INTERPLANETARY ASPECTS OF SPACE WEATHER

Richard G. Marsden

Research & Scientific Support Dept. of ESA, ESTEC, P.O. Box 299, 2200 AG Noordwijk, NL,
Email: Richard.Marsden@esa.int

ABSTRACT/RESUME

Interplanetary disturbances associated with solar wind streams, solar flares and coronal mass ejections (CMEs) are responsible for a significant fraction of the space weather-related effects occurring in geospace. The shocks driven by the interplanetary counterparts of CMEs, so-called ICMEs, can produce intense geomagnetic disturbances, while the energetic particle fluxes accelerated by the same shocks can be highly detrimental to humans and electronic systems in space. The wealth of observations acquired by space missions like SOHO and ACE have lead to a better understanding of many aspects ICMEs and their effects, but many questions remain unanswered. In this paper, the current state of knowledge concerning space weather-related aspects of solar wind disturbances and associated phenomena is reviewed, with a view to identifying some of the key questions that need answering in order to place space weather forecasting on a firmer footing.

1. INTRODUCTION

The solar wind and its frozen-in magnetic field constitutes an important physical link between the sun and geospace. Charged particles of all energies originating at the sun propagate through, and are affected by, the magnetised solar wind before reaching the Earth's magnetosphere. Large-scale solar wind structures such as coronal mass ejections (CMEs) and co-rotating interaction regions (CIRs) interact with the magnetosphere, generating magnetic storms and other disturbances. A prerequisite of accurate and timely space weather forecasting, therefore, is a detailed understanding of the interplanetary medium and its dynamic behaviour.

In this brief overview of the interplanetary aspects of space weather, we first review the basic phenomena of importance in this context: the interplanetary magnetic field (IMF) and its orientation; solar wind disturbances; solar energetic particles. We then discuss some of the open questions that remain to be answered in order to make significant progress in understanding the chain of events starting at the sun that lead to detrimental space weather-related impacts on geospace. Finally, we look at the future of heliospheric science as related to space weather studies.

2. BASIC PHENOMENA

2.1 Interplanetary Magnetic Fields

In the context of space weather effects, the fundamental coupling mechanism between the magnetised solar wind and the Earth's magnetosphere is magnetic reconnection between the IMF and the Earth's field. Reconnection occurs predominantly at the magnetopause, and because of the polarity of the Earth's field, the reconnection process is most efficient when the IMF has a southward direction (so-called "negative Bz"). In the following discussion of the effectiveness of solar wind disturbances in triggering geomagnetic storms, a common theme will be the presence of a large southward-directed IMF component. As we shall see, however, a southward-directed IMF in itself is not sufficient to trigger a large magnetic storm.

2.2 Solar Wind Disturbances

Solar wind disturbances responsible for space weather-related effects can be divided into two main categories: recurrent disturbances with a period of ~27 days that are associated with fast solar wind streams from coronal holes, and transient disturbances associated with the interplanetary counterparts of CMEs (so-called ICMEs) and/or ICME-driven shocks. Recurrent high-speed solar wind streams tend to dominate the inner heliosphere during the declining phase of the solar cycle, when the polar coronal holes are well developed and show significant equator-ward extensions. An example of such a coronal hole is the famous "Elephant's Trunk" that appeared in August, 1996 (Fig. 1). The geomagnetic disturbances associated with recurrent high-speed streams are the result of IMF compression at the leading edge of the stream. [1, 2]. In particular, as we shall see later, southward-pointing fields give rise to the strongest geomagnetic storms.

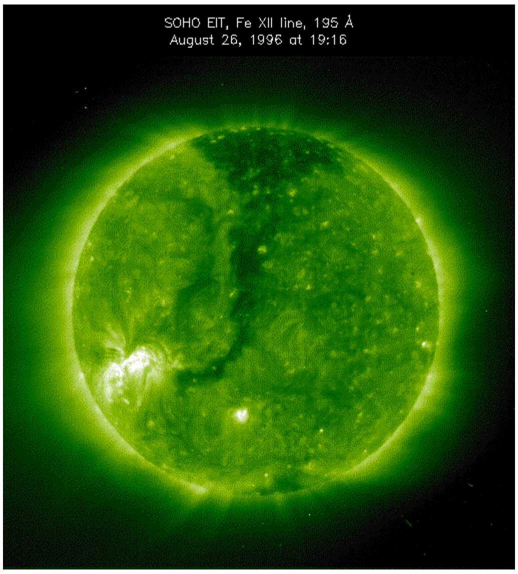

Fig. 1. SOHO/EIT image of the “Elephant’s Trunk” coronal hole, 26 August 1996.

The compression and draping of the IMF ahead of ICMEs is also responsible for the geo-effectivity of these structures. The effects are further enhanced if the internal field of the ICME has a strong southward component. Fast ICMEs can drive shock waves that trigger sudden storm commencements upon arrival at the Earth. In both cases (i.e., recurrent and transient solar wind structures), it is the combined effect of compression and southward IMF that drives magnetic reconnection at the day-side magnetopause, which in turn determines the strength of the geomagnetic response. In physical terms, since the rate of reconnection is proportional to the interplanetary convective electric field **V** x **B**, the quantity |VBz| is found to be a good measure of the geo-effectiveness of a given solar wind structure. This is illustrated in Fig. 2, where the rate of occurrence of different values of |VBz| is plotted for (I)CMEs, stream interactions, and quiet solar wind. Also shown is the corresponding value of the geomagnetic index Dst. Values of Dst < -100 nT represent major geomagnetic storms.

As can be seen from Fig. 2, (I)CMEs contribute the majority of |VBz| values greater than 5, and by implication, are responsible for the largest geomagnetic storms. ICMEs and the interaction regions associated with recurrent high-speed streams contribute equally to the occurrence of minor geomagnetic storms, while the quiet solar wind has relatively little effect. The geo-effectiveness of transient, ICME-related interplanetary disturbances is examined further in Fig. 3, where the events are divided into 3 categories: Storms that were triggered by the passage of an (I)CME; storms associated with an interplanetary shock without CME, and storms for which both a shock and CME were identified. From this study, 85% of events in which the Earth encountered both a shock and the ICME driving it were geomagnetically effective. This result can be understood if we recall that the formation of ICME-driven shocks requires a large speed differential between the ICME and the ambient solar wind. This in turn creates conditions conducive to IMF draping about the ICME, and hence the probability of a large southward directed IMF component in the compressed plasma ahead of the ICME.

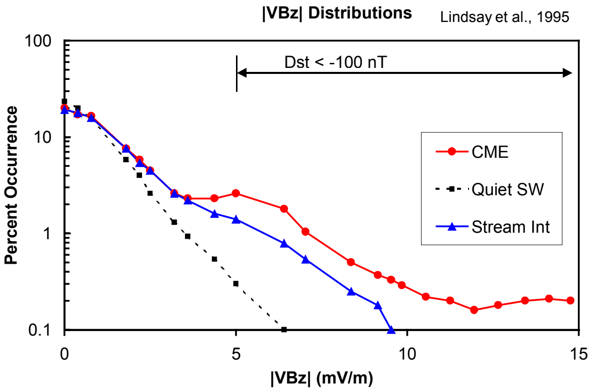

Fig. 2. Rate of occurrence of |VBz| for different solar wind types (adapted from [3]).

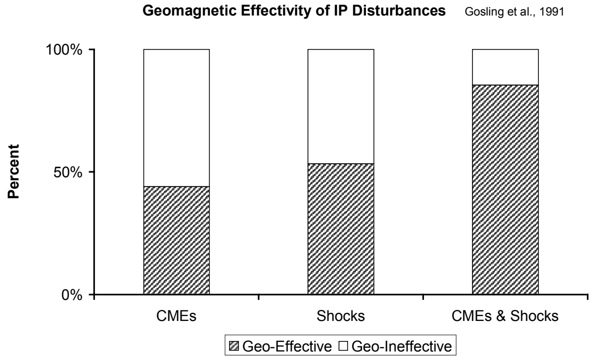

Fig. 3. Geomagnetic effectiveness of (I)CMEs, interplanetary shock disturbances, and shock/ICME events (adapted from [4]).

2.3 Solar Energetic Particles

It is beyond the scope of this article to present a thorough review of the origin and properties of solar energetic particles (SEPs) in interplanetary space. Several excellent reviews have appeared in recent years, and the interested reader is referred to these (e.g., [5, 6, 7] and references therein). Here we will focus on those aspects of SEPs that are of direct relevance to space weather. In this case, we are mainly concerned with large SEP events, since these pose the major radiation threat to astronauts in Earth orbit and, eventually, on deep space missions. Such large SEP events are now known to be produced by fast CMEs, whereby the particles are accelerated at the interplanetary shock wave driven by these transient solar wind structures. It is important to stress that only the largest and fastest CMEs produce SEPs of sufficient energy and in sufficient numbers to be of relevance in a space weather context [5]. Such events constitute only ~1 % of the total CME population. Nevertheless, the radiation hazard they represent is real, and it is important to understand the underlying characteristics of large SEP events in order to assess the risk associated with them. Significant progress has been made in recent years in this area [5], and we highlight some of the key points in the following.

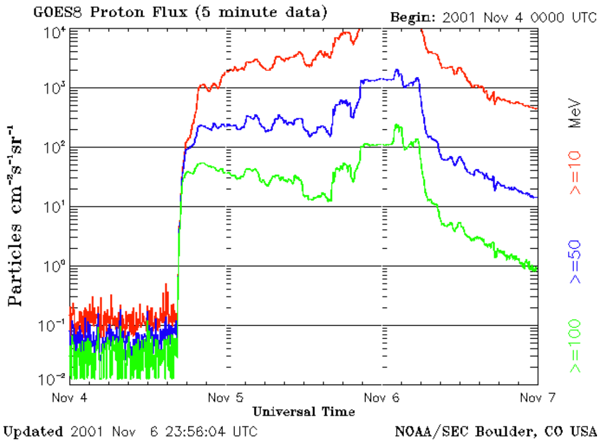

Fig. 4. Proton fluxes measured by the GOES8 satellite for the SEP event at the beginning of Nov 2001. Note the increase in flux associated with the passage of the strong interplanetary shock early on 6 November.

The intensity of SEPs measured at 1 AU depends on a number of factors. The speed of the CME and the shock it drives, together with the relative location of the source with respect to the observer, are the most important of these. While studies have shown that SEP intensity is well correlated with CME speed, it is also known that wave-particle interactions in the vicinity of the shock are able to limit the flux of SEPs streaming away from the shock [6]. A result of this process is that the intensity of SEPs of a given energy measured at a given location cannot exceed this so-called "streaming limit". The streaming limit only applies to the intensity of particles that are accelerated non-locally, and then propagate along the IMF to reach the observer. It does *not* apply to the intensities observed at the shock itself, which can be an order of magnitude (or more) higher than the initial "peak" reached just after the onset. It is the arrival of a fast CME-driven shock at the location of the observer, therefore, that produces the greatest radiation hazard. An example of such an event occurred on 4 November, 2001. The profiles for this event are shown in Fig. 4.

When considering the space weather hazard associated with SEPs, it is not just the peak intensity that is important. The spectral shape is equally relevant [6]. In many events, the intensity begins to fall off rapidly at energies above ~100 MeV. In such cases, the radiation dose accumulated behind the shielding afforded by typical spacecraft walls is not severe. There are cases however, as shown in Fig. 5, where the spectrum continues to much higher energies (1000s of MeV). The shielding needed to reduce the dose to acceptable levels in these cases is too substantial to be considered for typical manned space applications. The implications of, and possible solutions to, this problem are the subject of on-going study.

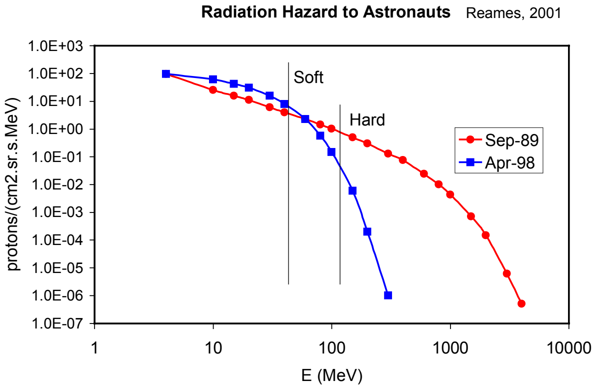

Fig. 5. Proton spectra from two events (Sep 89 and Apr 98) showing the differences in radiation hazard inside typical shielding afforded by a spacecraft wall (soft) and ~5 cm of Al (hard). Adapted from [6].

Not all fast CMEs that leave the sun produce large SEP events at 1 AU. As noted above, a necessary condition for the highest intensities is the arrival of the shock at the observer. Since interplanetary shock fronts rarely exceed 90° in longitudinal extent, the relative longitude of the source and the observer plays an important role in determining the SEP intensity profile at a given location. This is illustrated in Fig. 6, which shows typical SEP event profiles for observers at 3 solar longitudes. In all cases, the intensity profiles are determined by the changing magnetic connection of the observer to the shock front as it travels away from the sun. For example, events originating ~60° to the west

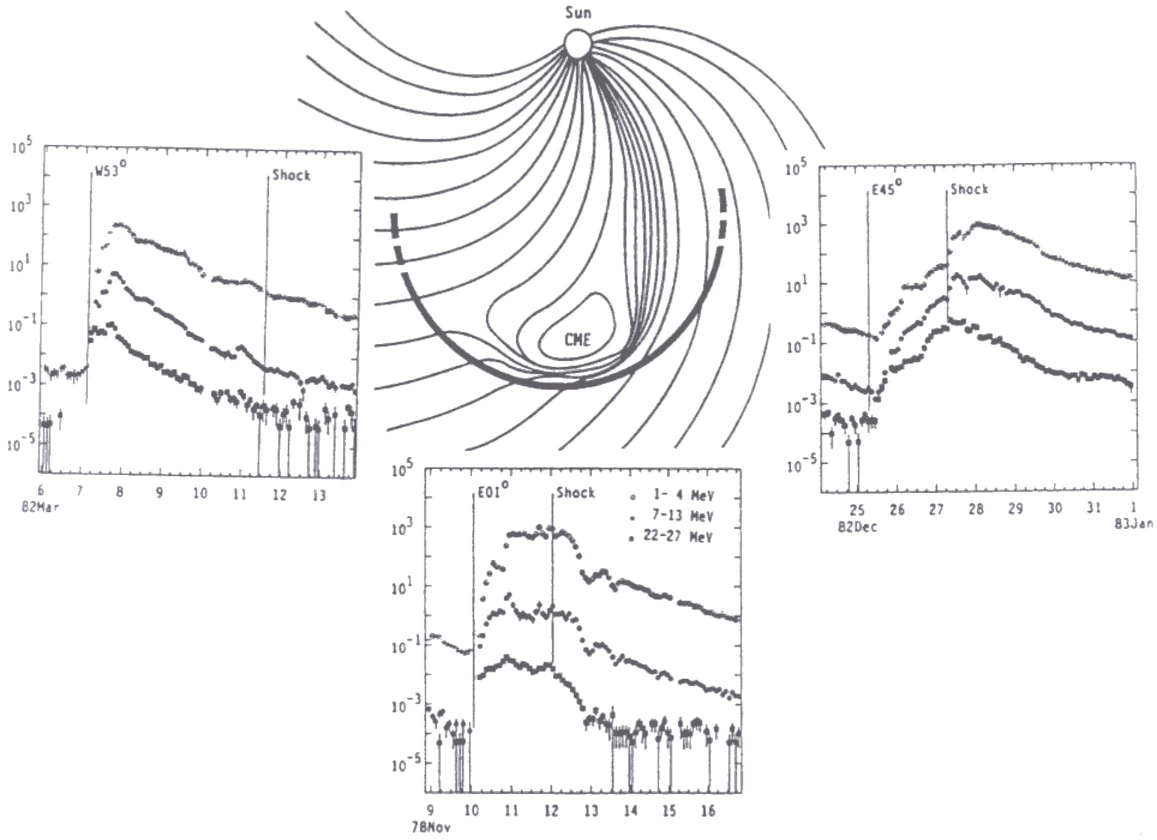

Fig. 6. Proton time-intensity profiles for observers at three different solar longitudes. For protons of ~10s of MeV, the time of peak intensity is dictated by the time of connection to the nose of the shock. From [8].

of the sun-Earth line are well connected initially, giving rise to a prompt onset. The CME shock, however, does not produce a major *local* enhancement at the Earth in this case, since only the flank is intersected. On the other hand, CMEs that originate close to central meridian (so-called "halo" CMEs) are likely to produce high-intensity SEP events at 1 AU. This is because the part of the shock front most efficient in accelerating particles, the "nose", passes over the Earth.

3. OPEN QUESTIONS AND FUTURE DIRECTIONS

One of the key questions that must be answered if we are to develop reliable predictive tools for space weather phenomena is the following. Which attributes of the (I)CME / ambient solar wind combination are most influential in producing large interplanetary shock waves, energetic particles, and geomagnetic disturbances? As we have seen, we have at least partial answers to some of these questions. Fast CMEs and shocks produce the highest intensity of energetic particles, and also tend to be associated with strong southward IMF. Our understanding is not sufficient at this point in time, however, to satisfy the requirements of an operational space weather predictive tool.

Another important question concerns the most efficient way of translating measurements of CME / ambient wind characteristics close to the sun into accurate predictions of effects at Earth. For progress to be made in this area, new observations are needed that will in turn lead to better models. The NASA STEREO mission for example, planned for launch in 2005, offers the possibility of greatly improving our understanding of the 3-dimensional structure of ICMEs. Other up-coming missions, like Solar Dynamics Observer (SDO), are directed towards gaining a better understanding of the magnetic processes at the sun that are ultimately responsible for the majority of space weather phenomena. On a global scale, the International Living With a Star programme ILWS has as one of its main objectives the development of the models and measurement strategies that are needed for an operational space weather programme. In addition to NASA missions like SDO, ESA's Solar Orbiter is also seen as part of ILWS.

As a final comment on the current status of our predictive abilities, it is instructive to read the following two extracts from the NOAA Space Environment Center Space Weather Outlook for 14 Nov – 10 Dec 2001: “Proton levels are expected to be at normal levels throughout the period barring a major proton-producing flare.” “Quiet to unsettled conditions expected … barring an Earth-directed CME.”

4. REFERENCES

1. Crooker N. U. and Cliver E. W., Postmodern View of M-regions, *J. Geophys. Res.,* 99, 23383, 1994.

2. Tsurutani B. T., et al., Interplanetary Origin of Geomagnetic Activity in the Declining Phase of the Solar Cycle, *J. Geophys. Res.,* 100, 21717, 1995.

3. Lindsay G. M. et al., Coronal Mass Ejection and Stream Interaction Region Characteristics and their Potential Geomagnetic Effectiveness, *J. Geophys. Res.,* 100, 16999, 1995.

4. Gosling J. T. et al., Geomagnetic Activity Associated with Earth Passage of Interplanetary Shock Disturbances and Coronal Mass Ejections, *J. Geophys. Res.*, 96, 7831, 1991.

5. Reames D., Solar Energetic Particles: Is There Time to Hide?, *Radiation Measurements*, 30, 297, 1999.

6. Reames D., SEPs: Space Weather Hazard in Interplanetary Space, *Space Weather*, Geophysical Monograph 125, AGU, 101, 2001.

7. Kahler S. W., Origin and Properties of Solar Energetic Particles in Space, *Space Weather*, Geophysical Monograph 125, AGU, 109, 2001.

8. Reames D. et al., The Spatial Distribution of Particles Accelerated by Coronal Mass Ejection-driven Shocks, *Ap. J.*, 466, 473, 1996.