Space Sci Rev (2008) 136: 45–65
DOI 10.1007/s11214-007-9165-7

STEREO Space Weather and the Space Weather Beacon

D.A. Biesecker · D.F. Webb · O.C. St. Cyr

Received: 6 May 2006 / Accepted: 20 February 2007 /
Published online: 8 June 2007

Abstract The Solar Terrestrial Relations Observatory (STEREO) is primarily a solar and interplanetary research mission, with one of the natural applications being in the area of space weather. The obvious potential for space weather applications is so great that NOAA has worked to incorporate the real-time data into their forecast center as much as possible. A subset of the STEREO data will be continuously downlinked in a real-time broadcast mode, called the Space Weather Beacon. Within the research community there has been considerable interest in conducting space weather related research with STEREO. Some of this research is geared towards making an immediate impact while other work is still very much in the research domain. There are many areas where STEREO might contribute and we cannot predict where all the successes will come. Here we discuss how STEREO will contribute to space weather and many of the specific research projects proposed to address STEREO space weather issues. The data which will be telemetered down in the Space Weather Beacon is also summarized here. Some of the lessons learned from integrating other NASA missions into the forecast center are presented. We also discuss some specific uses of the STEREO data in the NOAA Space Environment Center.

Keywords STEREO · Space weather · Coronal mass ejection · Solar wind · Forecasting

D.A. Biesecker (✉)
NOAA/Space Environment Center, 325 Broadway, Boulder, CO 80305, USA
e-mail: doug.biesecker@noaa.gov

D.F. Webb
Institute for Scientific Research, Boston College, Chestnut Hill, MA 02467, USA

O.C. St. Cyr
NASA/Goddard Space Flight Center, Greenbelt, MD 20771, USA

1 Introduction

1.1 Background on Space Weather

As society becomes increasingly reliant on technologically advanced systems for many of its day-to-day functions, our ability to predict and respond to the impacts of space weather gains greater importance. Among the systems most susceptible to geomagnetic disturbances are power grids, satellites, and aviation communications—systems upon which our reliance increases dramatically every year. The use of pagers and mobile phones has become almost ubiquitous. The global positioning system (GPS) is used heavily by the military, commercial airlines, the construction and extraction industries, and the shipping and boating industry, and is being introduced into automobiles. As the use of these systems, which are vulnerable to space weather, becomes more widespread, space weather disturbances will impact a wider array of people and human activities. A comprehensive text on telecommunications and the susceptibility of such systems to space weather is that of Goodman (2005). Also, summaries on the impact of space weather on technological systems are available in Lanzerotti et al. (1999) and Lanzerotti (2001).

One example of a space weather impact was the apparent loss of a communications satellite and associated widespread loss of services due to a space weather disturbance, which was described by Baker et al. (1998). They found that the combination of coronal mass ejections (CMEs), solar flares, and high speed solar wind streams led to a prolonged period of geomagnetically disturbed conditions during which the Galaxy 4 communications satellite was subjected to an intense population of highly energetic, relativistic electrons just prior to its loss. The Galaxy 4 satellite outage affected CBS, NPR, Reuters, ATM networks and many pagers. Since our society is becoming more dependent on advanced technological systems, we are increasingly vulnerable to malfunctions in those systems. A single civilian communications satellite can cost several hundred million dollars. There are now over 300 commercial spacecraft in geosynchronous orbit and entire new constellations of satellites are being placed into a variety of Earth orbits. If even a small percentage of these satellites exhibit severe problems due to the space environment, the costs will be significant (Odenwald et al. 2006).

The need to study, forecast and mitigate space weather effects is gaining increased attention at the national level. Specifically, the need to develop a coordinated plan to improve present capabilities in specifying and forecasting conditions in the space environment has led to the formation of national programs such as the U.S. National Space Weather Program (http://www.nswp.gov), NASA's Living With a Star (http://lws.gsfc.nasa.gov/), and ESA's Space Weather Programme (http://www.esa-spaceweather.net/). As a scientific pursuit, space weather is considered analogous to atmospheric weather, having both research and forecasting elements. In some sense, our knowledge and ability to build predictive models of space weather is equivalent to, yet distinctly different from, the early stages of atmospheric weather studies (Siscoe 2006; Siscoe and Solomon 2006). For a comprehensive overview of the recent state of the art in space weather research, readers are directed to the AGU Monograph *Space Weather* (Song et al. 2001) and to the text *Space Weather: The Physics Behind a Slogan* (Scherer et al. 2005).

The ultimate source for most space weather effects is the Sun and its activity. The NOAA Space Environment Center categorizes space weather in three convenient scales which are each related to the type of solar event driving them (Poppe 2000). All three scales rate space weather disturbances on a scale from one (1) to five (5), with one being considered 'minor' and five 'extreme'. The G (Geomagnetic Storm) scale is discussed in the next section. The

R (Radio Blackout) scale is based on the GOES X-ray flux measurement. High levels of X-ray flux result in significant enhancements of ionization of the ionosphere on the sunlit side of Earth, causing sudden ionospheric disturbances (SIDs) and communication problems. Note that extreme ultraviolet and radio emissions also contribute to ionospheric effects, but the X-ray flux serves as a useful proxy in their place. The S (Solar Radiation Storm) scale is measured against the flux of solar energetic particles (SEPs). These SEPs are accelerated in eruptive solar events. The most energetic SEPs (>1 GeV) arrive at Earth within tens of minutes, for magnetically well-connected events on the Sun's western hemisphere. The bulk of the particles in SEP events have lower energies (10–100 MeV) and begin to arrive tens of minutes to hours after solar onset. Eruptive events originating on the Sun's eastern hemisphere have delayed onsets relative to well connected events (Cane et al. 1988 and Fig. 2). These events cause ionospheric-related communications and navigation problems. The proton flux can remain elevated for days and can cause state changes or latch ups in electronic devices on satellites and hazardous conditions for astronauts and even airline crew and passengers.

In addition to the space weather scales, from which many alerts and warnings to customers are derived, there are many other products issued by the SEC. It is clear that there is room to improve many, if not all, of the existing products and there is a need for yet new products. There are numerous space weather products which one can imagine. The NOAA Space Environment Center maintains a list of those products which the forecast center has identified as the most needed. These are separated into two categories; high priority and highest priority. These are broad, subjective, categories with the placement of particular items in each category determined by the forecasters. Table 1 shows these high and highest priority items. Some of these can obviously be addressed by the STEREO mission. Since it would be presumptuous to identify which items could be addressed by the STEREO mission, we do not do so here. The applicability of STEREO to any need is limited only by the imagination of researchers.

1.2 CMEs and Space Weather

As mentioned previously, the third space weather scale is the G (Geomagnetic Storm) scale. Most of the energy imparted to the solar wind by a solar event is associated with the ejected plasma and magnetic fields that collectively are called a coronal mass ejection and usually take several days to reach Earth. However, the fastest CMEs travel from the Sun to the Earth in less than one day. Note that high speed wind streams also cause geomagnetic storms, but rarely do they produce very strong storms (e.g. Richardson et al. 2006). CMEs cause space weather disturbances, including the largest geomagnetic storms, in a number of ways. First, strong southward magnetic fields in the CME can reconnect with the predominately northward fields of the Sun-facing magnetosphere, producing strong induced fields and electric currents in the magnetosphere, the ionosphere, and at Earth's surface (Fig. 1). These southward field regions can occur both in the compressed plasma between the shock and CME and in the CME itself, which often contains magnetic field structures called magnetic clouds. Second, the impact of the CME compresses Earth's day side magnetosphere, which can leave high altitude geostationary satellites directly exposed to the solar wind. The third way CMEs drive space weather is through the production of SEP events, as discussed in the previous section.

Although recent strides have been made in our understanding of the relationship between CMEs and space weather, our current ability to forecast space weather disturbances caused by CMEs is still relatively poor. Improvements are needed both in our ability to predict if

Table 1 A list of the products and observations that NOAA Space Environment Center forecasters consider to be most needed

SEC highest priority needs[1,2,3]	SEC high priority needs[1,2,3]
SEP event forecasts, including start and end time, peak flux, time of peak, spectrum, fluence and probability of occurrence	Visualization of disturbances in interplanetary space
Solar wind data from L1 or further upstream	Geomagnetic activity predictions (1–7 days)
Solar coronagraph data	Geomagnetic storm end time forecast
Energetic e^- flux prediction for the International Space Station	Real-time estimates of geomagnetic indices
Regional geomagnetic activity nowcasts and forecasts	Real-time quality diagnostics (verification) of all warning/watch/forecast products
Ionospheric maps of Total Electron Content and scintillation (nowcast and forecast)	Statistical/numerical guidance for all forecast quantities
Geomagnetic indices (Ap, Kp, Dst) and probability forecasts	Magnetopause crossing forecasts based on L1 data
Solar particle degradation of polar HF radio propagation (nowcast and forecast)	Short-term (days) F10.7 and X-ray flare forecasts
Background solar wind prediction	Improved image analysis capability
	EUV index

[1] Items in each column are not necessarily in any priority order

[2] Required product lead times range from hours to days depending on the user and product

[3] Needed product quality (e.g. skill, accuracy) is user specific and remains to be determined in most cases

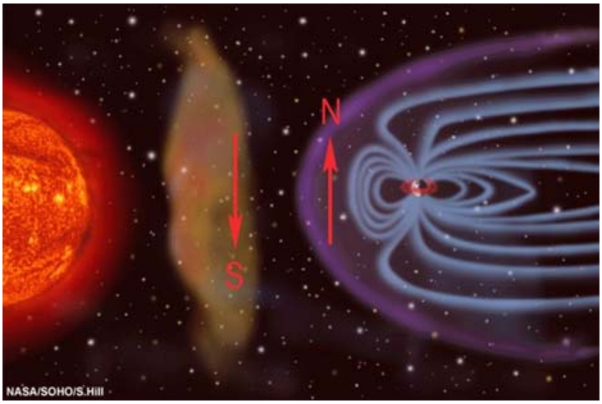

Fig. 1 A cartoon illustrating a CME in interplanetary space, with the southward component of magnetic field indicated. This is in contrast to the northward field of the Earth

and when a CME will impact Earth as well as in prediction of the magnitude and duration of the anticipated impact. The Large Angle Spectrometric Coronagraph (LASCO) and Extreme

Ultraviolet Imaging Telescope (EIT) observations from the Solar and Heliospheric Observatory (SOHO) have demonstrated an advancement in this prediction capability by reliably detecting halo CMEs—events that are directed along the Earth–Sun line and are visible as expanding 'halos' around the coronagraph occulting disk. Halo CMEs were first identified with the Naval Research Laboratory SOLWIND coronagraph (Howard et al. 1982) but only a handful were seen. With the increased sensitivity of the LASCO coronagraphs, however, it is now possible to detect almost all of these events. In addition, observations of the origin of the CME on the disk by EIT, GOES Soft X-Ray Imager (SXI), H-alpha, radio, etc., can be used to determine whether the CME is headed toward or away from Earth.

The associated surface activity of "frontside" halo CMEs can be well observed and, days later, when the CME passes near-Earth spacecraft, the physical structure of CMEs can be analyzed. Initial studies using LASCO data showed that frontside halo CMEs were associated with flaring active regions and filament eruptions within half a solar radius of Sun center and often accompanied at coronal wavelengths by circular, expanding fronts, or waves, and areas of dimming (e.g. Moses et al. 1997; Thompson et al. 1998).

The geoeffectiveness of halo CMEs has been examined in several studies by comparing the timings of the CME onsets with WIND and Advanced Composition Explorer (ACE) spacecraft data at 1 AU and with geomagnetic activity. Brueckner et al. (1998), St. Cyr et al. (2000) and Webb et al. (2000) found good correlations between frontside halo CMEs and moderate geomagnetic storms with a lag time of 2–5 days dependent on the phase of the cycle. Magnetic clouds preceded by interplanetary shocks usually signified the arrival at Earth of the CME structure.

Great strides have been made in theoretical modeling and simulations of CMEs (see Aschwanden 2006 for a recent review). Current models generally fall into the classes of dynamos, mass loading, tether release and tether straining. There are two kinds of CME simulations: analytical time-dependent MHD models, which provide insight into the physical mechanisms, and numerical time-dependent MHD simulations, which can reasonably reproduce observations given sufficiently accurate initial and boundary conditions.

The lesson from the SOHO data that pertains to the STEREO mission is that even moderately energetic CMEs, such as observed by LASCO near solar minimum, can be very geoeffective because they often contain coherent magnetic structures and move faster than the ambient solar wind. One dramatic example of this occurred in January, 1997 when an unremarkable halo CME, as seen by LASCO, was possibly associated with the failure of the Telstar 401 satellite (Webb et al. 1998; Reeves et al. 1998). The failure of Telstar 401 cannot be absolutely attributed to the geomagnetic storm, as Lanzerotti et al. (1999) showed in data from charge plate sensors on a nearby satellite (Telstar4), that the environment during "the interval of failure could be considered geomagnetically benign as compared to the disturbed levels of the previous day." The Telstar 401 failure occurred at just after 11 UT on January 11, more than a day after the extreme geomagnetic conditions ended at the Telstar4 satellite. According to the official failure report, the loss was attributed to "shoddy workmanship" (Lanzerotti et al. 1999). From the space weather viewpoint, one key element is to determine whether the CME is aimed toward Earth or not. With STEREO we also anticipate significant improvements in our ability to predict the timing and impact of CME-induced geomagnetic disturbances.

One key area where STEREO will not necessarily help with predicting CME related geomagnetic storms is the inability to predict, or even determine via remote sensing, the direction of the magnetic field in the CME or interplanetary CME. As mentioned at the outset of this section, it is primarily the existence of southward magnetic field which will determine the strength of a geomagnetic storm.

2 Use of the STEREO Instruments for Space Weather

At different periods during the STEREO mission the forecasting utility will emphasize different portions of the payload. Early in the mission, while the two spacecraft are still relatively close to Earth, the in situ instruments, the In Situ Measurements of Particles and CME Transients (IMPACT) Experiment (Luhmann et al. 2007) and the Plasma and Suprathermal Ion and Composition (PLASTIC) Experiment (Galvin et al. 2007), will likely be more useful to space weather as they will detect large scale structures in the solar wind. For example, either spacecraft may encounter interplanetary CME (ICME) shocks prior to their arrival at Earth. Also, solar energetic particles from activity east of about 45° west heliographic longitude will travel along interplanetary magnetic field lines and be detected by the lagging spacecraft minutes to hours before their arrival at Earth. Further, corotating interaction regions can be geoeffective, and these will be detected by the lagging spacecraft prior to their passage by Earth. Identification of potentially geoeffective features in the plasma electron, magnetic field, and energetic particle data from IMPACT should be straightforward. The ion compositional content from PLASTIC will be useful for identifying ICMEs and other structures in the solar wind.

As the STEREO spacecraft drift farther away from Earth, the SECCHI imaging instrument suite will become more important for space weather forecasting by providing observations that are not available from the Sun–Earth line. The eruption of Earth-directed CMEs will be detected by the Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI) EUVI, COR1, and COR2 experiments (Howard et al. 2007). Early in the mission, when the STEREO spacecraft are near the orbit of Earth, COR1 and COR2 will record halo CMEs produced by front-side sources detected with EUVI. This is currently done with the LASCO coronagraphs and EIT instrument on SOHO and these instruments will continue to provide data during the early phases of the STEREO mission. As the separation of the STEREO spacecraft increases, the different vantage points will allow determination of the velocity vector of the CME, as well as the material that will directly impact Earth. The velocity vector and its rate of change will be determined by triangulation techniques involving simultaneous stereo image pairs. Also, images from EUVI on the lagging spacecraft will show newly formed active regions prior to their appearance at the Sun's east limb (as seen from Earth). EUVI will also image other potentially geoeffective structures such as coronal holes and filament channels.

The strongest geomagnetic storms are caused by CMEs and it is clear that significant improvements still need to be made in forecasting these storms. This is expected to be a main area of focus for space weather research with STEREO, as it has been with SOHO. Accurate prediction of whether or not a CME will occur is a highly desired goal. There is significant activity in this area, as this is a goal of the NASA Solar Dynamics Observatory mission. Also NASA's Living With a Star Targeted Research and Technology program lists the forecasting of CME events prior to their eruption as a research priority (Gosling et al. 2003). When a CME does occur, there are still many parameters of a geomagnetic storm which need to be forecast. In particular, the first parameter to determine is the impact angle of the CME on the Earth. Will it hit Earth directly along its central axis or will it graze or miss Earth completely? In the case where the CME will hit Earth, the next parameters to forecast are the arrival time, geomagnetic storm strength, and geomagnetic storm duration. Much work has been done on the first two of these parameters during the past solar cycle, utilizing data from the SOHO mission. Many authors have examined the ability to predict CME arrival time based on available data, particularly the CME speed as measured by SOHO/LASCO. The typical error in arrival time has been found to be of order ±11 hours (Gopalswamy et al. 2000; Michalek et al. 2004). Less work has been done on predicting geomagnetic storm intensity, though Moon et al. (2005) has shown from a limited data set that a simple measure of CME impact parameter does correlate with geomagnetic storm strength.

STEREO Waves (SWAVES) will be used as a remote sensing instrument to produce radio dynamic spectra (Bougeret et al. 2007). These spectra will be used to track the propagation of shocks associated with Type II interplanetary radio bursts through the heliosphere (e.g. Kaiser et al. 1988). The comparison of dynamic spectra from the two spacecraft will give an estimate of the true location of the emission, and hence of the shock, by calculating the time delay between the observations.

The occurrence rate of CMEs follows the solar sunspot cycle in phase and amplitude. The rate of CMEs at solar minimum is about 0.5 per day and peaks at almost 6 per day at solar maximum (St. Cyr et al. 1999; Yashiro et al. 2004; Gopalswamy 2006). The primary STEREO mission will extend from late 2006 to late 2008, during the solar minimum activity phase. However, important geomagnetic storms can occur during any phase of the solar cycle and there will be plenty of CMEs to provide data of interest to researchers.

The global solar magnetic field and its extension into space will simplify during the approach to solar minimum and consequently the identification and tracking of individual CME events from the new STEREO viewpoint should be relatively straightforward. This simplicity, in turn, should aid our ability to investigate the origins of CMEs, their propagation through the solar wind, and their coupling to Earth's environment.

A real advance in our ability to predict the arrival of CMEs at Earth should be provided by the Heliospheric Imagers (HIs) on both STEREO spacecraft, which will track CMEs throughout their trajectory to Earth. This is an important new component of our space weather prediction capability, because of the straightforward ability to accurately predict the arrival of a CME at Earth. Though it is not yet known what the errors in estimated arrival times will be, the HIs should provide significantly smaller errors than current prediction techniques. Since the HIs will view CMEs traveling along the Sun–Earth line, image reconstruction will allow us to determine, for each Earth-directed CME, the direction of its central axis, its overall geometry and size, its mass and its velocity. Detection and limited tracking of CMEs between the Sun and Earth has already been demonstrated by the Solar Mass Ejection Imager (SMEI), an all-sky imager launched in January 2003 into Earth orbit (Howard et al. 2006; Webb et al. 2006). Although data latency limits its use in realtime forecasting, preliminary analyses of SMEI data suggest that such an instrument can detect most geoeffective CMEs and should decrease the errors in estimated arrival times.

The next step in advancing our understanding of this aspect of space weather lies in predicting the geoeffectiveness of CMEs, which is strongly governed by the southward component of its magnetic field, B_z. For at least some events, constraining the geometry of an embedded magnetic flux rope through the morphological appearance of the CME, may allow one to predict the magnetic field orientation, at least in the large scale (Cremades and Bothmer 2004). One area where advances might be expected is in predicting B_z resulting from pileup of the heliospheric plasma sheet in front of a CME. Odstrcil et al. (2005) was able to show that with good modeling of the background heliospheric structure and with a crude parameterization of a CME's initial properties in the low corona, the piled up field could be reasonably modeled. With the improved determination of CME properties that STEREO will provide, models can be better constrained and thereby produce better results.

The twin STEREO spacecraft will provide valuable platforms for detecting and studying SEP events. SEPs are known to be well associated with fast and wide CMEs and their attendant interplanetary shocks (Reames 1997). High energy (1 to hundreds of MeV) particles in an SEP event are thought to be accelerated in the shock near and ahead of a fast CME.

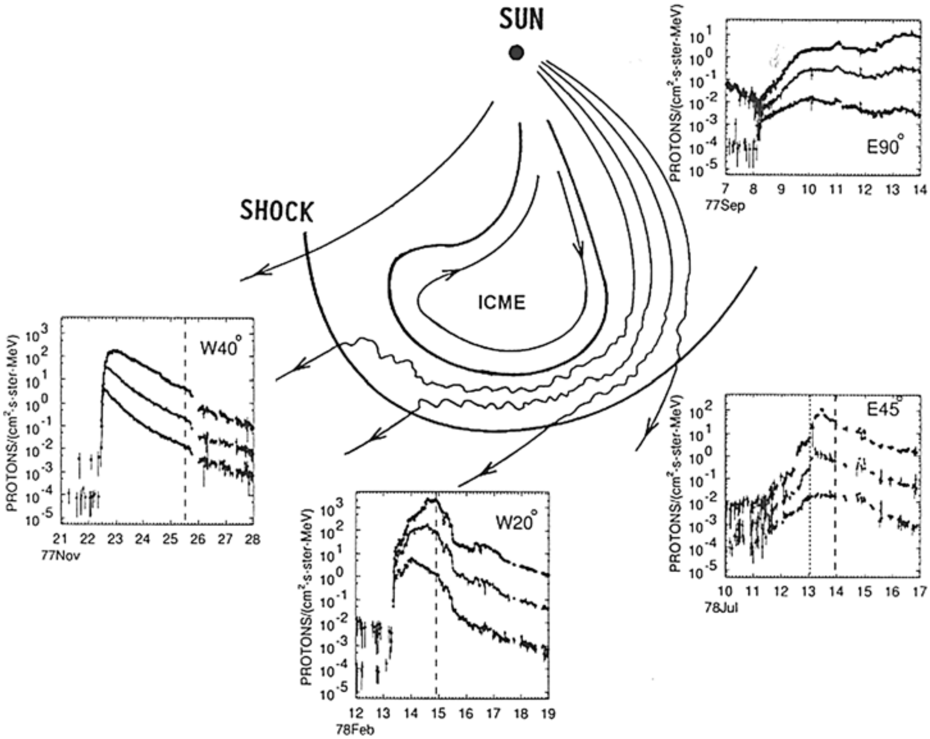

Fig. 2 A view of the ecliptic plane of the heliosphere with 4 inset images showing the SEP event profile expected for each of 4 observer locations relative to the ICME location. Representative *magnetic field lines* illustrate the interplanetary magnetic field and the ICME. For the well connected, W40 case, the SEP onset is prompt and the rise to the peak is rapid. As the observer moves towards the West (moving the ICME source location Eastward), the onset of the SEP event is delayed and the rise time to the event peak lengthens. Figure courtesy of Cane and Lario (2006; Fig. 2)

When the particles gain access to open field lines ahead of the shock, they can propagate into the heliosphere far from the acceleration site. The open field lines emanating from the Sun form an Archimedean spiral and the particles are forced to travel along this curved path (see Fig. 2). Thus, SEPs will have the most direct access and will arrive earliest at a point in space which is east of the SEP source longitude. Therefore, a particle detector on a spacecraft near Earth will be "well-connected" to SEP source regions at western solar longitudes (i.e. W40 degrees), and will see a prompt rise in particle flux (within tens of minutes). Therefore, the STEREO spacecraft lagging Earth (STEREO-B) will be well connected to field lines which are near Sun center as viewed from Earth. Its particle detectors can be used to predict the onset and size of a prompt SEP, as well as the onset of the CME associated with the SEP, at Earth. These are among the most important reasons to have a real-time Beacon available for the STEREO mission.

3 The Space Weather Beacon

The STEREO Space Weather Beacon mode is a continuous, real-time, low data-rate (633 bps) broadcast of the data from the STEREO instruments. The Beacon mode (e.g. St. Cyr

Table 2 The NOAA and NOAA partner ground stations that have agreed, as of January, 2007, to support the Space Weather Broadcast from STEREO

Site	Agency/Institute	Latitude, Longitude
Koganei, Japan	National Institute of Information and Communications Technology (NICT)	35.7N, 139.5E
Toulouse, France	Centre National d'Études Spatiales (CNES)	43.4N, 1.5E
Chilbolton, UK	Rutherford Appleton Laboratory (RAL)	51.1N, 1.4W
Wallops Island, VA	National Oceanic and Atmospheric Administration (NOAA)	37.9N, 75.5W
Boulder, CO	NOAA	40.1N, 105.2W
Fairbanks, AK	NOAA	65.0N, 147.5W

and Davila 2001) is desired for use by both civilian and military agencies for enhancing and providing continuity for space weather products. NASA will provide coverage through the Deep Space Network for about 6 hours per day for each of the STEREO spacecraft. Because of the value of the STEREO data, the NOAA Space Environment Center (SEC) has taken on the responsibility to establish a ground station network to ensure the Space Weather Beacon broadcast from both satellites is received continuously.

The ground stations enlisted to support the STEREO Beacon, as of the start of the prime science mission are given in Table 2. Due to the need to observe two spacecraft simultaneously, and continuously, it is clear that additional ground stations are needed to ensure complete tracking with a high reliability.

Upon receipt of the data at each ground station, each telemetry packet is transferred, as soon as it is received (approximately every 14 seconds), to the STEREO Science Center (SSC) via a socket connection over the internet. A complete discussion of the flow of data and Space Weather Beacon data from the spacecraft to the SSC is covered by Eichstadt et al. (2007). The SSC will make the Level 0 and higher level products available to the scientific community and to NOAA/SEC forecasters in near real-time, with a latency of about 5 minutes from the time the data are received at the ground stations. The data and products desired by NOAA will be fetched automatically from the SSC for integration into forecast specific tools.

The beacon data rate is 633.245 bits per second. This very low data rate necessitates careful choices of the data to be telemetered, as it is clear the full STEREO data set cannot be downlinked in the beacon. In general, the data that will be available in the beacon will be a subset of the full science data set, and will be averaged, binned, and/or compressed to maximize the number of observations which can be returned in real-time. Care has been taken to work with the instrument teams to ensure the resulting data will still be of value to the NOAA space weather forecasters. Some of the tools that are envisioned for use by the NOAA forecasters are described in Sect. 5. The beacon data is described more fully in each of the instrument papers in this volume, but we present here a centralized summary of the data. The data from PLASTIC, IMPACT, and SWAVES are, mostly, fixed and are summarized in Table 3. The beacon imagery content from SECCHI can be reprogrammed in-flight and is almost certain to change throughout the mission. It is expected the relative value of imaging data sets will change with the changing separation angle of the spacecraft,

Table 3 The data available in the Space Weather Broadcast from the PLASTIC, IMPACT, and SWAVES instruments. The Space Weather Broadcast is a low data rate (633 bps) continuous transmission of a subset of the full science data. The SECCHI instrument Space Weather Broadcast is described in the text

Instrument	Observable	Frequency	Units
IMPACT	Instrument status	1 per min	
IMPACT Magnetometer	B vectors	6 per min	nT
IMPACT Suprathermal Electron Telescope – U	Solar e^- flux at $5E^{\dagger,1}$ Non-solar e^- flux at 5E	1 per min	#/cm^2/s
IMPACT Suprathermal Electron Telescope – D	e^- flux at 5E	1 per min	#/cm^2/s
IMPACT Solar Wind Electron Analyzer	e^- density e^- bulk velocity e^- pressure tensor e^- heat flux $PAD^{\ddagger}$ at $2E^{\dagger}$ in 12 look directions	1 per min (computed from 2 second integration)	cnts/cm^3 km/s eV/cm^3 eV/cm^2/s cnts/cm^2/s
IMPACT	Solar Energetic Particle Instrument Suite Status	1 per min	
IMPACT Solar Electron Proton Telescope	e^- flux at 2E in 4 look angles e^- flux at 2E summed over look angles ion flux at 2E in 4 look angles ion flux at 2E summed over look angles	1 per min, 1 min average	/cm^2/s/sr/MeV /cm^2/s/sr/nucleon
IMPACT Low Energy Telescope	Proton flux at 1E in 2 look angles Proton flux at 2E summed over look angles He flux at 2E in 2 look angles He flux at 1E summed over look angles ^{3}He flux at 2E summed over look angles CNO flux at 3E summed over look angles Fe flux at 4E summed over look angles	1 per min, 1 min average	/cm^2/s/sr/nucleon
IMPACT High Energy Telescope	e^- flux at 1E Proton flux at 3E He flux at 3E CNO flux at 2E Fe flux at 1E	1 per min, 1 min average	/cm^2/s/sr/MeV /cm^2/s/sr/nucleon

Table 3 (*Continue*)

Instrument	Observable	Frequency	Units
IMPACT Suprathermal Ion Telescope	He flux at 4E CNO flux at 4E Fe flux at 4E	1 per min, 1 min average	/cm^2/s/sr/nucleon
PLASTIC	Solar Wind H density	1 per min, 1 min average	1/cm^3
PLASTIC	Solar Wind bulk H velocity (v_x, v_y, v_z)	1 per min, 1 min average	km/s
PLASTIC	Solar Wind H^+ temperature tensor	1 per min, 1 min average	K
PLASTIC	Solar Wind H^+ heat flux tensor	1 per min, 1 min average	J/m^2/s
PLASTIC	Solar Wind He^{++} peak distribution	1 per min, 1 min average	counts
PLASTIC	Solar Wind He^{++} peak energy step	1 per min, 1 min average	Step number
PLASTIC	Solar Wind He^{++} peak deflection step	1 per min, 1 min average	Step number
PLASTIC	Solar Wind He^{++} peak position	1 per min, 1 min average	Bin number
PLASTIC	Representative Solar Wind charge states	1 per 5 min, 5 min average	counts
PLASTIC	Suprathermal rates	1 per 5 min, 5 min average	counts
PLASTIC	Post Acceleration Field Value Microchannel Plate Value	1 per min, 1 min average	kV
SWAVES	every 100 kHz from 0.125 to 16.025 MHz	1 per min	

[†]Indicates items which can be changed in flight

[‡]PAD – Pitch Angle Distribution, with respect to B field

[1]E – Energy channel

as well as when advances are made in key areas of research. The number of SECCHI images to be included in the beacon has not yet been determined. The allocation for the SECCHI space weather data is 500 bits/second. The amount of image compression and binning applied will determine the number of images per hour which can be downlinked. Nominally 7 images can be downlinked if a lossy compression of a factor of 5 is applied and images are binned down to 256 × 256 pixels (8× binning). The amount of compression and binning are programmable on board and testing during the early stages of the mission will determine the optimal tradeoff of compression, binning, image cadence, and instrument. The SECCHI beacon images are taken from the regular science data sequence. There are no images taken in addition to a normal SECCHI image sequence, so the maximum cadence of images which can be included in the beacon is the regular sequence cadence. At the start of the mission, the highest priority is being given to the COR2 coronagraph data, as experience with SOHO (Sect. 5) shows that its expected value to forecasting geomagnetic storms is high. The data from the HI instruments are also being given high priority, as the ability to track CME's through the heliosphere and update forecasts in real-time is also valuable. Highly binned EUVI images can serve as an irradiance/flare monitor. The forecasting value of COR1 is less clear, so it is given a lower priority for inclusion in the beacon. However, if during the mission, the COR1 data are shown to be useful for forecasting, its priority can be raised. Another possibility is to include automated event detection bits.

4 Space Weather Tools and Projects

The STEREO Space Weather Group was formed in 2002 for the purpose of promoting the scientific community's involvement in preparing, well in advance of the launch of STEREO, to use STEREO data for space weather. More specifically, the Space Weather group has led in organizing the various efforts in software development, modeling efforts and research studies in preparation for using the STEREO observations as a tool for Space Weather. The public internet site for the group is available through the "Science: Space Weather" link on the home page of the STEREO Science Center at: http://stereo.gsfc.nasa.gov/. Any interested scientist, whether or not they are a member of the STEREO consortium, is invited to join in the group's efforts, as described on the website.

All pertinent details and information related to the STEREO Space Weather Group efforts are coordinated at the group's website and its activities are closely coordinated with those of the SSC, where the STEREO data, including the Beacon data, will be available. The purpose of the Space Weather Group is to help coordinate space weather efforts involving the STEREO mission and its instruments, including that of individual team members, and to help coordinate those efforts that lead to tools and products that can be tested and used before and after the STEREO launch. Other activities of the group include incorporating and interfacing STEREO data and space weather activities with: (1) Both imaging and in situ data from other existing space missions such as ACE, WIND, SOHO, Ulysses, the Transition Region and Coronal Explorer (TRACE), SMEI, Hinode, the GOES Soft X-ray Imagers (SXI); ground-based observations such as interplanetary scintillation (IPS), optical line and broadband emission, and radio; and future missions planned for the STEREO timeframe, such as the Solar Dynamics Observatory (SDO); (2) The Geospace community to understand the coupling of and geospace responses to CMEs and other transient disturbances by encouraging and participating in space weather campaigns; (3) The Community Coordinated Modeling Center (CCMC) and other simulation and modeling groups to use STEREO data as input to space weather models; (4) The SECCHI 3D Reconstruction and Visualization Team to develop models that have a space weather context; (5) The various virtual observatories that are being developed; (6) The International Heliophysical Year (IHY) program in 2007; (7) Meetings and workshops involving space weather; and (8) NASA's EP/O and PAO and other outreach activities.

Some of the tools and projects currently being developed for use with the STEREO observations for space weather applications are briefly described next, with references where available. These have been grouped into categories of Space Weather Tools, including those for CME Detection and CME-related Features Detection, Space Weather-Enabling Projects, and Data Browsers and Viewers. Each project description contains a title, the names of the main coordinators and their affiliations, and a brief description. Such projects are continually evolving, so this list should be considered only as an indication of the projects that will be available at the start of the mission. Undoubtedly, after launch, and as the STEREO data accumulates, the concepts of how to use these data for space weather purposes will evolve and new projects will be added.

SPACE WEATHER TOOLS:

Geometric Localization of STEREO CMEs (*V. Pizzo, D. Biesecker – NOAA;* Pizzo and Biesecker 2004)

A tool utilizing a series of lines of sight from two views to define the location, shape, size and velocity of a CME. This is to be automated and used to decide whether and when a CME will impact Earth.

WSA Model Predictions (*N. Arge – Air Force Research Laboratory; J. Luhmann – Univ. of California-Berkeley; D. Biesecker – NOAA;* Arge and Pizzo 2000)

The Wang-Sheeley-Arge and ENLIL 3D MHD solar wind models will be integrated. The combined model will provide routine predictions of vector solar wind velocity, density, temperature and magnetic polarity anywhere desired in the inner heliosphere. This model will be driven by ground-based magnetograph data.

CME Detection:

CACTUS – Computer Aided CME Tracking (*E. Robbrecht, D. Berghmans; Royal Observatory of Belgium;* Robbrecht and Berghmans 2005)

A near real-time tool for detecting CMEs in SECCHI images. The output is a quicklook CME catalog with measurements of time, width, speed, and near real-time CME warnings. It has been successfully tested on LASCO data and the tool is available at http://sidc.oma.be/cactus.

SEEDS – Solar Eruptive Event Detection System (*J. Zhang; George Mason Univ.*)

A tool for detecting, classifying and analyzing CMEs in SECCHI images. The output is an automatically generated CME catalog with measurements of time, width, speed, and near real-time CME warnings. It is being tested on LASCO data.

On-board Automatic CME Detection Algorithm (*E. De Jong, P. Liewer, J. Hall, J. Lorre, NASA/Jet Propulsion Laboratory; R. Howard, Naval Research Laboratory*)

An algorithm based on feature tracking which uses two successive images to determine whether or not a CME has occurred. The algorithm is intended to be run on-board the spacecraft.

CME-Related Features Detection:

Computer Aided EUVI Wave and Dimming Detection (*O. Podladchikova, D. Berghmans, A. Zhukov – Royal Observatory Belgium;* Podladchikova and Berghmans 2005)

A near real-time tool for detecting EUV waves and dimming regions. It is being tested on SOHO EIT images.

Velocity Map Construction (*J. Hochedez, S. Gissot – Royal Observatory Belgium*)

A program to analyze velocity flows on SECCHI images and to detect CME onsets & EUV waves. Also produces near-realtime warnings of fast CMEs and reconstructs 3D velocity maps of CMEs from 2D maps from each STEREO spacecraft.

Automatic Solar Feature Classification (*D. Rust, P. Bernasconi – Johns Hopkins University/Applied Physics Laboratory*)

A tool for detecting and characterizing solar filaments and sigmoids using recognition and classification in solar images. The goal is to measure magnetic helicity parameters and forecast eruptions using filaments and sigmoids.

SPACE WEATHER – ENABLING PROJECTS:

Identifying and Tracking CMEs with the Heliospheric Imagers (*R. Harrison, C. Davis – Rutherford Appleton Laboratory*)

A tool that uses triangulation to measure the speed and direction of CMEs in order to forecast their arrival at Earth. Simulations will be used to show how model CMEs can be identified and tracked with the HIs.

Structural Context of the Heliosphere Using SMEI Data (*D. Webb – Boston College/Air Force Research Laboratory; B. Jackson – Univ. of California-San Diego; e.g.* Jackson et al. 2006)

A tool that uses analyses of SMEI images to provide structural context of the heliosphere, especially for the HIs. It will also provide complementary observations of transient disturbances, especially those that are Earth-directed.

Interplanetary Acceleration of ICMEs (*M. Owens – Boston University*)

A program to construct acceleration profiles of fast ICMEs over a large heliocentric range using multi-point HI measurements to understand the forces acting on ejecta. This tool will aid in improved prediction of ICME arrival times at Earth.

Relationship Between CMEs and Magnetic Clouds (*S. Matthews – Mullard Space Science Lab.*)

A project to assess the potential geoeffectiveness of CMEs based on their association with magnetic clouds. This project is intended to determine which particular characteristics lead to the production of a magnetic cloud.

3-dimensional Structure of CMEs (*V. Bothmer, H. Cremades – University of Goettingen; D. Tripathi – Cambridge University;* Cremades and Bothmer 2004)

A program to compare analysis of SECCHI images on the internal magnetic field configuration and near-Sun evolution of CMEs with models based on SOHO observations. The goal is to forecast flux rope structure and make 3-dimensional visualizations of CMEs.

DATA BROWSERS AND VIEWERS:

STEREO Science Center Real-Time Data Pages (*W. Thompson – GSFC*)

The main public website for viewing real-time STEREO data. Available at the following URL: http://stereo-ssc.nascom.nasa.gov/mockup/latest_mockup.shtml.

Solar Weather Browser (*B. Nicula, D. Berghmans, R. Van der Linden – Royal Observatory Belgium*)

A user-friendly browser tool for finding and displaying solar data and related context information. The tool is available at http://sidc.oma.be/SWB/.

STEREO Key Parameter Browser (*C. Russell & IMPACT, PLASTIC & SWAVES teams; UCLA*)

An easily browseable merged key parameter data display including the in situ and SWAVES radio data.

Carrington Rotation In situ Browser (*J. Luhmann, P. Schroeder – Univ. of California-Berkeley*)

A browser for identifying in situ events and their solar sources over Carrington Rotation time scales. It includes near-Earth (ACE) data sets for third point views and image movies from SECCHI and SOHO (near-Earth). See: http://sprg.ssl.berkeley.edu/impact/data_browser.html.

JAVA-3D Synoptic Information Viewer (*J. Luhmann, P. Schroeder – Univ. of California-Berkeley*)

A JAVA applet for viewing 3-dimensional Sun and solar wind data based on synoptic solar maps and potential field models of the coronal magnetic field.

Radio and CME Data Pages (*M. Pick, M. Maksimovic, J.L. Bougeret, A. Lecacheux, R. Romagan, A. Bouteille – Observatoire de Paris-Meudon*)

A collection of ground radio imaging, spectra and movies, as well as SWAVES and SECCHI summary data on CMEs. Available at http://secchirh.obspm.fr/.

5 Space Weather Tools for the SEC Forecast Center

5.1 Lessons from the SOHO and ACE Missions

In the recent past and continuing, two non-NOAA missions, SOHO and ACE, were successfully utilized in the forecast center. Each of these missions followed a different path into the forecast center, and thus, are illustrative for bringing STEREO into the forecast center.

In the case of the SOHO mission, there were few, if any, expectations of the mission being used for space weather forecasting. However, one dramatic event in January, 1997, the effects of which were described in Sect. 1.1, quickly changed that. The event was a halo CME observed by SOHO/LASCO on January 6th (Burlaga et al. 1998) which was reported by D. Michels of the Naval Research Laboratory to a meeting of the International Solar Terrestrial Physics (ISTP) project, while the event was still in progress. It was predicted the event would arrive at Earth on January 10th, a remarkably good real-time prediction. This illustrated the ability to use the mission in a real-time way. The time for a typical CME to transit 1 AU ($\sim$3 days) implies that a latency of a few hours still allows time for a forecast to be made. This event, and subsequent halo CMEs, resulted in NOAA and the SOHO/LASCO team working together to make the data available to NOAA as quickly as possible.

However, it took more than just having available data, to do the forecasting. During normal business hours, the LASCO team examines the data and issues a report on all halo events, which includes a detailed description, including the speed of the event. The NOAA forecast center operates 24 hours a day, and can’t always wait for a report from the LASCO team. Thus, the same tools used by the LASCO team to plot height-time curves and derive speed estimates for the events were installed at the forecast center, with direct assistance and training from the LASCO team. Since then, the SOHO/LASCO data have been on prominent display in the forecast center, where they are used to help forecast geomagnetic storms. One

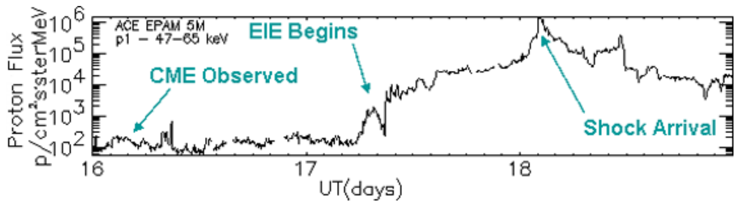

Fig. 3 An example of an energetic ion enhancement (EIE) with *arrows* indicating events of interest to forecasters. Plotted are 5 minute averages of 47–65 keV proton fluxes

lesson learned is that it was non-NOAA scientists who not only learned the value of the data for forecasting, but also demonstrated it. The close cooperation between the scientists and the forecast center, which included training on relevant tools, was also a key component.

In the case of the ACE mission, it was recognized from the start that its data would be important for forecasting. As is being done now for STEREO, NOAA organized a network of ground stations to receive ACE data in real-time. Because ACE, which monitors the solar wind, orbits the L1 Lagrange point, there is typically only about 1 hour of warning between when an event passes L1 and arrives at Earth, and extreme events arrive much more quickly. Thus, the data must be available in the forecast center within minutes of being acquired or it becomes less useful to forecasters. To meet this requirement, ACE broadcasts real-time data continuously and ground station processing gets the data to forecasters quickly.

The ACE data from the magnetometers and solar wind measurements were expected to be and are used daily by forecasters to monitor the state of the solar wind and to watch for arriving ICMEs. It was also recognized that the low energy proton channels of ACE/EPAM (Gold et al. 1998) would be useful for warning of approaching interplanetary shocks (Zwickl et al. 1998). An annotated example of an energetic ion enhancement (EIE) is shown in Fig. 3. Other than a study by Smith and Zwickl (1999) utilizing WIND data, there were no quantitative studies of these events from which forecasters could derive information to use in producing a forecast. Even the Smith and Zwickl study only discussed typical signatures that were needed to be certain a shock was on-coming, without providing specific values which could be used by forecasters to produce a product for customers. Thus, the forecast center undertook a study to provide themselves with the data necessary for forecasting shock arrival and subsequent geomagnetic storms (Smith et al. 2004).

Key elements of the Smith et al. study relevant to forecasting were: the use of the geomagnetic index K_P, which is a forecast center product; the establishment of a relationship between the intensity of energetic ion enhancements (EIE) and the resulting K_P; establishing thresholds of EIE flux above which forecasters could be confident of distinguishing an ICME source from a high speed stream source; looking specifically at overlapping events; and the role of B_z. Shown in Fig. 4 is a chart which shows quite a lot of information to the forecasters. If the flux of the EIE is seen to exceed $50 \times 10^4\ \mathrm{p\,cm^{-2}\,s^{-1}\,sr^{-1}\,MeV^{-1}}$ then a storm reaching a level of at least G1 ($K_P = 5$) will result. What is also clear is that EIE fluxes an order of magnitude smaller still have a slight chance of producing a severe geomagnetic storm.

5.2 Bringing STEREO into the Forecast Center

In this section, we describe some of the STEREO mission related tools which SEC has identified as desirable. Some of these tools will be developed in time for the start of the mission, while others may never be developed, depending on whether our preconceptions of

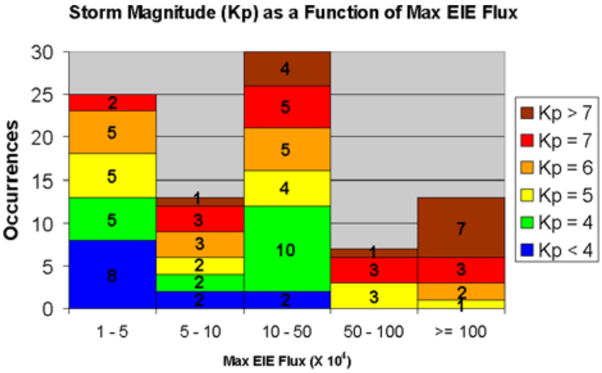

Fig. 4 An example from an internal forecast center document showing the number of geomagnetic storms as a function of the peak flux of the corresponding shock-associated EIE

the utility of the data turn out to be true and are commensurate with the resources needed for development. There are several important points to make about integrating STEREO data into the SEC forecast center. With the addition of so many data sets, it will be difficult for forecasters to inspect all of the relevant basic time series data or raw imagery from STEREO in addition to all of the data already used in the forecast center. Thus, algorithms which can aid in at least some simple interpretations of the data will be valuable. In addition, without tools to take advantage of the three-dimensional view provided by STEREO data, the full value of the STEREO data to forecasters will not be realized. It is hoped and expected that many of the projects described in Sect. 4 will be successful and will produce tools and products which can be transitioned to the SEC forecast center.

It is worth mentioning that there are substantial hurdles to be overcome for a tool to be useful for forecasters. First, the overall benefit the tool provides to forecasters must be clear. However, even when the benefits of a tool or model are clear, unless the forecasters have confidence that the tool is providing a good prediction at a certain time or for a specific event, they are unlikely to use the tool. Thus, it is vital for validation studies to have been performed, illustrating under what conditions a tool does or does not work.

The STEREO PLASTIC and IMPACT instruments provide a suite of observations which complement the NASA ACE mission (Stone et al. 1998; Garrard et al. 1998) data currently in use by NOAA forecasters. Thus, the only additional knowledge required for interpretation of the in situ data from these instruments will be recognizing how to account for the displaced location of the STEREO spacecraft relative to ACE. One obvious way to do this is to use the lagging STEREO-B spacecraft as a monitor of co-rotating structures. Whether it is a sector crossing or a high speed wind stream, the lagging spacecraft will encounter these structures before they sweep past Earth. One year into the mission, the lead time for corotating structures will be about 40 hours. There will be an obvious trade-off between the forecast lead time and the confidence in the forecast, as longer lead times mean greater time for a structure to evolve. Even given a temporally stable structure, small changes in spatial location can lead to significant observed differences, as was clearly shown by results from the HELIOS mission (e.g. Schwenn et al. 1981). Any temporal changes can be mitigated to some extent by ensuring the forecasters also have access to models of the solar wind. Thus, for forecasters, we envision a standard data display, similar to what forecasters use for ACE/SWEPAM data, showing solar wind density, speed and temperature (see http://www.sec.noaa.gov/ace/ACErtsw_data.html). Appended to this would be the same parameters from STEREO-B, with the lead time clearly identified on the horizontal axis. Overlaid on this would be the solar wind speed derived from the Wang-Sheeley model (Wang

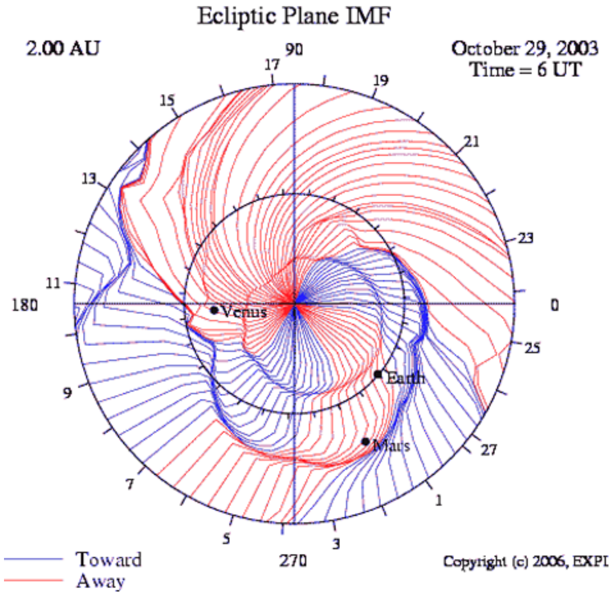

Fig. 5 The interplanetary magnetic field as computed with the HAFv2 model. A series of ICMEs are evident, in particular, one with a leading edge just beyond Mars and another just inside the orbit of Earth. Figure courtesy of Exploration Physics International, Inc. (EXPI), Huntsville, Alabama

and Sheeley 1990). Returning to a point made in the previous paragraph, adding the Wang-Sheeley solar wind model to this display aides the forecaster, as a variation on this model is currently used in the forecast center (Arge and Pizzo 1999). Note, the predictions from both STEREO-B and Wang-Sheeley are valid only for co-rotating structures and any interplanetary ejecta will invalidate the output of these models. Clearly forecasters will need something integrated into the tool, or good situational awareness, to identify times when the model output will be invalid due to the presence of ICMEs.

Another potential product would involve utilizing the STEREO-B solar wind data to provide a longer lead time for predicted K_p from models such as the Costello Geomagnetic Activity Index (e.g. Detman and Joselyn 1999; http://www.sec.noaa.gov/rpc/costello/index.html) and that of Wing et al. (2005). Because these models rely on data from the ACE spacecraft, they can only be used for short term warnings. It is obvious that adding STEREO-B data to these models would provide a longer lead time.

STEREO will provide important validation data both for the Wang–Sheeley model and the Hakamada-Akasofu-Fry version 2 (HAFv2) solar wind model (Fry et al. 2003). While the HAF model is not an official SEC forecast product, it is used by forecasters, and it has recently been adopted by the USAF Air Force Weather Agency. Both models can provide an ecliptic plane view of the heliosphere out to large heliocentric distances (see Fig. 5). The HAFv2 model output is available out to 10 AU, encompassing the orbits of Mars, Jupiter and Saturn. Currently, validations for each model can only be based on comparisons to ACE data. One data point of comparison for a model of the whole ecliptic plane is obviously inadequate. The addition of data from both STEREO spacecraft is still woefully inadequate, but will be a significant improvement over the current situation. This will be particularly true for Mars forecasts when Mars is not in conjunction with Earth but may be in conjunction with either of the STEREO spacecraft.

Improvements to SEC's SEP event prediction is consistently identified as a high priority need by the forecasters (see Table 1). Given the clear relationship between the shape and relative timing of SEP light curves and the longitude difference between the source region and Earth (Cane et al. 1988), adding the STEREO spacecraft SEP data should provide some of the desired improvement. Determining what needs to be done to create a tool which takes the real-time STEREO data and produces an improved SEP prediction at Earth has not yet been done.

Turning now to the remote sensing data, it is obvious that the three-dimensional information about ICMEs that STEREO will provide can be of great benefit for forecasters. However, there are currently a myriad of ideas on how the three-dimensional reconstructions can be done and how they can be displayed. Here, we outline one simple example that would be beneficial to forecasters. From a display perspective, rather than giving the forecaster complete control and the ability to view an event from any angle, the basic information needed can be reduced to three displays. First, the same ecliptic plane view, as illustrated in Fig. 5, is an obvious choice. This gives the forecaster the ability to see the relative location of the event and Earth, along with a way to see how it is evolving and accelerating. The display would also show the longitudinal extent of the ICME and its distribution of mass. Second, a view from perpendicular to the Sun–Earth line, in the ecliptic plane, would illustrate the latitudinal extent of the event and the distribution of mass. Third, and finally, the ability to also see a view from the perspective of an observer on Earth, looking in the direction of the Sun will be important. This would give the forecaster the information they need about whether the event will strike Earth. The same information could be derived from the first two views, however, this particular view would make it obvious from just a single picture.

Pictures and movies are always good to have, partly because they give forecasters a quick overview of the situation, but also because they are a quick way to validate the output of any model or tool. A tool that SEC researchers envision for the forecast center would be one which provides all of the desired parameters about CME-related geomagnetic storms in one place. As described in earlier sections, efforts are underway or planned on forecasting CME arrival time, CME impact angle and the resulting storm magnitude, and even on the basic question of whether the interplanetary CME will strike Earth. Asking a forecaster to perform all the image processing necessary to derive such information, even given acceptable models, would be too time consuming. Thus, automation of CME detection, CME speed determination, CME impact angle, and potentially other parameters will be needed. Much work has been done in this area (e.g. Robbrecht and Berghmans 2005) but much more work is needed. Automated tools which have a high rate of false positive results may be sufficient for a researcher, but are of little or no use for forecasters, who must act in real-time. Given an automated tool meeting forecaster needs, its output can then be fed into models which predict if the CME will hit Earth, and if so when, how strong the resulting storm will be and how long the storm will last. Putting these predictions into a single display for forecasters with the associated errors would be a significant benefit. By constantly updating the forecasted parameters, utilizing data from the SWAVES and SECCHI/HI instruments, it is hoped that forecasters would be provided with the best possible predictions throughout the entire transit of an ejection. As stated earlier, the imagery would be available to validate and check any of the parameters being predicted.

6 Summary

The NOAA Space Environment Center believes the STEREO mission will be a significant benefit for forecasters and has invested the effort to put together a ground station network to receive the STEREO data in real-time. But, the promise of the STEREO mission and the expected return from the mission is just that, a promise. When the data finally become available and the performance of the instruments is verified, then we will have a better idea of whether the promise will be realized. It is difficult to predict which elements of the program will be successful and ultimately beneficial to forecasters, either immediately or in the long term. In this paper, we focused primarily on the promise of projects and illustrated some of the features which are necessary for a successful product; primarily utility, ease of use, and validation. One thing to keep in mind is that with the changing elongation angles, the relative utility of STEREO will constantly evolve. This may also necessitate changes in the way data are interpreted as the mission progresses. However, there are no technical hurdles to the STEREO mission extending beyond its 2-year design life and, if the mission proves successful, the research advances made during the first one-half orbit of STEREO to the far-side of the Sun could be applied as each STEREO spacecraft completes its orbit, coming back towards Earth.

References

C.N. Arge, V.J. Pizzo, in *Proceedings of the 9 International Solar Wind Conference*, ed. by S.R. Habbal, R. Esser, J.V. Hollweg, P.A. Isenberg (1999), p. 569

C.N. Arge, V.J. Pizzo, J. Geophys. Res. **105**(A5), 10465 (2000). doi:10.1029/1999JA900262

M.J. Aschwanden, *Physics of the Solar Corona* (Springer, Praxis, 2006), Chap. 17

D.N. Baker, J.H. Allen, S.G. Kanekal, G.D. Reeves, EOS **79**(40), 477 (1998)

Bougeret et al., this volume (2007)

G.E. Brueckner, J.-P. Delabouniniere, R.A. Howard, S.E. Paswaters, O.C. St. Cyr, R. Schwenn, P. Lamy, G.M. Simnett, B. Thompson, D. Wang, Geophys. Res. Lett. **25**, 3019 (1998)

L. Burlaga, R. Fitzenreiter, R. Lepping, K. Ogilvie, A. Szabo, A. Lazarus, J. Steinberg, G. Gloeckler, R. Howard, D. Michels, C. Farrugia, R.P. Lin, D.E. Larson, J. Geophys. Res. **103**(A1), 277 (1998)

H.V. Cane, D. Lario, Space Sci. Rev. (2006). doi:10.1007/s11214-006-9011-3

H.V. Cane, D.V. Reames, T.T. von Rosenvinge, J. Geophys. Res. **93**, 9555 (1988)

H. Cremades, V. Bothmer, Astrophys. Astron. **422**, 307–322 (2004). doi:10.1051/0004-6361:20035776

T. Detman, J. Joselyn, in *Proceedings of the Ninth International Solar Wind Conference*, ed. by S.R. Habbal, R. Esser, J.V. Hollweg, P.A. Isenberg (1999), p. 729

J. Eichstadt, W.T. Thompson, J.B. Gurman, P. Schroeder, this volume (2007)

C.D. Fry, M. Dryer, Z. Smith, W. Sun, C.S. Deehr, S.-I. Akasofu, J. Geophys. Res. **108**(A2), 1070 (2003). doi:10.1029/2002JA00947

A. Galvin et al., this volume (2007)

T.L. Garrard, A.J. Davis, J.S. Hammond, S.R. Sears, Space Sci. Rev. **86**, 649 (1998)

R.E. Gold, S.M. Krimigis, S.E. Hawkins, III, D.K. Haggerty, D.A. Lohr, E. Fiore, T.P. Armstrong, G. Holland, L.J. Lanzerotti, Space Sci. Rev. **86**, 541 (1998)

Goodman, J.M. *Space Weather & Telecommunications*. Kluwer International Series in Engineering and Computer Science, vol. 782 (Springer, 2005)

N. Gopalswamy, A. Lara, R.P. Lepping, M.L. Kaiser, D. Berdichevsky, O.C. St. Cyr, Geophys. Res. Lett. **27**, 145 (2000)

N.J. Gopalswamy, Astrophys. Astron. **27**(2–3), 243–254 (2006)

J. Gosling, S. Antiochos, K. Baker, P. Bellaire, B. Blake, G. Crowley, J. Eddy, C. Goodrich, N. Gopalswamy, M. Hesse, N. Hurlburt, C. Jackman, J. Kozyra, B. Labonte, J. Lean, J. Linker, J. Mazur, T. Onsager, D. Sibeck, Targeted research and technology within NASA's living with a Star Program – Report of the Science Definition Team. NASA Document FP-2003-11586-GSFC, November 2003

R.A. Howard, D.J. Michels, N.R. Sheeley Jr., M.J. Koomen, Astrophys. J. **263**, L101 (1982)

R.A. Howard et al., this volume (2007)

T.A. Howard, D.F. Webb, S.J. Tappin, D.R. Mizuno, J.C. Johnston, J. Geophys. Res. **111**, A04105 (2006). doi:10.1029/2005JA011349.

B.V. Jackson, A. Buffington, P.P. Hick, X. Wang, D. Webb, J. Geophys. Res. **111**, A4 (2006). doi:10.1029/2004JA010942

M.L. Kaiser, M.J. Reiner, N. Gopalswamy, R.A. Howard, O.C. St. Cyr, B.J. Thompson, J.-L. Bougeret, Geophys. Res. Lett. **25**, 2501 (1998). doi:10.1029/98GL00706

L.J. Lanzerotti, D.J. Thomson, C.G. Maclennan, in *Modern Radio Science*, ed. by M.A. Stuchly (Oxford, University Press, Oxford 1999), pp. 25–50.

L.J. Lanzerotti, in *Space Weather*, ed. by P. Song, H.J. Singer, G.L. Siscoe. AGU Monograph, vol. 125, (2001), pp. 11–22
J. Luhmann et al., this volume (2007). doi: 10.1007/s11214-007-9170-x
G. Michalek, N. Gopalswamy, A. Lara, P.K. Manoharan, Astron. Astrophys **423**, 729 (2004). doi:10.1051/0004-6361:20047184
Y.-J. Moon, K.-S. Cho, M. Dryer, Y.-H. Kim, S.-C. Bong, J. Chae, Y.D. Park, Astrophys. J. **624**, 414 (2005). doi:10.1086/428880
D. Moses, F. Clette, J.-P. Delaboudinière, G.E. Artzner, M. Bougnet, J. Brunaud, C. Carabetian, A.H. Gabriel, J.F. Hochedez, F. Millier, X.Y. Song, B. Au, K.P. Dere, R.A. Howard, R. Kreplin, D.J. Michels, J.M. Defise, C. Jamar, P. Rochus, J.P. Chaunineau, J.P. Marioge, R.C. Catura, J.R. Lemen, L. Shing, R.A. Stern, J.B. Gurman, W.M. Neupert, J. Newmark, B. Thompson, A. Maucherat, F. Portier-Fozzani, D. Berghmans, P. Cugnon, E.L. Van Dessel, J.R. Gabryl, Solar Phys. **175**, 571 (1997). doi:10.1023/A:1004902913117
S. Odenwald, J. Green, W. Taylor, Adv. Space Res. **38**, 280 (2006). doi:10.1016/j.asr.2005.10.046
D. Odstrcil, V.J. Pizzo, C.N. Arge, J. Geophys. Res. **110**, A02106 (2005). doi:10.1029/2004JA010745
V.J. Pizzo, D.A. Biesecker, Geophys. Res. Lett. **31**, L21802 (2004). doi:10.1029/2004GL021141
O. Podladchikova, D. Berghmans, Solar Phys. **228**, 265 (2005). doi:10.1007/s11207-005-5373-z
B.B. Poppe, EOS **81**(29), 322 (2000)
D.V. Reames, in *Coronal Mass Ejections*, ed. by N. Crooker, J.A. Joselyn, J. Feynman, AGU Geophysical Monograph, vol. 99 (1997), p. 217
G.D. Reeves, R.H.W. Friedel, R.D. Belian, M.M. Meier, M.G. Henderson, T. Onsager, H.J. Singer, D.N. Baker, X. Li, J.B. Blake, J. Geophys. Res. **103**(A8), 17559 (1998). doi:10.1029/97JA03236
I.G. Richardson, D.F. Webb, J. Zhang, D.B. Berdichevsky, D.A. Biesecker, J.C. Kasper, R. Kataoka, J.T. Steinberg, B.J. Thompson, C.-C. Wu, A.N. Zhukov, J. Geophys. Res. **111**(A7), A07S09 (2006). doi:10.1029/2005JA011476
E. Robbrecht, D. Berghmans, Solar Phys. **228**, 239 (2005). doi:10.1007/s11207-005-5004-8
O.C. St. Cyr, J.T. Burkepile, A.J. Hundhausen, A.R. Lecinski, J. Geophys. Res. **104**(A6), 12493 (1999)
O.C. St. Cyr, R.A. Howard, N.R. Sheeley, S.P. Plunkett, D.J. Michels, S.E. Paswaters, M.J. Koomen, G.M. Simnett, B.J. Thompson, J.B. Gurman, R. Schwenn, D.F. Webb, E. Hildner, P.L. Lamy, J. Geophys. Res. **105**(A8), 18169 (2000)
O.C. St. Cyr, J.M. Davila, in *Space Weather*, ed. by P. Song, H. Singer, G. Siscoe, AGU Geophysical Monograph, vol. 125 (Washington DC, 2001), p. 205
K. Scherer, H. Fichtner, B. Heber, U. Mall, *Space Weather: The Physics Behind a Slogan*. Lecture Notes in Physics, vol. 656 (Springer, Berlin 2005). doi:10.1007/b1000037
R. Schwenn, K.-H. Mühlhäuser, H. Rosenbauer, in *Solar Wind 4*, ed. by H. Rosenbauer (1981), p. 118
G. Siscoe, Space Weather **4**, S01003 (2006). doi:10.1029/2005SW000178
G. Siscoe, S.C. Solomon, Space Weather **4**, S04002 (2006). doi:10.1029/2005SW000205
Z. Smith, W. Murtagh, C. Smithtro, J. Geophys. Res. **109**, A01110 (2004). doi:10.1029/2003JA010044
Z. Smith, R. Zwickl, in *Solar Wind Nine*, ed. by S.R. Habbal, R. Esser, J.V. Hollweg, P.A. Isenberg (1999), p. 577
P. Song, H.J. Singer, G.L. Siscoe, *Space Weather*. AGU Monograph, vol. 125 (2001)
E.C. Stone, A.M. Frandsen, R.A. Mewaldt, E.R. Christian, D. Margolies, J.F. Ormes, F. Snow, Space Sci. Rev. **86**, 1 (1998)
B.J. Thompson, S.P. Plunkett, J.B. Gurman, J.S. Newmark, O.C. St. Cyr, D.J. Michels, Geophys. Res. Lett. **25**, 2465 (1998). doi:10.1029/98GL50429
Y.-M. Wang, N.R. Sheeley Jr., Astrophys. J. **355**, 726 (1990). doi:10.1086/168805
D.F. Webb, E.W. Cliver, N.U. Crooker, O.C. St. Cyr, B.J. Thompson, J. Geophys. Res. **105**(A4), 7491 (2000). doi:10.1029/1999JA000275
D.F. Webb, E.W. Cliver, N. Gopalswamy, H.S. Hudson, O.C. St. Cyr, Geophys. Res. Lett. **25**, 2469 (1998). doi:10.1029/98GL00493
D.F. Webb, D.R. Mizuno, A. Buffington, M.P. Cooke, C.J. Eyles, C.D. Fry, L.C. Gentile, P.P. Hick, P.E. Holladay, T.A. Howard, J.G. Hewitt, B.V. Jackson, J.C. Johnston, T.A. Kuchar, J.B. Mozer, S. Price, R.R. Radick, G.M. Simnett, S.J. Tappin, J. Geophys. Res. **111**, A12101 (2006). doi:10.1029/2006JA011655
S. Wing, J.R. Johnson, J. Jen, C.-I. Meng, D.G. Sibeck, K. Bechtold, J. Freeman, K. Costello, M. Balikhin, K. Takahashi, J. Geophys. Res. **110**(A4) (2005). doi:10.1029/2004JA010500
S. Yashiro, N. Gopalswamy, G. Michalek, O.C. St. Cyr, S.P. Plunkett, N.B. Rich, R.A. Howard, J. Geophys. Res. **109**, A07105 (2004). doi:10.1029/2003JA010282
R.D. Zwickl, K.A. Doggett, S. Sahm, W.P. Barrett, R.N. Grubb, T.R. Detman, V.J. Raben, C.W. Smith, P. Riley, R.E. Gold, R.A. Mewaldt, T. Maruyama, Space Sci. Rev. **86**, 633 (1998)