Propagation characteristics of coronal mass ejections and their effects at the near-Earth environment

A Mujiber Rahman¹, P K Manoharan² & S Umapathy¹
¹School of Physics, Madurai Kamaraj University, Madurai 625 021, India
²Radio Astronomy Centre, Tata Institute of Fundamental Research, Uthagamandalam 643 001, India

E-mail: mujib73@gmail.com

Received 28 July 2010; accepted 18 August 2010

This paper deals with the geo-effective analysis of halo and partial halo coronal mass ejections (CMEs) observed during solar cycle 23. The analysis is based on lists of white-light CMEs and associated ICMEs and interplanetary shocks analyzed in recent studies [Manoharan P K, Gopalswamy N, Yashiro S, Lara A, Michalek G & Howard R A, Influence of CME interaction on propagation of interplanetary shocks, J Geophys Res (USA), 109 (2004), 6109, doi:10.1029/2003JA010300; and Manoharan P K, Evolution of Coronal Mass Ejections in the inner heliosphere: A study using white-light and scintillation images 2003, Sol Phys (Netherlands), 235 (2006) pp 345–368, doi: 10.1007/s11207-006-0100-y]. The link between the initial speed of the CME, its speed at 1 AU, speed of the associated IP shock, its strength, magnetic field within the CME and the geomagnetic storm have been studied using the spacecraft data and radio scintillation images from Ooty. The southward component of the CME magnetic field (Bz) and the geo-storm index (Dst) are highly correlated. But a large scatter is evident in this correlation as well as in correlations of speeds of the CME at the near-Sun and at 1 AU with arrival times of IP shock and ICME at the Earth. The preliminary results suggest that each CME has its own unique propagation signature, which is likely determined by the internal energy possessed by the CME and the interaction of the CME with the ambient (i.e., background) solar wind plasma and also with the preceding CME(s) occasionally encountered in the propagation path.

Keywords: Coronal mass ejections (CME), Solar wind, Geomagnetic storms

PACS Nos: 96.60.qe; 96.60.ph

1 Introduction

Coronal mass ejections (CMEs) are large expulsions of mass and magnetic field from the Sun into the heliosphere. They are responsible for non recurrent disturbances in the interplanetary medium, and their interactions with earth’s magnetosphere cause severe geo-effective storms. These mass ejections carry a bulk of solar material in the range 1011 - 1013 kg (ref. 1). The huge amount of energy involved in such ejection processes is believed to be stored in the magnetic fields surrounding the mass ejection site. The structure associated with CMEs has a typical spatial size of about 1 R\text{SUN} at the base of the corona and expands at velocities from a few tens to 2000 km s\textsuperscript{-1} (ref. 2). An understanding of the effects of CMEs on geo-space is essential for the solar-terrestrial studies for forecasting the space weather.

CMEs originate in the Sun from the regions where the magnetic field is closed and result from the catastrophic disruption of large scale coronal magnetic structures, such as coronal streamers. The huge amount of energy involved in such ejection process is believed to be stored in the magnetic fields surrounding the mass ejection site. On the Sun, magnetic field lines closed across a polarity inversion lines, disrupted are likely to be open and eject solar plasma into space. In the present study, CMEs near the earth has been analyzed by LASCO images and flare data.

CMEs are found to correlate with the occurrence of strong, non recurrent geomagnetic storms³. It was reported that ICMEs and IP shocks are associated with the CMEs. The interplanetary counterparts of CMEs are often called ICMEs. In this paper, this term is used in a more generic way, such that it comprises all CME effects in interplanetary space. The structure of ICME shows a number of plasma and magnetic field features associated with it when they reach at 1 AU. ICMEs mainly consist of ejecta (EJ), and/or magnetic cloud (MC). Excellent fast CMEs show association of interplanetary shocks⁴. It was
recognized long ago that IP shocks are one of the signatures of arrival of solar disturbance at the Earth. In the present study, the arrival of IP shock associated with each CME at 1 AU has been determined by the careful examination of interplanetary magnetic field data and solar wind plasma density, speed and temperature measurements obtained form the Wind spacecraft (MFI and SWE instruments) or ACE spacecraft (MAG and SWEPAM instruments).

CMEs play an important role in space weather studies. The Earth directed CMEs are the major cause for the severe geomagnetic storms and the primary factors determining the geo-effectiveness are the direction of propagation of CME, its speed, size, density and orientation and strength of the magnetic field at the near-Earth space. The earlier studies emphasized the importance of considering the background solar wind in the study of evolution of interplanetary disturbances in the distance between the Sun and the Earth. Since the solar wind is made up of steady and turbulent flows, discontinuities and shocks and also CME tends to locally adopt to the ambient solar wind\cite{5,6}, these are likely to contribute a significant change on the propagation of the CME. The recent study by Manoharan\cite{7} has also emphasized the importance of the interaction between the CME and the ambient solar wind as well as the CME-CME interaction during the propagation of the CME. The shock waves produced by the CME drive the solar energetic particles (SEPs) which can damage both electronic equipment and astronauts of the space flight orbiting around the earth.

The solar wind could not normally penetrate the magnetosphere. But, on certain occasions, only when the magnetic field in the interplanetary structure had a negative Bz component reaching the earth’s magnetic field to produce geomagnetic storms. In this study, the interplanetary counterparts of the CME i.e. ICME and IP Shock and the associated geomagnetic disturbance storm time index Dst have been identified from the available on-line data. Some cases show complex Dst onset and recovery structures. This is likely due to the multiple ICMEs arriving at the earth’s magnetosphere.

2 Data selection

In this study, the objective is to characterize the propagation properties of CMEs and their related shocks observed during 1997-2002. All shocks have been identified and their plasma and magnetic field properties have been analysed at 1AU. The CMEs considered in this study originated with $\pm 30^\circ$ from the centre of the Sun’s disk. The shocks associated with the interacting CMEs have also been considered as a special population. In this study, 91 IP shocks have been selected, which are associated with CMEs originating close to the centre of the Sun. The shock wave disturbances detected by the Wind spacecraft during 1997-2002 (http://www-spof.gsfc.nasa.gov/wind/) have been considered, supplemented with the shock lists obtained from Proton Monitor (PM) instrument on board SOHO mission (http://umtof.umd.edu/pm) and ACE spacecraft (http://www.bartol.udel.edu/ace). Solar wind data is obtained from Solar Wind Experiment instrument (Wind/SWE) instrument and from the website (http://web.mit.edu/space/www/wind/) and interplanetary magnetic data from Magnetic field Investigation (Wind/MFI) instrument (http://lepmfi.gsfc.nasa.gov/mfi/), 91 IP shocks and their associated interplanetary CMEs (ICMEs) have been identified. For each event, the shock onset time, shock speed, Mach numbers (Alfvenic Mach number, Ma and Magenetosonic Mach number, Ms) have been determined. Further, an IP shock has been considered only when its associated ICME measurements are available. Therefore, the IP shocks reported in this study represent a subset of CME-driven shocks.

For an IP shock at the earth, its potential CME near the Sun has been identified within a time frame of 1 to 5 days backward from the onset time of the shock. While tracing the CME origin to the Sun, the observed speed of the shock at 1AU has been taken into account and initial speed of the CME. The LASCO and EIT images, movies, and speed data obtained from the SOHO mission have been systematically cataloged (http://cdaw.gsfc.nasa.gov/). Moreover, it has been reported that most of the geoeffective CMEs originate close to the centre of the Sun\cite{9}. Therefore, in this study, 91 ICMEs and IP shocks, which are associated with CMEs originating $\pm 30^\circ$ from the disk centre of the Sun have been selected. The solar flare list is obtained from, ftp://ftp.sec.noaa.gov/, and the geomagnetic storm index values for all these 91 events were obtained from the World Data Centre, Kyoto (http://swdwww.kugi.kyoto-u.ac.jp/dstdir/index.html). Also, the time difference between ICME arrival time at 1 AU and IP shock arrival time at 1 AU for all 91 events have been calculated. This time difference is here we considered as $\Delta t$. 
3 Results and Discussion

In this study, 91 CME events originated close to the solar disk have been analysed. Initial speed of these events ranged 250 - 2500 km s\(^{-1}\). Travel times of these CMEs to 1AU indicate large scatter as a function of initial speed of CME. It indicates that the CME propagation is affected by its interaction with IP medium. Figures 1 and 2 show that the plots of time differences between the ICME onset time and IP shock onset time compared with their respective speeds at 1 AU indicate that the stand off time is likely also to be function of other parameters.

That is, the CME propagation is likely to be controlled by the energy (magnetic energy) supplied by the CME cloud itself. However, this term seems to vary from one event to the other.

The coronal mass ejection (CME) link to geomagnetic storms stems from the southward component of the interplanetary magnetic field contained in the CME flux ropes and in the sheath between the flux rope and the CME-driven shock\(^{10}\). In Fig. 3, the histogram is drawn between total number of events taken for the present study and their respective geomagnetic storm index, Dst, values. The geomagnetic effects have been seen on moderate to strong scale for 46 events out of total of 91 events. It is evident from the histogram that the larger fractions of these are moderate geomagnetic events (Dst ≤ -100 nT).

4 Conclusions

In the present study, propagation characteristics of 91 CME events originated from the disk centre (±30°) of the Sun have been studied. The time difference between ICME arrival time at 1 AU and IP shock arrival time at 1 AU is calculated. This time difference (Δt) is correlated with their respective speeds.

The correlation plots (Figs 1 and 2) clearly show that the propagation of CME is affected by its interaction with the interplanetary medium such as ambient Solar wind. This result is consistent with Manoharan et al.\(^{11}\)

Among 91 events, only 46 events are producing moderate to strong (Dst ≤ -100nT) and severe (Dst ≤ -300 nT) geomagnetic storms. From this, one can understand that since CMEs are the main source of geomagnetic storms, both the CME speed and the southward magnetic field it contains determine the strength of the storm.

![Figure 1](image1.png)  
Fig. 1 — ICME speed plotted as a function of time differences between the ICME onset time and IP shock onset time. (Δt = ICME onset time – IP shock onset time)

![Figure 2](image2.png)  
Fig. 2 — Shock speed plotted as a function of time differences between the ICME onset time and IP shock onset time

![Figure 3](image3.png)  
Fig. 3 — Histogram between no. of events and their respective geomagnetic storm index Dst values
References