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Examples of fast solar wind transients, their sources and the forecast of possible geomagnetic impact

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RESUMEN

Presentamos ejemplos de la observación interplanetaria de expulsiones de materia solar, incluyendo posibles nubes magnéticas, que generaron choques magnetosónicos de alta velocidad en el medio interplanetario. Estos eventos sucedieron antes y durante la era del programa ISTP. El ejemplo de 1982, cerca del punto máximo del 21avo ciclo solar fue observado por los satélites SOLWIND, ISEE, HELIOS y IMP que permitieron una amplia cobertura del medio interplanetario, en longitud y distancia en la heliosfera. El segundo evento ocurrió en mayo de 1998. Una detallada descripción de su origen solar es permitido por las observaciones con los instrumentos en la nave SOHO, mientras que las observaciones de las emisiones de radio y partículas energéticas y viento solar observado *in situ* fueron hechas con la nave Wind. De esta manera visitamos una vez más posibles herramientas para pronósticos de clima geomagnético y espacial que son: el monitoreo del Sol con sensores desplegados en un amplio rango de longitudes y distancias dentro de la heliosfera (< 1 AU), la gran resolución temporal y de intensidad luminosa del instrumento en SOHO que fotografía el Sol en longitudes de onda en el extremo ultravioleta , el coronógrafo solar, el receptor de emisiones remotas radiales y la observación local de iones con un rango energético de unos pocos MeV.

PALABRAS CLAVE: Viento solar, tormentas geomagnéticas, actividad solar.

ABSTRACT

We present examples of solar ejecta, including possible interplanetary magnetic clouds, which generated fast forward interplanetary shocks as they moved rapidly through the interplanetary medium. These events occurred before and during the ISTP era. The example from 1982, close to solar maximum, was observed by the SOLWIND, ISEE, HELIOS, and IMP spacecraft which provide wide coverage of the Sun and inner heliosphere. The second event occurred on May 1998. A detailed description of its solar origin is provided by observations from instruments on the SOHO spacecraft, while observations of the shock-generated radio emissions and energetic particles and near-earth solar wind magnetic fields and plasmas are provided by the Wind spacecraft. We revisit potential tools for space weather forecasting, namely: the power of monitoring the Sun with sensors located within a wide range of heliospheric longitudes and distances, the high resolution in time and light-intensity of the extreme ultraviolet imager and solar coronograph, the remote sensing of drifting radio emissions and the local observation of MeV energetic ions.

KEY WORDS: Solar wind, geomagnetic storms, solar activity.

1. INTRODUCTION

Coronal mass ejections (CME) are massive emissions of material from local or extended regions of the solar corona caused by sudden magnetic field reconfigurations in the atmosphere of the Sun (e.g. Gosling *et al.*, 1974; Webb and Hundhausen, 1987). An average CME ejects a mass of 10^{15} to 10^{16} gr and above average magnetic field. This field dominated plasma preserves better memory of its origin. This magnetized fluid or part of it, at 1 AU, often shows clear signatures of a flux-rope, which in many cases resembles the solution of the force free field equations (characterized by currents along field lines (Lundquist, S., 1950). For a recent discussion see Burlaga 1995; Lepping *et al*., 1997.

CMEs spanning a wide angular extension when observed from Earth are found to move in a path toward the Earth and have been called halo-CMEs (Howard *et al*., 1982). A differential in latitude, also longitude in the displacement of ejecta had been observed (G. Simmett's private communication, April 1998; Cane *et al*., 1997). CMEs which undergo gentle to explosive separation from the Sun carry a sample cross section of the Sun's outer regions, possibly encompassing a wide region from the photosphere to the low and medium coronal (see e.g. Wurz *et al*., 1998).

In this paper, we show two examples of fast, extended CMEs. The first was observed in 1982 by the SOLWIND coronagraph. The interesting feature of this event is that the resulting interplanetary shock and the energetic particles accelerated by it were observed by spacecraft spaced in heliolongitude and heliocentric distance. The observations point out the value of combining data from several locations as a means of improving space weather predictions. The second halo-CME was observed in 1998 by the SOHO/LASCO coronagraph (Brueckner *et al*., 1995). Examples of the excellent continuous solar and solar wind (SW) observations now available will be shown for this event.

Section 2 presents a brief description of the instruments and a limited description of their capabilities. In section 3 we present the SOLWIND coronograph observation of the July 12, 1982 CME at the Sun together with *in situ* monitoring of the CME material and associated shock at a wide range of heliolongitudes. In section 4 we present high-resolution solar observations by the SOHO EIT and LASCO instruments of the source and expansion of the May 2, 1998 wide angle CME. Remote and *in situ* observations at WIND, near the Earth's location, of its propagation in the interplanetary medium, will also be described. Discussion and conclusions are presented in Section 5.

2. INSTRUMENTATION

The event in July 1982 was observed by the NRL coronagraph on the SOLWIND spacecraft. We will discuss energetic particle observations made by the Goddard Space Flight Center instruments on the IMP 8 spacecraft [McGuire *et al*., 1986], which are near the Earth, and on Helios 1, which was located in a heliocentric orbit extending from 0.3 to 1 AU from the Sun. We will also use > 60 MeV particle data from the University of Kiel experiment on Helios 1 [Kunow *et al*., 1977]. Drifting radio emissions, type II radio bursts, are observed and tracked with the ISEE-3 radio receiver [see e.g. Bougeret *et al*., 1984]. This high sensitivity receiver has the capability to determine the longitude and (less accurately) the latitude of the source of these radio emissions. Near-Earth SW magnetic field and plasma parameters (one hour averages) are obtained from the NSSDC OMNI database, accessible through its WEB home page http://nssdc.gsfc.nasa.gov/omniweb/. The ground base signatures we will consider include the Mount Wellington (Tasmania-Australia) monitor counting neutron rates and Dst and Kp geomagnetic indices from the OMNI database.

The second event we will discuss, in May 1998, was observed by the high-sensitivity instruments on the SOHO and Yohkoh spacecraft. Solar soft X-ray observations are available from the Yohkoh SXR instrument and from the thermal X-ray instruments on Yohkoh and GOES. Observations of the low corona at 195 Å are provided by the Extreme-Ultraviolet Imaging Telescope (EIT) on SOHO [Delaboudinière *et al*., 1995]. EIT is an extremely sensitive instrument that is able to see the manifestations in the low corona of the photospheric type blast waves known as Moreton waves, apparently associated with the lift-off the CME (see e.g. Thompson *et al.*, 1998). The CME was observed by the SOHO/LASCO white-light coronograph. The LASCO instrument has about 200 times the dynamic range of the SOLWIND coronograph and is sufficiently sensitive to be able to observe, for the first time, density variations carried out by the steady outflow of coronal material within a few solar radii from the Sun (Brueckner *et al.*, 1995). The energetic particle observations in this event are from the EPACT experiment [Von Rosenvinge *et al*., 1995]. Drifting radio emissions (type II radio bursts) are tracked by the WAVES/Wind instrument which has better frequency coverage than the ISEE-3 radio-receiver, with the capability to locate the origin of radio emissions in three dimensions [Bougeret *et al*., 1995]. We will also use 5 min. *in situ* observations of the IMF and moments of the SW plasma from the WIND Magnetic Field Investigation (MFI) and SW Experiment (SWE) (Lepping *et al*., 1995; Ogilvie *et al.*, 1995).

3. JULY 12-15, 1982 SUN-EARTH CONNECTION EVENT

This event occurred at the start of the decline from maximum of solar cycle 21 (see e.g. Cane *et al.*, 1988). On July 12 at 1232 UT, the SOLWIND white light coronograph detected a «remnant», a commonly used designation of a possible CME which could not be resolved with the time resolution available (Plate 1, bottom figure, left side). The CME was associated with an X-type flare in an active region located 41° East from Earth. A sudden commencement at Earth indicated the arrival of the related shock at Earth at 1415 UT on July 13, suggesting a 1 AU transit speed of 1340 km s^{-1}.

At the time of this event, observations of the SW and energetic particles were being made by spacecraft at various longitudes and heliocentric distances. Helios 1 was near 0.5 AU and ~ 45° W from Earth, while the ISEE-3 and IMP-8 spacecraft provided observations near Earth (see inset in top figure, left side). Plate 1, right, shows near-Earth observations. The ISEE-3 radio data (Plate 1, top panel on the right) show very intense, drifting kilometric type-II radio emissions (-500-70 kHz). These start around 1600 UT on July 12 and extend to the time of shock passage, providing a clear signature of the shock propagating from the Sun towards Earth. The IMP-8 4.2-6 MeV and 43-63 MeV energetic particle (panels 8 and 9) show the slow rise in the intensities of the shock energized particles (SEP) expected following an eastern event [Cane *et al.*, 1988; Reames *et al.*, 1996] because the spacecraft connection to the shock is initially poor but improves as the shock advances towards the Earth. Peak intensities were observed at and following the time of passage of the shock, which is indicated by the SC time (solid

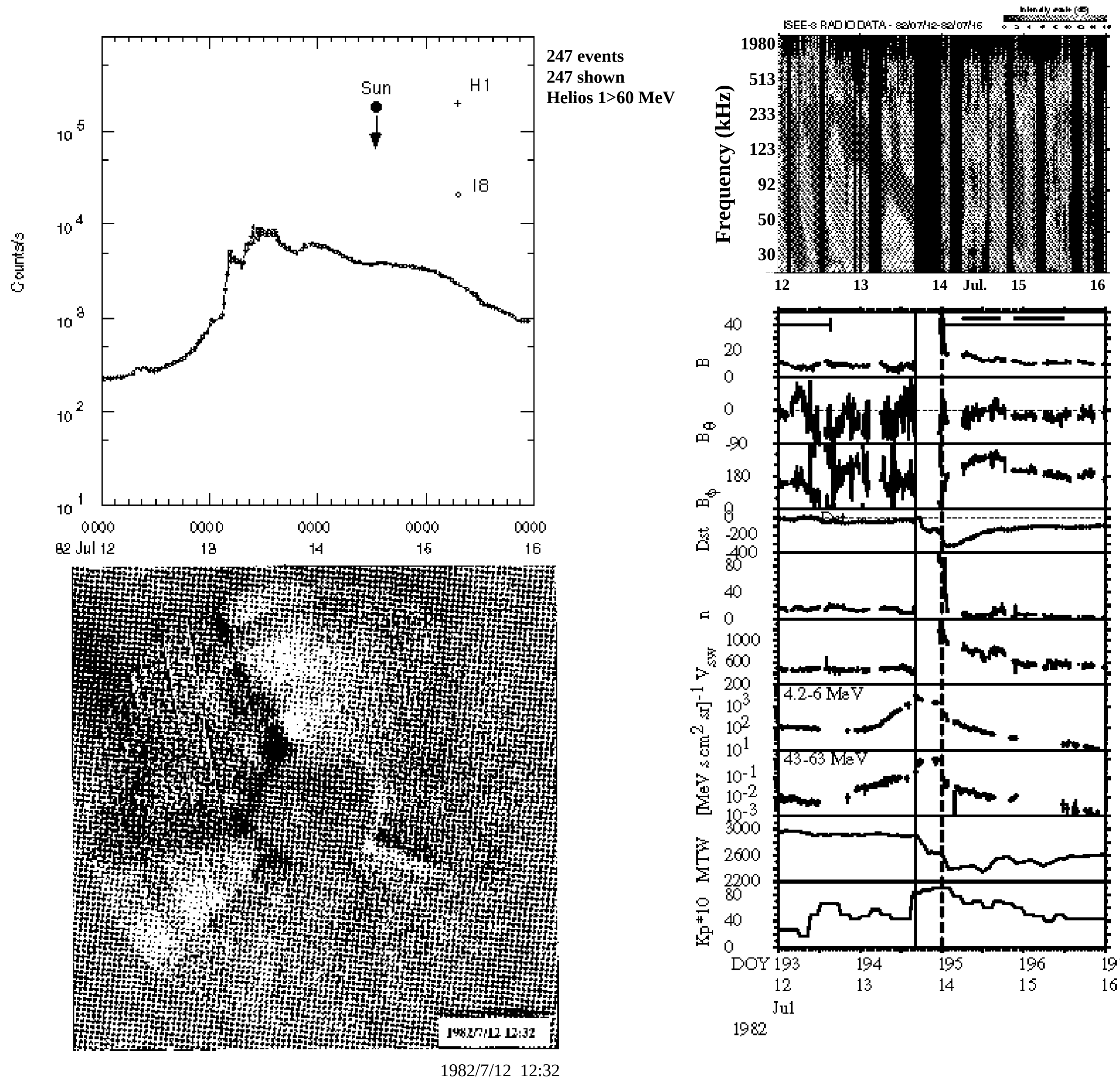

Plate 1. The left side presents in separate figures the image of a “remnant” in the Sun corona by the SOLWIND-white light coronograph and the anticoincidence observation of >60MeV shock accelerated particles at Helios 1. The inset shows the location of the event on the Sun relative to IMP-8 and Helios 1.

The right hand side Figure shows near Earth observations from top to bottom: spectrogram of radio intensity versus frequency; the magnitude, polar and azimuthal angles of the IMF, the Dst geomagnetic index,; the SW density in cm^{-3}, and speed (km/s), two shock energized particle ranges, the neutron counts at Mount Wellington, and ten times the geomagnetic Kp index (multiplied by a factor of 10) as time series.

line). This figure also suggests that CME-related material was encountered following the shock, commencing at the time indicated by the vertical dashed line. The signatures of CME-related material include: an interval of bidirectional SW heat fluxes detected by the Los Alamos plasma experiment on ISEE-3 (horizontal line with bars at the ends, panel 2); bidirectional ~1 MeV particle flows detected by the Goddard instrument on ISEE-3 (horizontal lines, panel 2); and depressions in the energetic ion intensity (panels 8 and 9). The Mount Wellington neutron monitor data shows a classic «two-step» cosmic ray depression (panel 10), with the first step following shock passage and the second step associated with entry into the CME-related material. The Dst parameter indicates a similar evolution of the ensuing magnetic storm [panel 5] and the geomagnetic Kp index reached its maximum value of 9 during this time interval [panel 11]. The observations suggest that the CME-related material extended in longitude at least 41° from the solar event. The speed of the ejected plasma and IMF was greater than a typical high-speed stream (~ 740 km/s) [see e.g. Chotoo *et al*., 1998].

At Helios 1, the energetic particle intensities rise gradually ahead of the shock which passed by at 0310 UT on July 13 and reach maximum behind the shock. Such a profile is typical of a shock from a far-eastern event (Cane *et al.*, 1988; Reames *et al*., 1996) and provides a means of linking the shock at Helios 1 with the July 12th event rather than, for example, with an event behind the western limb which is nearer central meridian at Helios 1 but cannot be observed at Earth. From the point of view of space-weather prediction, we note that, had the Helios 1 plasma and particle data been monitored in real time, the high likelihood of the arrival of an energetic shock at Earth, located in heliolongitude between Helios 1 and the solar event, could have been predicted. Based on the 14 hour transit time from the Sun to Helios 1 at 0.5 AU, an arrival time at Earth ~28 hours after the solar event (17 UT on July 13) might have been expected. In fact, the shock arrived four hours earlier (13 UT), suggesting that the speed of this particular shock was higher near the nose of the shock than at the flank, as tends to be the case [Cane, 1985].

4. EXAMPLE 2: MAY 2-4, 1998 SUN-EARTH CONNECTION EVENT

Images on the left, Plate 2, show the May 2, 1998 event. It occurred approximately a year after the beginning of solar cycle 23. On May 2, 1998 EIT/SOHO observed a strong eruption (X-flare) in the low corona near the photosphere. The event was located near central meridian at South (S)17°-West (W)20°. The time of the event on the Sun (1340 UT) is indicated by the observation of type-III radio bursts followed by intense, drifting type II radio emissions, the signature of propagating shock in the low corona. A halo-type CME, surrounding the whole occulting disk and indicative of an earthward-directed CME, was subsequently observed by the LASCO/SOHO white light coronograph. In the plane of the sky, an expansion speed of ~750 km/s can be inferred from the LASCO observations. The Wind/WAVES instrument detected several manifestations of a decametric type-II and a type IV radio burst at ~8 solar radii. Preliminary analysis of these drifting radio emissions indicate a driven IP shock with velocities between 900 and 1500 kms^{-1}. Panel 2 from the bottom, on the right side of Plate 2, clearly indicates with MeV SEP the start of the event, on May 2. It suggests the presence of a very strong IP shock coming from a near central region of the Sun's corona [Cane *et al*., 1988; Reames *et al.*, 1996]. The 2nd to 8th panels in Plate 2, right side, show from May 2 to 4 the rotation of the field, the smooth decrease in SW velocity, protons density, protons temperature and plasma β (proton). These parameters indicate that at the time of this event on the Sun an interplanetary magnetic cloud was passing the Earth location generating strong geomagnetic disturbances as indicated by the bottom panel. This earlier event was observed also to originate from the same active region in the form of a halo-CME on April 30 (EIT and LASCO instruments in SOHO). Announcing the imminent arrival of the ejecta to Earth there is an extra, spike-like, enhancement in the flux of SEP in the 2.1-2.4 (2-2.4) MeV H^+ (He^{++}) range starting around 2100 UT, May 3 and peaking sharply at shock passage (0200 UT, May 4) (2nd panel from bottom, Plate 2, right side). Type-II radio bursts were observed at 0100 UT, May 4 in the ~ 90 KHz range. These radio emissions are consistent with fundamental type-II radio emissions and with the local-plasma densities at/after passage of the shock.

The *in situ* SW observations show a hot, magnetic-field-dominated structure after the shock, followed by a dense region of plasma moving at a mean speed close to 800 kms^{-1}. The arrival of the IP shock at 1 AU gives a transit speed of ~ 900 kms^{-1} for the event, which is more or less consistent with the *in situ* SW speed. The ejecta generates extremely disturbed geomagnetic conditions with intervals of a geomagnetic index Kp = 9 (the maximum value) from 0300 to 0600 UT, May 4, 1998, due in part to extremely intense (> 40 nT) southward oriented magnetic field). Later the geomagnetic Kp index reached a value of 8, the result of an interval with a ram pressure reaching above 50 nPa. This is an interval characterized by brief spikes in the SW speed reaching 1100 kms^{-1}. The complex signatures of an ejecta traveling at speeds above 800 kms^{-1} were observed in the following days.

For this event, the main elements are a precise determination on the location (near central meridian) and initial direction of propagation of the event towards the Earth. Another important element is the accurate determination of the initial speeds of the CME and associated shock at the Sun (considering LASCO/SOHO and WAVES/WIND). A warning of the imminent arrival of the shock is provided by the ramping up of the MeV particle intensities ahead of the shock related to the «local» spike-like enhancement associated with shock passage, commencing approximately at 2100 UT on May 3.

5. SUMMARY AND CONCLUSIONS

These two examples belong to the class of CMEs which eject plasma and magnetic field into space at speeds well above the velocity of the ambient SW in the general direction of Earth. These speeds also exceeded the typical speed (~740

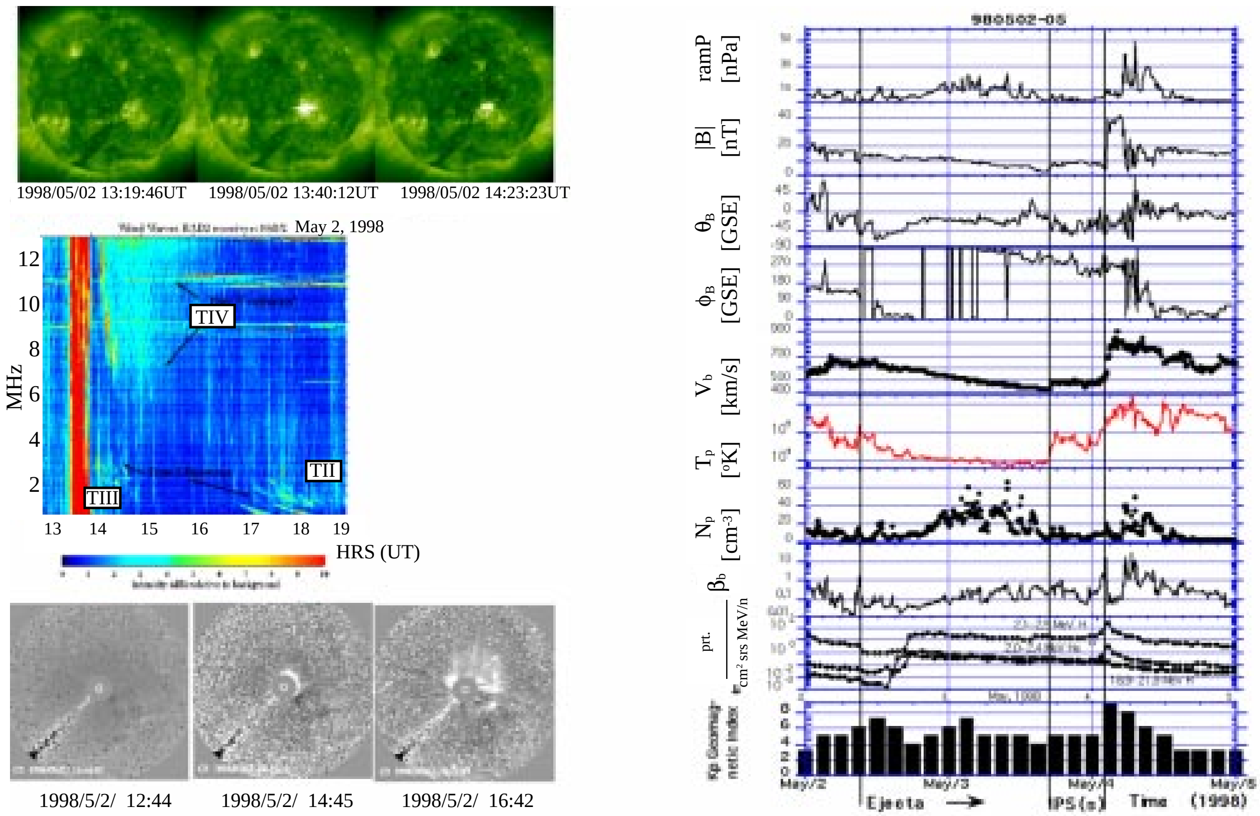

Plate 2. The top left presents three images of the low corona region of the Sun taken with the EIT/SOHO instrument which shows the active region 8210 (~S17W17) before, at and after the X-flare at 1340 UT on May 2, 1998. The middle image on the left shows the radio emission spectrogram from 1300 to 1900 UT. On the left the intense type III radio burst mark the start of the X-flare. From ~1410 to 1600 UT is shows Type IV radio burst emissions in an extended region above 8 MHz, and between 1410 to 1900 UT drifting radio emissions (Type II radio bursts) between ~ 4 MHz. The bottom images presents the Sun corona with its streamers on the left, the appearance in the NW of the CME leading edge, in the middle, and it fast expansion in all directions at a later time, on the right.

The figure on the right side of Plate 2 shows from top of bottom: tha SW ram Pressure in nPa, the Wind/MFI intensity of the IMF in nT, the latitud and azimuthal orientation of the IMF in GSE; the Wind/SWE SW speed in kms^{-1}, proton density in cm^{-3} and temperature in °K, the plasma β (only protons), three meV shock energized particles (SEP) from Wind/EPACT [2.1-2.5 MeV H^+ 2.0-2.4 MeV He^{++}, 18.8-21.9 MeV H^+], and the preliminary global geomagnetic Kp index from NOAA, as time series.

km/s) of high-speed SW observed by Ulysses during its swing over the polar regions of the Sun. A strong forward shock is generated ahead of the ejected material in each case which, at least in the July 1982 event, clearly extended more than 90° from the solar event. The compressed plasma and field SW ahead of the ejected material generated in both cases severe geomagnetic disturbances (Kp ~ 9) when interacting with the magnetosphere. These extraordinary geomagnetic disturbances continued as a consequence of the southward oriented magnetic fields associated with the passage of the ejected material.

An aim of space-weather forecasting is to provide several hours advance warning of the arrival of fast SW transients which may seriously affect the geomagnetic environment. The first event shows an example where observations at multiple locations separated in heliolongitude and heliocentric distance can play an important role- when such observations are available which is not the case at the current time, with occasional exceptions (e.g. Mulligan *et al*., 1998). There have been several studies of CME-associated shocks using Helios 1 and 2 and near-Earth observations during a period of time which included the solar maximum during the 21 solar cycle (e.g. Cane *et al*., 1994, 1997; Lepping *et al*., 1990). The location of the Helios spacecraft at different heliolongitudes, and distances closer to the Sun, would have enabled reliable predictions of the possible time of arrival of transient interplanetary structures which would be expected to cause severe geomagnetic disturbances had the data monitored in real-time. In both cases the bottom panels (on the right side of Plates 1 and 2) indicate that SW conditions were already disturbed before the arrival at Earth of the presented events. This would suggest that further enhancement of severe space weather may be the result of the interaction between two strong SW streams.

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