Interplanetary shock characteristics and associated geosynchronous magnetic field variations estimated from sudden impulses observed on the ground

C. Wang,[1] H. Li,[1,2] J. D. Richardson,[3] and J. R. Kan[4]

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[1] Interplanetary (IP) shocks disturb the magnetosphere-ionosphere system resulting in geosynchronous magnetic field changes and sudden impulses observed by ground-based magnetometers. We extend the implications of a previous statistical study and show that sudden impulses (SIs) can be used to estimate some parameters at the L1 point and geosynchronous orbit, including the change of the square root of solar wind dynamic pressure across the shock and the associated geosynchronous magnetic field changes near the subsolar region. It should be pointed out that the relationship between magnetospheric field change and SIs amplitude and the solar wind dynamic pressure is not a single valued one, but a statistical relationship is useful in cases when interplanetary data are not available. Empirical formulae deduced from observations can be used to estimate certain IP shock characteristics and geosynchronous magnetic field changes from sudden impulse data observed on the ground, with the prediction efficiency as high as 90% and 86%, respectively. These estimates are useful for studying historic, pre-space era data or if the L1 and geosynchronous data are not available at some future time.

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1. Introduction

[2] Interplanetary (IP) shocks are accompanied by large changes in the solar wind dynamic pressure and thus significantly affect the magnetosphere and perturb the magnetosphere-ionosphere system. The manifestations of those disturbances include changes in the magnetic field at geosynchronous orbit and sudden impulses (SIs) observed by ground-based magnetometers.

[3] Observations show that almost all sudden impulses are caused by IP shocks, with the positive SIs caused by fast forward interplanetary shocks [*Siscoe et al.*, 1968; *Smith et al.*, 1986] and the negative SIs caused by fast reverse interplanetary shocks [*Akasofu*, 1964; *Nishida*, 1978]. A physical model of the geomagnetic sudden commencement/impulse has been proposed by *Araki* [1994]. Quantitative studies reveal a good correlation between the SI amplitude at the low-latitudes stations at noon and the change in the square root of the solar wind dynamic pressure at the shock/discontinuity [*Russell et al.*, 1992, 1994a, 1994b]. *Wang et al.* [2006] surveyed interplanetary shocks and storm sudden commencements (SSCs) observed between 1995 and 2004 and found that about 75% of SSCs are associated with IP shocks. SSCs are the sudden rises in magnetic field strength at the beginning of the initial phase of a geomagnetic storm, whereas sudden impulses can also occur during the main phase of a storm or even outside the interval of a storm period.

[4] *Wang et al.* [2009] performed a statistical survey of the relation between geosynchronous magnetic field changes and sudden impulses to interplanetary shocks observed from 1998.02 to 2005.04. They found 216 of the 250 IP shocks (or ~88%) produced geosynchronous magnetic field responses observed by GOES satellites and SIs as detected by the change in the SYM-H index. The change of the square root of the solar wind dynamic pressure across an IP shock and the change of the associated magnetic field (ΔB_z) at geosynchronous orbit in the subsolar region (9 to 15 h local time) are both strongly correlated with the amplitude change of sudden impulses (ΔSYM-H) on the ground. Therefore, the ground-based geomagnetic field observations of SIs can be used to estimate some parameters of an IP shock such as the change of the solar wind dynamic pressure across the shock and the enhancement of the geosynchronous magnetic field near the subsolar region. Although the relationship is not one to one, some statistically important information can be gained by such studies. These estimates are useful and important for

[1]State Key Laboratory of Space Weather, Center for Space Science and Applied Research, Chinese Academy of Sciences, Beijing, China.
[2]Also at Graduate School of Chinese Academy of Sciences, Beijing, China.
[3]Kavli Institute for Astrophysics and Space Research, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA.
[4]Geophysical Institute, University of Alaska Fairbanks, Fairbanks, Alaska, USA.

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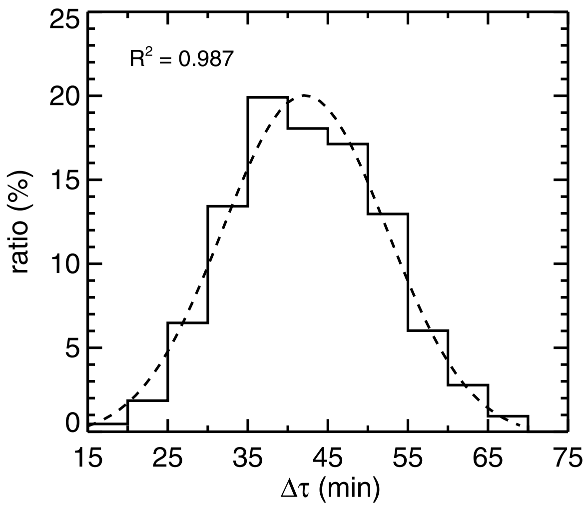

Figure 1. Distribution of the observed time lag $\Delta\tau$ associated with IP shocks from 1998.02 to 2005.04. The ordinate is the ratio of the number of IP shocks with the time lag in a 5 min interval to the total number. The dashed line denotes a Gaussian fit to the data. R^2 is the coefficient of determination.

studying historic events before the space era using the existing archived geomagnetic field observations and could be used if the spacecraft data are not available in the future. Section 2.1 derives the empirical formulae relating the SYM-H index data to IP shocks and geosynchronous parameters based on observations from 1998.02 to 2005.04 [*Wang et al.*, 2009]. Section 2.2 tests the predictive capability of these formulae using observations from 2005.04 to 2008.09. The summary is given in section 3.

2. Results

2.1. Empirical Formulae

[5] As described in *Wang et al.* [2009], we identified IP shocks at the L1 point in the spacecraft ACE 64 s time-resolution solar wind data (http://www.srl.caltech.edu). Then we calculated the key parameters, such as the shock speed and strength, for each shock. The approach to find IP shocks and calculate shock parameters can be found in our previous work [*Wang et al.*, 2009]. The shock list could be found in Table A1 in Appendix A. Please note that sharp discontinuities with pressure pulses are not necessarily shocks, which should satisfy the Rankine Hugoniot relationship and the up-stream Mach number has to be greater than 1. We discard events with Mach number less than 1 in our statistical study. The 1 min resolution magnetic field data from the spacecraft Geostationary Operational Environmental Satellite 8 (GOES-8), GOES-9, GOES-10, GOES-11, and GOES-12, all at geosynchronous orbit (http://goes.ngdc.noaa.gov) were searched to identify the disturbances caused by IP shocks. Most of the geosynchronous magnetic field responses are observed by two or more GOES satellites. The geomagnetic indices SYM-H [*Iyemori*, 1990], which is essentially the same as the hourly Dst index except that the SYM-H index provides 1 min time resolution (http://swdcwww.kugi.kyoto-u.ac.jp), is used to determine the amplitudes of SIs and their association with IP shocks. The data sets from the time period of 1998.02 to 2005.04 are used to derive the empirical formula between the SYM-H index and (1) the change of the square root of the solar wind dynamic pressure across the shock and (2) the change of the geosynchronous magnetic field. The observations made during time period of 2005.04 to 2008.09 are used to check the validity of these relations.

[6] We identified a total of 250 IP shocks in ACE data from 1998.02 from 2005.04; 216 or ~88% of these shocks caused responses in the geosynchronous magnetic field that were observed by GOES satellites. Furthermore, all of the 216 IP shocks that generated changes in the geosynchronous magnetic field also caused changes in the SYM-H index.

[7] We define the time period from the arrival time of an IP shock at the L1 point and the start time of the associated SI as the time lag (or time delay) $\Delta\tau$. We choose these 216 IP shocks to perform a statistical study to investigate the relationship between the amplitude of the sudden impulse (ΔSYM-H) and the time lag $\Delta\tau$. ΔSYM-H is calculated as the difference of the initial SYM-H before a SI and the maximum value of SYM-H during it. Figure 1 shows the distribution of the observed $\Delta\tau$, which is roughly Gaussian; the coefficient of determination is 0.987. The time lag $\Delta\tau$ ranges from 15 to 70 min, with an average of ~44 min. About 80% $\Delta\tau$ are between 30 and 60 min.

[8] Figure 2 shows that as ΔSYM-H increases, roughly speaking, the time lag $\Delta\tau$ becomes shorter, although the linear correlation is not strong. This result is not a surprise, since the time lag $\Delta\tau$ depends on several factors, including the shock propagation speed, orientation, and the distance from the L1 point to the magnetopause, which is mainly determined by the solar wind dynamic pressure, whereas ΔSYM-H is a function of upstream and downstream densities and velocities at the IP shock. There exists no linear relationship between these two variables, in fact, there should not be any unique relationship between the strength of SIs and the time lag. Therefore, we cannot make a reliable estimate of the time lag just based on ΔSYM-H observations unless more information is included.

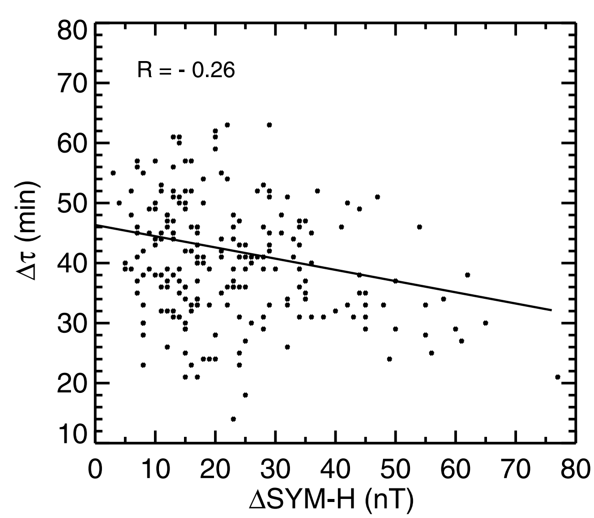

Figure 2. The amplitude of sudden impulse (ΔSYM-H) versus the time lag $\Delta\tau$ during 1998.02 to 2005.04. The parameter R is the linear coefficient.

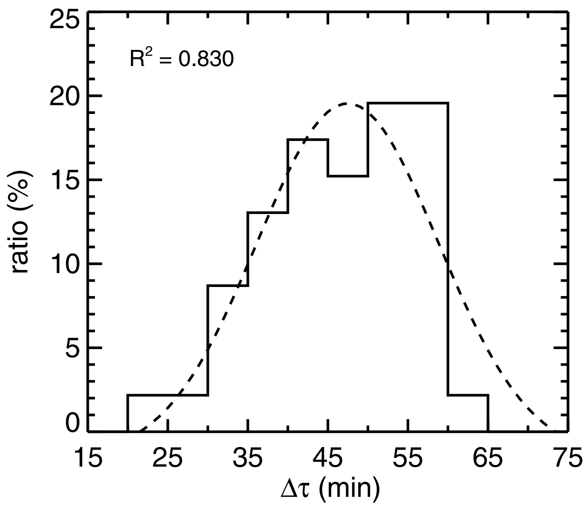

Figure 3. Distribution of the observed time lag $\Delta\tau$ associated with IP shocks from 2005.04 to 2008.09. The ordinate is the ratio of the number of IP shocks with the time lag in a 5 min interval to the total number. The dashed line denotes a Gaussian fit to the data. R^2 is the coefficient of determination.

[9] As obtained in *Wang et al.* [2009], the correlation coefficients between the amplitudes of sudden impulses (ΔSYM-H) and the change of square root of solar wind dynamic pressure ($\Delta\sqrt{P_d} = \sqrt{P_{d2}} - \sqrt{P_{d1}}$) are 0.83, 0.69, and 0.69 for the upstream solar wind dynamic pressure P_{d1} ranges 0.0–1.5, 1.5–2.5, and 2.5–4.0 nPa, respectively. The empirical formulae for the amplitude of the sudden impulses (ΔSYM-H) and the change of the square root of solar wind dynamic pressure across IP shocks can be written as:

$$\Delta\mathrm{SYM-H} = 13.88 \times \Delta\sqrt{P_d} + 6.69\,(\text{for all values of } P_{d1}), \tag{1a}$$

$$\Delta\mathrm{SYM-H} = 14.54 \times \Delta\sqrt{P_d} + 3.93\,(0.0 < P_{d1} < 1.5\,\mathrm{nPa}), \tag{1b}$$

$$\Delta\mathrm{SYM-H} = 14.73 \times \Delta\sqrt{P_d} + 7.93\,(1.5 \le P_{d1} < 2.5\,\mathrm{nPa}), \tag{1c}$$

$$\Delta\mathrm{SYM-H} = 13.13 \times \Delta\sqrt{P_d} + 5.94\,(2.5 \le P_{d1} < 4.0\,\mathrm{nPa}). \tag{1d}$$

Russell et al. [1994a] gave an empirical formula of this relationship for northward interplanetary magnetic field. The empirical formula was ΔSYM-H = 18.4 × $\Delta\sqrt{P_d}$ if the change in the H component was normalized by the local time and ΔSYM-H = 15.4 × $\Delta\sqrt{P_d}$ if it was not. They thought that it was physically impossible to have a response for no solar wind pressure change and thus chose a median slope of line passing through zero. In practice, if we have ΔSYM-H and want to estimate $\Delta\sqrt{P_d}$, we do not know the upstream solar wind dynamic pressure P_{d1}, so we would use equation (1a) to make a rough estimate of $\Delta\sqrt{P_d}$ based on the ground observations ΔSYM-H. In this paper, we follow their approach to constrain the fits to pass through the origin. Thus, equation (1a) becomes

$$\Delta\mathrm{SYM-H} = 18.01 \times \Delta\sqrt{P_d}\,(\text{for all values of } P_{d1}) \tag{1'}$$

and it can be rewritten as

$$\Delta\sqrt{P_d} = 0.056 \times \Delta\mathrm{SYM-H}(\mathrm{nPa})^{1/2}. \tag{1}$$

It might be expected SYM-H responses to solar wind dynamic pressure changes during storm times are not as simple as those during nonstorm times; however, we see no significant difference in relationship between $\Delta\sqrt{P_d}$ and ΔSYM-H for cases where Dst <−30 nT and cases where Dst >−30 nT.

[10] As shown in *Wang et al.* [2009], the change of the geosynchronous magnetic field *z* component and the amplitude of sudden impulses (ΔSYM-H) are highly correlated, with a correlation coefficient of 0.86, probably because they are both mainly driven by changes in the Chapman-Ferraro current in the subsolar region (9–15 h local time). The empirical formula relating to ΔSYM-H on the ground and ΔB_z at geosynchronous orbit near the subsolar region can be written as

$$\Delta\mathrm{SYM-H} = 0.6 \times \Delta B_z + 6.74. \tag{2'}$$

[11] The above equation can be rewritten as

$$\Delta B_z = 1.67 \times \Delta\mathrm{SYM-H} - 11.23(\mathrm{nT})(\Delta\mathrm{SYM-H} \ge 7\mathrm{nT}). \tag{2}$$

[12] Therefore, we can roughly estimate the change of the square root of solar wind dynamic pressure across an IP shock and the change of the geosynchronous magnetic field near the subsolar region from the ground geomagnetic observations of SIs, by using equations (1) and (2), respectively. We next use observations between 2005.04 and 2008.09 to check the validity of these formulae.

2.2. Statistical Test

[13] During the time period of 2005.04–2008.09, we identified 46 IP shocks in the ACE solar wind data. All of these shocks resulted in geosynchronous magnetic field disturbances and corresponding effects in the SYM-H index. We use these 46 events to estimate shock and geosynchronous parameters based on the empirical formulae obtained above and compare these estimations with the observations.

[14] Figure 3 shows the distribution of the observed $\Delta\tau$ for the time period of 2005.04–2008.09. The time lag $\Delta\tau$ ranges from 20 to 60 min, with an average of ~46 min, which is consistent with the results for the time period of 1998.02–2005.04. Even though we can not estimate accurately the time lags $\Delta\tau$ based on the ground geomagnetic observations, we know roughly the range and distribution.

[15] Figure 4a shows the predictions of the change of the square root of solar wind dynamic pressure across the IP shock derived from equation (1). The solid line indicates the perfect match. The parameter R is the linear correlation coefficient and PE is the prediction efficiency. We adopt the

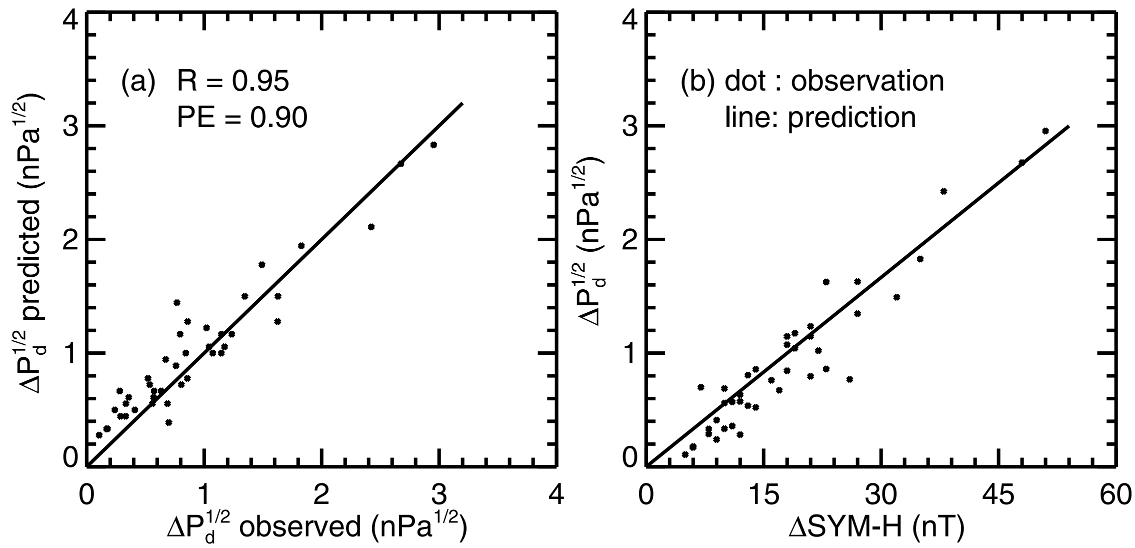

Figure 4. Estimations of the change of the square root of solar wind dynamic pressure across IP shocks using equation (1) and the ΔSYM-H data compared with the observations. (a) The estimations compared with the observations. The solid line indicates the perfect match. The parameter R is the linear correlation coefficient and PE is the efficiency. (b) The $\Delta\sqrt{P_d}$ plotted versus ΔSYM-H. The dots denote the observations, and the solid line represents the estimation from equation (1).

prediction efficiency (PE) [*Agterberg*, 1984] to quantify the accuracy of the estimated value compared with the measurement, which is defined as:

$$\mathrm{PE} = 1 - \frac{\text{variance of the residual}}{\text{variance of the data}}. \tag{3}$$

The residual is the difference between the measured data and the estimation. In order to give a more intuitive comparison of the estimations with the observations, Figure 4b compares the estimated $\Delta\sqrt{P_d}$ from equation (1) (solid line) with the measurements (points). The estimations are in good agreement with the observations, with a efficiency of 90% and a linear correlation coefficient between the estimations and the data of 0.95.

[16] As an example of the use of these formulae, we apply equation (1) to the September 1859 super magnetic storm, the first recognized space weather event *Cliver and Svalgaard* [2004]. In an attempt to reproduce the geomagnetic disturbance, *Li et al.* [2005] input an extremely large solar wind density enhancement of almost 40 particles/cm^3, moving at about 1200 km/s. Before the arrival of the shock, the solar wind had a density of 5 particles/cm^3, moving at 450 km/s. The variation of the square root of the dynamic pressure was then calculated to be about 8.51 nPa^{-1}. The calibrated

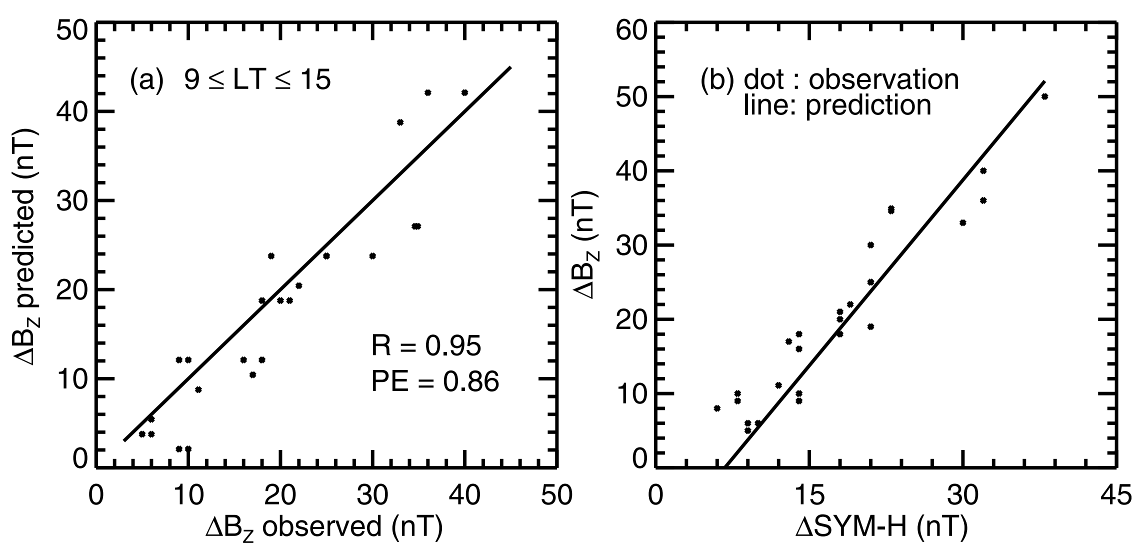

Figure 5. Estimations of the change of geosynchronous magnetic field (ΔB_z) near the subsolar region compared with observations. The format is the same as in Figure 4.

Table A1. Interplanetary Shocks Observed by ACE (1998.02–2008.09)[a]

YY	MM	DD	hh	mm	Flag	Shock Normal	ρ_1/ρ_2	V_{sn}	M_{f1}	M_{f2}
1998	2	17	22	25	0	(−0.805, 0.152, −0.574)	0.79	383.6	0.93	0.66
1998	2	18	7	52	1	(−0.919, 0.044, 0.392)	0.67	450.1	1.55	0.87
1998	3	4	10	57	1	(−0.729, 0.017, −0.684)	0.51	325.9	1.29	0.46
1998	4	23	17	30	1	(−0.978, −0.025, −0.209)	0.35	388.2	1.79	0.45
1998	4	30	8	48	1	(−0.772, −0.421, 0.476)	0.19	330.8	5.19	0.53
1998	5	1	21	20	1	(−0.793, 0.280, −0.541)	0.30	520.2	1.65	0.31
1998	5	3	16	58	1	(−0.790, 0.600, −0.123)	0.36	435.2	2.75	0.58
1998	5	8	9	20	1	(−0.767, 0.640, −0.033)	0.47	582.5	1.25	0.47
1998	5	15	13	56	0	(−0.155, −0.987, 0.044)	0.25	98.6	0.78	0.54
1998	5	29	15	3	1	(−0.455, 0.879, −0.146)	0.40	393.1	1.62	0.47
1998	6	13	18	57	1	(−0.693, 0.712, −0.111)	0.32	324.0	2.32	0.41
1998	6	25	15	42	0	(−0.886, −0.098, 0.453)	0.60	404.4	0.92	0.46
1998	7	5	3	14	1	(−0.949, 0.017, 0.314)	0.74	698.4	3.88	2.00
1998	7	31	9	14	1	(−0.572, −0.319, −0.756)	0.62	344.0	1.39	0.68
1998	8	6	6	42	1	(−0.932, 0.361, 0.033)	0.57	449.8	1.67	0.70
1998	8	10	0	6	1	(−0.439, −0.137, 0.888)	0.48	309.8	2.39	0.83
1998	8	26	6	20	1	(−0.704, −0.491, −0.513)	0.35	644.0	4.58	0.93
1998	9	24	23	13	1	(−0.934, −0.232, −0.272)	0.38	690.9	2.46	0.58
1998	10	2	6	54	1	(−0.854, 0.409, −0.321)	0.35	743.8	2.96	0.65
1998	10	18	19	0	1	(−0.692, −0.242, −0.680)	0.45	317.1	2.74	0.92
1998	10	23	12	33	1	(−0.740, 0.148, −0.656)	0.41	511.0	2.10	0.54
1998	11	7	7	36	1	(−0.921, 0.083, −0.381)	0.43	463.3	1.64	0.43
1998	11	8	4	20	1	(−0.839, 0.302, −0.452)	0.48	658.0	1.84	0.61
1998	11	30	4	17	1	(−0.891, −0.453, 0.026)	0.40	431.0	2.27	0.66
1998	12	1	2	54	1	(−0.404, −0.017, −0.914)	0.74	261.2	1.22	0.74
1998	12	21	22	51	1	(−0.964, −0.037, −0.263)	0.56	412.8	1.41	0.59
1998	12	28	17	32	1	(−0.337, −0.597, −0.728)	0.60	229.2	1.82	0.95
1999	1	13	9	58	1	(−0.913, −0.362, 0.191)	0.52	408.4	1.66	0.71
1999	1	22	19	45	1	(−0.913, 0.380, −0.149)	0.63	691.0	1.39	0.73
1999	2	11	7	47	1	(−0.954, −0.109, 0.278)	0.55	417.6	1.85	0.67
1999	2	17	6	21	1	(−0.948, −0.240, −0.207)	0.60	530.2	1.42	0.67
1999	2	18	2	7	1	(−1.000, −0.015, −0.025)	0.33	688.3	3.09	0.58
1999	2	28	20	33	1	(−0.959, 0.263, −0.102)	0.76	443.3	1.36	0.91
1999	3	10	0	40	0	(−0.885, −0.128, 0.448)	0.59	476.9	2.45	1.25
1999	4	16	10	34	1	(−0.755, 0.487, 0.440)	0.55	411.4	2.03	0.89
1999	5	5	14	58	1	(−0.660, −0.693, 0.290)	0.35	374.0	2.04	0.52
1999	5	18	0	2	1	(−0.994, 0.106, −0.038)	0.34	444.3	2.30	0.55
1999	6	26	2	17	−1					
1999	6	26	19	23	1	(−0.992, 0.045, 0.115)	0.38	452.4	2.03	0.46
1999	6	27	22	29	1	(−0.401, −0.648, −0.648)	0.57	379.4	1.67	0.75
1999	7	2	0	22	1	(−0.980, −0.014, −0.196)	0.39	643.8	1.97	0.49
1999	7	6	14	15	1	(−0.999, −0.015, 0.040)	0.47	467.5	1.83	0.68
1999	7	8	3	57	0	(−0.236, 0.754, −0.613)	0.76	242.5	1.96	1.17
1999	7	26	23	33	1	(−0.761, 0.537, 0.364)	0.65	382.5	1.32	0.69
1999	8	4	1	14	1	(−0.973, 0.013, −0.230)	0.45	410.7	1.69	0.53
1999	8	8	17	44	1	(−0.847, −0.362, −0.389)	0.71	427.2	1.31	0.79
1999	8	15	9	37	1	(−0.982, −0.127, −0.139)	0.42	406.7	1.76	0.50
1999	8	22	22	48	1	(−0.752, −0.470, 0.462)	0.81	430.5	1.24	0.90
1999	8	23	11	29	1	(−0.951, 0.297, 0.089)	0.69	467.2	1.46	0.84
1999	9	12	3	20	0	(−0.799, −0.355, 0.486)	0.44	519.0	3.06	1.04
1999	9	15	7	17	1	(−0.786, 0.617, 0.048)	0.44	525.3	1.48	0.47
1999	9	15	19	40	1	(−0.850, −0.029, 0.526)	0.44	537.8	1.79	0.58
1999	9	22	11	44	1	(−0.616, 0.264, 0.742)	0.33	389.3	2.25	0.38
1999	9	26	14	26	1	(−0.673, −0.686, 0.277)	0.75	371.7	1.20	0.78
1999	10	21	1	37	1	(−0.810, 0.415, 0.414)	0.34	403.7	2.07	0.47
1999	10	28	11	25	0	(−0.811, 0.020, 0.585)	0.66	420.3	1.95	1.18
1999	11	13	12	13	1	(−0.891, 0.449, 0.065)	0.57	473.2	1.70	0.72
1999	11	19	23	57	1	(−0.668, 0.089, 0.739)	0.65	372.8	1.13	0.59
1999	12	11	12	0	1	(−0.030, −0.532, −0.846)	0.54	114.0	1.68	0.60
1999	12	12	15	13	1	(−0.636, −0.230, −0.736)	0.43	419.6	1.97	0.54
1999	12	26	21	25	1	(−0.984, −0.177, −0.002)	0.72	494.5	1.38	0.83
2000	1	11	13	38	1	(−0.564, −0.652, −0.507)	0.64	397.9	1.47	0.74
2000	1	22	0	21	1	(−0.559, 0.393, −0.730)	0.51	282.5	1.77	0.63
2000	1	27	13	55	1	(−0.984, −0.178, 0.016)	0.56	417.2	1.73	0.73
2000	1	30	18	44	0	(−0.929, 0.351, −0.119)	0.71	755.2	2.68	1.70
2000	2	5	14	48	1	(−0.954, −0.300, −0.008)	0.70	460.3	1.91	0.99
2000	2	11	2	11	1	(−0.989, −0.115, −0.094)	0.36	558.7	2.15	0.62
2000	2	11	23	18	1	(−0.849, −0.515, 0.118)	0.29	602.4	3.27	0.53
2000	2	14	6	54	1	(−0.974, 0.188, 0.129)	0.54	679.7	1.83	0.77
2000	2	20	20	44	0	(−0.736, 0.581, 0.347)	0.16	286.9	0.72	0.37
2000	4	6	16	3	1	(−0.980, 0.075, −0.184)	0.32	663.7	3.67	0.63
2000	4	24	8	50	1	(−0.425, 0.895, −0.137)	0.64	329.6	1.36	0.66

Table A1. (continued)

YY	MM	DD	hh	mm	Flag	Shock Normal	ρ_1/ρ_2	V_{sn}	M_{f1}	M_{f2}
2000	5	17	21	40	1	(−0.887, 0.122, 0.445)	0.74	546.0	1.01	0.63
2000	6	3	8	4	1	(−0.896, −0.382, 0.225)	0.72	434.4	1.49	0.90
2000	6	4	14	22	1	(−0.998, 0.060, 0.018)	0.47	628.9	2.68	0.97
2000	6	8	8	40	1	(−0.990, −0.025, −0.138)	0.30	872.4	4.00	0.55
2000	6	11	7	16	1	(−0.978, −0.083, 0.191)	0.58	562.8	1.52	0.72
2000	6	23	12	26	1	(−0.671, −0.019, −0.741)	0.38	522.5	2.43	0.59
2000	7	10	5	56	1	(−0.861, 0.496, −0.112)	0.48	491.3	1.84	0.60
2000	7	11	11	21	1	(−0.959, 0.255, 0.121)	0.48	496.1	1.78	0.59
2000	7	13	9	16	1	(−0.211, −0.966, 0.148)	0.52	226.6	1.32	0.47
2000	7	17	7	40	1	(−0.573, 0.713, −0.405)	0.57	469.9	1.26	0.53
2000	7	19	14	47	1	(−0.671, 0.315, 0.671)	0.27	478.4	2.94	0.42
2000	7	26	17	54	1	(−0.944, 0.328, −0.027)	0.47	402.4	1.56	0.59
2000	7	28	5	43	1	(−0.995, −0.030, 0.096)	0.35	491.1	2.16	0.45
2000	7	28	9	9	1	(−0.782, −0.298, 0.547)	0.61	452.4	1.66	0.82
2000	8	10	4	7	1	(−0.981, 0.155, 0.115)	0.50	432.4	1.32	0.49
2000	8	11	18	9	1	(−0.723, −0.059, −0.688)	0.49	589.3	1.78	0.59
2000	8	14	21	36	1	(−0.834, 0.410, −0.370)	0.37	513.0	2.15	0.50
2000	9	4	12	41	1	(−0.956, 0.254, −0.146)	0.46	494.2	1.31	0.38
2000	9	6	16	12	1	(−0.994, −0.037, 0.099)	0.40	560.3	2.68	0.65
2000	9	15	3	58	1	(−0.613, 0.675, 0.411)	0.66	430.3	7.07	3.89
2000	9	17	16	57	1	(−0.721, 0.691, −0.050)	0.51	768.4	2.28	0.87
2000	9	30	10	37	1	(−0.912, 0.359, 0.201)	0.78	446.3	1.03	0.70
2000	10	3	0	7	1	(−0.986, −0.113, −0.119)	0.45	468.0	1.49	0.47
2000	10	4	13	36	1	(−0.953, −0.180, 0.245)	0.80	520.2	1.47	0.95
2000	10	5	2	39	1	(−0.920, −0.048, 0.388)	0.41	520.3	2.95	0.75
2000	10	28	9	7	1	(−0.826, 0.562, 0.039)	0.46	422.7	2.30	0.71
2000	10	31	16	30	1	(−0.893, −0.237, 0.384)	0.32	465.6	2.75	0.63
2000	11	4	1	33	1	(−0.990, 0.133, −0.046)	0.27	414.3	1.04	0.80
2000	11	6	9	15	1	(−0.926, 0.172, −0.336)	0.39	631.1	2.58	0.68
2000	11	11	4	0	1	(−0.956, 0.276, 0.094)	0.41	906.8	1.88	0.75
2000	11	26	5	0	1	(−0.875, −0.129, 0.467)	0.59	456.3	2.22	0.97
2000	11	26	11	23	0	(−0.527, −0.850, −0.005)	0.39	407.9	2.65	1.28
2000	11	28	4	55	1	(−0.812, −0.085, −0.577)	0.43	529.6	1.47	0.49
2000	11	29	3	5	1	(−0.724, 0.399, −0.563)	0.67	526.5	1.79	0.99
2000	12	3	3	18	1	(−0.991, 0.116, 0.067)	0.66	500.4	1.33	0.73
2001	1	10	15	19	1	(−0.767, −0.174, 0.618)	0.34	288.8	0.88	0.52
2001	1	13	1	40	1	(−0.227, 0.111, 0.968)	0.33	182.7	1.32	0.36
2001	1	17	15	30	1	(−0.883, −0.165, −0.438)	0.48	409.9	2.40	0.83
2001	1	23	10	4	1	(−0.985, −0.038, −0.166)	0.23	583.6	3.45	0.45
2001	1	31	7	22	1	(−0.720, 0.621, 0.310)	0.40	416.5	2.22	0.56
2001	2	12	20	45	1	(−0.837, −0.210, −0.505)	0.63	445.9	1.59	0.79
2001	3	3	10	38	1	(−0.869, 0.126, −0.479)	0.47	470.9	1.60	0.42
2001	3	19	10	26	−1					
2001	3	27	1	8	1	(−0.499, 0.362, −0.787)	0.20	290.2	3.60	0.35
2001	3	27	17	14	1	(−0.669, 0.608, −0.427)	0.51	377.4	1.07	0.37
2001	3	31	0	22	1	(−0.615, 0.315, −0.723)	0.33	580.3	3.82	0.75
2001	3	31	21	37	0	(−0.652, 0.622, −0.434)	0.39	598.9	0.63	0.56
2001	4	4	14	22	1	(−0.806, 0.452, 0.382)	0.25	603.3	2.53	0.42
2001	4	7	16	58	1	(−0.949, −0.314, 0.008)	0.23	584.5	1.86	0.36
2001	4	8	10	30	1	(−0.917, −0.379, −0.122)	0.30	720.3	3.40	0.58
2001	4	11	13	12	1	(−0.625, −0.657, 0.422)	0.41	509.8	2.22	0.60
2001	4	11	15	27	1	(−0.501, −0.499, 0.707)	0.50	606.4	2.13	0.95
2001	4	13	7	3	1	(−0.973, 0.145, 0.178)	0.33	840.6	1.98	0.45
2001	4	18	0	5	1	(−0.931, −0.358, 0.070)	0.22	517.3	3.44	0.30
2001	4	21	15	4	1	(−0.886, 0.459, 0.068)	0.39	374.0	2.41	0.71
2001	4	28	4	32	1	(−0.946, −0.305, −0.112)	0.32	882.5	4.46	0.83
2001	5	8	9	30	1	(−0.993, −0.049, −0.110)	0.52	433.5	1.02	0.29
2001	5	12	9	22	1	(−0.553, −0.481, −0.681)	0.78	436.9	1.07	0.74
2001	5	27	14	16	1	(−0.974, −0.116, 0.195)	0.44	625.2	2.42	0.72
2001	6	7	8	51	1	(−0.996, 0.003, −0.090)	0.63	472.9	1.40	0.71
2001	8	3	6	24	1	(−0.940, 0.186, 0.285)	0.26	434.1	2.42	0.46
2001	8	5	11	55	1	(−0.908, 0.088, 0.411)	0.73	537.6	1.34	0.87
2001	8	12	10	48	1	(−0.561, 0.026, 0.827)	0.24	271.8	2.07	0.33
2001	8	17	10	14	1	(−0.972, −0.035, −0.234)	0.27	504.7	3.19	0.44
2001	8	27	19	18	1	(−0.717, 0.042, 0.696)	0.35	510.7	2.35	0.52
2001	8	30	13	29	1	(−0.786, −0.145, 0.601)	0.54	492.1	2.07	0.84
2001	9	14	1	16	1	(−0.865, −0.450, 0.223)	0.39	440.3	2.28	0.55
2001	9	29	9	5	0	(−0.906, 0.317, 0.280)	0.49	739.8	3.63	1.83
2001	9	30	18	45	0	(−0.880, 0.425, −0.212)	0.63	556.3	3.04	1.15
2001	10	11	16	19	1	(−0.997, −0.081, −0.018)	0.36	578.6	2.97	0.62
2001	10	14	17	7	1	(−0.998, 0.059, 0.000)	0.69	454.8	1.15	0.67
2001	10	21	16	12	1	(−0.994, −0.061, 0.096)	0.33	638.4	2.70	0.50

Table A1. (continued)

YY	MM	DD	hh	mm	Flag	Shock Normal	ρ_1/ρ_2	V_{sn}	M_{f1}	M_{f2}
2001	10	25	8	2	1	(−0.873, 0.037, 0.487)	0.26	463.2	5.50	0.69
2001	10	28	2	40	1	(−0.874, 0.486, −0.019)	0.39	519.6	2.38	0.59
2001	10	31	12	52	1	(−0.959, −0.069, −0.276)	0.35	434.0	2.02	0.48
2001	11	19	17	35	1	(−0.967, −0.136, −0.217)	0.48	634.6	2.35	0.74
2001	11	30	17	26	1	(−0.910, 0.382, 0.164)	0.67	363.8	1.44	0.84
2001	12	23	22	18	1	(−0.889, −0.106, 0.445)	0.31	344.1	2.20	0.49
2001	12	29	4	45	1	(−0.991, 0.042, 0.128)	0.28	480.6	3.21	0.49
2001	12	30	19	30	1	(−0.994, 0.096, 0.045)	0.41	651.4	1.90	0.49
2002	1	10	15	44	1	(−0.736, −0.364, −0.571)	0.48	546.9	2.05	0.85
2002	1	31	20	37	1	(−0.883, −0.089, 0.460)	0.50	413.1	1.81	0.85
2002	2	17	2	8	1	(−0.458, −0.695, 0.553)	0.31	238.5	1.79	0.27
2002	3	18	12	36	1	(−0.986, −0.168, 0.014)	0.26	503.1	3.95	0.56
2002	3	20	13	4	1	(−0.964, −0.077, 0.255)	0.62	883.0	1.22	0.57
2002	3	22	3	21	1	(−0.786, 0.319, 0.529)	0.65	447.2	1.70	0.91
2002	3	23	10	52	1	(−0.840, 0.161, 0.517)	0.32	460.1	2.28	0.43
2002	3	25	0	57	1	(−0.796, 0.370, 0.479)	0.79	694.5	1.36	0.98
2002	4	17	10	20	1	(−0.896, −0.444, 0.002)	0.23	444.8	1.84	0.16
2002	4	19	8	1	1	(−0.955, −0.293, −0.049)	0.45	746.6	1.76	0.52
2002	4	23	4	14	1	(−0.892, 0.449, 0.053)	0.37	666.2	4.17	0.99
2002	5	10	10	29	1	(−0.947, −0.204, 0.249)	0.40	433.1	1.80	0.48
2002	5	11	9	24	1	(−0.880, −0.032, 0.475)	0.36	406.8	1.88	0.44
2002	5	18	19	18	1	(−0.919, −0.363, 0.151)	0.30	520.3	4.00	0.67
2002	5	20	3	0	1	(−0.948, −0.279, 0.155)	0.60	582.8	2.06	0.99
2002	5	21	20	59	0	(−0.258, −0.041, −0.965)	0.60	142.0	0.74	0.19
2002	5	23	10	14	1	(−0.809, −0.123, −0.575)	0.51	727.8	2.83	0.98
2002	5	30	1	31	1	(−0.613, 0.636, −0.469)	0.50	439.5	1.96	0.76
2002	7	17	15	24	1	(−0.892, −0.321, −0.318)	0.32	506.0	2.09	0.43
2002	7	19	9	31	1	(−0.693, −0.677, −0.249)	0.39	507.3	2.61	0.69
2002	7	19	14	41	0	(−0.427, −0.831, −0.356)	0.66	553.1	2.79	1.40
2002	7	22	4	50	1	(−0.712, 0.195, 0.674)	0.51	445.2	1.61	0.59
2002	7	25	12	59	1	(−0.844, −0.175, 0.507)	0.67	565.5	1.65	0.90
2002	7	29	12	39	1	(−0.839, 0.145, 0.525)	0.36	490.8	2.61	0.68
2002	8	1	4	22	1	(−0.685, 0.726, −0.056)	0.43	427.1	1.48	0.46
2002	8	1	22	17	1	(−0.970, −0.232, −0.079)	0.60	484.4	1.21	0.52
2002	8	18	18	9	1	(−0.881, 0.219, 0.420)	0.23	603.5	5.39	0.56
2002	8	26	10	50	−1					
2002	9	7	16	8	1	(−0.932, −0.331, 0.147)	0.33	639.0	3.12	0.55
2002	10	2	22	12	1	(−0.444, 0.670, −0.596)	0.50	256.2	1.42	0.49
2002	11	9	17	54	1	(−0.961, 0.255, −0.111)	0.55	429.6	1.97	0.85
2002	11	11	11	51	1	(−0.992, −0.086, 0.095)	0.63	683.5	1.73	0.99
2002	11	16	23	5	1	(−0.719, 0.689, −0.096)	0.60	388.4	1.62	0.71
2002	11	20	10	18	1	(−0.708, 0.630, 0.321)	0.53	335.9	1.39	0.66
2002	11	26	21	8	1	(−0.927, −0.316, 0.201)	0.35	597.4	2.28	0.48
2002	12	22	9	40	1	(−0.829, −0.464, 0.314)	0.71	527.9	1.75	0.98
2002	12	22	12	13	1	(−0.964, −0.074, −0.257)	0.82	573.0	1.01	0.74
2002	12	24	13	13	1	(−0.931, −0.198, 0.306)	0.64	556.2	1.46	0.81
2003	2	17	23	0	0	(−0.654, −0.222, 0.723)	0.72	628.1	2.29	1.64
2003	3	20	4	19	1	(−0.760, 0.236, 0.605)	0.62	735.1	1.43	0.69
2003	3	26	16	50	1	(−0.725, −0.688, −0.035)	0.49	326.6	0.87	0.30
2003	4	8	0	14	1	(−0.928, −0.093, 0.361)	0.39	382.6	2.12	0.64
2003	4	28	18	33	1	(−0.943, −0.285, −0.173)	0.66	549.6	1.19	0.63
2003	5	9	4	54	1	(−0.778, 0.593, 0.208)	0.44	797.5	2.10	0.56
2003	5	29	11	50	1	(−0.776, −0.097, 0.623)	0.60	611.4	2.42	1.23
2003	5	29	18	29	1	(−0.928, −0.098, 0.359)	0.40	817.0	1.55	0.38
2003	5	30	15	50	1	(−0.957, −0.266, 0.118)	0.63	910.1	2.26	1.17
2003	6	18	4	27	1	(−0.840, −0.539, −0.063)	0.69	558.5	1.55	0.89
2003	6	20	7	54	1	(−0.986, −0.169, −0.012)	0.36	605.3	1.76	0.40
2003	7	6	12	22	1	(−0.873, 0.481, −0.077)	0.52	614.7	1.34	0.48
2003	8	17	13	39	1	(−1.000, −0.011, −0.002)	0.52	598.4	2.47	0.98
2003	10	24	14	47	1	(−0.999, −0.025, −0.044)	0.36	683.1	3.42	0.63
2003	10	26	8	8	1	(−0.750, 0.504, −0.428)	0.76	476.2	1.04	0.80
2003	10	26	18	30	1	(−0.995, −0.054, −0.083)	0.65	665.9	1.53	0.80
2003	10	28	1	30	1	(−0.883, −0.310, −0.352)	0.52	670.2	1.54	0.57
2003	11	4	6	0	1	(−0.883, 0.459, −0.096)	0.28	792.5	4.39	0.83
2003	11	6	19	19	1	(−0.416, 0.818, −0.397)	0.40	400.3	2.89	0.73
2003	11	15	5	18	1	(−0.858, −0.194, 0.476)	0.51	761.5	2.33	0.73
2003	11	20	7	27	1	(−0.958, 0.123, −0.260)	0.31	675.1	3.55	0.63
2003	11	22	10	0	1	(−0.902, 0.241, 0.358)	0.64	609.5	1.17	0.61
2003	11	30	2	45	1	(−0.761, 0.527, −0.378)	0.72	377.8	1.13	0.56
2003	12	7	13	41	1	(−0.437, −0.348, 0.829)	0.50	366.3	2.09	0.76
2004	1	6	19	25	1	(−0.900, −0.333, 0.283)	0.53	674.2	1.42	0.54
2004	1	22	1	3	1	(−0.994, −0.034, 0.101)	0.27	731.4	3.56	0.44

Table A1. (continued)

YY	MM	DD	hh	mm	Flag	Shock Normal	ρ_1/ρ_2	V_{sn}	M_{f1}	M_{f2}
2004	1	23	14	20	1	(−0.749, −0.383, −0.541)	0.52	521.6	1.50	0.59
2004	4	3	8	54	1	(−0.020, −0.245, 0.969)	0.56	87.6	1.06	0.28
2004	4	9	1	48	0	(−0.993, 0.096, 0.073)	0.63	613.7	2.84	1.50
2004	4	10	19	24	1	(−0.632, −0.583, 0.510)	0.38	439.9	2.74	0.71
2004	4	12	4	24	1	(−0.739, −0.069, 0.671)	0.47	385.9	1.70	0.60
2004	4	12	17	34	1	(−0.527, −0.411, 0.744)	0.35	362.2	2.40	0.60
2004	4	24	8	7	1	(−0.949, 0.102, −0.297)	0.59	528.8	1.66	0.81
2004	4	26	15	16	1	(−0.991, 0.046, 0.126)	0.48	553.9	1.65	0.72
2004	5	10	21	57	1	(−0.936, 0.352, 0.014)	0.67	417.6	1.05	0.52
2004	7	16	21	5	1	(−0.964, −0.236, −0.119)	0.53	470.2	1.49	0.58
2004	7	22	9	53	1	(−0.736, −0.629, 0.252)	0.27	420.4	2.54	0.43
2004	7	24	5	41	−1					
2004	7	26	22	26	0	(−0.938, −0.183, 0.295)	0.33	1002.7	5.84	1.29
2004	7	30	20	30	1	(−0.948, 0.278, 0.153)	0.38	556.6	1.92	0.47
2004	8	1	1	46	0	(−0.850, 0.527, −0.012)	0.56	576.5	2.95	1.50
2004	8	29	9	16	1	(−0.987, 0.148, −0.064)	0.45	468.3	1.79	0.62
2004	9	22	5	52	1	(−0.972, 0.233, −0.013)	0.51	582.5	2.18	0.78
2004	10	2	2	29	−1					
2004	10	27	11	17	1	(−0.970, −0.085, −0.228)	0.59	432.5	1.46	0.67
2004	11	7	2	6	−1					
2004	11	7	9	59	1	(−0.712, −0.659, 0.242)	0.33	408.4	3.28	0.74
2004	11	7	17	52	1	(−0.819, −0.510, 0.264)	0.49	652.3	1.97	0.73
2004	11	9	9	13	1	(−0.616, −0.114, −0.779)	0.27	764.2	4.87	0.56
2004	11	9	18	20	1	(−0.910, 0.118, −0.397)	0.26	754.5	1.66	0.29
2004	11	11	16	43	1	(−0.528, −0.313, −0.790)	0.44	437.0	2.63	0.75
2004	12	11	12	55	1	(−0.487, 0.723, −0.490)	0.33	334.3	2.02	0.48
2004	12	29	12	34	1	(−0.526, −0.712, 0.466)	0.68	284.7	1.02	0.56
2005	1	1	10	6	1	(−0.928, −0.339, 0.156)	0.57	503.8	1.42	0.62
2005	1	7	8	40	1	(−0.873, −0.445, 0.200)	0.65	522.5	1.62	0.95
2005	1	17	7	15	1	(−0.910, 0.245, 0.335)	0.55	697.6	3.28	1.40
2005	1	17	10	42	1	(−0.311, −0.495, 0.812)	0.68	440.8	1.02	0.58
2005	1	21	16	49	1	(−0.987, −0.008, −0.160)	0.30	1030.0	5.17	0.79
2005	2	17	22	4	0	(−0.821, 0.562, 0.103)	0.47	341.0	0.02	0.04
2005	4	29	15	3	0	(−0.615, −0.768, 0.180)	0.68	320.3	2.27	1.23
2005	5	6	12	4	1	(−0.929, −0.357, 0.099)	0.56	414.0	1.87	0.85
2005	5	7	18	19	0	(−0.819, 0.351, −0.453)	0.61	351.1	0.88	0.36
2005	5	20	3	15	1	(−0.766, 0.542, 0.346)	0.61	403.3	1.38	0.99
2005	5	29	9	3	1	(−0.955, −0.150, 0.257)	0.51	484.8	1.47	0.52
2005	6	12	6	52	1	(−0.604, −0.233, −0.762)	0.32	265.3	1.49	0.39
2005	6	14	17	54	1	(−0.853, 0.106, 0.512)	0.42	541.4	2.59	0.72
2005	6	16	8	10	1	(−0.913, −0.215, 0.346)	0.59	601.4	1.44	0.64
2005	7	10	2	48	1	(−0.908, 0.287, 0.305)	0.55	483.0	1.87	0.76
2005	7	16	1	51	0	(−0.822, 0.261, 0.506)	0.67	373.9	0.67	0.30
2005	7	16	16	16	1	(−0.938, −0.001, 0.346)	0.58	427.7	1.34	0.55
2005	7	17	0	53	1	(−0.834, 0.533, 0.144)	0.48	450.9	1.35	0.42
2005	7	27	18	50	0	(−0.142, −0.652, 0.745)	0.44	78.9	0.54	0.69
2005	8	1	6	6	1	(−0.524, −0.491, −0.696)	0.59	417.8	1.56	0.69
2005	8	23	19	38	0	(−0.811, 0.584, 0.044)	0.68	506.4	2.11	1.18
2005	8	24	5	38	1	(−0.822, 0.490, 0.292)	0.45	538.9	2.18	0.64
2005	8	24	8	29	0	(−0.558, −0.030, 0.829)	0.67	581.6	2.42	1.54
2005	8	25	13	8	1	(−0.628, 0.775, −0.080)	0.43	540.0	1.92	0.57
2005	9	2	13	40	1	(−0.944, −0.125, 0.304)	0.51	587.6	2.00	0.69
2005	9	9	13	17	1	(−0.799, −0.161, 0.579)	0.27	428.6	3.18	0.56
2005	9	12	6	4	1	(−0.936, 0.333, 0.113)	0.45	990.3	1.54	0.70
2005	9	13	9	1	0	(−0.076, −0.959, 0.275)	0.92	162.4	0.29	0.27
2005	9	15	8	30	1	(−0.732, −0.355, 0.582)	0.31	577.7	2.92	0.43
2005	12	30	23	46	1	(−0.937, 0.333, −0.109)	0.65	603.5	1.47	0.76
2006	1	1	13	31	1	(−0.644, 0.235, 0.728)	0.54	431.9	1.46	0.58
2006	4	8	23	16	1	(−0.687, −0.228, −0.690)	0.76	317.0	1.32	0.89
2006	4	13	11	13	1	(−0.930, −0.307, 0.204)	0.64	520.0	1.54	0.99
2006	7	9	20	51	−1					
2006	8	18	15	51	1	(−0.998, 0.039, 0.045)	0.59	477.9	1.86	0.87
2006	8	19	10	51	1	(−0.772, 0.570, 0.281)	0.57	458.6	1.61	0.74
2006	8	21	15	56	1	(−0.579, 0.610, −0.542)	0.78	349.4	1.33	0.97
2006	9	3	23	29	1	(−0.890, −0.094, 0.445)	0.42	441.6	2.37	0.74
2006	12	14	13	53	0	(−0.803, 0.560, 0.204)	0.27	909.7	5.31	1.44
2006	12	16	17	23	1	(−0.587, 0.809, −0.009)	0.35	474.8	2.60	0.49
2006	12	18	9	21	1	(−0.802, −0.581, 0.140)	0.46	354.5	1.61	0.41
2007	2	12	9	12	1	(−0.949, −0.306, 0.071)	0.48	376.2	1.68	0.67
2007	5	7	7	30	−1					
2007	9	27	10	53	1	(−0.993, 0.076, 0.090)	0.46	437.4	1.79	0.56
2007	10	25	10	40	−1					

Table A1. (continued)

YY	MM	DD	hh	mm	Flag	Shock Normal	ρ_1/ρ_2	V_{sn}	M_{f1}	M_{f2}
2007	11	12	21	27	1	(−0.332, −0.460, 0.824)	0.62	219.5	1.03	0.46
2007	12	17	2	4	1	(−0.885, −0.347, 0.311)	0.42	415.0	2.35	0.72
2008	1	12	11	34	1	(−0.732, −0.624, −0.274)	0.73	334.9	1.31	0.69
2008	4	23	2	24	1	(−0.900, −0.426, 0.088)	0.72	453.1	1.06	0.69
2008	4	30	14	56	1	(−0.912, 0.312, 0.265)	0.64	388.0	1.33	0.68
2008	5	28	1	25	−1					
2008	7	22	6	10	0	(−0.379, 0.799, −0.468)	0.80	173.3	0.64	0.21
2008	8	8	22	51	1	(−0.451, −0.852, 0.265)	0.75	249.1	1.03	0.67

[a]YY-MM-DD hh:mm: the UT of IP shocks; Flag: 1 denotes a shock; 0 denotes a shocklike structure; −1 denotes the plasma data gap for upstream; shock normal: shock normal vector; ρ_1/ρ_2: density ratio of upstream (ρ_1) and downstream (ρ_2) of a shock; V_{sn}: shock normal speed; M_{f1}, M_{f2}: upstream and downstream fast Mach number, respectively.

and reduced Colaba (Bombay/Mumbai) magnetic data for the 1–2 September 1859 storm revealed the peak initial phase amplitude was about 120 nT [*Tsurutani et al.*, 2003]. By the use of equation (1), the change of the square root of solar wind dynamic pressure across this shock is estimated to be 6.72 nPa$^{1/2}$, ~20% lower than the value (8.51 nPa$^{1/2}$) inferred by *Li et al.* [2005]. The difference might come from the contribution from the southward IMF (Interplanetary Magnetic Field) and the uncertainties about the estimation of the solar wind parameters.

[17] Figure 5 plots the estimations of the change of geosynchronous magnetic field (ΔB_z) near the subsolar region (9–15 h local time) using equation (2) with the ΔSYM-H as input against the measurements. Once again, the estimations are in good agreement with the observations, with an efficiency of 86% and a linear correlation coefficient between the estimations and the data of 0.95.

3. Summary

[18] Interplanetary (IP) shocks disturb the magnetosphere-ionosphere system in a significant way, resulting in geosynchronous magnetic field changes and sudden impulses observed by ground-based magnetometers. In this study, we use the amplitude of sudden impulses (ΔSYM-H) observed on the ground to estimate some parameters at the L1 point and geosynchronous orbit. These estimates are of particular use in studying events before the space era and could provide proxies for future times if we do not have spacecraft at the L1 point and at geosynchronous orbit. However, the reader should note that there is not a unique solution and these are statistical estimates.

[19] We use 250 IP shocks identified in the ACE data between 1998.02 and 2005.04. Two hundred sixteen or ~88% of these shock events caused geosynchronous magnetic field changes observed by GOES spacecraft and all these 216 IP shocks caused sudden impulses observed on the ground. We used these 216 cases to derive empirical relations between the SI amplitude(ΔSYM-H) and (1) the time lag $\Delta\tau$ (the time lag ranges from 15 to 70 min, which has weak correlation with the SI amplitude (ΔSYM-H) on the ground), (2) the change of the square root of the solar wind dynamic pressure across an IP shock $\Delta\sqrt{P_d}$

$$\Delta\sqrt{P_d} = 0.056 \times \Delta \mathrm{SYM-H} (\mathrm{nPa})^{1/2}, \tag{3b}$$

and (3) the geosynchronous magnetic field z component ΔB_z in the subsolar region (9–15 LT)

$$\Delta B_z = 1.67 \times \Delta \mathrm{SYM-H} - 11.23(\mathrm{nT})(\Delta \mathrm{SYM-H} \geq 7\mathrm{nT}). \tag{3c}$$

[20] To check the validity of these relationships, we identified 46 IP shocks observed by ACE from 2005.04 to 2008.09. All of these shocks produced geosynchronous magnetic field disturbances and corresponding effects in the SYM-H index. The estimations for change of the square root of solar wind dynamic pressure across an IP shock ($\Delta\sqrt{P_d}$) at the L1 point and the geosynchronous magnetic field z component (ΔB_z) in the subsolar region (9–15 h LT) are in good agreement with observations, with the efficiencies of 90% and 86%, respectively. Most of the time lags are in the range of 30 to 60 min. In this way, we could use the sudden impulses (SIs) observed on the ground to make estimate of conditions at the L1 point and at geosynchronous orbit. If the SI amplitudes at the low-latitudes stations near the noon instead of the SYM-H index are used, it could be expected that the prediction efficiencies would be improved, which will be investigated in our future work.

Appendix A: The List of Interplanetary Shocks Observed by ACE

[21] Using the ACE 64 s time resolution solar wind data, we apply an autosearch computer program to find potential interplanetary shocks (IP shocks) and shocklike solar wind structures and then visually inspect each event during 1998.02–2008.09. The shock parameters are calculated by using the shock fitting procedure proposed by *Lin et al.* [2006]. The shocks are listed in Table A1.

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J. R. Kan, Geophysical Institute, University of Alaska Fairbanks, 930 North Koyukuk Dr., Fairbanks, AK 99709, USA. (ffjrk@uaf.edu)

H. Li and C. Wang, State Key Laboratory of Space Weather, Center for Space Science and Applied Research, Chinese Academy of Sciences, PO Box 8701, Beijing 100190, China. (cw@spaceweather.ac.cn)

J. D. Richardson, Kavli Institute for Astrophysics and Space Research, Massachusetts Institute of Technology, 37-655, Cambridge, MA 02139, USA. (jdr@space.mit.edu)