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What Can We Learn from the Geoeffectiveness of the Magnetic Cloud on 2012 July 15–17?

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Abstract

An interplanetary shock and a magnetic cloud (MC) reached the Earth on 2012 July 14 and 15 one after another. The shock sheath and the MC triggered an intense geomagnetic storm. We find that only small part of the MC from 06:45 UT to 10:05 UT on 2012 July 15 made contribution to the intense geomagnetic storm, while the rest part of the MC made no contribution to the intense geomagnetic storm. The averaged southward component of interplanetary magnetic field (B_s) and duskward-electric fields (E_y) within the MC from 10:05 UT, 2012 July 15 to 09:08 UT, 2012 July 16 (hereafter MC_2), are 15.11 nT and 8.01 mV m^{-1}, respectively. According to the empirical formula established by Burton et al. (hereafter Burton equation), the geoeffectiveness of MC_2 should be -655.42 nT, while the geoeffectiveness of MC_2 is -324.68 nT according to the empirical formula established by O'Brien & McPherron (hereafter OM equation). However, the real geoeffectiveness of MC_2 is 39.74 nT. The results indicate that the Burton equation and the OM equation cannot work effectively. The geoeffectiveness of MC_2 shows that large and long duration of B_s or E_y cannot guarantee the occurrence of an intense geomagnetic storm if the solar wind dynamic pressure is very low. If we use 0.52 as γ, the geoeffectiveness of MC_2 is 40.36 nT according to the empirical formula established by Wang et al., which is very close to the observed value, indicating that the empirical formula established by Wang et al. is much better than the Burton equation and the OM equation.

Key words: Solar coronal mass ejections – Solar-terrestrial interactions – Solar wind

1. Introduction

Geomagnetic storm is a worldwide continuous intense disturbance of the geomagnetic field. The basic condition for the occurrence of a geomagnetic storm is that the solar wind has a long duration of southward interplanetary magnetic field (IMF) so that southward component of IMF can reconnect with Earth's field, and then allows the solar wind energy transport into the Earth's magnetosphere (Dungey 1961; Gonzalez et al. 1994). The southward component of IMF (hereafter referred to as B_s) is a key factor for the occurrence of a geomagnetic storm. Gonzalez & Tsurutani (1987) proposed that $B_s > 10$ nT and the associated interplanetary duskward-electric fields (hereafter referred to as solar wind electric field: E_y) >5 mV m^{-1} last for more than 3 h, then an intense geomagnetic storm (Dst < -100 nT) will happen. Echer et al. (2008) claimed that they observed that around 70% of the storms follow the interplanetary criteria of $E_y > 5$ mV m^{-1} for at least 3 h. Around 90% of the storms used in the study followed a less stringent set of criteria: $E_y > 3$ mV m^{-1} for at least 3 h. It is evident that the contribution made by solar wind dynamic pressure has not been mentioned. Ji et al. (2010) also checked the criteria for the occurrence of intense geomagnetic storm and conditions suggested for the solar wind to cause intense

geomagnetic storms did not include solar wind dynamic pressure. It is generally accepted that the intensity of a geomagnetic storm only depends on the solar wind electric field with solar wind dynamic pressure making no contribution. For example, Wang et al. (2003) established an empirical formula relating the geomagnetic storm intensity to the solar wind parameters, which is only the function of E_y and its duration, and identified that $E_y > 5$ mV m^{-1} and the duration >3 h always caused intense geomagnetic storms. In fact, the injection term in the empirical formula established by Burton et al. (1975) (hereafter referred to as Burton equation) and the injection term in the empirical formula established by O'Brien & McPherron (2000) (hereafter referred to as OM equation) are only the function of E_y, while the decay term in the OM equation mainly depends on τ, which is also a function of E_y. According to the Burton equation and the OM equation, the intensity of a geomagnetic storm solely depends on the E_y. The Burton equation and the OM equation have been widely accepted in the community.

A halo coronal mass ejection on 2012 July 12 was observed by STEREO A, B and the Large Angle Spectral Coronagraphs on SOHO. Hess & Zhang (2014) studied the detail evolution of the ejecta front and the shock front from the Sun to the Earth,

and fitted the two fronts to a simple but physics-based model. The shock reached the Earth on 2012 July 14, while the ejecta that drove the shock reached the magnetosphere on 2012 July 15. The shock and the ejecta triggered an intense geomagnetic storm with the minimum of Dst −139 nT. The ejecta is a magnetic cloud (MC). However, the property of the geoeffectiveness of the MC has not been deeply studied. Are the criteria proposed by Gonzalez & Tsurutani (1987) correct? Whether the geoeffectiveness of the MC calculated by the Burton equation or by the OM equation is consistent with the real situation? To answer these questions, the geoeffectiveness of part of the MC will be calculated according to the Burton equation and the OM equation and then compared with the real situation. This is the motivation of the study. The organization of the rest part of the article is as follows. Section 2 is the data analysis. Summary and discussion is presented in Section 3.

2. Data Analysis

2.1. Data Source and Observation

The time resolution of the solar wind data used in this study is 1 min, which is available at https://omniweb.gsfc.nasa.gov/, while the geomagnetic activity index used in this study is the SYM-H index, which can be treated as high time resolution of Dst index (Wanliss & Showalter 2006), can be obtained from the website at http://wdc.kugi.kyoto-u.ac.jp/. The solar wind data during 2012 July 14–17 are shown in Figure 1. The shock driven by the MC reached the magnetosphere at 18:09 UT, 2012 July 14, which is indicated by the first vertical dashed line. The sheath region is the solar wind between the shock and the MC. The magnetic field in sheath region usually fluctuated dramatically, while the magnetic field changes gradually in the MC and the proton β is low (Zurbuchen & Richardson 2006). The start time of the MC is 06:45 UT, 2012 July 15 indicated by the second vertical dashed line. The end time of the MC is 04:19 UT, 2012 July 17, which is indicated by the fifth vertical dashed line.

2.2. The Geoeffectiveness of the MC

The main phase of the geomagnetic storm is the period between the first and third vertical solid red lines in the last panel shown in Figure 2. The main phase of the storm is constituted by the two parts. The first part of the storm main phase is the period between the first and the second vertical solid red lines, which is caused by the sheath region. The second part of the storm main phase is the period between the second and the third vertical red lines (hereafter MC_1), which is caused by small part of the MC. The solar wind between the third and fourth vertical dashed lines is also part of the MC (hereafter MC_2). The MC_3 is the solar wind between the

fourth and fifth vertical dashed lines shown in Figure 1. The MC is constituted by MC_1, MC_2 and MC_3. The start and the end time of MC_2 is 10:05 UT, 2012 July 15 and 09:08 UT, 2012 July 16, respectively.

The evolution of SYM-H* (pressure corrected SYM-H) can be written as follows:

$$d\text{SYM-H}^*/dt = Q - D \tag{1}$$

where Q and D are the injection and decay terms of the ring current, respectively. For the OM equation, we use Q_{om} and D_{om} to indicate the injection and decay terms of the ring current, respectively. For the Burton equation, we use Q_b and D_b to indicate the injection and decay terms of the ring current, respectively.

If we use the OM equation to calculate the geoeffectiveness of MC_2, then the geoeffectiveness of MC_2 calculated by the OM equation is $\Delta\text{SYM-H}^*_{om}$, which is calculated as below,

$$\Delta\text{SYM-H}^*_{om} = \int_{t_s}^{t_e} (Q_{om} - D_{om})dt \tag{2}$$

where t_s and t_e are the start and the end time of MC_2, $\Delta\text{SYM-H}^*_{om}$ is the pressure corrected SYM-H$_{om}$ during the interval between t_s and t_e. According to the OM equation, the derived $\Delta\text{SYM-H}^*_{om}$ caused by MC_2 is −324.681 nT. Similarity, according to the Burton equation, the derived $\Delta\text{SYM-H}^*_b$ caused by MC_2 is −655.415 nT. However, the observed $\Delta\text{SYM-H}^*$ caused by MC_2 is 39.74 nT. It is evident that the geoeffectiveness of MC_2 calculated by the OM equation or by the Burton equation greatly deviates from the real situation.

3. Discussion

E_y is always larger than 5 mV m^{-1} and B_s is always larger than 10 nT within MC_2. The averaged E_y and P_d in MC_2 is 8 mV m^{-1} and 15.11 nT, respectively. The duration of MC_2 is 22^{h}3^m. It is evident that the solar wind parameters of MC_2 satisfy the criteria to produce an intense geomagnetic storm proposed by Gonzalez & Tsurutani (1987). However, MC_2 did not produce an intense geomagnetic storm. Why? The averaged P_d of MC_2 is 0.84 nPa, which is very low. This may be the reason why MC_2 did not produce an intense geomagnetic storm. This case study indicates that large and long duration of B_s or E_y ($B_z >$10 nT and the duration $>$3 h, or $E_y > 5$ mV m^{-1} and the duration $>$3 h) cannot guarantee the occurrence of an intense geomagnetic storm if the solar wind dynamic pressure is very low, implying that the criteria for the occurrence of an intense geomagnetic storm should include the conditions for both solar wind electric field and the solar wind dynamic pressure. In this context, the criteria proposed by Gonzalez & Tsurutani (1987) are not suitable because the criteria ignored the function of the solar wind dynamic pressure. The
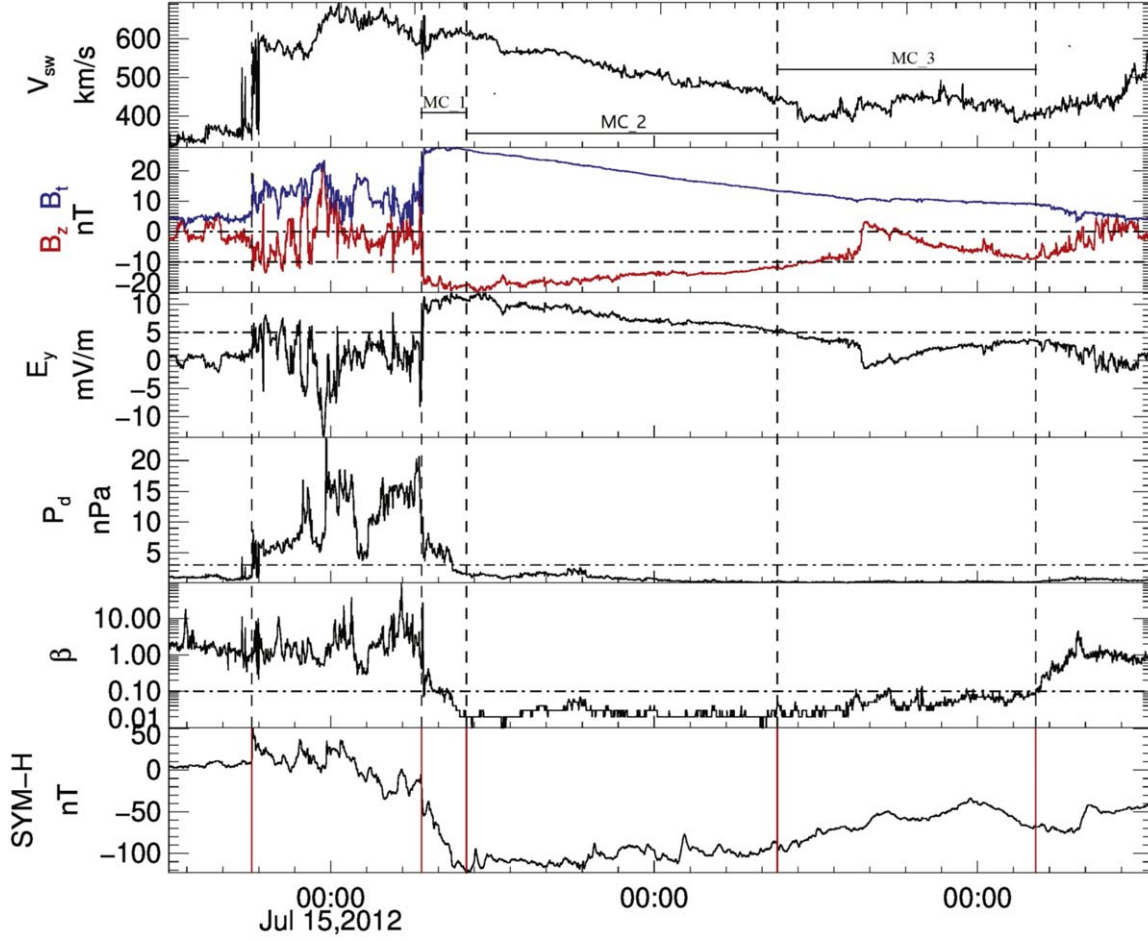
Figure 1. The observations of solar wind data from 2012 July 14 to 17. From top to bottom, it shows solar wind speed (V_{sw}), blue and red lines for total magnetic field (B) and the z-component of B (B_z) respectively, solar wind electric field (E_y), solar wind dynamic pressure (P_d), proton β, and SYM-H. The horizontal dotted–dashed lines in the second panel indicate 0 and -10 nT, respectively. The horizontal dotted–dashed line in the third panel detonates $E_y = 5$ mV m^{-1}. The horizontal dotted–dashed line in the fourth panel detonates $P_d = 3$ nPa. The horizontal dotted–dashed line in the fifth panel detonates $\beta = 0.1$. The first and second vertical dashed lines indicate the time when the shock reached the magnetosphere and the start time of the MC. The last vertical dashed line indicates the end time of the MC.

geoeffectiveness of MC_2 derived from the OM equation or the Burton equation greatly deviates from the observation, indicating that the relationship between the intensity of a geomagnetic storm and the solar wind parameters described by the OM and Burton equations is not suitable if solar wind dynamic pressure is very low.

The injection term of the ring current in the empirical formula established by Wang et al. (2003) (hereafter WCL equation) is written as below,

$$Q_w = \begin{cases} -4.4(E_y - 0.49)(P_d/3)^\gamma & E_y > 0.49 \text{ mV m}^{-1}, \\ 0 & E_y \leqslant 0.49 \text{ mV m}^{-1}, \end{cases} \quad (3)$$

where P_d is the solar wind dynamic pressure, γ is 0.2 in the WCL equation. If we select γ as 0.52, the geoeffectiveness of MC_2 calculated by the WCL equation is 40.36 nT shown in Figure 3, which is very close to the observed intensity caused by MC_2.

If $P_d < 3$ nPa, $(P_d/3) < 1$, then $|Q_w| < |Q_{om}|$, and the larger γ, the lower $(P_d/3)^\gamma$, indicating that injection term of the ring current derived by the WCL equation decreases as the solar wind dynamic pressure decreases, which is consistent with the real situation.

To further verify the importance of the solar wind dynamic pressure to the intensity of a geomagnetic storm, we compare the geoeffectiveness of the MC_1 calculated by the OM, Burton and WCL equations with the real situation. The geoeffectiveness of
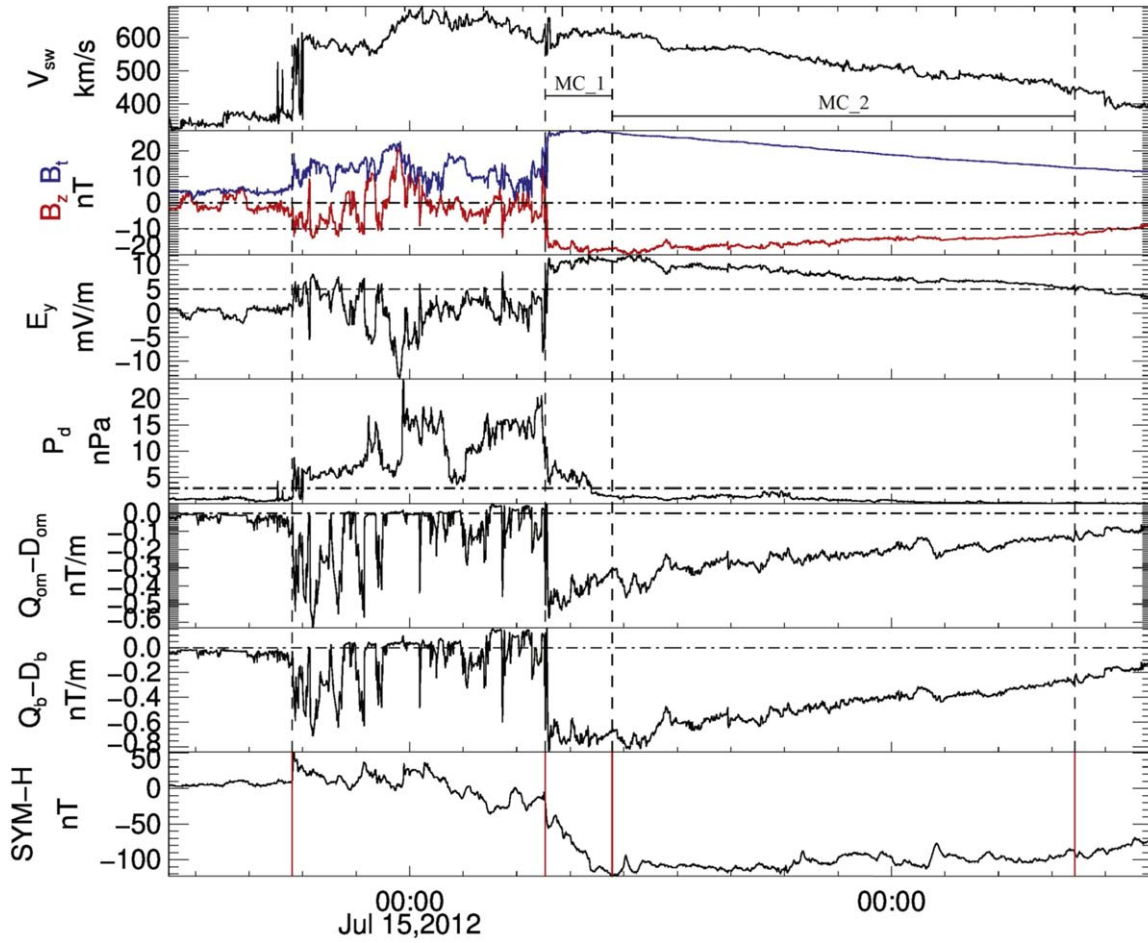
Figure 2. The observations of solar wind data from 2012 July 14 to 17 and its geoeffectiveness. From top to bottom, it shows solar wind speed (V_{sw}), blue and red lines for total magnetic field (B) and the z-component of B (B_z) respectively, solar wind electric field (E_y), solar wind dynamic pressure (P_d), the difference between the injection term (Q_{om}) and decay term (D_{om}) of the OM equation, the difference between the injection term (Q_b) and decay term (D_b) of the Burton equation, and the SYM-H index. The horizontal dotted–dashed lines in the second panel indicate 0 and 10 nT, respectively. The horizontal dotted–dashed line in the last panel detonates $\beta = 0.1$.

MC_1 calculated by the OM and Burton equations are −81.674 nT and −138.568 nT, respectively. The geoeffectiveness of MC_1 calculated by the WCL equation is −101.042 nT when γ is set as 0.5. The observed geoeffectiveness of MC_1 is −101.975 nT. It is evident that the WCL equation is much more accurate than the OM and Burton equations. The reason that the geoeffectiveness of MC_1 calculated by the WCL equation is larger than that calculated by the OM equation is that the averaged P_d of MC_1 is 4.34 nPa. This also proves that the solar wind dynamic pressure is an important factor for the intensity of a geomagnetic storm. Why is the solar wind dynamic pressure an important factor for the intensity of a geomagnetic storm? The possible explanation is that the solar wind with larger dynamic pressure will compress the magnetosphere closer to the Earth and then more solar wind energy enters the magnetosphere and then lead to a stronger storm.

The common property of the Burton equation, the OM equation and the empirical formula established by Wang et al. (2003) is that a geomagnetic storm only depends on solar wind electric field with solar wind dynamic pressure making no contribution. However, the case study made by Cheng et al. (2020) and the results of this study proved that solar wind pressure is also an important parameter besides solar wind electric field. The statistical study made by Zhao et al. (2021) and Le et al. (2020) found that the empirical formula established by Wang et al. (2003) is much more accurate than the Burton and OM equations. Noted that more study should be made to help us to understand the interaction between solar wind and magnetosphere to produce a geomagnetic storm.
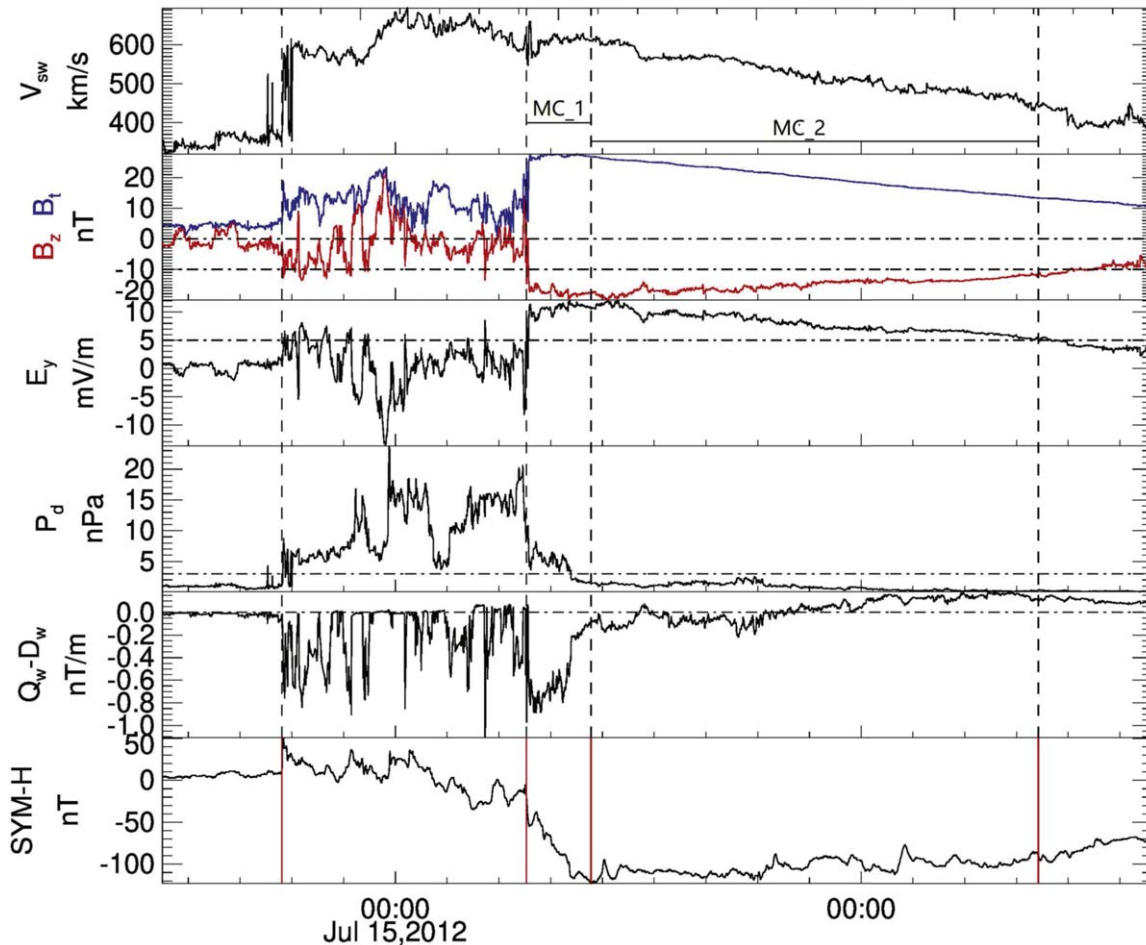
Figure 3. The observations of solar wind data from 2012 July 14 to 17 and its geoeffectiveness. From top to bottom, it shows solar wind speed (V_{sw}), blue and red lines for total magnetic field (B) and the z-component of B (B_z) respectively, solar wind electric field (E_y), solar wind dynamic pressure (P_d), derived $Q_w - D_w$, and SYM-H. The horizontal dotted–dashed lines in the second panel are indicate 0 and −10 nT, respectively. The horizontal dotted–dashed line in the third panel detonates $E_y = 5$ mV m^{-1}. The horizontal dotted–dashed line in the fourth panel detonates $P_d = 3$ nPa. The first and second vertical dashed lines indicate the time when the shock reached the magnetosphere and the start time of the MC. The last vertical dashed line indicates the end time of the MC_2.

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