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Space weather observations using the SOHO CELIAS complement of instruments

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Abstract. The Solar and Heliospheric Observatory (SOHO) spacecraft located at L1 is well outside the Earth's magnetosphere and has been observing the Sun continuously since December 1995, except for relatively brief periods due to spacecraft operational interruptions. While a variety of instruments on the SOHO spacecraft investigate the solar properties important to an improved understanding of the Sun and its effect on space weather, the present work is limited to the observations provided by the Charge, Element, and Isotope Analysis System (CELIAS) proton monitor (PM) and Solar Extreme Ultraviolet Monitor (SEM) instruments and their relationship to other space weather observations. The CELIAS observations consist of particle and EUV/soft X-ray solar flux measurements. A brief description of the CELIAS instrumentation and examples of the precursor information signaling the possibility of coronal mass ejection events observed by the CELIAS/SEM are presented. In addition, the entire SEM database since commissioning is presented on both expanded and compressed timescales in order to provide both the long-term weather trends and short-term storm data. The SEM data presented are full-disk observations and have a 15 s sampling rate.

1. Introduction

Space weather in its broadest sense includes the full range of external phenomena that affect the Earth and its environment. These external phenomena are the solar wind plasma, solar photons, electric and magnetic fields, dust, and cosmic rays. The most important driver of the "local" day-to-day space weather variability is the dynamic character of the Sun's short-wavelength electromagnetic radiation and particle emissions. Geomagnetic storms, one of the space weather elements of most concern, are produced by coronal mass ejections (CMEs). The CMEs are large plasma clouds ejected from the Sun, typically flowing faster than the surrounding solar wind, causing shock fronts [*Gosling*, 1990]. The Charge, Element, and Isotope Analysis System (CELIAS) instrument makes in situ measurements of the CME plasma at L1 on board the Solar and Heliospheric Observatory (SOHO). Using these data, a detailed analysis of the January 1997 CME event has been previously carried out by *Wurz et al*. [1998, 2000]. Analysis of the characteristics of other CMEs propagating toward the Earth, including those discussed here, is in progress.

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Upon arrival at the Earth, CMEs can severely distort the magnetosphere and thereby induce large currents, many of which cause failure in Earth-based power grids. Such severe particle storms can increase the average solar wind power deposited in the Earth's magnetosphere by a thousandfold. Such increases severely affect the Earth's atmosphere and lead to an expansion of the auroral zone to lower altitudes and latitudes. An excellent review of ionospheric storms and their effects has been given by *Buonsanto* [1999] and references therein.

In addition to solar particle storms, a direct and significant disturbance of the ionosphere, and the atmosphere generally, results from ionization, dissociation, excitation, and heating by the extreme ultraviolet (EUV) and soft X-ray photon bursts (solar flares) [*Opal*, 1973]. Whether or not significant particle bursts (CMEs) accompany all EUV/soft X-ray transient events remains to be determined, but the short-wavelength electromagnetic bursts, which are observed by the CELIAS Solar Extreme Ultraviolet Monitor (SEM), are often found to significantly exceed the full-disk "quiet" solar radiation background. Solar soft X-rays, EUV radiation, and relativistic electrons from intense solar flares produce prompt effects in the Earth's ionosphere, such as a sudden increase in total electron content (SITEC), sudden frequency deviations (SFD) at 15 Mhz, sudden phase anomalies (SPA) at 60 Khz, and increased *D* region absorption [*Garriott et al*., 1967]. These effects provide direct evidence of increased ionization at low latitudes and altitudes. Possible adverse effects include changes in atmospheric drag on satellites, errors in Global Positioning Systems (GPS) and in VLF navigation systems, and disruption of HF communication and UHF satellite links due to scintillations [*Buonsanto*, 1999].

The particle and electromagnetic weather discussed above

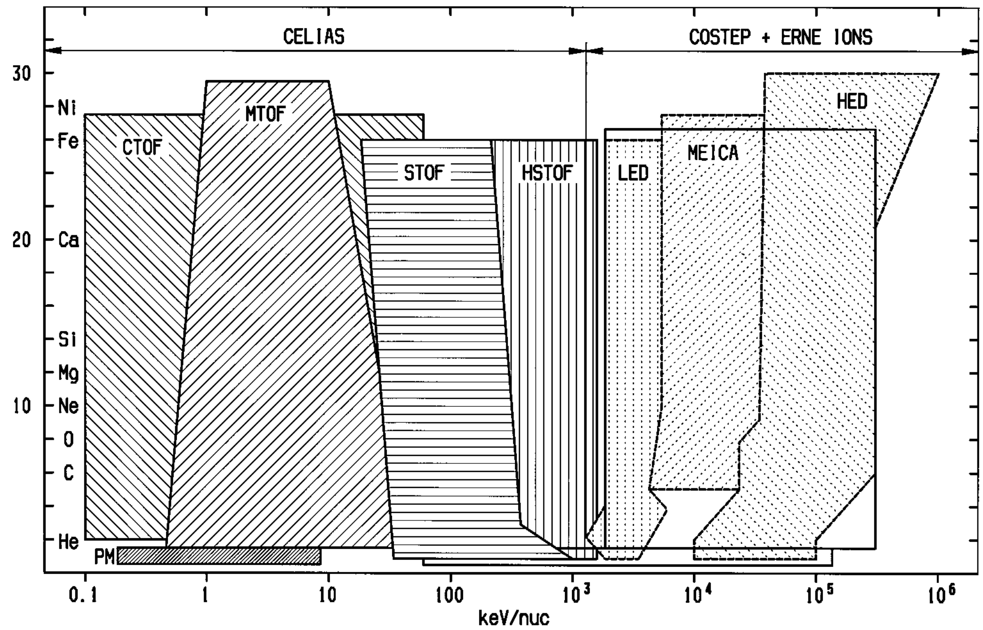

Figure 1. Energy range of SOHO particle instruments CELIAS and CEPAC.

can also have significant adverse effects on astronauts and on high-altitude aircraft pilots, whose health may be compromised by exposure to intense fluxes of energetic particles. It is therefore important that a simple, highly reliable, early warning storm watch system be available in real time (i.e., within minutes) [*Feynman and Gabriel*, 2000]. The SOHO/CELIAS instrumentation currently provides near-real-time (typically 1–30 min) observations of solar wind plasma parameters by a proton monitor [*Ipavich et al.*, 1998] and of the solar EUV radiation by the SEM [*Judge et al.*, 1998]. Modest operational modifications would permit the SOHO data to meet the real-time early warning objectives. In the results to be presented here, we have chosen specific data samples to illustrate the multifaceted aspects of a developing "solar storm."

2. CELIAS Instrumentation

The CELIAS instrumentation consists of (1) a set of particle-measuring instruments that determine the charge, mass, and energy of low- and high-speed solar wind, suprathermal ions, and low-energy solar flare particles and (2) a solar EUV monitor which measures the absolute solar full-disk flux in the extreme ultraviolet and soft X-ray spectral regions [*Hovestadt et al.*, 1995].

The scientific purpose of the particle measurements is to determine the charge, elemental, and isotopic composition of the solar wind and from those measurements infer the composition of the Sun as well as that of the lower-energy particles in the local interstellar space. Figure 1 shows the energy range per nucleon covered by the CELIAS instruments (CTOF, MTOF, STOF, and HSTOF, which is the "high"-energy range of STOF) as well as that of the COSTEP and ERNE instruments [*Müller-Mellin et al.*, 1995], which are supplied by another research group to measure still higher energies. A detailed discussion of the CELIAS instrumentation is given by *Hovestadt et al.* [1995]. Briefly, the CTOF instrument is a time-of-flight instrument that measures the charge state of the detected particles, MTOF measures the mass with high resolution, and STOF measures the suprathermal particle charge states. The MTOF instrument includes a proton monitor which provides supplemental and important data, making it possible to determine proton bulk speed, thermal speed, and density as well as the north-south flow direction of the solar wind. The proton monitor (PM) is described in detail by *Ipavich et al.* [1998].

The scientific purpose of the electromagnetic irradiance measurements is to determine the full-disk absolute value of the solar flux and its variation in the EUV and soft X-ray wavelength regions. The SEM data are used to cross calibrate EUV/UV instrumentation aboard the SOHO spacecraft, to provide the He ionization rates crucial in modeling the very near local interstellar medium [*Möbius et al.*, 1995], and to provide absolute EUV/soft X-ray irradiances required to understand the variability of the Earth's upper and middle atmosphere. The SEM part of the CELIAS complement of sensors is detailed by *Judge et al.* [1998]. Briefly, SEM is a transmission-grating spectrometer which measures the full-disk solar EUV/soft X-ray flux integrated in time over a 15 s sampling period. The central-order data channel measures the integrated flux over a 0.1–50 nm band pass and is spectrally limited by a transmission grating and a serial set of aluminum films. The first-order channel covers the 30.4 nm wavelength range and extends from 26 to 34 nm. A derived solar flux which includes only the soft X-rays may be obtained from the two directly measured fluxes and an adopted nominal solar spectrum [*Judge et al.*, 2001]. The derived soft X-ray flux covers the spectral range from 0.1 to 5 nm.

3. SOHO CELIAS Database

The data for both the first-order and the central-order channels of the SEM from January 1, 1996, to January 31, 2000, are shown in Figure 2. These data are provided primarily to show the trend in solar activity since the most recent solar EUV minimum. The data sets are necessarily shown on a compressed timescale in order to permit a full half solar cycle of

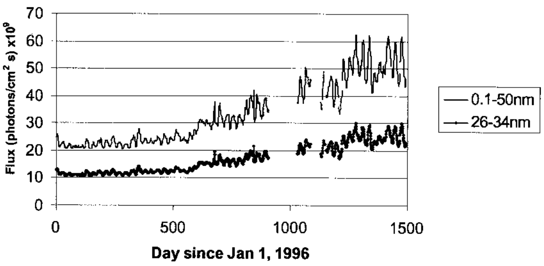

Figure 2. CELIAS/SEM full disk solar EUV flux at 1 AU from January 1, 1996, through January 1, 2000.

data to be presented. What can be seen immediately is that the flux increases by a factor of 2–3 in both channels as the solar activity increases from solar minimum to solar maximum. Moreover, in both data sets the "27 day" Carrington rotation period (the average synodic period at the equator) is a striking and persistent feature. The variations are due to persistent solar active regions that may last several months, with amplitudes which vary by 10–15% in the EUV and by 30 and 45% in the central-order channel during solar minimum [*Ogawa et al.*, 1998], and the percentage variation is maintained as solar maximum is approached. Preliminary analysis of the solar soft X-ray data extracted from the central-order channel indicates an increase of X-ray flux by over an order of magnitude from solar minimum to solar maximum in the 0.1–5 nm band pass. Superimposed upon the 27 day fluctuations is an ever more densely packed forest of electromagnetic bursts, in addition to occasional noise bursts due to high energy protons [*Judge et al.*, 2001]. Factors of 2 to 3 changes in the solar EUV input in the Earth's atmosphere are well known [*Feng et al.*, 1989] and explain the solar cycle variation of the thermosphere; however, the solar cycle variation of the soft X-ray flux shortward of 10 nm is a very poorly understood component of the Sun's radiative output [*Lean*, 1991]. Thus measurement of the soft X-ray flux and its variation as obtained by the SEM during the solar cycle will provide reliable data on this portion of the solar spectrum.

The data from the PM and SEM since the launch of SOHO are both available through the CELIAS instrument Web site http://www.cx.unibe.ch/phim/soho/. Both data sets are continuously available since December 1995 and are remarkable in the similarity of their general features, suggesting a persistent coupling between particle flux variability and short-wavelength solar electromagnetic radiation behavior. To illustrate the coupling we will focus here on the well-established flare and CME events (LASCO: http://www.nrl.navy.mil) set in motion on April 7, 1997 (Plates 2a and 2b), and the June 6, 2000, solar flare and its consequences (Plate 3) as observed by SEM, PM and other relevant solar observing instruments.

In Figure 3a we show the multifaceted morphology of the April 7, 1997, flare and associated events, as well as full-disk solar images taken by the Extreme Ultraviolet Imaging Telescope (EIT) and the Large Angle and Spectrometric Coronagraph Experiment (LASCO) for "global" context. This flare corresponds to a C class X-ray solar flare as observed by the GOES 8 X-ray detector (ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SOLAR_FLARES/XRAY_FLARES/). It was seen first by the SOHO SEM, then by the high-energy electron detector on SOHO, and then by the arrival of protons which were observed by COSTEP, as shown in Figures 3a and 3b. Since this was a clearly identified CME event, the opportunity to investigate the spectral, temporal, and flux characteristics of the flare associated with the proton event advancing toward Earth is evident. Our current understanding of the severity of damage that may result from a variety of solar eruptions, and their relationship to possible precursor data sets, has been reviewed by *Feynman and Gabriel* [2000]. It is clear that we now have excellent data sets provided by SOHO and other spacecraft with which to advance this understanding and thereby characterize and possibly forecast space weather.

An excellent example of the PM data pertaining to space weather is given in Figure 4 for 0800–1400 UT on June 8, 2000, associated with the June 6 solar flare, where the solar wind speed and density (CELIAS/PM data) together with the GOES 8 magnetic field strength for the same time interval are shown. The shock, a propagating discontinuity in particle density, velocity, and magnetic field, observed by the PM on SOHO is followed ~30 min later by an abrupt increase in the geosynchronous magnetic field strength (the delayed response is due to the time of travel from SOHO to the Earth). In addition, a second solar wind density increase is observed at ~1230 UT, which is again followed by another jump in the geosynchronous magnetic field strength. The propagation time of the shock, moving at an average propagation speed of ~1000 km/s from the Sun to SOHO, is ~41 hours, as can be estimated by comparing the June 6 solar EUV precursor data (CELIAS/SEM) with the solar wind data (CELIAS/PM) shown in Plates 3a and 3b, respectively.

4. EUV Precursor Events Observed by CELIAS/SEM

During major solar events, as observed on April 7, 1997, and on June 6, 2000, both the central-order and the 30.4 nm first-order channels on the SEM measure significant increases in solar EUV and soft X-ray flux that are associated with a CME release on the Sun. Such events are superimposed upon a persistent 27 day Carrington rotation modulation of the solar flux. The broadband channel, which includes soft X-ray observations, registers events, almost continuously, that appear in the data as spikes or hash on a compressed scale. The 30.4 nm channel also shows a variance of 10–15% during the 27 day Carrington rotation as discussed earlier. However, during a major flare, the 30.4 nm channel can increase by 25% or more in 1 or 2 min [*Ogawa et al.*, 1998]. It is this sudden increase in the 30.4 nm channel that characterizes an EUV precursor event that may be followed by a peak in the soft X-ray flux several minutes later. It is well known that about half of the CME events are associated with solar flares, but the temporal dependence of the radiation enhancement associated with a CME is not well characterized and may precede or follow the birth of a solar particle storm [*Phillips*, 1992; *Zirin*, 1988]. Detailed analysis of the flare characteristics may lead to an accurate determination of which flares indicate the impending arrival of CME particles at Earth. Since the CME particles are slow compared to the speed of light, flare events will arrive at Earth hours or days before the CME particles even if the flare follows the CME event, as long as the time delay is short compared to the Sun-Earth travel time of a CME. There is as yet no known simple characterization of the correlation between flares and CME events. Furthermore, it was only recently, with the advent of the SEM database, that solar flares have been continuously monitored in the EUV. It is now possible to use the continuously available SEM data along with solar X-ray measurements from the GOES spacecraft to in-

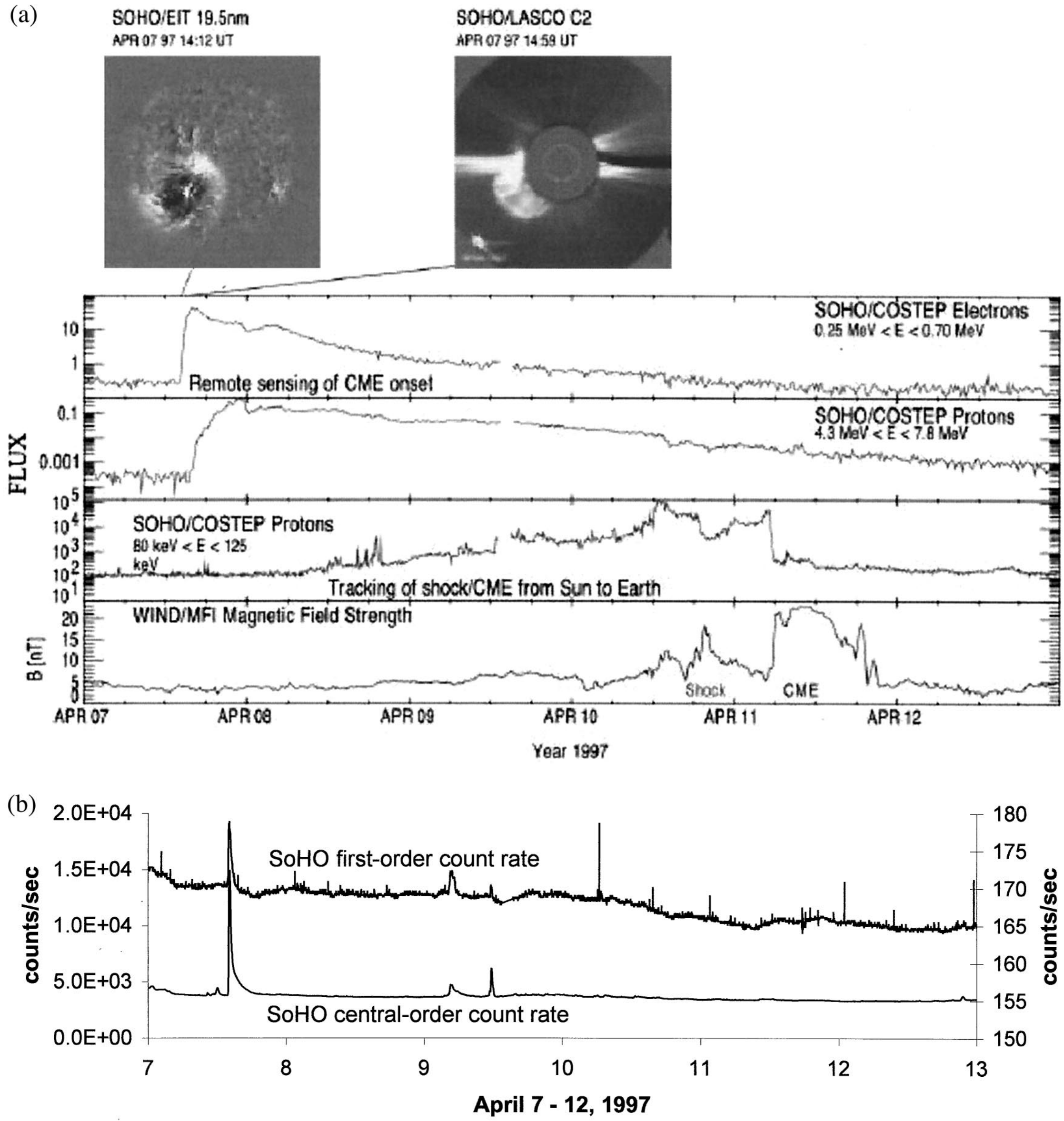

Figure 3. (a) SOHO/EIT/LASCO/COSTEP EUV, white light, electron, and proton observations for the onset phase of the particle/CME event on April 7, 1997. The EIT running difference images taken at 195 A show a shock (Moreton-like) wave in the southeastern portion of the lower corona which was running across the solar disk at speeds of several hundred km/s. The LASCO observations show the halo CME associated with the shock wave. The times of the individual LASCO/EIT images are marked in the intensity-time profiles of 0.25–0.7 MeV electrons and 4.3–7.8 MeV protons (time resolution 1 min). (b) CELIAS/SEM first-order and central-order channels, 15 s data at L1 from April 7, 1997, through April 12, 1997.

vestigate the temporal and spectral behavior of the electromagnetic signature of a flare associated with a CME event. A systematic and detailed study of the differences in the temporal signatures between the two channels, coupled with the behavior of the GOES soft X-ray data, may provide timely predictive information about the character of solar CME events prior to their arrival at Earth. This suggestion is based on an analysis of data such as that shown in Figures 3 and 4.

5. Concluding Remarks

The SOHO/CELIAS complement of instruments has made nearly continuous measurements of solar output in the extreme ultraviolet and soft X-ray spectral regions, as well as the charge, mass, and energy of low- and high-speed solar wind, suprathermal ions, and low-energy solar flare particles since the launch of SOHO in December 1995. The simultaneous measurements made by all sensors of the CELIAS set of instruments provide a historical record of space weather trends and events from the solar minimum of solar cycle 23 to solar maximum, and the measurements are continuing. Understanding the interactions of the Sun-Earth system, and ultimately forecasting solar weather, is the basis of today's space weather efforts. The data provided by the CELIAS instruments provide specific measurements for future investigations into the relationship between solar-driven particles and the solar flare electromagnetic signature, which may foretell the impending ar-

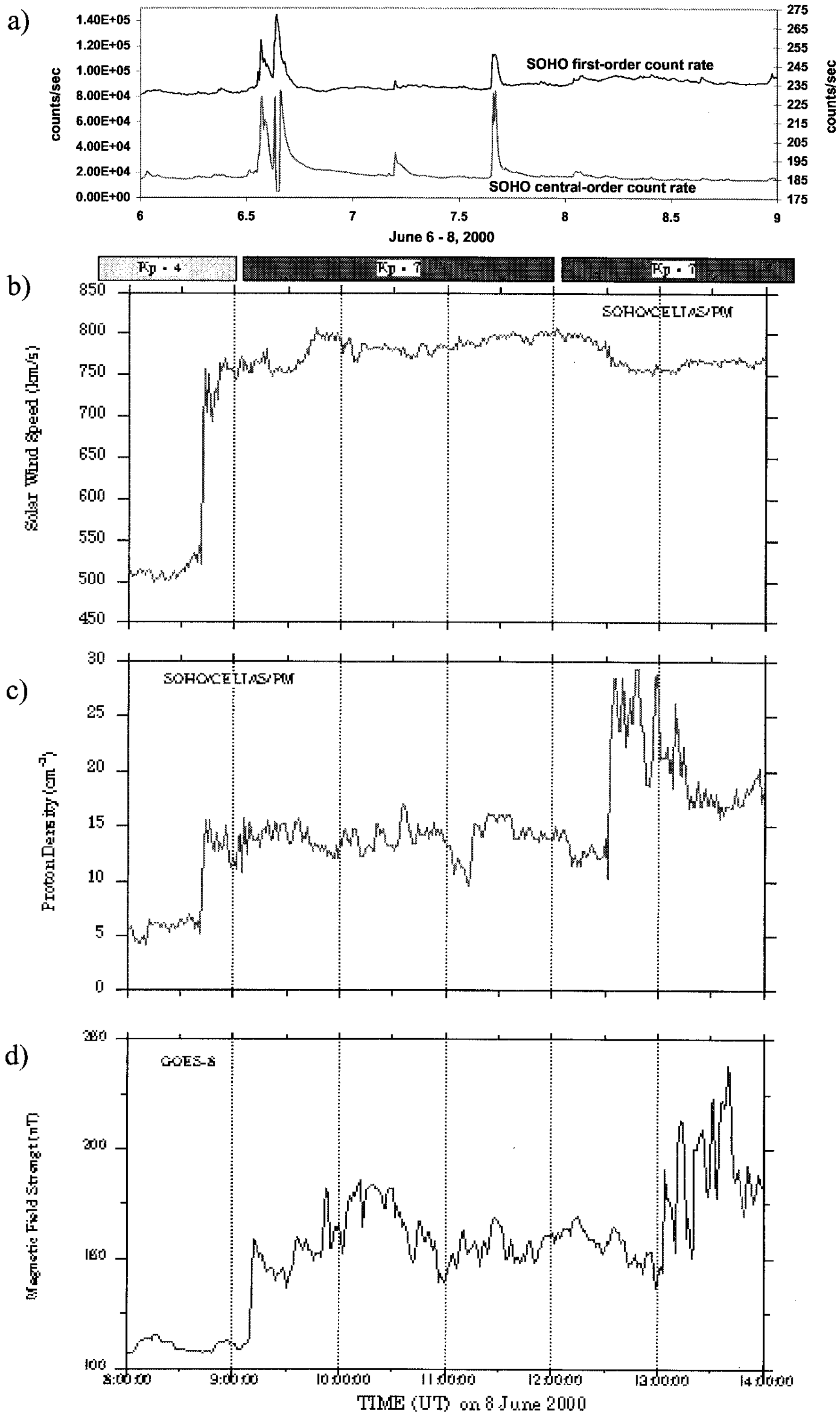

Figure 4. PM speed and density for 0800–1400 UT, June 8, 2000, and the GOES 8 magnetic field strength for the same interval are shown in Plates 3b–3d. Plate 3a shows the SEM precursor 5 min average data occurring 41 hours prior to the PM proton event onset. The scale on the right corresponds to the first-order count rate, and that on the left is the central-order count rate.

rival of a CME. The June 6, 2000, EUV/soft X-ray flux behavior is an excellent example of the spectral and temporal structure of a flare event which was associated with a CME.

More information on the CELIAS complement of instruments and access to CELIAS data sets are available at the CELIAS instrument Web site: http://www.cx.unibe.ch/phim/soho/.

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