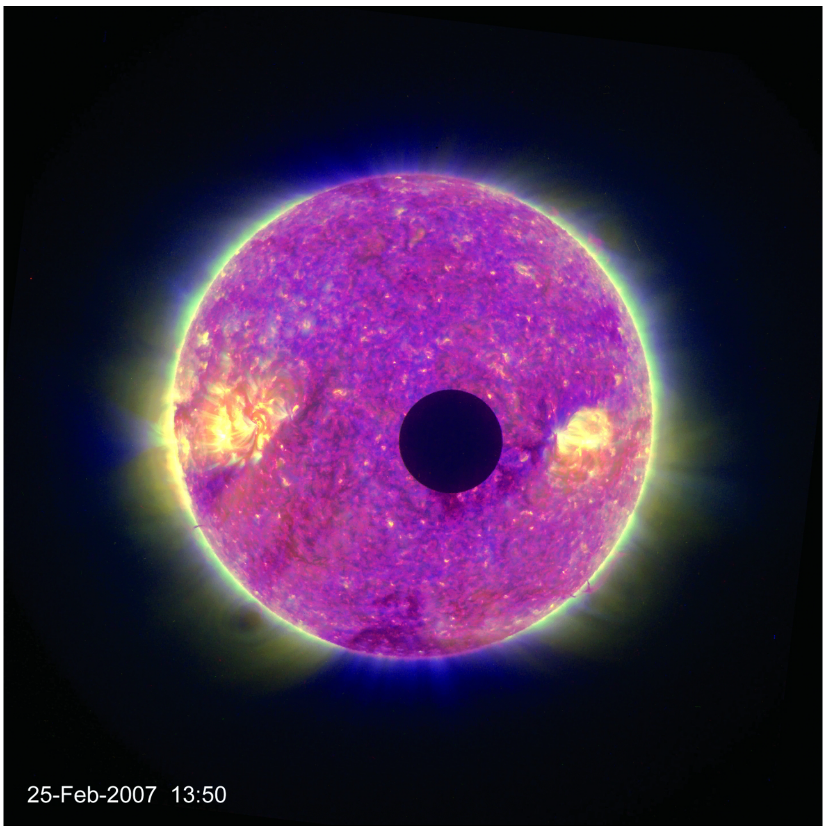
STEREO: Beyond 90 degrees



A proposal to the Senior Review
of
Heliophysics Operating Missions
February, 2008

I. Data Accessibility

Community use. Although STEREO is one of the youngest missions of the Heliophysics Great Observatory (HGO), data from STEREO are already being incorporated into many science investigations and some of the same services currently using observations from older assets of the HGO. Over 120 meeting presentations and over 70 publications have already made use of STEREO data. There have been 17 Science Working Group meetings and 8 STEREO-themed special sessions at major meetings including AGU, EGU and COSPAR. Examples of services using STEREO data include the Space Weather Browser from the Royal Observatory of Belgium, and the SolarSoft Latest Events service maintained by the Lockheed-Martin Solar and Astrophysics Laboratory. The NOAA National Space Weather Prediction Center uses STEREO Beacon data on a regular basis, and serves them via a website similar to that used for serving ACE Real Time Solar Wind data. Also, the asteroid and comet-hunting community and more recently the variable star community (see next section) have become avid users of the STEREO data.

Accessibility. All STEREO science data are accessible on the Web through the STEREO Science Center (SSC) archive and PI sites. The data in the SSC archive are identical to those on the PI sites, and are maintained by regular mirror processes running several times per day. Over 11 terabytes of data have been served over the web by the SSC in 2007.

Although tools for accessibility are already in existence, a number of browse tools that will enhance accessibility are under development by the instrument teams. A daily browse tool based on the SECCHI images and beacon in-situ data is maintained on the SSC website. Customized browse pages are also available from the SECCHI, IMPACT, PLASTIC, and SWAVES instrument pages. For example, daily Javascipt movies of data from the SECCHI telescopes can be viewed at various resolutions at http://secchi.nrl.navy.mil/index.php?p=js_secchi. Additional SWAVES data are available from the *Centre de Données de la Physique des Plasmas* in France. The NOAA Space Weather Prediction Center provides a browser of the beacon data patterned after their ACE browser. The SECCHI/COR1, SECCHI/HI, and SWAVES teams are providing higher-level data products (e.g. event catalogs) to direct researchers to the most interesting data sets. IMPACT will be adding a similar event list based on shocks, ICMEs, stream interactions, and SEP events. The STEREO Space Weather website at NRL, accessible through the SSC website, contains links to ancillary data for major events observed by many of the STEREO instruments.

Research access. The Virtual Solar Observatory (VSO) [Hill et al., 2004] acts as the primary access point for all STEREO data, with the SSC as the data provider. This maximizes the use of existing resources without duplication, and enables collaborative data analysis with other solar observatories. As well as the main VSO search page at www.virtualsolar.org, the SSC is working on mission-specific interfaces into the VSO database. Efforts are also underway to incorporate the STEREO data into the Virtual Heliospheric Observatory (vho.nasa.gov). Data are available from the individual PI and Co-I institutions, and in the case of some of the in-situ and radio data at the CDAWeb website at the NSSDC. A list of all access sites is maintained at http://stereo-ssc.nascom.nasa.gov/data.shtml.

Space weather. In addition to the normal science data provided by the instrument teams, STEREO also provides instantaneous beacon data to the space weather community. These data are used extensively by the NOAA Space Weather Prediction Center. The Solar Influences Data Analysis Center at the Royal Observatory of Belgium is working on using STEREO coronagraph beacon images to automatically detect coronal mass ejections through their CACTUS (Computer Aided CME Tracking) project. The Community Coordinated Modeling Center (CCMC - http://ccmc.gsfc.nasa.gov) is modeling both the ambient solar wind and selected eruptive events in support of STEREO data interpretation. The Global Oscillation Network Group (GONG – http://gong.nso.edu) is providing daily updated magnetograms, synoptic maps and potential field source surface models that can be used in analyzing prevailing coronal magnetic field geometry and solar wind sources on a near real-time basis.

Publications. The STEREO publications database can be accessed at: http://stereo-ssc.nascom.nasa.gov/stereo-lit/. This database is restricted to already published journal articles and proceedings. Many pre-publication works are made available by the authors through the Solar Physics E-Print Archive at http://solar.physics.montana.edu/cgi-bin/eprint/default_page.pl.

References

Hill, F. et al., "The Virtual Solar Observatory: status and initial operational experience", *Proc. SPIE, 5493*, 163-169, 2004.

II. Scientific highlights to date

As of this writing, the STEREO Mission is just completing its first year of science operations, so much of the work highlighted below is in progress and pre-publication. The highlights fall into two distinct categories, namely those that are in keeping with the primary science goals of STEREO and those that are purely serendipitous.

Primary Science

The four primary science goals of the STEREO mission are:

- Understand the causes and mechanisms of CME initiation
- Characterize the propagation of CMEs through the heliosphere
- Discover the mechanisms and sites of energetic particle acceleration in the low corona and the interplanetary medium
- Develop a 3D time-dependent model of the magnetic field topology, temperature, density, and velocity structure of the ambient solar wind

During this first year just completed and for all ensuing years, including those during any extended mission, these four goals have been and will continue to be pursued. Some of these prime science results thus far include:

3-D reconstruction results

Reconstruction of Coronal Loops. Classical stereoscopy can be performed on a variety of coronal structures with curvi-linear characteristics, such as coronal loops, and flare and post-flare loops. The first year of the STEREO mission provided data for small-angle stereoscopy (<40 deg), which are suitable for direct 3D viewing with anaglyph, polarized or shuttered glasses. The second year will provide data with larger separation angles (45-90 deg), but 3D reconstruction is still feasible with numerical techniques. A 3D reconstruction of the geometry of 30 loops within a single active region is shown in Figure 1. The reconstruction was developed by applying a triangulation method to highpass-filtered EUVI images [Aschwanden et al., 2008]. The 3D reconstruction of these loops reveals their true height, loop inclination angles, coplanarity, and circularity. The true shape of loops cannot be determined with traditional 2D imagery from a single viewpoint. The knowledge of the exact 3D geometry of a loop with respect to the observers line-of-sight has important consequences for determining the correct vertical density scale height (used in hydrostatic models), the aspect angle of loop cross-sections (used in inferring electron densities from optically thin emission measures), the absolute flow speeds (used in siphon flow models), the correct loop length (used in loop scaling laws), as well as the 3D vectors of the coronal magnetic field (used in testing theoretical magnetic field extrapolation models).

The same 3D reconstruction technique can be applied to quiescent and eruptive filaments to study their height-time evolution, which allows calculating and localizing currents and Lorentz forces that drive the launch of a CME. A particularly interesting task is to test whether the criterion of the kink instability, if fulfilled in erupting filaments, can be used to predict CME onsets.

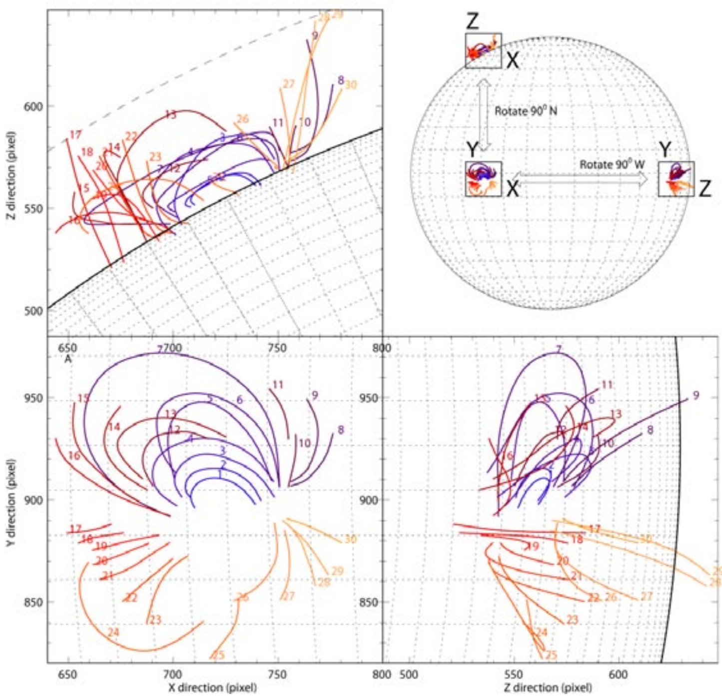


Figure 1. 3D Reconstruction of loops within a single active region using SECCHI/EUVI observations from STEREO [Aschwanden et al., 2008].

CME reconstruction. STEREO's two viewpoints do not provide enough information for tomographic reconstruction of CMEs, but forward modeling techniques using simple models can reveal much about the CME's 3D structure. On November 16, 2007, a CME was observed in STEREO-A and –B. It was much brighter in A than in B. Since it had a "typical" flux-rope appearance, the graduated cylindrical shell model of Thernisien et al. [2006] was applied and the white light images that STEREO-A and B would see for this model were computed [Thernisien et al., 2008]. This forward modeling technique had been applied to LASCO CMEs from a single viewpoint, but this is the first time that the technique was applied to the two STEREO viewpoints. In this technique the orientation, size and location are defined by the EUVI observations, not by fitting the coronagraph observations. Then the height of the cylindrical shell and the electron density within the shell is determined by matching the observed brightness distribution to the computed one in the two viewpoints. The resulting model shown in Figure 2 does an excellent job in reproducing the observed brightness in the two viewpoints and also enables a determination of the propagation direction.

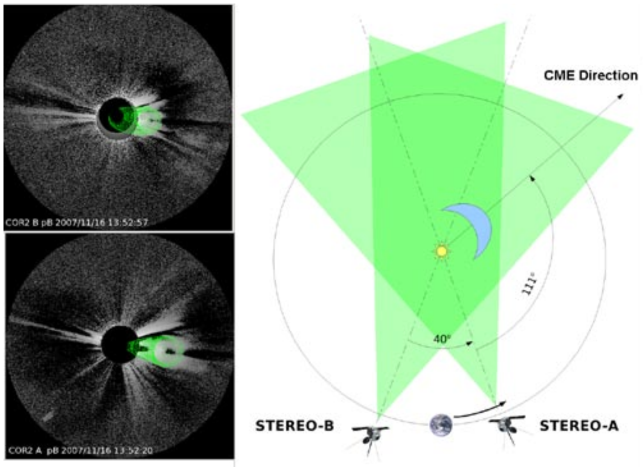


Figure 2. Forward-Modeling of the Nov. 16 CME. The SECCHI/COR2 observations are shown in the left panels. The wireframe of the model is shown in green. The CME geometry as derived by the model fit is shown on the right [Thernisien et al., 2008].

Polar jet reconstruction. Polar coronal jets are impulsive narrow ejections of plasma from the Sun's polar coronal holes. It is widely believed that they are powered by magnetic reconnection between open and closed magnetic fields and they thereby represent an ideal test bed for studying such fundamental processes. Moreover, their mass content may account for a significant fraction of the fast solar wind mass. Patsourakos et al. [2008] performed the first stereoscopic observations of a benchmark polar coronal jet with SECCHI on STEREO. The observations took place on 7 June 2007 over the north polar coronal hole. EUVI images from the two STEREO spacecraft were used, having an orbit separation of almost 10° at this time. A sample of the results of Parsourakos et al. [2008] is given in Figure 3. The first 3 columns (with Ahead above and Behind below) show co-temporal snapshots of the jet as seen in the 195, 171 and 304 Å channels. The jet exhibits a helical structure on both spacecraft. Note that the helical structure is seen face-on in STEREO-A and edge-on in STEREO-B. They concluded that the helical structure of the jet is real and does not result from projection effects, which are inherent to single view-point images. The existence of a helical structure in jets is a critical element of MHD models of polar jets. The fourth column of Figure 1 contains mass isosurfaces from the MHD jet model of Pariat et al. [2008] as seen from two perspectives with a separation similar to our STEREO observations. The helical structure in the jet is evident. Therefore, STEREO observations place strong constraints on the initiation of polar coronal jets which could not have been possible by single-point observations.

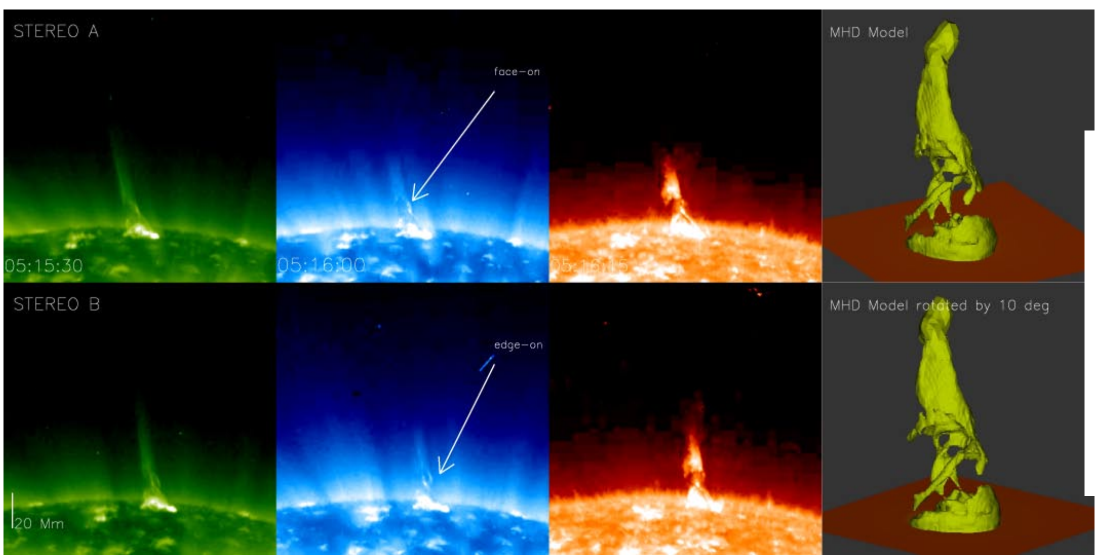


Figure 3. Polar jets observed simultaneously by both STEREO spacecraft and the resultant model interpretation [Patsourakos et al., 2008]

The Magnetic Cloud of May 21-23, 2007 and its Solar Origin

A primary objective of the STEREO mission is to study the origin and evolution of coronal mass ejections from the Sun to Earth using both *in situ* and remote sensing observations. As of early 2008, only one magnetic cloud has been observed in STEREO's *in situ* data since the spacecraft had sufficient separation for multipoint observations. This cloud, observed by Wind, ACE and STEREO-B on May 21-23, 2007, and its solar origins have been studied extensively [Huttunen et al., 2008; Li et al., 2008; Liewer et al., 2008; Popecki et al., 2007]. Analysis of remote and *in situ* observations indicate that a complex CME with an associated filament eruption was the most probable solar source of this cloud. Here we briefly summarize some of the results.

Multipoint in situ observations of the magnetic cloud. The separated STEREO spacecraft together with Wind and ACE at L1 were used to study the three-dimensional structure and spatial extent of the magnetic cloud of May 21-23, 2007 [Huttunen et al., 2008]. The large angular separation between the observing spacecraft facilitates a study of the large-scale structure of the magnetic cloud. This cloud has been associated with a partial halo CME on May 19, 2007 at ~12:50 UT and with a disappearance of a solar filament in active region 10956 (left panel of Figure 4), making this an intriguing event for studying the relationship between the magnetic cloud and coronal structure using global MHD modeling.

The middle panel of Figure 4 demonstrates that the STEREO and L1 satellites recorded very different solar wind conditions due to their different crossing distances from the center of the magnetic cloud. Initial analysis of the in-situ data reveals that STEREO-B crossed the magnetic cloud closest to its center, while Wind traversed the cloud further away from the axis. STEREO-A recorded highly different solar wind plasma and magnetic field conditions from those seen at the locations of STEREO B and Wind, and probably crossed only the leg of the magnetic cloud. STEREO-A's SECCHI/EUVI image in Figure 4 shows two large coronal holes bracketing the active region where the CME originated. The magnetic cloud was embedded between the high-speed streams from these coronal holes. The overtaking stream distorted the end portion of the magnetic cloud and caused shock-like disturbance that appeared to propagate and steepen inside the cloud. The different solar sources are observable as distinctions in the in situ solar wind composition, shown in the right panel [Galvin et al., 2007].

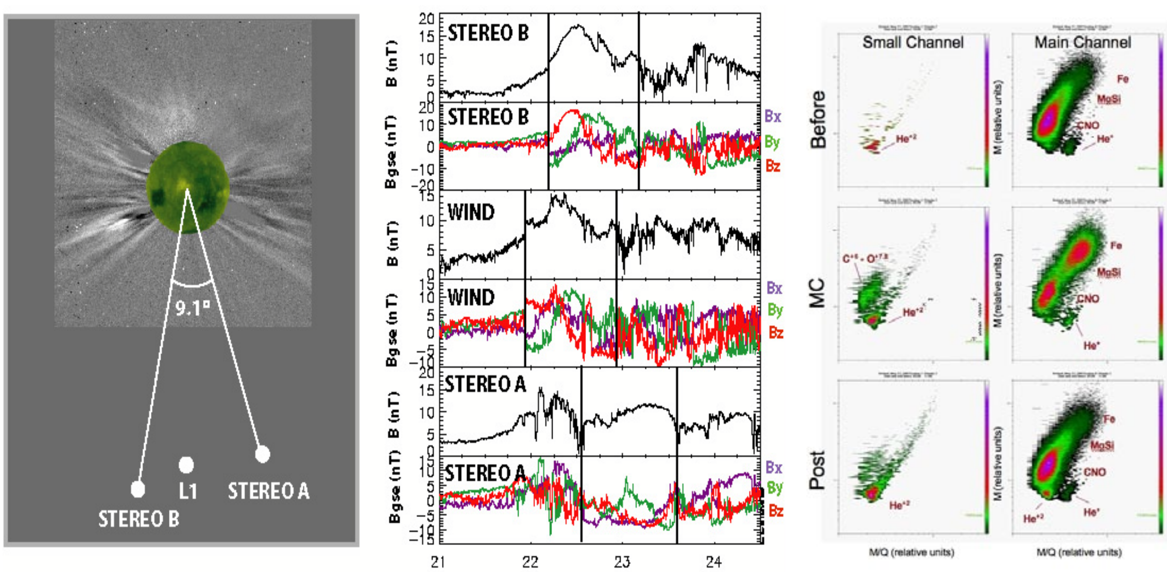


Figure 4. Left: Locations of the observing satellites and the STEREO A EUVI image at 195 Å on May 19, 2007 at 12:32:00 UT plotted on to a STEREO A COR1 difference image on May 19, 2007 at 15:52:32 UT, showing a partial halo event. Middle: Magnetic field magnitude and components in GSE coordinates measured by the STEREO and Wind satellites. The pair of solid lines bound the interval of a magnetic cloud-like solar wind conditions at each satellite. [From Hutttunen et al., 2008]. Right: Solar wind heavy ion composition observed on STEREO B from periods prior, during and after the passage of the magnetic cloud [Galvin et al., 2007].

Stereoscopic Analysis of STEREO/EUVI Observations of May 19, 2007 Erupting Filament. A filament eruption, a B 9.5 X-ray flare and coronal dimming accompanied the initiation of the CME thought to be responsible for the magnetic cloud. Stereoscopic observations from the SECCHI/EUVI telescopes were used to analyze the behavior of the filament before and during the eruption and its relation to other solar signatures of the event [Liewer et al., 2008]. The eruption of the filament and the sharp rise of the flare occurred nearly simultaneously (within the resolution of SECCHI/EUVI's 10 min. cadence) on May 19, 2007 at 12:51 UT, followed by coronal dimming (seen starting at 13:00) and an EUV wave [Thompson et al., 1999].

The filament could be followed in STEREO/SECCHI/EUVI 304Ǻ data from about 12 hours before to about 2 hours after the eruption. STEREO A and B were separated by about 8.5°, sufficient to use tie-pointing and triangulation to reconstruct the filament in 3D [see Aschwanden et al., 2008]. Reconstructions were performed at eight times prior to the eruption by manually tie-pointing filament features seen in simultaneous STEREO-A and B images and using triangulation to determine the three-dimensional coordinates of the points in a heliocentric coordinate system. In the top of Figure 5, the filament with STEREO-B tie-points is shown at two times on May 19, just prior to the eruption at 12:21 UT and as it erupts at 12:51. Prior to the eruption, the filament is a simple loop lying in a plane, e.g., it shows no twist or writhe. The filament undergoes episodic brightenings associated with activity near the footpoint located in the active region neutral line, but shows little change in length or height, although some change in the angle of inclination are observed (visible only in the 3D reconstructions). In the bottom of Figure 5**,** the reconstructions at the two times (12:21 and 12:51 UT) are shown from two viewpoints. At 12:21 (yellow reconstruction), the filament is a simple planar loop whereas at 12:51 (red), the filament is twisting as it erupts and breaks off at the leg terminating in the bright flare site (active region neutral line). The twist in the filament is not evident from either the STEREO-A or STEREO-B viewpoint; only a view of the 3D reconstruction from the side reveals the twisted nature of the filament as it erupts. Although the filament is a simple planar loop prior to eruption, stereoscopic viewing of movies of the filament show transient brightening of helical flux tubes which appear to wind around the filament. The filament is active throughout the 12 hour period preceding the eruption, but no dramatic pre-eruptive signature is seen.

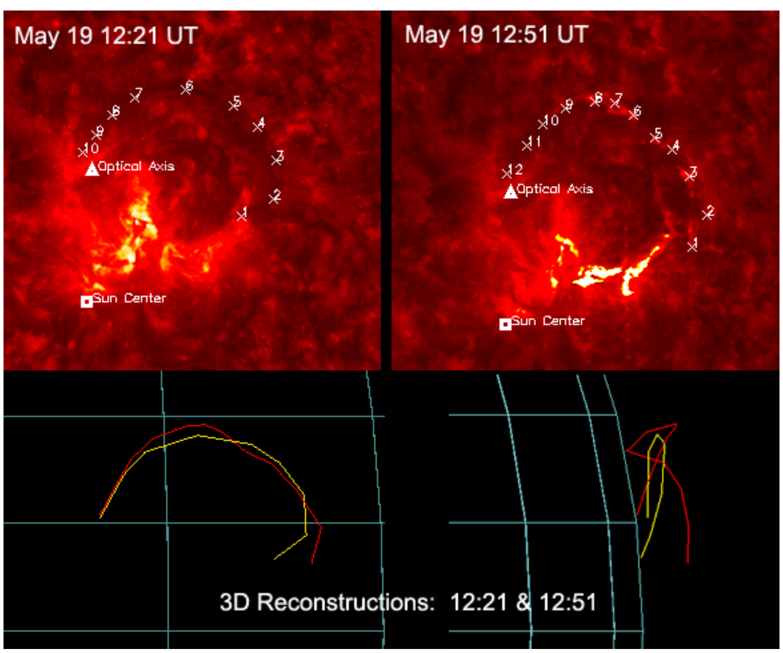


Figure 5. Top: STEREO B EUVI 304 images of the filament with the tie-points at two times on May 19, 2007: just prior to the eruption at 12:21 UT and as it erupts at 12:51. In the bottom of the figure, the 3D reconstructions for the two times (12:21 and 12:51) are overlaid and displayed from two different viewpoints. The twist is only apparent in the reconstruction. [*From Liewer et al., 2008].*

Source Region of the May 19, 2007 CME. AR 10956 gave rise to many coronal mass ejections as it traversed the solar disk in May 2007 in addition to a fast CME (958km/s) on May 19, when AR10956 was at the solar central meridian. A total of 24 flares (GOES, 22B+2C) and a number of eruptions (see LASCO or SECCHI/COR1 CME catalogs) originated from different neutral lines in the region. Despite the moderate size and magnitude, AR10956 had a complex magnetic configuration with multiple neutral lines, highly non-potential coronal loop structures and energized sigmoids [Li et al., 2008]. Potential field source surface (PFSS) models, based on MDI magnetograms, of both the coronal field models and the active region are shown in Figure 6. A four-sector coronal field structure and highly inclined coronal streamer arcade high over the active region (left) and the multipolar topology of the flux systems (right) can been seen; both likely participate in the eruption producing the May 19 CME. The filament that erupted with a B9.5 flare at ~12:48UT on May 19, 2007 lies at the neutral line underlying the black arcade. The total unsigned magnetic field of the region decreased ~16% in two days before this eruption.

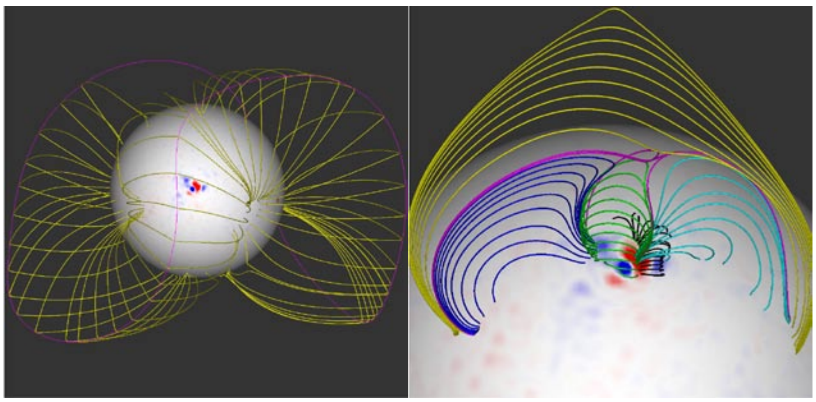


Figure 6. PFSS model approximations of the coronal magnetic field. Left: the global coronal magnetic field structure of May 2007 with AR10956 at center. Right: coronal field lines over AR10956. The erupting neutral line/filament channel is overlaid with the low-altitude black arcade. Flux systems that likely participate in the eruption process are color coded as green (central arcade), blue (a side arcade), aqua (the side arcade over the erupting neutral line), purple (magnetic spine that separates flux topologically) and yellow (large scale overlying field arcade) [*From Li et al., 2008]*.

The December 2006 Large Solar Energetic Particle Event.

The Solar Energetic Particle (SEP) suite of IMPACT includes four sensors that measure composition and energy spectra from ~50 keV/nuc to ~100 MeV/nucleon. In early December, 2006 there was a sudden, unexpected outburst of solar activity that included four X-class flares with associated solar energetic particle (SEP) events. Although the SIT and SEPT sensors had not yet been commissioned, the LET and HET sensors were already in operation and the December events provided an excellent opportunity to test and optimize their on-board particle identification systems, and to cross-calibrate their response with other near-Earth instruments. The IMPACT boom suite instruments also provided a picture of the associated in-situ ICME shown in Figure 7a.

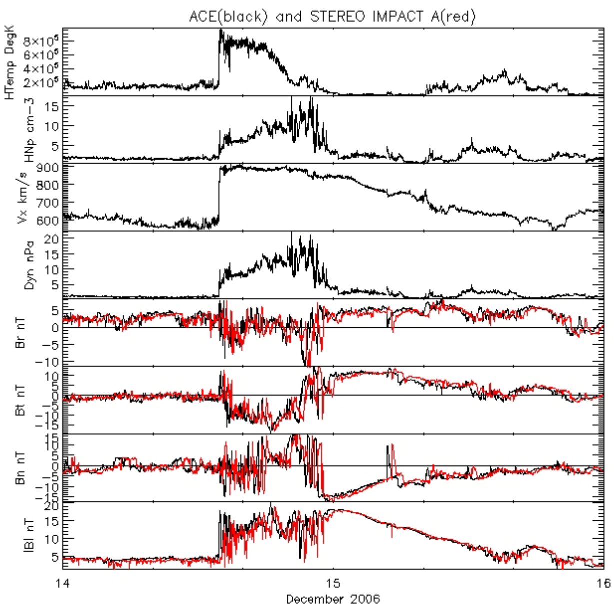


Figure 7a. Magnetic field measurements from closely-spaced STEREO A, B and ACE and the plasma measurements from ACE for the December 2006 first STEREO ICME. The PLASTIC instrument was not yet fully commissioned at the time of this event.

The time history of species ranging from electrons to Fe is shown in Figure 7b. The first two large x-ray events occurred near the east limb, and the accelerated particle profiles were merged because of the poor magnetic connection. Unfortunately, there are no CME data from either SECCHI or SOHO from these east limb events. The following Dec. 13 and 14 SEP events were both well connected due to the rotation of the active region to the western disk, and were associated with SOHO-LASCO CMEs with velocities of 1573 and 1041 km/s, respectively. When the shock from the December 13th ICME arrived at Earth ~1.5 days later it was still accelerating ions up to ~10 MeV/nuc [Mewaldt et al., 2007a]. While the Dec. 5 and 6 events were relatively Fe poor (right panel of Figure 7), with the onset of the December 13 event the Fe/O ratio increased by a factor of ~50, resulting in the most Fe-rich of the large SEP events of solar cycle 23.

Well-connected events are often Fe-rich while east-limb events are typically Fe-poor. This may be because well-connected events often include particles accelerated at the flare site as well as particles

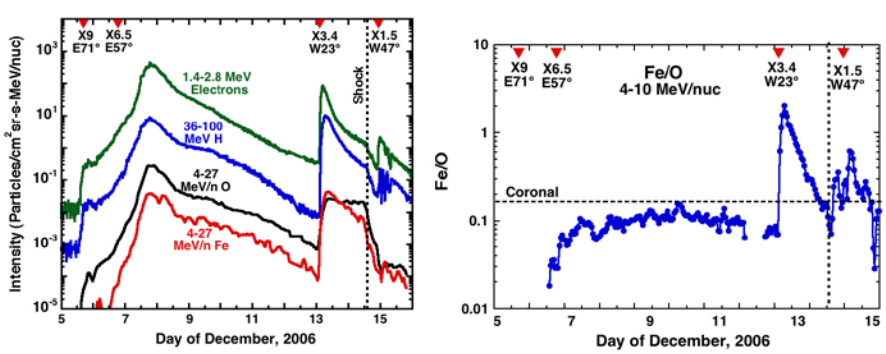


Figure 7b: (Left): Electron and proton intensities from HET and O and Fe intensities from LET based on real-time particle identification during the Dec. 2006 SEP events. The occurrence of X-class flares and the shock from the Dec. 13 event are indicated. (Right): The Dec. 5 and 6 events are Fe-poor relative to the corona, while the Dec. 13 event is very Fe-rich. The Dec. 14 event is highly variable because the spacecraft were inside the Dec 13 ICME at the time [see Mulligan et al. 2007].

accelerated by the CME-driven shock [Cane et al., 2006]. However, in another model [Tylka et al., 2005] the Fe-rich composition results from preferential acceleration of suprathermal ions at quasi-perpendicular shocks (believed to have a higher injection threshold that favors suprathermal over thermal ions.) The Fe-rich suprathermal ions are assumed to be a remnant from previous small Fe-rich events. Once solar activity resumes with Cycle 24 (first cycle 24 AR just reported Jan 4, 2008), STEREO (along with near-Earth spacecraft) will test these models by observing SEP events from multiple longitudes, and by comparing the SEP and suprathermal-ion compositions at these locations.

The charge histogram of LET composition data from the December events in Figure 8 (center) shows that sixteen species are resolved. Fifteen of these are identified on-board and most of these are also identified in SIT and HET. The December SEP events provided an excellent chance to test the on-board particle identification software when the Ahead and Behind were together and close to near-Earth spacecraft such as ACE. Figure 8 (right) shows spectra from LET and two ACE instruments, where it can be seen that there is good overall agreement. All species are observed to have a similar energy spectrum with the spectra of heavier species rolling over at lower energies due to charge-to-mass dependent acceleration and transport effects [e.g., Cohen et al. 2005].

The proton energy spectra in Figure 8 (left) are based on LET and HET data >2 MeV, with ACE/EPAM data used at lower energies because the SEPT and SIT doors were not yet open. Both events had hard power-law spectra at high energies (the December 13 event was among the hardest of the solar cycle and also produced a ground level event). The HET response in these events agrees well with that of NOAA's GOES satellites. Hard energy-spectra such as these are thought to originate at quasi-perpendicular shocks, where acceleration is more efficient [Giacalone 2005]. Of the twenty largest solar proton events of solar cycle 23 (based on the fluence of >30 MeV protons), these December events rank #11 and #15. (When corrected for longitude, the December 5/6 event is #6). STEREO will investigate the role of shock geometry in shaping SEP energy spectra and composition by measuring the same SEP events at different longitudes.

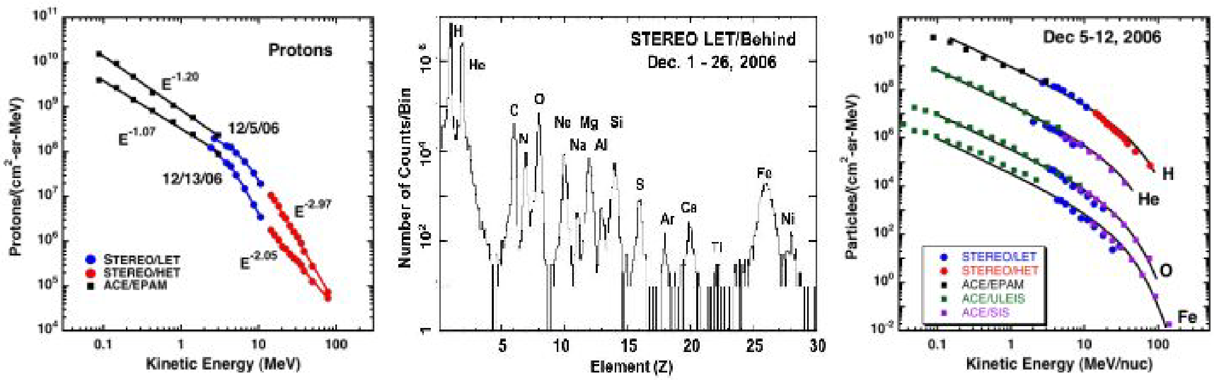


Figure 8: (Left): Proton fluence spectra measured by HET, LET, and ACE/EPAM [Mewaldt et al. 2007b]. (Center): SEP composition data from LET resolves 16 species, 15 of which are identified by on-board analysis [Mewaldt et al., 2007a]. (Right): A fit to the O energy spectrum is shifted in energy and intensity to show that the H, He, O, and Fe spectra all have a common shape with spectral breaks that occur at differing energy/nucleon because of charge-to-mass dependent acceleration/transport effects [see Cohen et al., 2005].

Multipoint Studies of Ion Acceleration in Co-rotating Interaction Regions

Co-rotating interaction regions (CIRs) develop when a fast solar wind stream overtakes a slower solar wind stream. The compression region that forms at the boundary can strengthen into a pair of shocks, typically beyond 1 AU, that propagate away from the stream interface outward (forward) and inward (reverse) and can accelerate particles to ~30 MeV/nucleon [see, e.g., Richardson 2004 and references therein]. As long as the stream structure persists, the interaction region co-rotates with the Sun, and recurrent CIR-associated particle intensity increases appear over many solar rotations.

The launch of STEREO near solar minimum has provided an opportunity to study CIR-associated ion events, which are an important source of the low-energy interplanetary particle populations during periods of low solar activity [Reames, 1999]. The STEREO *in-situ* instruments provide complete compositional and spectral information with high sensitivity from solar wind and suprathermal energies (PLASTIC) to energies of several MeV/nucleon (IMPACT). STEREO measurements of the different CIR source populations (solar wind and pickup ions) with their completely different distribution functions and mass-to-charge ratios provide the opportunity to study mass-per-charge dependent injection and acceleration processes as a function of V_{sw}, B, and shock parameters at two different longitudinal vantage points.

Sample CIR observations from STEREO/PLASTIC are shown in Figures 9 and 10. Figure 9 shows 5

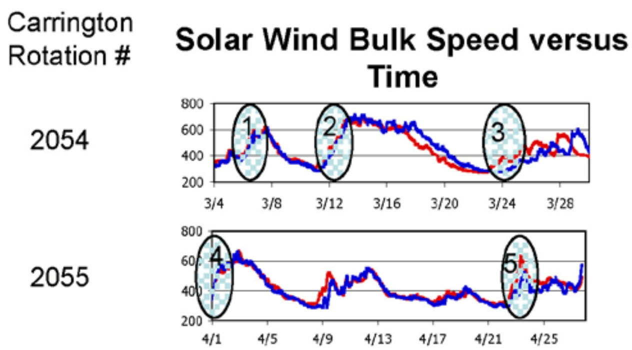


Fig. 9. Solar wind speed as measured with PLASTIC onboard STEREO-A (red) and STEREO-B (blue) in 2007, with 5 stream interaction regions selected for study by Simunac *et al.* [2007].

stream interface (SI) regions observed in early 2007, Figure 10 (left) shows the solar wind speed and density for SI #2, and Figure 10 (right) shows the differential energy flux spectra of pickup He^+ for the four 2-hour periods marked on the left by vertical bars. Figure 10 clearly shows the continuous increase of the maximum energy of the pickup ions with increasing solar wind speed and the temporal development of a suprathermal tail in the high-speed stream. Comparing the acceleration of pickup He^+ with the acceleration of solar wind protons and He^{2+} will help to clarify the details of mass-per-charge dependent injection and acceleration processes that are observed in many shock-acceleration environments.

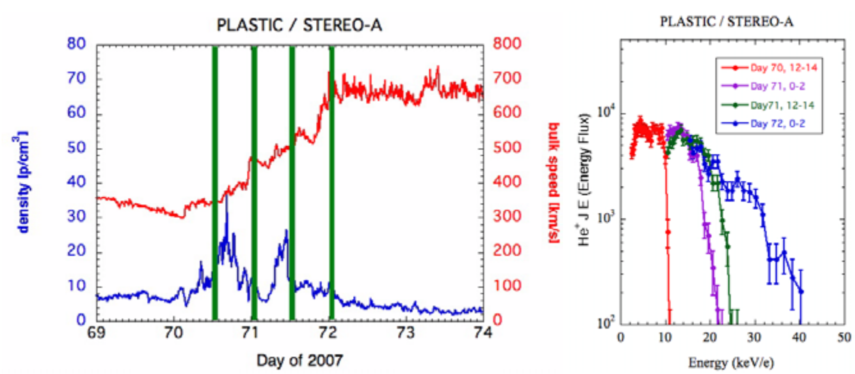


Figure 10 (left) Solar wind speed and density during stream interaction region #2 of Fig. 9. The vertical bars indicate the time periods of the pickup ion energy spectra shown in right panel [Klecker *et al.,* 2007]. (right) Pickup He^+ energy flux (relative units) for four 2-h time periods during the transition from low-speed to high-speed solar wind. The last time periods shows the development of a suprathermal tail [Klecker *et al.*, 2007].

At higher energies (~0.1-10 MeV/nucleon), LET, SIT, and SEPT in the STEREO/IMPACT suite have also been observing CIRs; example H and He spectra from two events are shown in Figure 11. The measurements made by these different instruments agree well with each other and with similar instruments on ACE over ~9 orders of magnitude in intensity. As is typical of CIRs, the spectra become very steep and fall off rapidly at high energies.

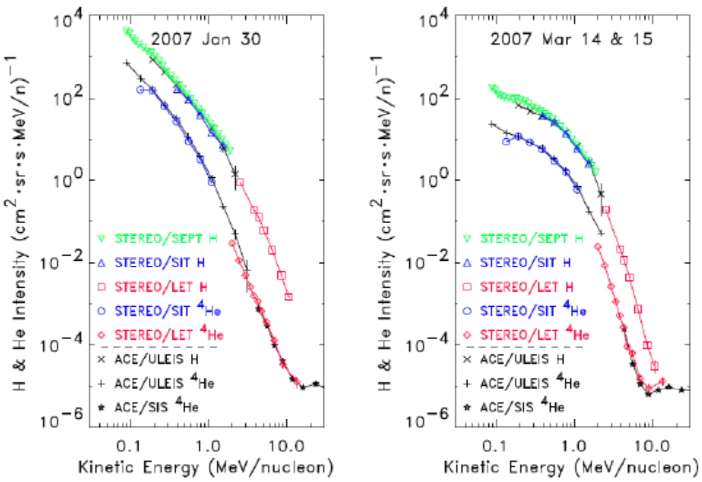


Figure 11. Proton and helium intensity spectra during CIR events in the time periods indicated, combining data from SEPT, SIT, and LET on STEREO with ULEIS and SIS on ACE. At the highest energies, He flattens out as the intensity falls to that of the anomalous cosmic ray background.

Multipoint observations of CIR particle intensities, spectra, and composition may help distinguish between temporal and spatial changes in the acceleration and transport of these particles. Such studies are underway using STEREO/IMPACT instruments [e.g., Leske et al. 2007, Gomez-Herrero et al. 2007], as illustrated by the time profiles in Figure 12. When the two spacecraft were close together the agreement between the two was excellent, but as they move further apart differences in the CIR time profiles are apparent and it is becoming increasingly difficult to match features observed at one spacecraft with those seen at the other. To first order the timing differences are roughly as expected from the co-rotation time lag between the two spacecraft, which currently can be as large as ~3 days. Many of the different features seen at Ahead and Behind can not be accounted for by merely a simple time shift, but may be due to transient disturbances in the solar wind affecting connection to or transport from the co-rotating shock, or by temporal changes in the CIR shock itself. By mid-2009, the two STEREO spacecraft will be ~100° apart in longitude, and will continue to separate from each other by 45° per year. *In-situ* observations by instruments on other spacecraft such as ACE, Wind, and SoHO, at a point roughly midway between the two STEREO spacecraft, will be extremely useful to help interpret the STEREO observations as they attain ever greater separations.

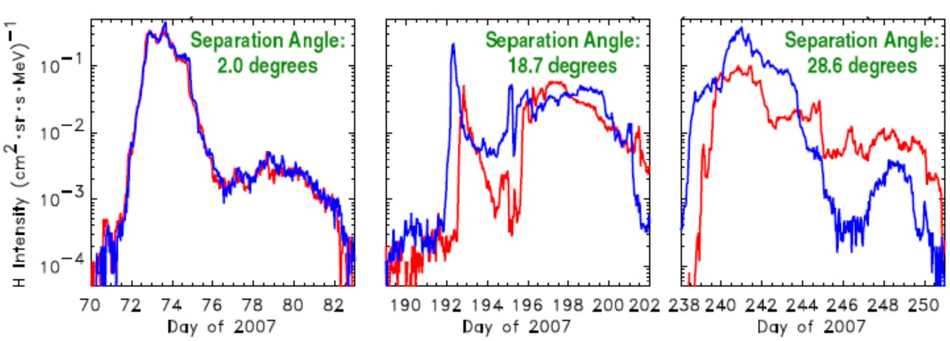


Figure 12. Proton intensities at 1.8-3.6 MeV from IMPACT/LET on STEREO-Ahead (red) and STEREO-Behind (blue) during 3 different CIR events in 2007. The separation of the two STEREO spacecraft in heliographic longitude is indicated for each time period.

Remote Imaging of Co-rotating Interaction Regions in the Solar Wind

Probably the most unexpected result from SECCHI's heliospheric imagers are their ability to image the slow solar wind and co-rotating interaction regions as well as the CMEs they were designed to image. Sheeley et al. [2008] compared SECCHI Heliospheric Imager-2 (HI2) images from the Behind spacecraft with in situ plasma and magnetic field measurements from the Wind spacecraft. During May-September

2007, HI2B observed a succession of density wavefronts sweeping past Earth, which, fortuitously, was moving slowly through the HI2B field of view as the spacecraft receded from the planet. As each of these wavefronts moved past Earth, the Wind spacecraft, located only 200 Earth radii sunward, observed a corresponding succession of density compressions in front of recurrent solar wind high-speed streams. Moreover, no HI2B wavefronts occurred during the intervals between streams. Sheeley et al. [2008] constructed elongation versus time maps of the HI2B wavefronts and fit the resulting tracks, assuming that the real acceleration occurred near the Sun (5-15 R_{sun}) and that the curvature of the tracks was due to the geometry of motion (sky-plane angle, radial speed, and starting time). They found that the wavefronts originated far from the sky-plane (as observed from Behind), as one would expect for motions directed toward Earth. This result also explains the large apparent size of the wavefronts and the high apparent speed (i.e. angular speed) as projection effects of passing close to the Behind spacecraft.

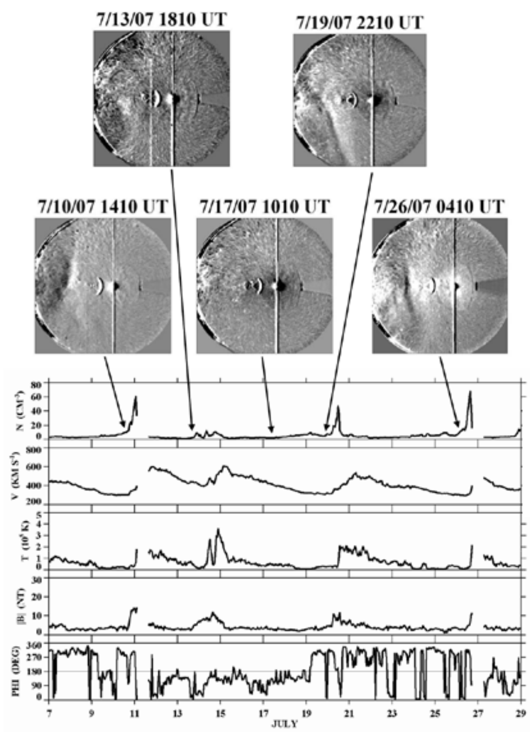


Figure 13. A sample of HI2B images at selected times during the passage of several high-speed streams. [From Sheeley et al., 2008].

Solar Wind Sources at Solar Minimum

The solar minimum solar wind is expected to be the best test of current magnetogram-based global models of the coupled corona and heliosphere. STEREO in-situ measurements with PLASTIC and IMPACT, together with ACE and Wind, provided an unprecedented triple-point simultaneous measure of the model performance at 1 AU. In particular, it provides a way to test not only the accuracy of the solar wind source mapping in 3D, but also the assumption of steady co-rotation at this quiet phase of the solar cycle.

The SECCHI EUVI beacon images (figure 14) show the low to mid-latitude coronal holes that dominated the ecliptic solar wind sources during early 2007 (left frame), and similar images for late 2007 (right frame) when a large southern polar coronal hole extension became important. The ability of the Wang-Sheeley-Arge [Arge and Pizzo, 2000] solar wind model used by the NOAA Space Weather Prediction Center to replicate the solar wind speeds observed at L1 during these two periods is shown in figure 15.

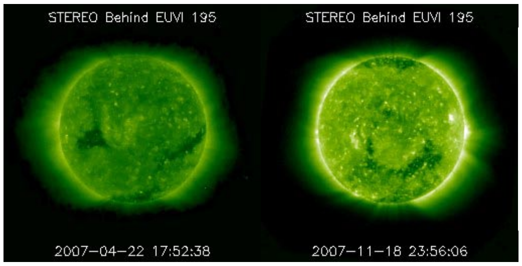


Figure 14. SECCHI EUVI beacon images from STEREO-B, showing the dominant southern midlatitude high speed solar wind sources (dark areas) that prevailed in early 2007 (left) and the large, fragmented southern polar hole extension source that provided high speed streams in late 2007.

The agreement of the measurements with the modeled speeds for several consecutive Carrington Rotations in late 2007 (right panel figure 15, with Carrington Rotation boundaries indicated) is clearly worse than for Carrington rotations from early 2007 (left panel). Examination of the source maps for the model confirm that the contributions from the polar coronal hole edges and the southern polar coronal hole extension seen in the late 2007 images is the main distinction between the two periods. But it was not clear whether the model uncertainties imply the solar wind was less steady at 1 AU in 2007 because it came from these regions rather than mid-latitude sources.

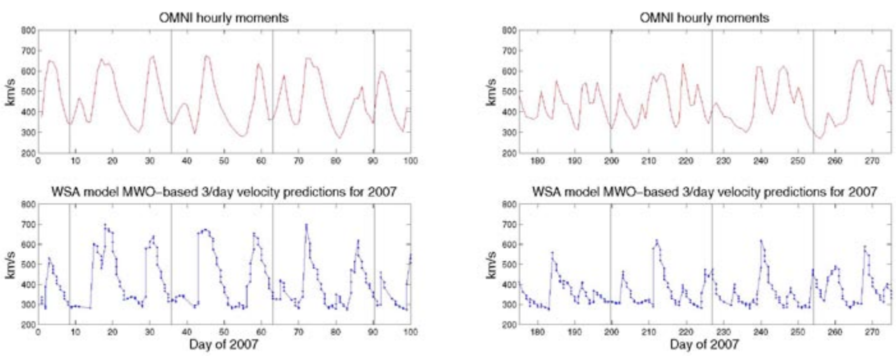


Figure 15. Several solar rotations of OMNI L1 solar wind velocities (top panels of each figure) compared to the WSA model solar wind velocities at the bottom for early 2007 (left) and late 2007 (right). The lack of model agreement in late 2007 could be due to source mapping errors in the model or to inherent unsteadiness in the solar wind structure. STEREO, when separated in late 2007, is used to test its steadiness (Fig. 16).

In late 2007 the STEREO spacecraft were separated by about 45 degrees heliolongitude from each other. The comparison of the late 2007 STEREO-A and B solar wind speeds as time progressed in 2007 (figure 16) indicated that the agreement between the spacecraft measurements continued to be good into the later period. Thus STEREO tells us that the model mapping uncertainties associated with the polar hole edge and extension contributions in figure 16 is not a measure of the unsteadiness of this source, but only of the difficulty in mapping with present models.

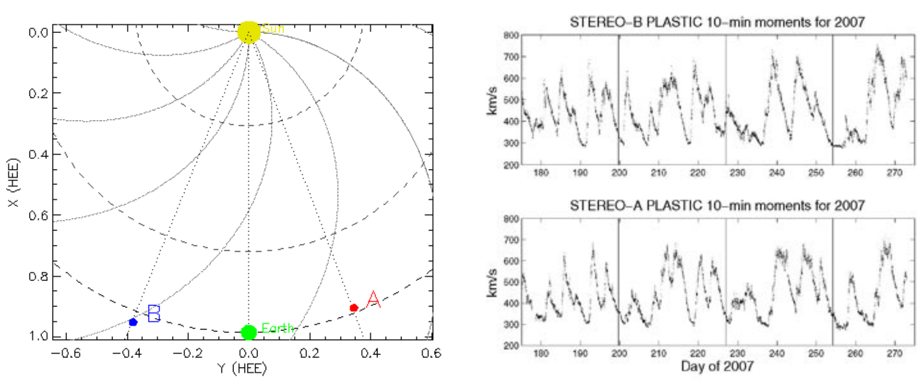


Figure 16. Comparison of STEREO-A and -B measurements of the solar wind velocities in late 2007, from PLASTIC. Both these measurements and the IMF polarities measured by IMPACT magnetometers suggest a fairly steady co-rotating structure exists in late 2007. Thus the lack of model agreement in Fig. 15 (right frame) is due to source mapping difficulties rather than to solar wind unsteadiness.

Upstream Events Observed over Large Regions by STEREO-A, ACE, and Wind

As STEREO-A moved away from Earth in the upstream direction, it offered a unique opportunity to study ions streaming off Earth's bow shock over a vastly larger scale than previously possible (see Figure 17 left panel). These "upstream events" are few eV to few hundred keV ion intensity enhancements of short (< few hours) duration. Using simultaneous measurements of >40 keV upstream ions observed at ACE, Wind, and STEREO-A between 2007, day 1 through 2007, day 181, Desai et al. [2007] investigated their spatial distributions by calculating the occurrence probabilities of simultaneous event detection as a function of lateral and radial separation between L1 and STEREO-A. Figure 17 (right) shows a sample period that includes coincident events. The main results of Desai et al. [2007] are (1) STEREO-A observed upstream events even when it was separated from Earth by ~1750 R_E and ~3800 R_E in the radial and lateral directions, respectively, (2) The occurrence probability (~20-30%) for measuring simultaneous upstream events at L1 and STEREO-A was far greater than that expected from accidental coincidences. (3) The occurrence rate of simultaneous upstream events at L1 and STEREO-A is significantly higher inside rarefaction regions of high-speed solar wind flows (>500 km s^{-1}) that follow co-rotating compression regions and when there exist anti-sunward propagating Alfvén waves. These new results confirm the global nature of the source region and place limits on the spatial size of the interplanetary structures that could either accelerate the ions in the first place or at the very least provide them with easier access by facilitating their scatter-free transport from the Earth's foreshock into the far upstream regions traversed by STEREO-A. These structures were identified as large amplitude Alfvén waves with spatial scales of the order of 0.03 AU or more that are embedded in and get convected past Earth by high-speed solar wind streams in rarefaction regions that follow the compression regions.

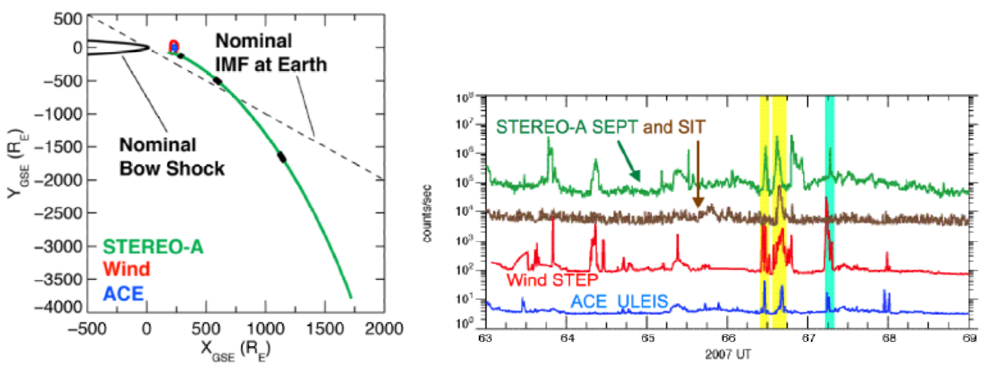


Figure 17. (left) Configuration of STEREO-A, Wind, and ACE for detecting simultaneous ion events from the Earth's bow shock. (right) Example of coincidences when STEREO-L1 separation was 580 Earth radii. *Yellow* highlighting shows triple STEREO/ACE/Wind coincidence; *blue* highlighting is an example of a discarded period since the count rate increase at each spacecraft was not sufficiently large. [Desai et al., 2007].

An Extended Magnetic Reconnection X-line in the Solar Wind

Observations by a flotilla of five well-separated spacecraft of oppositely directed plasma jets (figure 18) within an extended, bifurcated current sheet in the solar wind have demonstrated [Gosling et al., 2007] the tremendous spatial scale over which magnetic reconnection can occur in a space plasma. Reconnection is an important plasma mechanism for converting magnetic energy to bulk flow energy and particle heating and often manifests itself in spectacular ways in space, solar, astrophysical and laboratory plasmas. Measurements obtained in the solar wind by STEREO-A and B, ACE, Wind, and Geotail on 11 March 2007 have revealed that reconnection occurred within an extensive current sheet along a line (the reconnection X-line) that extended at least 4.26 x 10^6 km = 668 Earth radii = 6.12 solar radii = 0.0284 AU, and persisted for more than 5.3 hours. These minimum values are the largest yet obtained from direct measurements in a space plasma. Determinations of X-line lengths and reconnection durations are important because, along with reconnection rates, those quantities determine how much magnetic flux is reconnected in an event. Present estimates of X-line lengths and reconnection persistence are limited by the spatial extents and orientations of current sheets present in the solar wind and by available spacecraft separations. Opportunities for considerably extending the above lower limits will occur in coming years as the STEREO spacecraft drift ever farther from the Sun-Earth line (where ACE, Wind and Geotail reside) and should reveal new limits on energy transfer and the spatial and temporal extent of the reconnection process in space plasmas.

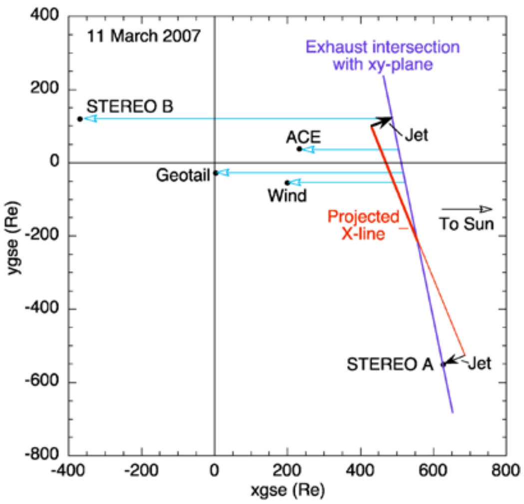


Figure 18. The positions of STEREO A and B, ACE, Wind, and Geotail on 11 March 2007 projected onto the GSE XY-plane. The violet line indicates the intersection of the current sheet with the XY plane at the time when STEREO A observed the anti-sunward-directed exhaust jet from the extended reconnection site. The red line shows the projection of the X-line onto the XY-plane at that time, the thick (thin) portion corresponding to that part of the X-line lying above (below) the XY-plane. Black arrows are projections of the oppositely directed jets observed by STEREO A and B. Blue arrows indicate the motion of the exhaust intersection as the X-line was carried anti-sunward by the nearly radial flow of the solar wind. The lengths of the blue arrows are proportional to the predicted lags relative to STEREO A for the exhaust encounters at the other spacecraft. Those lags ranged from 105 to 320 minutes and were consistent with the exhaust intersection being nearly planar, as drawn [after Gosling et al., 2007].

STEREO Serendipitous Science Results

In addition to the STEREO primary science goals, several results thus far fall purely into the category of serendipity, where the spacecraft were either in the right place at the right time or some unanticipated instrument capability exists. Some examples of these two categories are:

Tales of Comet Tails

The SECCHI Heliospheric Imager has already made valuable contributions to cometary science. When the doors were first opened on the Behind HI instrument in January 2007, the extremely bright Comet McNaught was in the field of view. Its beautifully striated tail showed evidence of a long-sought tail component consisting of neutral iron. This work by Fulle et al. [2007] claimed the honor of the first scientific publication from STEREO. Later, the HI instrument on the Ahead spacecraft witnessed the collision between a coronal mass ejection (CME) and Comet Encke which led to a spectacular detachment of the comet's ion tail as shown in Figure 19. The analysis [Vourlidas et al., 2007] suggests that the disconnection was likely triggered by magnetic reconnection, in which the oppositely directed drapped magnetic fields around the comet were crunched together by the magnetic fields in the CME. The comet fields suddenly linked together, reconnecting, to release a burst of energy that detached the comet's tail. It is expected that further analysis of this event, including detailed modeling, will lead to new insights into the interaction between the magnetized CME plasma and planetary obstacles, and to better understanding of the drivers of space weather. Still more recent observations of Comet Loneos show frequent tail disruptions by high speed streams in the solar wind.

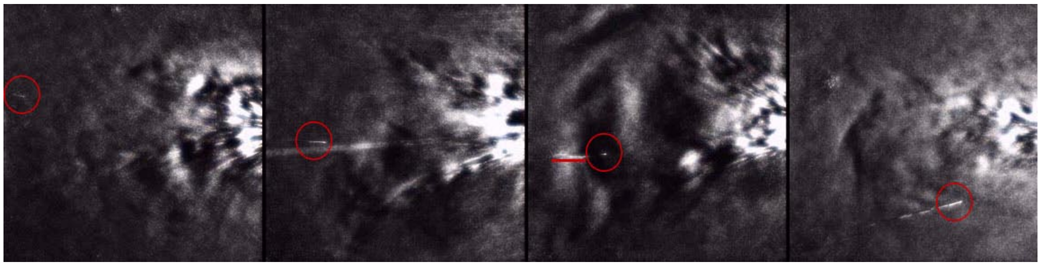


Figure 19. Selected frames from the full observing sequence of the comet-CME interaction. Comet Encke is shown inside the red circle. The stellar background has been removed and an image taken 2 hours earlier has been subtracted from each frame. From left to right, the images were taken on 2007, April 10 at 00:50UT, April 19 at 4:50UT, April 20 at 20:50UT, and April 25 at 19:30. The disconnection is shown in the 3rd frame and the tail is carried away by the CME front. The comet tail re-grows quickly and is visible in the last frame.

Strong whistler waves in the radiation belts

A key longstanding problem in space and astrophysical plasmas is determining the mechanism that accelerates electrons to relativistic energies. Although it has long been known that Earth's magnetosphere is an extremely efficient accelerator of relativistic particles that make up the Van Allen trapped radiation belts, the mechanisms via which this acceleration occurs remain a source of controversy and processes occurring on a variety of timescales have been proposed. The radiation belts consist of an inner belt at ~1.5 R_e (Earth radii) and a more dynamic outer belt at ~4 R_e , both trapped on Earth's dipole magnetic field lines. The trapped particles gyrate around the geomagnetic field, bounce between the northern and southern hemispheres and drift around Earth. For a 1 MeV electron in the outer belts, the timescales for these motions are approximately 0.0001s, 0.5s and 3000s. Energization and/or scattering can occur when electric and/or magnetic fields vary on timescales that are shorter than, but comparable to, one of these scales. Understanding the dynamics of energization and loss in the Van Allen radiation belts is critical because the MeV electrons can damage spacecraft systems.

Based on STEREO measurements, Cattell et al. [2008] report the discovery of obliquely-propagating whistler-mode waves, shown in Figure 20, in the radiation belt with electric field amplitudes more than an order of magnitude larger than other whistlers. Discovery of the large amplitude waves was enabled by the 'intelligent' S/WAVES Time Domain Sampler, which stores in memory and transmits the largest amplitude waves observed within a given interval. During a passage through Earth's dawn-side outer radiation belt, whistler-mode waves with amplitudes more than ~240 mV/m were observed by the S/WAVES instrument. These waves are an order of magnitude larger than previously observed for whistlers in the radiation belt. Although the peak frequency is similar to whistler chorus, there are distinct differences, including the lack of drift in frequency and the oblique propagation with a large longitudinal electric field component. Simulations show that these large amplitude waves can energize an electron by the order of an MeV in less than 0.1s or scatter an electron by 10s of degrees, explaining the rapid enhancement in electron intensities observed between the STEREO-B and STEREO-A passage during this event. They can also explain the simultaneous SAMPEX observations of relativistic electron microbursts. Our results show that the usual theoretical models of electron energization and scattering via small-amplitude waves, with timescales of hours to days, may be inadequate for understanding radiation belt dynamics.

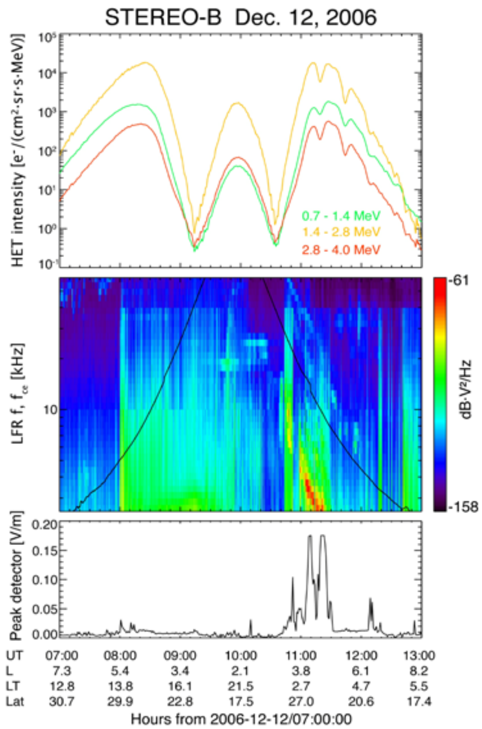


Figure 20. Overview of radiation belt observations on Dec. 12, 2006 obtained as STEREO-B moved from an L of 9 and LT (local time) ~12 to a perigee L=2.1 and LT~22 and back out to L=6 and LT ~5. The 'L' value tags a geomagnetic field line by the radial distance in R_e at which the field line crosses the equatorial plane. The top panel shows the intensity of electrons in three bands, 0.7-1.4 MeV, 1.4-2.8 MeV and 2.8- 4 MeV, from the IMPACT HET (High Energy Telescope). Note that the amplitude modulation seen on the morning-side is due to spacecraft rotation. The middle panel plots the power spectrum of the wave electric field from 2.5 kHz to 60 kHz. The black line indicates the value of f_{ce} calculated from the magnetic field measured by the IMPACT magnetometer. The bottom panel shows the peak electric field in one dipole channel seen in each minute by the TDS peak detector (sampled at 125 kHz). Note that this peak detector saturated during several minutes in the region of interest.

Stellar variability studies with STEREO's Heliospheric Imager

STEREO's Heliospheric Imagers are ideally placed for observing stellar variability. The nature of the synoptic observations means that stars can be tracked continuously through the two cameras on both spacecraft for up to 180 days. In some cases, it has taken ground based astronomers years to accumulate enough data to study just one star's variability. The same analysis can be done using just a few days of HI data. Figure 21 illustrates the HI capabilities. HI can see stars down to at least 12th magnitude, and the spatial coverage of the instruments means that many hundreds of stars can be tracked in parallel.

The photometry of the instruments is truly astounding and stable enough that we aim to explore the possibilities for astro-seismology and exo-planet research. This work is being carried out by researchers at the Rutherford Appleton Laboratory, the Open University and the University of Birmingham.

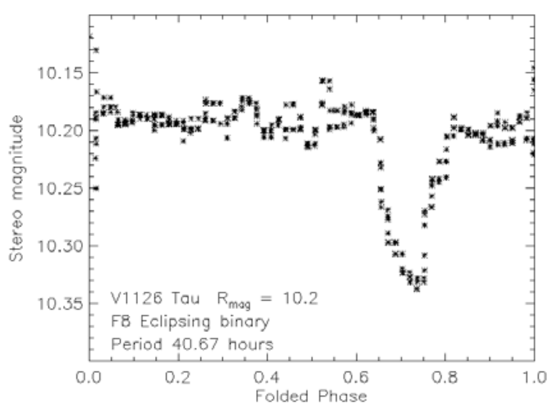


Figure 21. A 10th magnitude eclipsing binary that has been folded in phase. The intensity changes by 14%.

Interplanetary Dust

The S/WAVES instruments often detect impulsive signals that appear to be associated with dust impacts against the spacecraft body, very similar to the long-studied impulsive signals due to dust impacts on Voyager and Cassini at Saturn's ring plane crossings [e.g. Gurnett et al., 1983]. At times, the occurrence rate of these impulsive signals becomes extremely high (a least once per minute), indicating large regions of interplanetary space with much higher than nominal dust concentrations. Figure 22 shows the first year of STEREO-A plotted in ecliptic longitude versus distance. The color coded areas show where dust detection rates are low (white) and high (red) as detected by S/WAVES. Also shown are the locations where all 7 known wire antenna breakages on other spacecraft (all believed to be the result of micrometeorite hits) have occurred, covering the interval from 1979 to present. The probability for all of these antenna breakages to coincide by chance with the high dust concentration areas is less than 1%. This implies that the dust distribution pattern is very long-lived. Many of the dust impulses correspond to occasions when the SECCHI coronagraphs and heliospheric imagers record 'debris' in their fields of view. This debris, reported by orbiting coronagraphs for decades, is thought to be small pieces of insulating blanket liberated during a micrometeorite impact and floating past the lens out of focus and backlit.

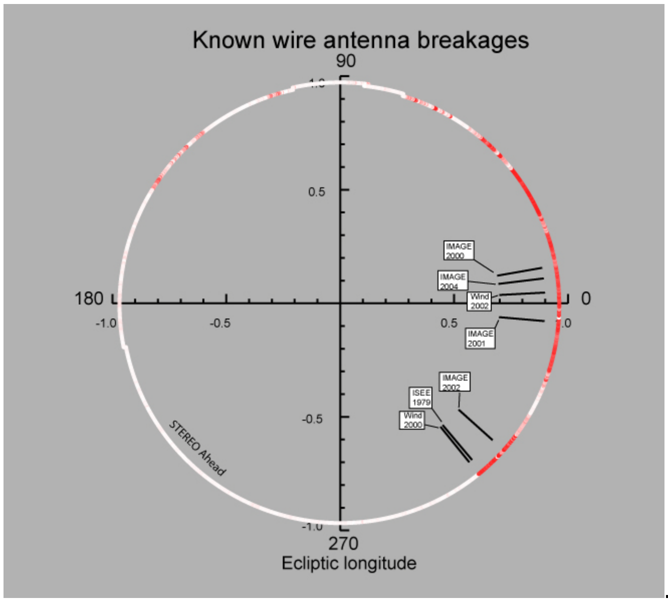


Figure 22. The location of high concentrations of dust (red areas) encountered by STEREO WAVES on the Ahead spacecraft's first orbit of the sun (Dec. 15, 2006- Nov 25, 2007). Also shown are the locations of known wire antenna breakages over the past several decades [Kaiser et al., 2007].

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III. Scientific Objectives FY09-FY12

Three factors will combine to make the science of the STEREO extended mission new and exciting. First, the spacecraft will continue to separate, changing our viewpoints on the Sun and heliosphere. By January 2011, the spacecraft are about 180 degrees apart and will provide, for the first time, a complete view of the entire sun. This will be very important for space weather forecasting, allowing active regions to be observed and characterized long before they appear on the solar East limb seen from Earth. This whole

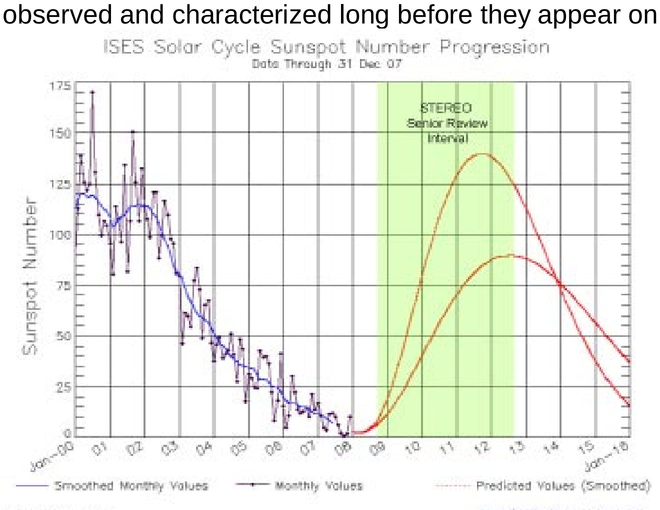

Figure 23. The timing and size of the maximum of cycle 24 are being hotly debated, but clearly the STEREO extended mission encompasses the rise to maximum activity and perhaps beyond.

sun view will also provide important 'ground truth' for predictions of solar active regions based on helioseismology measurements (SOHO and SDO). Second, the rise towards solar maximum will enable observations of increased solar activity and more complex solar wind conditions in the new cycle (see

Figure 23), enabling a comparison between solar activity minimum events already observed and solar activity maximum events in the future. Finally, during this time period there will be numerous opportunities to coordinate observations with other mission in ways which will enhance both the returns of the STEREO mission, the Heliophysics Great Observatory (HGO) fleet and international interplanetary missions in general.

Unlike many of the heliophysics missions, the STEREO spacecraft are continually receding from Earth which directly affects the telemetry link. Table 1 shows the angular and linear separation of the two spacecraft as a function of time. Corresponding to these are the supportable downlink rates for dual 34-m capability (STEREO is compatible with both 34-m and 70-m DSN networks). Throughout the nominal two year prime mission, the goal of 5 GB of data from each spacecraft is easily achieved. This data retrieval rate can be supported well into the third year of the mission before dropping to a lower rate. In about August 2009, the data rate must drop to 160 kbps using 34-m tracking antennas (full data rate still available with 70-m dish). This approximate 40-50% decrease in daily data volume will require a change in the cadence and/or data compression of the imaging instruments as well as decreases in the cadence of the non-imaging instruments (and possible use of data compression for them as well). In FY11, the data rate must decrease even further. However, this future decrease in the overall data rate in no way limits the ability of the STEREO mission to continue pursuing the primary science goals (see beginning of previous section) or those specific goals indicated below.

Table 1. Separation as a function of time and associated downlink rates for 34-m antennas.

Date	Separation (degrees)	Separation (AU)	Downlink (kbps)	Pass Duration	Daily data volume
Jan 2007	0	0	720	4hr	5Gb
Aug 2008	67	1.10	480	4	5Gb
May 2009	96	1.49	360	5	5Gb
Aug 2009	109	1.63	160	5	2Gb
Oct 2010	162	1.98	96(B)	5	1Gb
Mar 2011	173	2.00	96(A)	5	1Gb

As is evident in the previous section, STEREO has already played an important role in the Heliophysics Great Observatory. Most research to date has involved data from not only the STEREO instruments, but data from many other spacecraft as well. In addition, a substantial modeling effort has been part of the STEREO program since its inception. This strong participation in the HGO will continue into the future and will address nearly half (20:41) of the itemized research focus areas in the NASA Sun-Solar System Roadmap for Science and Technology 2005-2035. A number of key areas for extended mission focus are given below with the Roadmap objectives to which they are related noted in parentheses.

Multipoint Observations

In-situ observations of ICMEs (F4.2, F4.3, H1.1, J2.1 J3.2). ICME ejecta represent the actual coronal plasma and magnetic field expelled into heliospace during a CME. Thus their detection and characterization is essential for any detailed correlation study with their coronal sources imaged by SECCHI, SOHO, and Hinode, or any detailed Sun-to-1 AU numerical modeling analysis of an event's solar origins - including the CME connections to the solar dynamo.

The locations of the STEREO Spacecraft for 2010 through 2012, shown in Table 1, suggest we will be beyond the limits of nominal multipoint detection of most individual ICME ejecta or clouds with STEREO alone. However the presence of near-Earth measurements on ACE and Wind will continue to allow multipoint detections of the typical ejecta which are on the order of ~60-90 degrees [e.g. Gopalswamy, 2006]. The multipoint measurements provide double or triple constraints on models of the propagated coronal material, finally permitting conclusive tests of regularly used simplified ejecta models such as the cylindrical magnetic flux rope. Moreover, because some studies suggest the ejecta nature may change with the solar cycle, the extended mission measurements will provide a basis for comparison with the early cycle ICMEs observed during the prime mission. Similarly, by comparisons with ejecta studies from previous cycles, our picture of the role the CMEs play in the coronal field evolution will be made clearer.

In-situ observations of solar wind structure (F2.3, F4.2, F4.3, H1.3, J3.2). During periods of low solar activity, stable stream structure in the solar wind plasma and interplanetary field related to the slowly evolving coronal conditions allows heliospheric plasma and field forecasting with a 27 day solar rotation lead time. The prime STEREO mission enabled the investigation of the assumptions of steadiness of this co-rotating structure including comparisons with global state of the art models of the steady solar wind and its coronal source regions (see earlier discussion of current results). In particular, the multipoint measurements allowed an assessment of the ability to use STEREO-B observations to anticipate the observations at ACE/Wind and STEREO-A at the nominal co-rotation delay time for their (changing) relative helio-longitudes.

At solar maximum the combination of the more rapidly evolving solar magnetic field and the presence of greater numbers of CMEs compromises the picture of a quasi-steady co-rotating interplanetary medium. STEREO multipoint measurements at ~90 deg and greater separations from ACE/Wind will provide a measure of the extent to which the use of models of co-rotating ambient structure breaks down. In particular, it will show if they are usable at all at solar maximum, or if time-dependent 3D models are required even outside of the disturbances created by CMEs due rapidly evolving solar wind sources.

Observations of large SEP events (F2.1, F2.2, J1.1, J1,2, J2.1, J2.2, J3.1, J3.3). Solar Energetic Particle (SEP) events represent one of the most sought after measurements of space weather interest as well as the component of space weather least modeled. NASA's fleet of robotic and human explorers will rely on improved understanding of SEP generation and propagation as we continue toward a return to the Moon and beyond. One of the reasons these events are not amenable to modeling is that their physics is complex and remains only partially understood. In addition, the boundary conditions provided by the corona and interplanetary medium play a major role in determining the SEP event characteristics and detectability.

Areas of interest that will be addressed include the role of flare contributions to large SEP events, as well as the importance of the geometry of the observer connection to the CME/ICME shock and the impact of several CME/ICME events in close succession (e.g. cannibalistic ICMEs [Gopalswamy et al., 2001]). The number of SEP events detected is related to the frequency of CME/ICME shocks and their associated flares, both of which increases at solar maximum. During the relatively quiet activity conditions of the prime mission, only a few modest events were detected on both spacecraft, or on one STEREO spacecraft and ACE/Wind, allowing only limited investigation of the spatial extent and variations of the SEPs in the context of the surroundings. The extended mission provides the opportunity to substantially increase the multipoint contextual and 1 AU SEP event data base for both analyses of the outstanding questions, and toward the creation of more realistic SEP event models.

Connections of In-situ phenomena to Imaging and Radio

CME source/ICME case studies on the approach to solar Max (F4.2, F4.3, H1.1, H1.3, J2.1, J3.2). As the solar activity maximum conditions approach, the evolution of the Sun's magnetic field is expected to produce an evolving coronal setting for the initiation of CMEs. Previous studies have shown a trend in ICME North-South magnetic field 'bipolar' signatures in the ICME coronal ejecta or magnetic cloud signatures that reverse sign sometime around solar max. It has been suggested that this reversal reflects the solar polar field reversal's effects on CMEs. However, a phase shift between cloud polarity and the cycle reversal was found that indicates a more complicated association. In particular, the Hale cycle of active region polarity is out of phase with the polar field polarity cycle.

CME initiation mechanisms have been proposed that involve both parallel and anti-parallel (e.g. breakout) coronal field configurations in the CME source region. In addition, it has been suggested that the CMEs that may give rise to the relatively simple ICME ejecta known as magnetic clouds are generated mainly when the coronal large scale field is more dipolar as it is around solar minimum. The number of clouds gives way to many more complex events, but does this result from a more complicated coronal field setting for CMEs as the Sun becomes active, or to a real change in the CME initiation mechanisms? The question of whether the mechanisms evolve with the cycle as the active region polarity changes with respect to the overlying large scale field orientation, or as active regions become more complex, numerous, and proximate, can be investigated in detail with the STEREO imaging and in-situ measurements together with SOHO/ACE/Wind observations together as the Sun proceeds through its next polar field reversal in ~2010-2012.

Quadrature Observations of CMEs and ICMEs (F4.3, H1.1, H1.3, J2.1, J3.2). Not since the Helios and Solwind spacecraft missions in the late seventies and early eighties has there been the opportunity to regularly observe CMEs at the limb with an imager on one spacecraft and their ICME consequences on another spacecraft ~90 degrees away – a configuration known as quadrature. This perspective, which will be available on multiple platforms with the STEREO and SOHO/ACE/Wind constellation, will make it possible to obtain accurate records of CME/ICME radial evolution and propagation. In particular, the SECCHI HI imagers will for the first time be tracking the disturbance to the detecting spacecraft in some cases.

Previous quadrature observations suggested that CMEs slower than the ambient solar wind speed up and those faster than the ambient wind slow down, implying some ac/deceleration process at work. Current models of propagating CMEs/ICMEs simulate the deceleration and also the structural changes expected due to the fact that the ambient medium is usually non-uniform, sometimes described as a high speed wind bisected by a low speed belt, but often more complex. However it has not been possible to confirm model predictions. The STEREO extended mission configuration provides the best opportunity to confirm some long-held ideas of what happens to the initial loop-like structures observed erupting from the corona during a CME before they reach Earth.

STEREO's increasing separation has already allowed approximate quadrature studies of some small events observed during the solar minimum (see earlier description of the results from an event in May, 2007). However these were not yet in the optimal quadrature configuration. This will be realized at the beginning of the STEREO extended mission with the use of both spacecraft (one for imaging and one for in-situ measurements) when they are separated by ~90 degrees. As the separation increases the quadrature observations will be made with the combination of either of the STEREO spacecraft and SOHO for images or ACE/Wind for in-situ. The start of quadrature observation opportunities will thus be realized around the onset of solar maximum and end with the opportunities to observe many large CMEs from the side with STEREO that are observed at SOHO as haloes and at ACE as ICMEs. It is noteworthy that toward 2011-2012 we will have imagers observing effectively the entire 360 degrees solar disk for the first time in history, and at a solar max.

Solar Wind Source Evolution from min to max phase (F2.3, F4.3, H1.3, J2.1, J3.2). STEREO operations commenced during an exceptionally deep and prolonged declining phase of the solar cycle. During the first year of the mission the high speed streams characteristic of the declining phase and solar minimum dominated the observed solar wind. In some cases the observed structures can be well-modeled using magnetogram-based coupled corona and solar wind models, but in other cases the models and data do not agree very well. These results are being used to understand the nature of the different solar wind source regions: polar coronal holes and their extensions and boundaries, and low and mid-latitude open field regions, including those rooted near active regions. Ultimately this knowledge will be used to improve the physical assumptions in the models concerning the nature of the sources- especially their steady versus transient nature. STEREO continues to provide heliolongitude-separated measurements that allow an assessment of the steadiness of the solar wind structure. We expect as the cycle progresses to observe the solar wind structure evolving from its now nearly steady co-rotating state to a more rapidly evolving state in response to the more active coronal field evolution. We will be able to investigate the timing and characteristics of that evolution, including the growing contributions of ICMEs to the differences measured by the two spacecraft (and ACE/Wind).

One aspect of these studies that is especially interesting from a long term solar behavior point of view is that the current cycle appears to be quite anomalous compared to the two previous cycles, in terms of its solar magnetic field behavior. In addition to an unusually slow declining phase of cycle 23, the magnetographs have shown that the solar polar fields are weaker than those at previous cycles by a factor of 2-3. Helioseismology measurements indicate that this is related to a slower meridional circulation bringing decayed active region flux to the poles- part of the mechanism dynamo theorists consider responsible for the cancellation of old cycle polar flux, polar field reversal, and the seeding of the tachocline with flux for the new cycle active regions.

One result of these differences is two classes of significantly divergent solar activity maximum predictions. Researchers who consider the solar polar flux to be important predict a much weaker cycle maximum than the previous two, while those who use dynamo theory models predict a comparable or larger maximum. Thus this cycle will be a true test of our understanding of the solar dynamo and its consequences for the heliosphere. Some consequences have already been observed in the recent solar wind measurements that show unusual mid-latitude high speed wind contributions (see earlier discussion in results to date section). STEREO observations will be used to record the evolution of this anomalous cycle using both the solar wind source images from SECCHI and the distributed in-situ measurements of the solar wind and interplanetary field structure. STEREO will also be observing any associated unusual CME activity trends. This is a potentially history-making cycle for heliophysics and can be exploited with the instrumental resources available to us by the timing of the STEREO mission.

New Interpretations of STEREO observations made possible in the future by SDO (F1.1, F2.1, H1.2, J2.1). SDO (Solar Dynamics Observatory) will be launched at the end of 2008 with several new capabilities for coronal imaging and solar magnetic field observations that can improve ongoing efforts to interpret the STEREO distributed measurements in the quadrature configuration described above. First, the provision of extremely high cadence full-disk high resolution EUV images will allow diagnostics of the eruptive activity observed to date with SECCHI and SOHO on an unprecedented time-scale. This capability should revolutionize our ability to answer the long-standing questions related to the flare-CME relationship. Some measurements in images, radio, and in-situ solar energetic particle (SEP) data indicate a flare follows the initiation of a CME while others indicate it may occur at an arbitrary time or not at all. Timing studies will be possible using the SDO images in relation to the SECCHI images and STEREO SEP measurements and S/WAVES radio bursts that finally resolve this ambiguity, which is important to understanding what happens on the Sun during the explosive transient events of both types.

Second, the availability of full-disk vector magnetograms from SDO will provide the modelers of STEREO events with a powerful new boundary condition with which to initiate their simulated CMEs. While prime mission modeling using time-dependent scalar magnetograms from ground-based GONG magnetographs and SOHO MDI, and local vector magnetograms from Hinode will push the state-of-the-art, the more global view of the vector field on the Sun's surface will provide a much more accurate perspective on the overall energization of the coronal magnetic fields. This includes energizations of several active regions on the disk simultaneously during solar maximum conditions when eruptions multiple eruptions, are common. Of particular interest will be any widespread or global events that occur. At least one or two such events typically occur per solar cycle. With STEREO providing distributed in-situ and multi-perspective imaging capability for comparisons, STEREO data providers and modelers are poised to use the SDO observations to investigate the nature of these highly complex and important extreme events.

STEREO support for other missions, planned and future

Planetary Space Weather Studies: Messenger (H4.3, J4.3, J4.4). During the extended mission, Messenger enters its orbit around Mercury in March 2011. One of the Messenger goals is the observation of the Mercury-Sun and Mercury-solar wind interaction and its consequences. Messenger will rely on other heliospheric spacecraft to provide contextual information about the state of the solar wind and the presence of any flare or ICME activity that may impact them. The STEREO imaging will of course add to SOHO and SDO imaging in terms of characterizing the general state of the Sun and the prevailing active regions, but a critical advantage to the planetary missions is provided by the STEREO ability to provide information concerning portions of the Sun invisible from Earth. A number of the processes that will be investigated are dependent on solar EUV flux and knowledge of the presence of flaring on the disk as seen from the planet. In the past, calculations based on the rotation of the non-uniform corona's emissions observed at Earth were used to estimate the EUV and X-ray fluxes at the planets, based on the often poor assumption (at solar max especially) that they are not evolving. STEREO imaging provides a greatly superior way of estimating the relevant EUV fluxes at solar system locations significantly far in heliolongitude from Earth. In addition, because the STEREO spacecraft are in the ecliptic plane at separated helio-longitudes, they also provide a distributed network for monitoring interplanetary conditions - including solar wind plasma, interplanetary field, and energetic particles away from the Earth-Sun line. Considering the expected non-stationary solar wind conditions in the heliosphere around solar max, and also the expected likelihood of significant numbers of CMEs/ICMEs, STEREO will be of great value in establishing the local heliospheric conditions at Mercury. Similarly, the multiple image viewpoints will allow unprecedented deduction of the directionality of the CMEs heading into the heliosphere, and their likelihood of impacting the planets or interplanetary spacecraft. If Venus Express is still operating at the time, it too will enjoy this resource for heliospheric space weather information provided by the presence of STEREO. STEREO is already being used by the Venus Express team in their studies of the response of the Venus-solar wind interaction to ICME events at Venus.

Interaction between the heliosphere and the local interstellar medium (F2.1, F3.4). Pickup ions originate from neutral atoms entering the heliosphere that become freshly ionized due to various mechanisms, and are subsequently "picked up" by the solar wind. Because the pickup process generates speeds up to twice the solar wind speed (in the spacecraft frame), these ions can be easily injected into acceleration mechanisms. As indicated earlier, pickup ions have been observed as a source population for particle acceleration at shocks and CIR compression regions.

Due to the combined effects of the Sun's gravity and ionization, the neutral interstellar He flow through the inner solar system forms a distinctly shaped gravitational focusing cone on the downwind side of the Sun, from which the interstellar parameters have been derived. Studies of pickup ions have shown substantial temporal and spatial variations in their flux, the reason for which is only partially known, thus limiting the accuracy of interstellar parameter studies. Untangling spatial from temporal variations requires a three-dimensional constellation of heliospheric spacecraft. STEREO provides two additional simultaneous in-ecliptic measurements separated in solar longitude. These will be combined with near-Earth in-ecliptic observations with ACE and the future measurement of the neutral He flow at 1 AU with IBEX.

The IBEX mission is scheduled for launch in 2008. IBEX will be recording global fluxes of energetic neutral atoms (ENAs) over the whole sky in the energy range from 10 eV to 6 keV. The ENAs of primary interest come from the termination shock (TS). There are ENA losses on their way from the TS inward to 1 AU. One of these loss mechanisms is charge exchange with solar wind protons, which is effective up to at least 100 keV. (Photoionization is expected to be of lesser importance since the energies/velocities of the ENAs are mostly outside the line width of the solar Ly-alpha.) As IBEX will be doing full sky observations, it is important for their mission objectives to know the full 3D solar wind distribution near Earth's orbit. Modeling will be crucial, and "ground truth" solar wind data from the two STEREO longitudes, combined with L1 measurements from SOHO, ACE, and Wind, have an important role.

SEP event, shock, and southward Bz forecasting for Space Weather uses (F2.1, H1.3, J2.2, J3.1). Major goals of space weather forecasting continue to be the measurement and prediction of solar energetic particle (SEP) events and of fast ICMEs with large southward interplanetary fields at Earth. For SEP events, the existence and strength/speed of the relevant shocks of ICMEs enroute can be better evaluated than during previous solar maxima from the side views provided by the SECCHI heliospheric imager and by the radio triangulations of the moving shock position versus time. In addition to providing a means of predicting when a shock will hit Earth, the apparent time evolution of the shock can be used to interpret any SEPs that are observed at Earth in advance of its arrival in terms of intensities of accompanying energetic storm particle events.

Whether or not southward magnetic field is involved in an observed ejection is a much more difficult problem, but may be deduced via MHD modeling of the observed STEREO events based on solar magnetic field observations. In particular, the prediction of a contribution by the ICME sheath to the southward Bz in the ICME disturbance may be regularly achievable. STEREO's view of Earth-approaching ICMEs from the side can be used to experiment with such model predictions of southward fields, as the HI signatures may represent the sheath portion of the ICME.

In all these ways, STEREO's extended mission provides a test-of-concept for future space weather monitoring missions that may have the option to choose a quadrature-like viewpoint. The fact that all of this will occur as we move from solar activity minimum into a solar maximum period is also advantageous because of the transition from individual well-observed CMEs to more chaotic conditions with the expected large number of events.

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IV. **Technical and Budget**

Spacecraft status and operations. STEREO was launched on October 26, 2006 at 00:52 UT and spent several weeks in eccentric Earth-centered orbits with apogees near the moon. On December 15, 2006 (both spacecraft) and again on January 21, 2007 (Behind spacecraft only), close swing-bys of the moon were used to insert the two spacecraft into orbit around the sun. Ahead was placed in an orbit slightly smaller than Earth's so that it circles the sun in about 343 days instead of 365. Behind is slightly further away from the sun than Earth, orbiting every 388 days. As viewed from the sun, Ahead and Behind separate from each other at about 45 degrees per year, with Earth approximately bisecting the angle.

The official start of the prime mission occurred when both spacecraft reached heliocentric orbit. Technically, this occurred on January 21, 2007, but for budget simplicity it is carried as February 1, 2007. Thus, the STEREO Mission has completed year one of its prime mission. Year two (Feb. 1, 2008 to Jan 31. 2009) continues full mission operations and science analysis. Year three (Feb. 1, 2009 to Jan. 31, 2010) is currently budgeted to be a year of data analysis only; no mission operations.

To date, all spacecraft systems with one exception have performed nominally. The one exception was the failure of an X-axis inertial measurement unit (gyro) on the Ahead spacecraft in the late Spring of 2007. The spacecraft immediately switched to the backup unit and has been running flawlessly since. In the case that this backup unit also fails, the spacecraft attitude can be maintained using the SECCHI guide telescope.

The spacecraft thruster systems, used mostly for the occasional momentum 'dump', have enough hydrazine on each spacecraft to survive for more than 100 years.

STEREO began automated unattended tracks on April 30, 2007. To date, 95% of the tracks have been nominal and tracking station problems account for nearly all of the other 5%. The Missions Operations Center (MOC) at Johns-Hopkins Applied Physics Laboratory is now staffed only 5 days a week, 8 hours per day. During this first year of operations both manned and automated, the daily data rate collected from each spacecraft has routinely exceeded the required 5 Gb per day by about 40%.

Instrument status and operations. By the time of insertion into heliocentric orbit, all instruments had completed their initial check-outs and commissioning and were collecting routine data. Only two instrument problems have occurred, neither of them serious enough to jeopardize the scientific goals of the mission. They are:

- Effective loss of the STE-U on both spacecraft due to sunlight reaching the detectors probably via some second surface reflection not found during spacecraft testing. This loss results in decreased sensitivity to electrons in the few keV range arriving from the solar direction. However, backscattering of these particles into the oppositely directed STE detector and some overlap with SWEA partially fill this important gap.
- Interference in the S/WAVES instrument on the Behind spacecraft. This interference is associated with the IMPACT boom and likely due to a faulty ground wire. The interference occurs at 16 and 100 kHz. This limits S/WAVES ability to do three-antenna direction finding below 100 kHz on all but the strongest solar events. This is not a serious limitation and time-of-flight direction finding and use of Wind/WAVES direction finding has filled the missing capability.

V. **E/PO**

The STEREO E/PO program is a multi-faceted effort involving projects at a number of different institutions [see Peticolas et al., 2007 for a description of pre-launch programs]. These projects will be described in a pair of proposals to be submitted to the mission E/PO call later this year. Here we give a short overview of our activities thus far in Phase E and our plans for the future.

Formal Education: STEREO E/PO team members have developed lesson plans connecting standards based material taught in middle and high school to STEREO mission applications. The IMPACT team has developed a series of lesson plans teaching magnetism and supported their dissemination via a series of teacher workshops in California and elsewhere. The S/WAVES team is currently completing work on classroom materials that will allow high school students to use real radio receivers to understand radio triangulation and trigonometry and to explain the basics of space radio astronomy at the middle school level. SECCHI's TOPS (Top Teachers of Physical Science) program teaches pre-service K-8 teachers principles of physics using space data to illustrate their expression in the Sun. A text and CD for this one-semester course are in preparation. The STEREO Science Center (SSC) has also produced a CD concerning the space weather for use by teachers of grades 4-12.

Informal Education: STEREO/SECCHI imagery is distributed to museums and science centers through a number of channels including the NASA Museum Alliance, ViewSpace, and the AstroBulletins Network. Sonification projects conducted by IMPACT and S/WAVES are primarily (although not exclusively) oriented towards using sonification in museum and science center environments. The PLASTIC team has a close partnership with the Christa McAuliffe Planetarium (CMP) in Concord New Hampshire, supporting many outreach events. The STEREO project also assisted in the development a privately produced 3D show about STEREO currently being shown in science museums.

Plans for the Future: STEREO plans to be involved in two proposals to be submitted to the mission E/PO proposal call next summer. One of these will be lead by Laura Peticolas of the IMPACT Team and will create space weather "event-templates" for local or regional events at science centers which incorporate sonification and magnetism materials the group has already developed. We will partner in that with the WIND team. Another proposal lead by Therese Kucera will cover the remaining STEREO activities. These activities will be continuation of activities mentioned above, including the distribution of imagery and related materials to museums, the CMP partnership, production of hard copy materials, TOPS, and the completion of the S/WAVES radio astronomy and triangulation materials.

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Appendix B. STEREO Acronyms

ACE - Advanced Composition Explorer

AGU - American Geophysical Union

APL - Applied Physics Laboratory

AR - Active Region

AU - Astronomical Unit

CACTUS - Computer Aided CME Tracking

CCMC - Community Coordinated Modeling Center

CDAWeb - Coordinated Data Analysis

CIR - Co-rotating interaction regions

CME - Coronal Mass Ejection

CMP - Christa McAuliffe Planetarium

COR1 - SECCHI Inner Coronagraph

COR2 - SECHHI Outer Coronagraph

COSPAR - Committee On SPAce Research

DSN - Deep Space Network

EGU - European Geosciences Union

EPAM - Electron, Proton, and Alpha Monitor

EPO - Education and Public Outreach

EUV - Extreme UltraViolet

EUVI – SECCHI Extreme UltraViolet Imager

FY - Fiscal Year

GB – GigaByte

GOES - Geostationary Operational Environmental Satellite

GONG - Global Oscillation Network Group

GSE - Geocentric Solar Ecliptic

GSFC - Goddard Space Flight Center

HET – IMPACT High Energy Telescope

HGO - Heliophysics Great Observatory

HI - SECCHI Heliospheric Imager

IBEX - Interstellar Boundary Explorer

ICME - Interplanetary coronal mass ejection

IMPACT - In-situ Measurements of Particles and CME Transients Investigation

JHU - Johns Hopkins University

kbps - Kilobits per second

L1 - First Lagrangian Point

LASCO – SOHO Large Angle and Spectrometric Coronagraph

LET – IMPACT Low Energy Telescope

MAG – IMPACT Magnetometer

Mbits – Megabits

MDI – SOHO Michelson Doppler Imager

MHD - MagnetoHydroDynamics

MO&DA - Mission Operations and Data Analysis

MOC - Mission Operations Center

NASA - National Aeronautics and Space Administration

NOAA - National Oceanic and Atmospheric Administration

NRL - Naval Research Laboratory

NSSDC - National Space Science Data Center

OMNI – OMNIWeb database

PFSS - Potential Field Source Surface

PI - Principal Investigator

PLASTIC - PLAsma and SupraThermal Ion Composition Investigation

POC - Payload Operations Center

PS - Project Scientist

S/WAVES - STEREO Waves Investigation

SAMPEX - Solar Anomalous and Magnetospheric Particle Explorer

SDO - Solar Dynamics Observatory

SECCHI - Sun Earth Connection Coronal and Heliospheric Investigation

SEP - Solar Energetic Particle

SEPT – IMPACT Solar Electron Proton Telescope

SIT – IMPACT Suprathermal Ion Telescope

SOHO - Solar and Heliospheric Observatory

SOWG - Science Operations Working Group

SSC - STEREO Science Center

STE – IMPACT Suprathermal Electron Telescope

STEREO - Solar TErrestrial RElations Observatory

STP - Solar Terrestrial Probes

SWEA – IMPACT Solar Wind Electron Analyzer

SWG - Science Working Group

TOPS - Top Teachers of Physical Science

VHO - Virtual Heliospheric Observatory

VSO - Virtual Solar Observatory

WSA - Wang-Sheeley-Arge