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L Laughlin

Niescja E. Turner
Trinity University, nturner1@trinity.edu

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GEOEFFECTIVENESS OF CIR AND CME EVENTS: FACTORS CONTRIBUTING TO THEIR DIFFERENCES

LAURA K. LAUGHLIN[1]
Physics and Astronomy Department, Clemson University, Clemson, SC, 29634

AND

NIESCJA E. TURNER
Department of Physics & Space Sciences, Florida Institute of Technology,
150 W. Universtity Blvd., Melbourne, Florida, 32901

ABSTRACT

Recent work has shown that solar wind-magnetosphere coupling is more efficient for CIR-driven events than for CME-driven events. The study herein looks into the individual physical parameters of Corotating Interaction Regions (CIRs) and Coronal Mass Ejections (CMEs) and looks to isolate particular characteristics that leads to greater coupling of energy from the solar wind into the magnetosphere for certain classes of magnetic storms. While it is clear that these two types of events are distinct in their outcome, it is not known what in the nature of the events leads to these different results. The variation level in the *z*-component of the Interplanetary Magnetic field (IMF) and the Alfvénic Mach number one hour prior to the onset of a CIR or CME event are investigated as possibly related to the coupling efficiency. While there was no significant correlation between any particular characteristic and energy coupling efficiency, the most promising result came from the Alfvénic Mach number and its effect on the energy efficiency of the storm main phase. The Alfvénic Mach numbers of CIR and CME events had the strongest connection to the main phase energy efficiency. More study is needed on the connection between the Alfvénic Mach number as it relates to energy efficiency. Different or combinations of characteristics of these storms may also shed more light on the necessary conditions for a more geoeffective event.

Subject headings: Sun: Coronal Mass Ejections (CMEs), solar wind and solar-terrestrial relations

1. INTRODUCTION

The conditions under which Earth can be a habitable place for life forms are very connected to our dependence on our Sun. Almost all geomagnetic activity on Earth is driven by the Sun and the regularity of its energy output. However, due to the cycles of solar activity and solar wind properties, the balance and flow of energy received by the Earth can vary. These irregularities in solar output may result in magnetic storms or disturbances in the Earth's magnetic field (Turner 2000). The Sun provides the Earth with energy in the form of solar wind ions and electrons that move toward Earth. The solar wind carries with the Interplanetary Magnetic Field (IMF) via frozen-in flux.

1.1. *Reconnection*

As the Interplanetary Magnetic Field (IMF) field lines make contact with the Earth's magnetic field lines, the anti-parallel colliding field lines are broken by the contact, reconnected, and redirected backwards towards the night side of the Earth, stretching out behind the Earth into what is known as the magnetotail. This process is known as reconnection. Reconnection allows a transfer of energy from the solar wind to the Earth's magnetopause, the area of balance between the impinging plasma and the Earth's geomagnetic field. Reconnection is dependent on the Bz component of the magnetic field specifically. The reconnection process becomes more active with Bz field lines pointing in a southward direction.

[1] Southeastern Association for Research in Astronomy (SARA) NSF-REU Summer Intern
Electronic address: llaughl@clemson.edu; neturner@fi t.edu

1.2. *Ring Current and Dst*

After energy from the solar wind is transferred to the magnetotail, particles make their way to the ring current, which is a ring of ions and electrons around the Earth's equator (Tascione 1994). As the influx of new particles move into the ring current, they cause an increase in the ion density and energy which is the sign of a magnetic storm on Earth. According to Gonzalez et al. (1994), a magnetic storm is a middle- to low-latitude geomagnetic variation caused by an intensified ring current quantified by an index known as the Storm-Time Disturbance (Dst). Dst measures the variations of the horizontal component of the Earth's magnetic field due to the ring current (Lu 2006) and therefore the strength of a magnetic storm.

1.3. *Phases of Magnetic Storms*

A magnetic storm is composed of two phases: a main phase and a recovery phase. Prior to the onset of a storm, the Dst sometimes rises slightly, indicating a rise in dayside magnetopause currents. The main phase is the actual storm itself with a steady decrease in Dst. This is the time of ring current enhancement with high energy ions and electrons (Gonzalez et al. 1994). During the recovery phase the Earth's magnetosphere slowly returns to a normal state. The high energy particles are dissipated. Energy is given off in the form of Joule heating, auroral processes, ring current injections, and the formations of plasmoids (leftover bubbles of plasma) (Turner 2000).

1.4. *CIRs and CMEs*

The Sun has a highly active and continually-changing level of energy output due to solar cycle variations and coronal holes. Coronal holes are openings or breaches in the Sun's outer surface out of which high-speed streams of solar plasma are emitted. These streams can be recurrent because of the Sun's 27 day rotation cycle (Tsurutani 2006). The solar events that result from these coronal holes are known as Corotating Interaction Regions (CIRs). In comparison, there are other outbursts of solar energy called Coronal Mass Ejections (CMEs) that result in giant bubbles of plasma (Turner 2000). For many reasons, CIR and CME events are very different with characteristics specific to their type. CME or other ejecta-related events tend to be shorter, more intense, with higher solar wind speeds, although they ultimately seem to deposit less energy. This type of event is more common during solar maximum activity. CMEs register greater changes in Dst and have very high values for energy input to the storms. CIRs, on the other hand, may not be as intense in their onset, but they have been shown to have greater overall geoeffectiveness (they are more efficient in their energy output to input). CIR events tend to be associated with times of solar minima and rapidly varying Bz magnetic fields (Turner et al. 2006). However, one of the most obvious differences between CIR and CME events is in their recovery phases. With a CME event, at the beginning of the recovery phase, the influx of high energy particles and ions from the ring current to the Earth's magnetosphere is cut off as particles decay and return to more stable values. With a CIR event, the recovery process tends to be a more continuous and drawn-out process as new particles are still being injected into the ring current during recovery (Tsurutani 2006).

1.5. *Motivation*

While there are easily seen differences between these two kinds of magnetic events, there are a great many questions as to what makes this distinction, and why these storms act the way they do. What physical characteristic, perhaps even prior to the onset of the storm, contributes to the difference in outcome and geoeffectiveness? Some of the most obvious differences in the two kinds of events are in their recovery phases, however, differences are seen in their main phases as well which gives rise to the belief that something prior to the peak of the storms accounts for these differences in characteristics. Thus the hour before the onset of the storm was observed. The purpose of the research done herein is to try and isolate a difference between CIRs and CMEs that is already known but to see its effect on the rate of reconnection and energy coupling efficiency. The variance in the Bz component of the magnetic field and Alfvénic Mach number were observed in relation to the energy efficiency of the storm looking for any connecting trend. If there is no apparent connection, then hopefully these comparisons will give clues as to what quality of the storm is responsible for the difference. Reconnection requires a mainly southward magnetic field. With a more consistently southward field, the solar wind may have more opportunity to deposit energy from the Sun in the form of high energy particles and ions. The rate at which solar energy is transferred to the magnetopause through reconnection may also affect overall geoeffectiveness of storms. An Alfvénic wave is an oscillating wave that travels in the same direction as the magnetic field. The Mach number of the Alfvénic wave relates the rate of transfer of information in relation to the solar wind speed itself. Some hypothesize that the Alfvénic Mach number could be connected to a higher reconnection rate of the field lines and thus a more efficient transfer of energy to the Earth's magnetopause.

2. PREVIOUS WORK

While Gonzalez et al. (1994) and Turner (2000) among others have defined what a magnetic storm is and analyzed the energy coupling therein, little is known about their inner characteristics that make CIR and CME events fundamentally different. Turner et al. (2006) have looked into the energetics of CIR events and noted that CIR events are not as intense as CME events, but tend to be more geoeffective in their output to input ratio. A study done by Tsurutani (2006) suggested that the fluctuation of the Bz component at the onset of the storm was the cause of weaker onset of CIR events and the nearly continuous plasma injections in the recovery phase caused the storm to be more geoeffective. A study done by Turner et al. (2006) found that CIR events, while less intense, are more efficient in energy transfer particularly by auroral precipitation. However, it has been suggested by Lu et al. (2006) that the ability to determine overall geoeffectiveness is dependent on the accuracy of the epsilon parameter which may be in question. Mitchell et al. (2007) showed that CIR events that begin without an initial shock from the solar wind driver 24 hours prior to the onset of a storm are more efficient in energy transfer during the main phase while CIR events with initial shocks are more efficient in the recovery phase.

3. METHODOLOGY

To try and isolate a differentiating trend between the energy efficiency and the Alfvénic Mach number or Bz component, there were a number of different steps. This study used the same events as studied in Mitchell et al. (2007) and used a similar criterion of Dst cutoff to define each storm. The raw data needed were collected by two satellites: WIND and ACE. WIND data were used from 1995 to 1998. From 1998 to 2004, data were taken by the ACE satellite. Using Interactive Data Language (IDL), several new programs were written for this study. A new program was created to observe conditions of the storms one hour prior to their onset working backwards from the storm's onset. A new program was also created to calculate the Alfvénic Mach number. The energy efficiency of the storms was calculated by the equation below based on conditions during the main phase and at 80% recovery.

$$\text{energy efficiency} = \frac{(\text{output})}{(\text{input})} \tag{1}$$

$$\epsilon = \frac{4\pi}{\mu_o} v\, B^2\, sin^4 \left(\frac{\theta}{2}\right) l_0^2 \tag{2}$$

In Equation 1, the formula for energy efficiency is shown. The output is based on several variables such as ring current injection, Joule heating north and south, and auroral precipitation north and south. The input is based on the epsilon parameter shown in Equation 2. In the epsilon parameter, v is the solar wind velocity, B is the magnetic field, and l_0 is a representative length of the coupling area available for solar wind-magnetosphere interactions (Turner 2000). The data generated from the ACE and WIND satellites isolating the desired storm characteristics were given on an hour and minute basis. Variables were read in and sorted as CIR or CME events. The variables needed to calculate the energy efficiency of the storm during the hour prior to the beginning of the onset of the storm were given on an hour basis. The Alfvénic Mach number and Bz magnetic field were given per minute. To compare these values to energy efficiency, the Mach number and variance needed to be averaged over the course of the hour prior

TABLE 1
CORRELATIONS AMONG COMBINED CIR AND CME EVENTS

Parameter	Sample Size	Correlation Value
EE/Bz Variance Main Phase	108	-0.046
EE/Bz Variance Recovery Phase	126	-0.025
EE/Alfvénic Mach number Main Phase	108	0.212
EE/Alfvénic Mach number Recovery Phase	126	0.094

TABLE 2
CORRELATIONS AMONG INDIVIDUAL CIR AND CME EVENTS

Parameter	Storm Type	Sample Size	Correlation Value
EE/Bz Variance Main Phase	CIR	54	-0.113
EE/Bz Variance Main Phase	CME	54	-0.050
EE/Bz Variance Recovery Phase	CIR	60	0.126
EE/Bz Variance Recovery Phase	CME	66	-0.034
EE/Alfvénic Mach Main Phase	CIR	54	0.177
EE/Alfvénic Mach Main Phase	CME	54	0.236
EE/Alfvénic Mach Recovery Phase	CIR	60	0.0988
EE/Alfvénic Mach Recovery Phase	CME	66	0.095

to the onset of the storm and matched to their corresponding energy efficiency based on the kind of event being observed as well as the phase. Correlations were calculations for the main and recovery phases, looking at the connection between the Bz variance and Alfvénic Mach number with CIR and CME events combined. Correlations were also calculated between the individual characteristics and energy efficiencies during both the main and recovery phases. Scatter plots were made in IDL for combined as well as individual characteristics. The correlation values were analyzed for their significance based on sample size to find the most relevant connection.

4. OBSERVATIONS

Plots generated for CIR and CME events do not show a significant correlation between energy efficiency and Alfvénic Mach number or Bz variance as shown by the correlation values in Tables 1 and 2. However, the strongest connection among the parameters seems to be between the Alfvénic Mach number and energy efficiency in the main phase. With the combination of CIR and CME events a correlation of 0.212 can be seen among a 108 sized sample of events which yields close to a one percent significance as can be seen in Figure 3. The strongest individual correlation shown from this study was due to the Alfvénic Mach number for CME events during the main phase shown in Figure 2. In contrast is the same storm parameter shown for CIR events in Figure 1. From a study of 54 events, a correlation of 0.236 can be seen. CIR events had a higher correlation number than CME events in terms of the Bz variance in both the main and recovery phases. CME events had the highest connection to energy efficiency with their Alfvénic Mach number during the main phase while CIR and CME events were almost equal during their recovery phases.

5. DISCUSSION

Despite the fact that visually, some of the greatest distinctions between CIR and CME events are in the recovery phase, these results show that these parameters prior to the onset of the storm have a greater impact on the main phase of the event. This result was expected as the storm characteristics one hour prior would have the greatest effect. Most of the graphs give rather inconclusive results. However, the correlation between the Alfvénic Mach number of CIR and CME events, shown in Figure 3, and the main phase energy efficiency gives rise to the idea that the speed at which the solar wind reconnects to

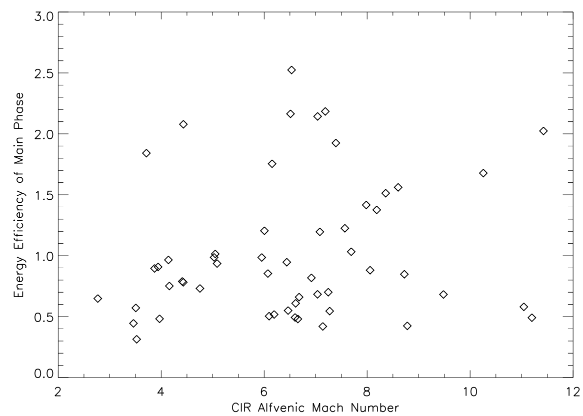

FIG. 1.— **CIR Events: Main Phase**

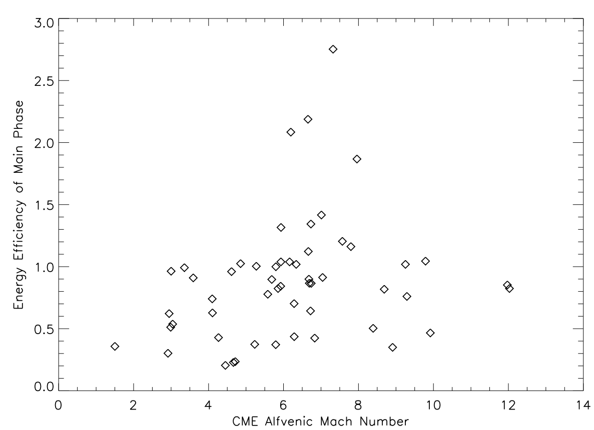

FIG. 2.— **CME Events: Main Phase**

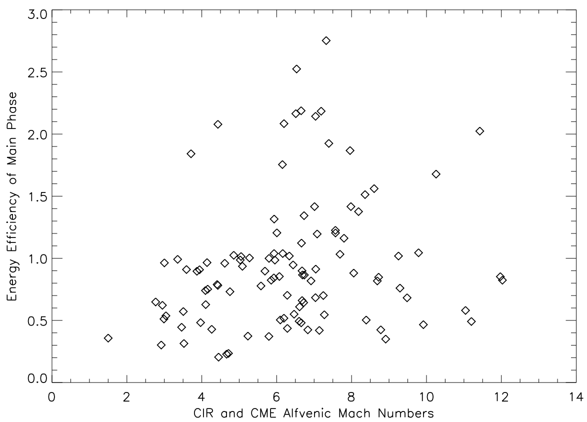

FIG. 3.— **CIR and CME Events: Main Phase**

the Earth's magnetic field prior to the beginning of the storm generates a more efficient event. This connection showed close to one percent significance. There also seems to be a connection among the CME Alfvénic Mach numbers and their effect on the energy efficiency during the main phase. It is already known that overall CIR events are more efficient yet this study has shown that among CME events, a higher Alfvénic Mach number can create a more efficient event. As seen in Table 2, the strongest connection of the study involves Alfvénic Mach number as related to energy efficiencies during the main phase.

6. CONCLUSIONS

The question of what causes greater energy efficiency among certain classes of magnetic storms still has no conclusive answer. However, it is now known that the speed at which the solar wind reconnects with the Earth's magnetic field holds the greatest promise. Furthermore, characteristics observed prior to the onset of the storm have their greatest effect on the main phase rather than the recovery phase. CME events have the strongest connection between the Alfvénic Mach number and energy efficiency particularly during the main phase as well.

7. RECOMMENDATIONS FOR FUTURE STUDY

Based on the results of this study, a closer look at the Alfvénic Mach number and perhaps also the magnetosonic Mach number may yield a connection. Other parameters should also be considered since there was not a particularly strong connection between the energy efficiency and these conditions individually. Combinations between several parameters at once may also prove useful.

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