantifying the strength of the IPS, the IPS Mach number is defined as the ratio of the shock speed relative to the slow downstream speed to the sound speed in the downstream. We can calculate

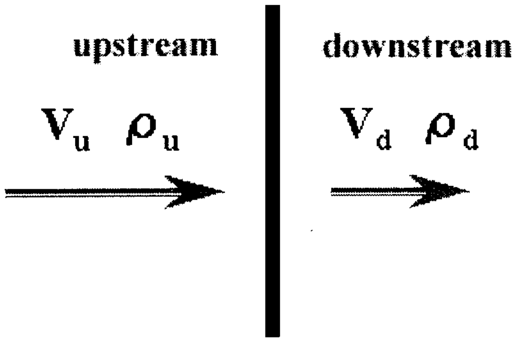

Fig. 1.— The Shock discontinuity between two supersonic fast and slow streams in the spacecraft(observer's) frame.

the shock speed and the IPS Mach number by the following equations(Kallenrode, 2000):

$$V_s = \frac{\rho_u V_u - \rho_d V_d}{\rho_u - \rho_d} \quad (1)$$

$$M = \frac{V_s - V_d}{C_d} \quad (2)$$

, where ρ_u, V_u are solar wind mass density and velocity in the upstream and ρ_d, V_d in the downstream described in Figure 1, V_s is shock speed and C_d is sound speed of the downstream medium. IPS Mach number ranges from 1 to 6 with average at 1.7 (Kallenrode, 2000).

(b) Magnetic Cloud(MC)

The CME is a spatially distinct plasma structure observed outside of the Sun by coronagraph. The expanding plasma structure carrying the magnetic field patterns of their parent CME in the solar wind is called interplanetary CME(ICME). Physical properties of the ICMEs are roughly similar to those of the CMEs. The ICMEs are classified into the MCs and the Ejectas by magnetic structure. An MC is an extension of the flux ropes in eruptive filaments into interplanetary space. The MC shows stronger enhancement of magnetic field strength over 10 nT at 1 AU and distinct magnetic flux rope structures, but the Ejecta does not (Burlaga, 1995).

As the eruption like the CME moves outward, it pushes and compresses the interplanetary medium ahead of it. An IPS is formed by the gradual steepening of this pressure during its outward propagation. Behind the IPS lies a region of compressed plasma, followed by the eruption itself. The IPS is travelling supersonically relative to the slow solar wind ahead of it (Foukal, 1990).

The MC is usually depicted as a bundle of twisted magnetic field lines (Kallenrode, 2000). According to the definition by Burlaga et al. (1981), the observational signatures of the MC consist of the followings: (a) Enhanced magnetic field strength($|B|$ keeps the value over 10 nT compared to the average value 5 nT at 1 AU), (b) A large and smooth rotation of the magnetic field direction through 180 degree over 1-2 days, characterized by large and coherent changes in latitude angle, and (c) Low proton temperature and low proton plasma-β.

(c) High Speed Stream(HSS)

The HSS is a long-lived stream with typical speed over 700 km/sec from the coronal holes. The streams corotate with the spiral magnetic field geometry of the solar wind. The most obvious feature of streams observed near 1 AU is the characteristic rise (over about 1 day) and slow decay (over several days) of the solar wind speed and the plasma temperature (Foukal, 1990).

The IPS seems to be generated within the solar wind by steepening of the compressed region at the leading edge of the HSS. The IPS driven by the HSS has profiles of the solar wind speed and plasma temperature decreasing slowly from the peak values for over 3 days after the IPS.

(d) Blast Wave

If most of solar wind parameters decrease rapidly within a few hours after the jump, we call the IPS as the blast-wave type shock. The feature is similar to characteristic of a blast wave. The blast-wave type shock can be created by a short-lived impulse. The Type II radio bursts in the solar corona probably cause blast waves (Kallenrode, 2000). Smith & Dryer (1990) suggested that for long duration of solar eruption shocks behave as classical piston-driven shock waves that propagate through the background solar wind and for short duration of solar eruption the shocks behave like blast waves.

III. DATA ANALYSIS

ACE orbiting the Sun-Earth L1 point stays in a relatively constant position outside of the Earth's magnetosphere as the Earth revolves around the Sun. Thus, it can detect the IPS in front of the Earth before the IPS hits the Earth's magnetosphere.

ACE observed total 68 IPSs in the year 2000 of maximum solar activity. Discarding the reverse shocks, 48 forward shocks are reported. We investigated the physical properties of these forward IPSs with data of the interplanetary magnetic field magnitude, latitude and longitude in RTN coordinates from MAG instrument, and the solar wind temperature, proton speed, proton density from SWEPAM instrument onboard on ACE spacecraft. The IPSs are classified by their shock drivers by examining the profiles of solar wind parameters. The IPS drivers are mainly categorized as ICME, HSS and others (Berdichevsky et al., 2000).

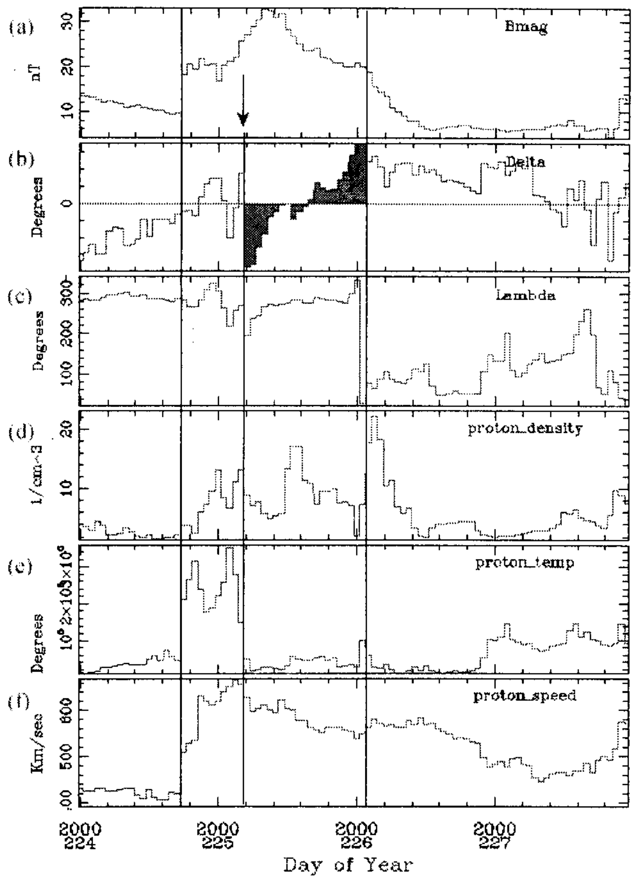

Fig. 2.— An IPS on August 11, 2000 [Day Of the Year(DOY), as an example of IPS driven by an MC. The left-most vertical solid line indicates the time of the IPS and the grey region marks the magnetic flux rope of the MC.

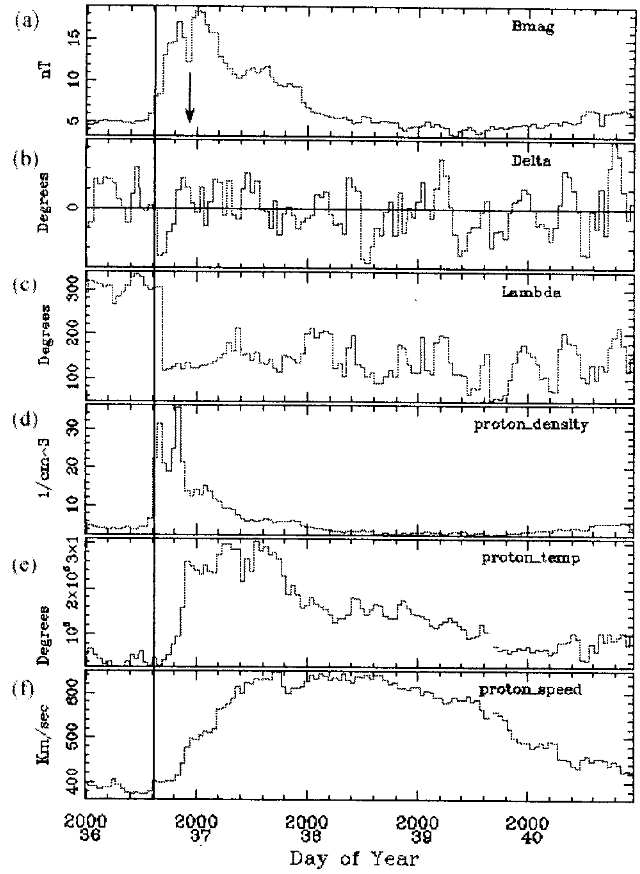

Fig. 3.— An IPS driven by the Ejecta on Februrary 5, 2000 [DOY 36]. The vertical solid line indicates the time of the IPS.

IV. RESULTS

(a) IPS driven by ICME

The Figure 2 is an example of the IPS driven by an MC. It shows the solar wind parameter profiles of the shock occurred on 6:10 pm August 11, 2000 in UT. The Figure 2a shows the magnetic field strength as a function of time observed by ACE. Figure 2b and 2c show the latitude(δ) and the longitude (λ) of the magnetic field in RTN coordinates. Figure 2d-2f show the solar wind density, plasma temperature, and the speed. The magnetic field strength maintains larger than 10 nT after the jump shown in Figure 2a. The slow rotational change of the latitude for about a day in Figure 2b gives the evidence of the magnetic flux rope structure. The low plasma temperature keeps for the passage of ICME as shown in Figure 2e. Shown profiles are consistent with the typical observational signatures of the MC defined by Burlaga et al. (1981). Thus, this shock is certainly driven by the MC. The vertical line in the Figure 2 indicates the time of the IPS and the arrow points the front boundary of MC. The Figure 3 is also an example IPS driven by the Ejecta occurred on 1:40 pm February 5, 2000 in UT. The solar wind parameters are displayed in the same format as that in Figure 2. This IPS is inferred to be driven by the Ejecta because of less magnetic field strength enhancement and indistinct magnetic structure as shown in Figure 3a and 3b. The arrow in figure indicates the estimated front boundary of Ejecta.

The IPS driven by the MC has larger magnetic strength enhancement and distinct magnetic flux rope structure than the IPS driven by the Ejecta (Burlaga et al. 2001). Among the analyzed 48 forward IPSs, 27 IPSs are classified to be driven by the ICME. In detail, 10 shocks are driven by the MC and 17 shocks by the Ejecta.

The solar eruption as a shock driver pushes the IPS like a piston adding the pressures, the IPS propagates faster than its driver. The time-lag between IPS and ICME ΔT is defined by the equation below:

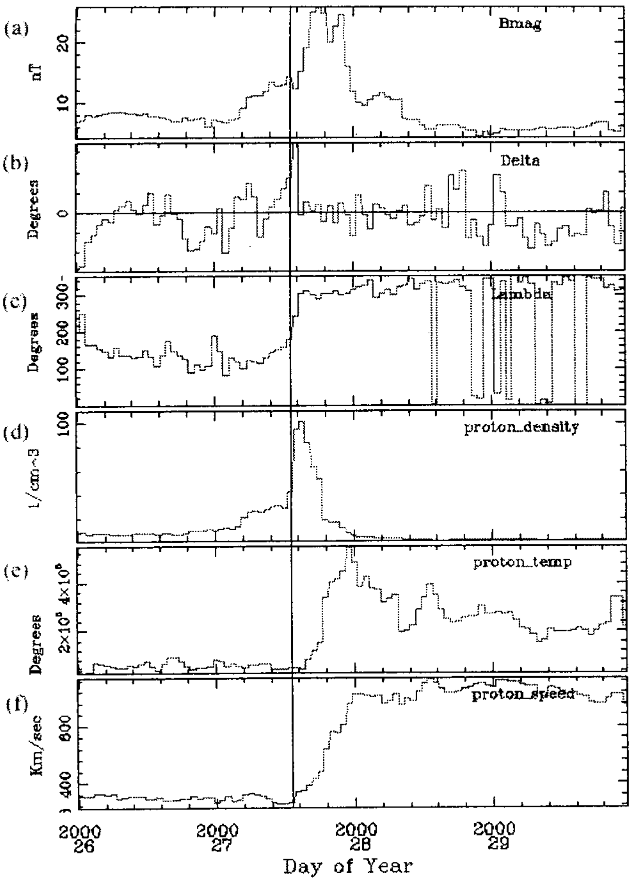

Fig. 4.— An IPS driven by the HSS on January 27, 2000 [DOY 27]. The vertical solid line indicates the time of the IPS.

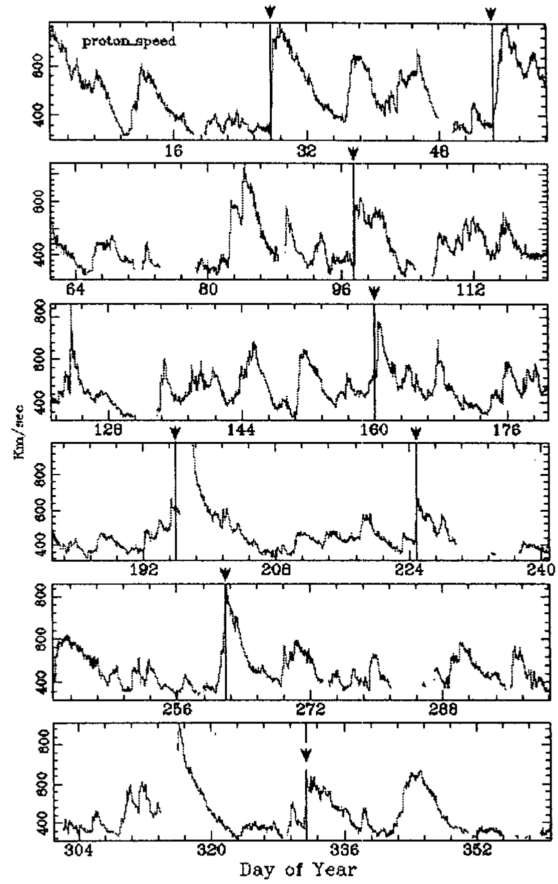

Fig. 5.— Solar wind speed profile for the year of 2000. The arrows indicate the times of the IPSs driven by the HSSs.

$$\Delta T = T_{ICME} - T_{SHOCK} \quad (3)$$

ACE observed the ICMEs at 10-19 hours after the passage of the IPSs with the averaged value of 12.8±3.2 hours.

(b) IPS driven by HSS

The solar wind parameter profiles of around an IPS occurred on 2:00 pm January 27, 2000 in UT are shown in the Figure 4. The solar wind parameters are displayed in the same format as in Figure 2. Most of solar wind parameters of speed, density and plasma temperature have peaks at the time of shock in rapid rising and decreases somewhat slowly. There is no enhancement of magnetic strength and magnetic flux rope structure of the IPS driven by the ICME. It is an example of the IPS driven by the HSS, because of more higher jump than general solar wind speed and some long increase of physical parameters after the jump. 8 IPSs are classified to be driven by the HSSs out of total 48 IPSs.

Figure 5 is the solar wind speed profile during the year of 2000. The HSSs are observed by the interval of solar rotation. The arrows in the figure indicate the times of IPSs driven by the HSS in this classification. Here we defined the HSS as the streams with the solar wind speed over 600km/sec. 8 HSSs out of 17 HSSs could drive the IPSs.

(c) Blast-wave type IPS

The Figure 6 shows the solar wind parameters profiles of IPS observed on 2:10 am February 11, 2000 in UT. After the shock discontinuity, most of the solar wind parameters decrease rapidly within a few hours. This tendency is explained in case the shock driver has smaller energies and shorter duration time than the classical IPS driven by solar eruptions of CME. Because the feature is similar to blast wave driven by Type II radio burst in solar corona, it can be classified as the blast-wave type IPS. 8 IPSs are classified into the blast-wave type IPSs.

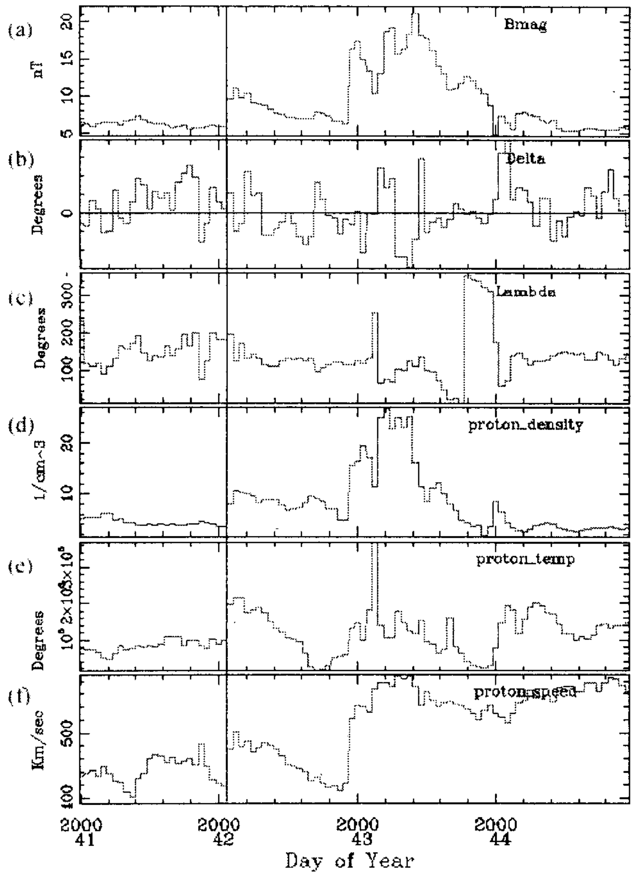

Fig. 6.— A Blast-wave type IPS on February 11, 2000 [DOY 42]. The vertical solid line indicates the time of the IPS.

(d) CLASSIFICATION OF IPSs

The analyzed forward IPSs are listed on the Table 1. The letters in the column of IPS drivers of B, H, I(E), I(M), and U mean, respectively, Blast-wave type, HSS, ICME(Ejecta), ICME(MC), and Unidentified.

Shown in Figure 7 and Table 2, out of the selected 48 forward IPSs, 27 shocks (56.2%) are driven by the ICME, 8 shocks are formed by the HSS (16.7%), 8 shocks are classified into blast-wave type shocks (16.7%) and the other remaining 5 IPSs are unidentified because of vague solar wind parameter profiles as an IPS drivers. 27 IPSs driven by the ICME are subclassified into 10 IPSs driven by the MC with distinct magnetic flux rope structure and 17 IPSs driven by the Ejecta without distinct magnetic flux rope structure.

V. DISCUSSION AND CONCLUSION

We classified the 48 forward IPSs observed by ACE in solar maximum year 2000 by their shock drivers. According to our analysis, the significant shock drivers are mainly the ICME and the HSS. The IPSs formed by

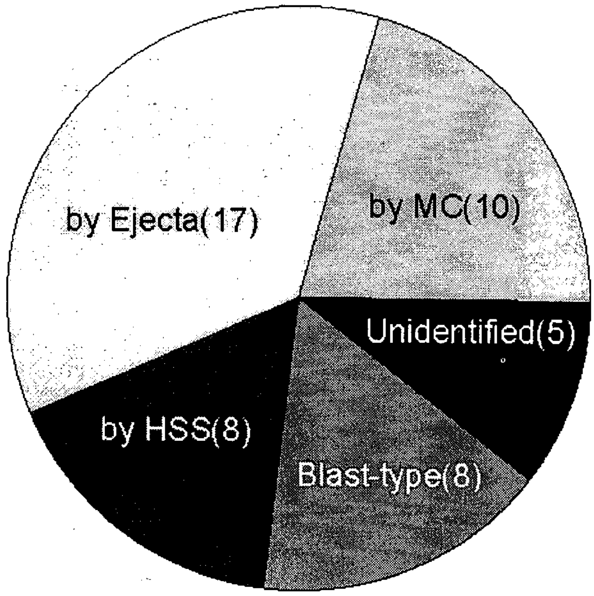

Fig. 7.— Types of the IPS drivers.

the ICMEs have the tendencies that physical parameters, such as speed, temperature, and density, have the rapid rise and decrease slowly. The enhancement of magnetic strength and smooth change of latitude in magnetic field are evidences of the ICME. If the solar wind speed following the IPS jumps up to the speed over 600km/s and maintains the high speed for long duration, the IPS is considered as driven by the corotating HSS blown out from the coronal hole.

The ICMEs are classified into two subclasses of the MC and the Ejecta by the trend of physical properties of magnetic field structure. The MCs have large enhancements of magnetic field strength and distinct magnetic flux rope structures in comparison with the Ejectas.

Some IPSs have a quite different solar wind profiles from those of the shocks driven by the ICME or the HSS. If there are small jump and rapid decrease of solar wind parameters after the peak defined as shock discontinuity, the IPS is classified into blast-wave type IPS. It is triggerd by smaller energy and shorter duration of the shock driver.

The criteria of the shock drivers are applied to IPSs occurred in 2000, the year of maximum solar activities. Out of 48 forward IPSs, 27 shocks (56.2%) are driven by ICME, 8 shocks are formed by HSS (16.7%), 8 shocks are classified into blast-wave type shocks (16.7%) and drivers of the other remaining 5 IPSs are unidentified. From the results of this classification, we confirmed that the ICME and the HSS are major shock drivers.

In the following researches on the properties of the ICME and the HSS as important shock drivers, we need to find the critical values of the solar wind density, velocity, and magnetic field strong enough to drive the

Table 1. List of the forward IPSs occurred in the year 2000 with the observation time, the IPS driver type and the time-lag between the IPS and the ICME

DOY	Date-Time[UT]	Driver	ΔT(hour)	DOY	Date-Time[UT]	Driver	ΔT(hour)
11	Jan 11, 13:40	I(E)	10	208	July 26, 17:55	B	
22	Jan 22, 00:23	I(M)	17	210	July 28, 05:43	B	
27	Jan 27, 14:00	H		210	July 28, 09:10	I(E)	18
36	Feb 05, 14:50	I(E)	10	213	July 31, 18:16	I(E)	15
42	Feb 11, 02:10	B		223	Aug 10, 04:07	H	
42	Feb 11, 23:15	I(E)	10	224	Aug 11, 18:10	I(M)	19
45	Feb 14, 06:56	U		227	Aug 14, 21:36	U	
51	Feb 20, 20:45	H		250	Sep 06, 16:13	I(E)	12
53	Feb 22, 11:43	I(E)	13	261	Sep 17, 16:57	H	
97	April 06, 16:04	H		277	Oct 03, 00:08	I(M)	14
115	April 24, 08:52	U		278	Oct 04, 13:36	B	
123	May 02, 10:45	I(E)	10	279	Oct 05, 02:41	I(M)	13
129	May 08, 06:01	I(E)	13	286	Oct 12, 21:45	I(M)	14
138	May 17, 21:39	I(E)	9	302	Oct 28, 05:41	B	
155	June 03, 08:03	B		302	Oct 28, 09:08	I(M)	13
156	June 04, 14:23	I(E)	12	305	Oct 31, 16:30	I(E)	10
160	June 08, 08:41	H		309	Nov 04, 01:34	I(E)	11
175	June 23, 12:27	I(E)	17	311	Nov 06, 09:15	I(M)	11
192	July 10, 05:57	B		324	Nov 19, 01:43	U	
193	July 11, 11:23	I(M)	18	331	Nov 26, 05:00	H	
195	July 13, 09:18	H		331	Nov 26, 11:24	I(E)	13
197	July 15, 14:15	I(M)	6	333	Nov 28, 04:57	U	
201	July 19, 14:48	I(E)	11	334	Nov 29, 05:23	I(M)	10
207	July 25, 13:22	B		338	Dec 03, 03:21	I(E)	17

(Remarks: B-Blast-wave type, H-HSS, I(E)-ICME(Ejecta), I(M)-ICME(MC), U-Unidentified)

Table 2. Classification of the IPS drivers

IPS driver		Number of IPS	
ICME	MC	10	27(56.2%)
	Ejecta	17	
HSS			8(16.7%)
Blast wave type			8(16.7%)
Unidentified			5(10.4%)

IPS. Furthermore, it is necessary to find the criteria for magnitude of the solar eruption such as CMEs, flares, and coronal radio bursts causing such ICME. The distinctive effects on the Earth space environments due to the IPSs driven by the ICMEs and the HSS and blast-wave type IPS could be simulated by MHD models. These series of researches can make dream of forecasting the effectiveness of the IPS encountering the Earth come true.

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