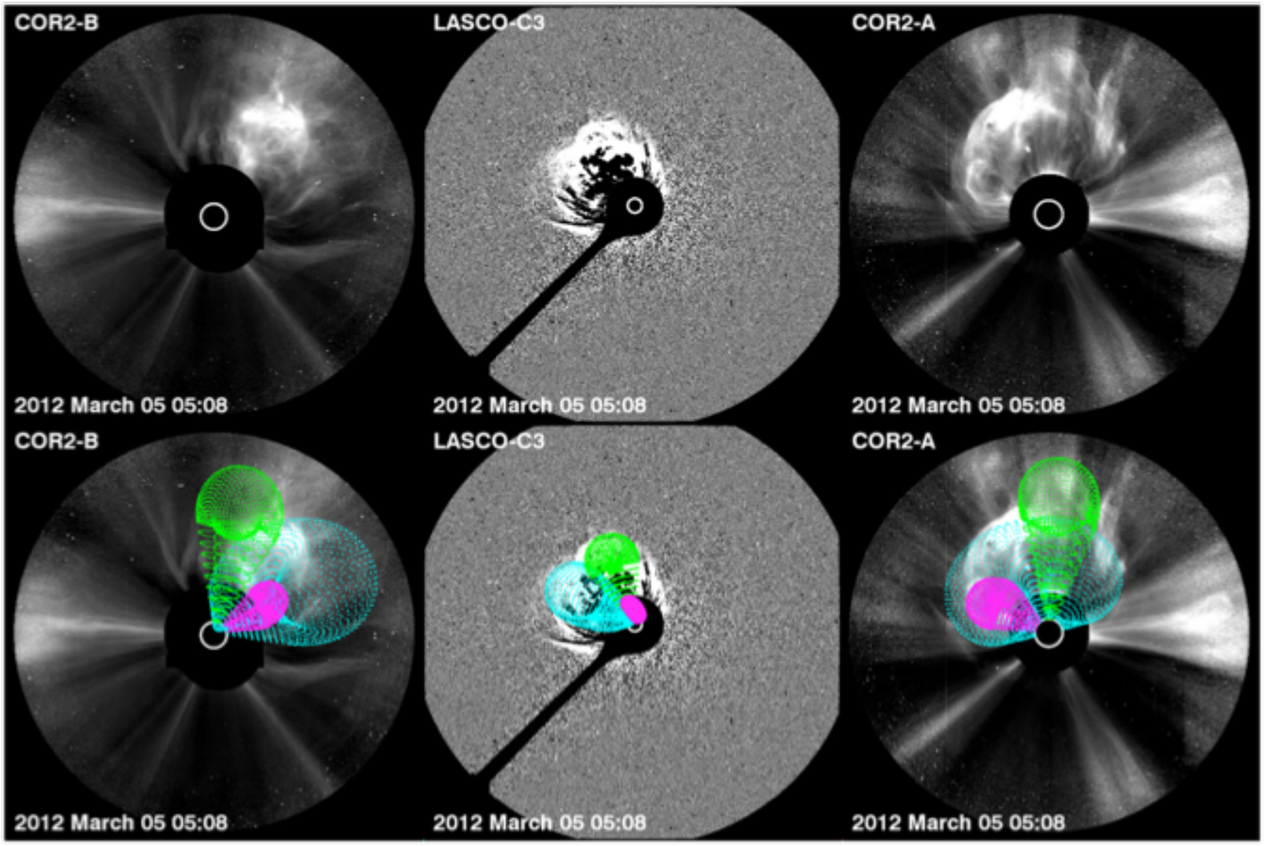
STEREO

A PROPOSAL TO THE SENIOR REVIEW OF HELIOPHYSICS OPERATING MISSIONS

FEBRUARY 2017



Analysis of the interactions of three CMES made possible by STEREO. Interaction of CME-3 (blue) with CME-1 (magenta) and CME-2 (green) at 6.8, 13.4, and 13.1 $R_\odot$, respectively. The separate fronts of all three CMEs are most evident in the COR2-A (top right). From Colaninno & Vourlidas (2015).

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Solar TErrestrial RElations Observatory (STEREO)

I. Executive Summary

The STEREO Mission, with its broad longitudinal coverage of the sun and heliosphere and its combination of in situ and remote sensing instrumentation, has revolutionized our ability to consider and understand the sun and heliosphere as an integrated system. STEREO's unique vantage point makes it a key component of the Heliophysics Observatory fleet, expanding its scope through the inner heliosphere. The importance of the STEREO point of view will continue to increase as new missions are launched into the inner heliosphere.

The STEREO mission was launched in late 2006 and completed its prime phase in 2009 January, after nearly two years of heliocentric operations. STEREO has now completed over a decade of science operations. Its data are freely available at the STEREO Science Center and instrument team websites and used by scientists all over the world, resulting in over 1,280 STEREO based publications in the refereed science literature.

STEREO has been making important progress on its ten prioritized science goals, which are focused in three broad areas: understanding space weather throughout the inner heliosphere, studying solar corona over 360 degrees, and taking advantage of the coverage of the full heliosphere. STEREO-based research has expanded our understanding of the factors affecting CME passage from the Sun through the heliosphere, the physics of solar energetic particles, and predicting and measuring the effects of space weather through the solar system. STEREO far side observations have enhanced our understanding of the evolution of active regions and CMEs not directly impacting (but sometimes still affecting) Earth. STEREO's unique capabilities have also made possible new investigations into the structure and origins of the solar wind.

With the upcoming solar minimum we will continue our studies of space weather, including its variations over the solar cycle, but we will also consolidate some of our science goals, making room for a new set of goals focused on the study of the corona and solar wind at solar minimum. We will be able to provide unique data from near the L5 point to help with prototyping future missions to that area and to provide vital support and context for the soon to be launched Solar Probe Plus and Solar Orbiter missions.

Section II describes mission status, including operations during the recent superior conjunction and STEREO-B recovery efforts. In Section III, we describe data accessibility and impact, and progress on and plans for our Prioritized Science Goals. Section IV provides an overview of the technical state of the mission, and Section V discusses budget issues. The mission archive plan is discussed in Appendix A. Additional appendices cover publications (B), spacecraft and instrument status (C), Roadmap research focus areas (D), and acronyms (E).

The following individuals were among those involved in the writing of this proposal on behalf of the STEREO Science Working Group: J. Luhmann (UCB), R. Mewaldt (Caltech), A. Galvin and C. Farrugia (UNH), D. Ossing and A. Vourlidas (JHU/APL), W. Thompson (Adnet), E. Christian, G. De Nolfo, N. Gopalswamy, J. Gurman, T. Kucera and R. MacDowell (GSFC). Numerous members of the Principal Investigator (PI) teams submitted early drafts.

II. Mission Status

IIa Launch, orbital design, and IMU

The *STEREO* spacecraft were launched on a single Delta II vehicle on 2006 October 25 (October 26 UT) and inserted into heliocentric orbits in 2006 December (STEREO-A) and 2007 January (STEREO-B) using lunar phasing orbits and three lunar swingbys. Since the STEREO-B spacecraft (also known as *Behind*) was placed in an orbit with semi-major axis slightly larger than Earth's, and STEREO-A (a.k.a. *Ahead*) in an orbit slightly smaller, each spacecraft appeared to drift away from the Earth-Sun line by 22° per year through opposition (2011 February), when each spacecraft was roughly 90° from the Earth-Sun line, and then to approach the Earth-Sun line on the far side of the Sun until superior conjunction (2015 January - July). The prime mission was designed for two years' operation starting with the STEREO-B heliocentric orbit insertion, with engineering sufficient to sustain an extended mission of up to five years' duration — which we have exceeded.

The only major spacecraft subsystem failures in the 10 years after launch were the loss of the inertial measurement units (IMU, discussed below) and 2 battery cells on STEREO-B (see Section IIc).

The primary IMU failed on the STEREO-A spacecraft on 2007 April 11 and the primary IMU on STEREO-B began degrading in 2012. The backup IMUs were put into service to replace each of the primaries. In 2013, to preserve the remaining IMU lifetime on STEREO-A, the Mission Operations team at Johns Hopkins University Applied Physics Laboratory (JHU/APL) devised a method for maintaining pointing accuracy during scientific observations using the star tracker on each spacecraft for roll reference, and the SECCHI guide telescope for pitch and yaw. The IMUs would be powered on only in case of anomaly and for momentum managements; it was thought that would extend the usable lifetime of the remaining IMUs for some years to come. After the backup IMU on STEREO-B failed on 2014 January 5, this reduced gyro operations concept using the degraded primary IMU was deployed on STEREO-B as well. The primary IMU failed on STEREO-B on 2014 October 1.

In 2015, after superior conjunction, to further conserve the limited IMU lifetime (estimated at ~60 days of continuous use); the STEREO-A observatory was configured to use the IMU only for fault protection, mainly prolonged star tracker outages, which occur once every couple of years. This configuration change was done after demonstrating that instrument calibration rolls and momentum management could be done successfully without the high rate IMU data. There have been changes to the spacecraft autonomy rules on STEREO-A to prevent a loss of attitude control similar to what happened on STEREO-B (see below). For instance, if even a single gyro within the IMU is producing bad data, only the solar presence detectors on all sides of the spacecraft will be used for attitude determination.

IIb Superior conjunction and science data return

During 2015 the two STEREO spacecraft went through superior conjunction, during which time they were behind the Sun as seen from Earth. Science data return was significantly reduced for a 15-month period centered about superior conjunction to protect the high gain antenna (HGA) feed on both STEREO spacecraft. As the Sun-spacecraft-Earth angle approached zero, the parabolic HGA focal point for solar radiation began aligning with the HGA feed assembly resulting in sustained high temperatures of the feed assembly. To prevent damage, the HGA was off pointed to use the HGA side lobes to maintain daily communications and return limited science for this period. Heavily subsampled telemetry for the IMPACT, PLASTIC, and S/WAVES instruments was recorded for this 15-month period and downlinked completely in November

2015. During this 15 month period, as the space weather beacon signal was too weak for the NOAA antenna partners to receive due to the HGA off pointing, additional DSN 34m supports were added each day to provide some real-time space weather data. STEREO-A returned to nominal daily science operations on 2015 December 28. Since then the average daily science data return has met or exceeded the prime science requirement of 5 Gbits per day from STEREO-A.

Each STEREO spacecraft is hard-wired to put itself into safe mode, with power-positive attitude, in the event of 72 hours' passing without contact from earth. This system reset essentially power cycles the spacecraft. The slow orbital drift rate resulted in an unprecedented communication blackout of 3.5 months for STEREO-A and 2 months for STEREO-B, so that a system reset would occur 35 times for STEREO-A and 20 times for STEREO-B during superior conjunction. It was determined that subsampled scientific observations could be carried out during the communications blackout and recorded on each spacecraft's solid-state recorder (SSR). Only the S/WAVES team decided to make use of this opportunity; the other instrument teams decided to avoid issues with the repeated power cycling of high voltage systems (IMPACT and PLASTIC) or that the data volume returned from such operations did not justify the operational risk (SECCHI).

In 2015, after superior conjunction, an increase in guidance and control (G&C) fine pointing loss and the magnitude of the attitude roll error was noted on STEREO-A. While the observatory continues to meet pointing requirements, the impact to SECCHI imaging science has been minimized by tuning guidance and control (G&C) parameters.

IIc Status of the STEREO-B spacecraft

On 2014 October 1, the mission operations team was testing the transition of spacecraft autonomy on the STEREO-B spacecraft when dual single point failures followed one another in quick succession. After the spacecraft reset, the star tracker failed to acquire guide stars in a timely fashion, so the onboard autonomy rules caused the remaining primary IMU to be powered on in order to maintain a power-positive attitude. Unfortunately, the IMU not only experienced the failure of a ring laser gyro, but the onboard monitoring and control software continued to regard the bad and highly biased data coming from the IMU as still valid. It is suspected that the spacecraft turned away from the sun and may have fired thrusters to reduce the phantom rotational rates. Communications were lost as the battery depleted, leaving the spacecraft in an uncontrolled rotation. NASA convened a Failure Review Board and produced a set of recommendations for spacecraft recovery.

By implementing the NASA Failure Review Board recommendations, the first recovery attempt began with carrier detection by the DSN on 2016 August 21. At a spacecraft range of ~2 AU, the observatory was found to be rotating slowly about its principal axis of inertia for which the uncontrolled attitude allowed some solar array input and continuous uplink and downlink communications on the low gain antenna at emergency data rates. Over the next 22 days, significant obstacles to recovery were overcome with a collaborative effort of the JHU/APL engineering team, NASA GSFC, DSN, JPL Radio Science, FDF, SSMO scheduling, and Mission Operations teams. This consisted of:

- Reliably commanding a rotating spacecraft with uncontrolled attitude at a distance of 2 AU
- How to power on the spacecraft that was never designed to be off without collapsing the battery voltage
- Acquiring telemetry at higher rates than the emergency data rate from a spacecraft that is rotating with an uncontrolled attitude
- Warming a frozen propulsion subsystem with a degraded battery and limited solar array input with an uncontrolled attitude

•Configuring, loading, and verifying processor tables and parameters with very limited telemetry
•Conducting an autonomous momentum dump in the blind and transitioning to C&DH standby mode and successfully receiving telemetry on the HGA indicating star tracker lock and decreasing system momentum.

However, system momentum level remained above the threshold for re-establishing attitude control with the reaction wheels. Due to the uncontrolled attitude, communication degraded and the last detection of the carrier was on 2016 September 23.

At the ~2 AU spacecraft range, while few telemetry packets were received, much was learned. During the first attempt to re-establish attitude control on STEREO-B in 2016 August, from limited telemetry it was determined that 2 out of 11 pressurized battery cells were not functioning. While this degraded the main bus voltage by ~ 6 volts, there remains sufficient battery voltage to return the spacecraft and all instruments back to nominal daily science operations once attitude control is restored.

From the limited data, despite the lower battery voltage, the STEREO-B observatory has proved to be a resilient spacecraft capable of surviving under an array of circumstances that it was not designed to accommodate. Consequently, the hope of recovery persists. Monthly battery conditioning and communications recovery efforts are continuing and a second recovery attempt may be possible in late 2017.

Since the status of STEREO-B is still in doubt, the science and technical sections that follow discuss the cases of one- and two-spacecraft mission extensions, and we are including two proposed budgets, for one- and two-spacecraft operations respectively (see Section V).

III. Science and Science Implementation

IIIa. Data Accessibility and Impact

A Note on Hyperlinks: Rather than spelling out URL’s, which tends to introduce awkward line breaks in the text, we provide a hyperlink (in blue and underlined) for each Internet-accessible resource mentioned in this proposal. The hyperlinks should be clickable in the PDF version of this document.

Research and space weather uptake. Data from STEREO have been incorporated into many scientific investigations and many services that use data from multiple assets of the Heliophysics System Observatory (HSO). Since the launch of STEREO in 2006 October, some 1280 refereed publications have made use of STEREO data, and STEREO data are regularly featured at scientific conferences (see Section IIId and Appendix B).

The services using STEREO data include the SolarSoft Latest Events service maintained by the Lockheed-Martin Solar and Astrophysics Laboratory, the Integrated Space Weather Analysis System from NASA Goddard Space Flight Center, and the University of Science and Technology’s DREAMS Website in China. The NOAA Space Weather Prediction Center uses STEREO space weather data on a regular basis, and serves them via a Website similar to that used for serving ACE realtime solar wind data. The UK Met Office (responsible for space weather in the UK) uses STEREO data in their predictions and research-to-operations work. Also, the asteroid and comet-hunting communities have become avid users of the STEREO data, and even the variable star community has found the data valuable.

Data Accessibility. All STEREO science data are accessible on the Web through the STEREO Science Center (SSC) archive. The data in the SSC archive are obtained from servers at the PI sites by regular mirror processes running several times per day. The STEREO and SSC Websites together served ~36 Tbytes of data in 2015, and ~53 Tbytes in 2016. The lower volume in 2015 reflects the drastically reduced telemetry rates and several month (mid-March through June 2015) blackout during superior conjunction.

The Virtual Solar Observatory (VSO) 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. The Virtual Heliospheric Observatory (VHO) serves PLASTIC solar wind, IMPACT magnetometer and particle data, and S/WAVES intensity spectra. The Heliophysics Data Portal (HDP, formerly "VSPO") provides access to STEREO data from many different sources, including the VSO and VHO. SPASE descriptions for almost all STEREO science data products have been registered within the Space Physics Data Facility, as well as most browse data products. Data are also available from the individual PI and Co-Investigator (Co-I) institutions, and in the case of some of the in situ and radio data at the CDAWeb website at the Space Physics Data Facility (SPDF). A list of all access sites is maintained on the STEREO Science Center Website.

Adherence to standards has allowed STEREO data to be easily incorporated into a number of online browse tools, including the ones used for space weather mentioned above. Interactive plots of in situ and radio data, together with the data themselves, are available through the CDAWeb. The HDP maintains an extensive list of STEREO-related services.

A number of other browse tools that enhance accessibility have been developed by the instrument teams. In addition to the NOAA beacon mode site noted above, 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 S/WAVES instrument sites. For example, daily Javascript movies from the SECCHI telescopes can be viewed at various resolutions at a SECCHI movies Webpage, and the IMPACT team combines STEREO and ACE realtime data to create displays emphasizing the solar system context of the multipoint measurements. Additional S/WAVES data are available from the Centre de Données de la Physique des Plasmas in France. The SECCHI/COR1, SECCHI/HI, and S/WAVES teams are providing higher-level data products (e.g. event catalogs) to direct researchers to the most interesting data sets. Additional event lists combine IMPACT and PLASTIC data on shocks, ICMEs, stream interactions, and SEP events, and another list of suprathermal events is provided by the PLASTIC team. These latter lists are archived on the SSC website as Level 3 data products. The STEREO Space Weather website at NRL contains links to ancillary data for major events observed by many of the STEREO instruments.

The data products available from the STEREO project are now in a mature state. CDF versions of the Level 2 data for the IMPACT SEP suite are in the process of being added to the ASCII versions of these data. Since the last Senior Review, the French IRAP Plasma Physics Data Center (CDPP) is now serving higher level S/WAVES products associated with direction finding and wave polarization capability and offers various tools based on the SECCHI observations. A new SECCHI HI Level 2 product, based on a sophisticated analysis by the Southwest Research Institute, is now available for STEREO-A. Space weather packets from the IMPACT, PLASTIC, and S/WAVES instruments—stored onboard during the 15 month period when the STEREO-A spacecraft was in reduced operations or completely out of contact on the far side of the Sun—were processed by the SSC after these data were finally read out with the resumption of normal operations. These data can be used to fill in for the higher resolution data that are missing during the solar conjunction period. All these data products are archived within the SSC.

The remote sensing and in situ data being actively delivered to the SSC and SPDF form the major core of the STEREO long-term archive.

Space Weather Beacon. 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, as well as the NASA Goddard Space Weather Research Center. The Community Coordinated Modeling Center (CCMC) is modeling both the ambient solar wind and selected eruptive events in support of STEREO data interpretation.

Publications. The SSC maintains a database of published journal articles and proceedings on the SSC Website. Many pre-publication works are made available by the authors through the Solar Physics E-Print Archive and arXiv.

IIIb. Assessment of scientific progress, FY2015 - FY2017

In our 2015 Senior Review proposal, we set out ten prioritized science goals (PSGs) organized into three goal sets for STEREO mission science in 2016-2020. Here we report on progress on those goals, including descriptions of selected science results from some of the many STEREO related papers published in recent years, and discuss updates and additional goals for the future. All the goals, both current and future, are entirely achievable with the single STEREO-A spacecraft, although, of course, the recovery of STEREO-B would be beneficial. After each PSG name, we include in parentheses the Research Focus Areas from the 2014 - 2033 Heliophysics Roadmap to which the science is relevant (see Appendix D for a list of focus areas).

Goal Set 1: Characterize space weather throughout the inner heliosphere

PSG 1-1 Understand the evolution of the large scale structure of CMEs/ICMEs (W3, W4)

Statement of Goal. Advances in understanding CMEs, enabled by multi-perspective imaging on STEREO, have shown that flux-rope fits to the CME ejecta, in both the corona and to its ICME counterpart at 1 AU, often provide a remarkably good description of their topology. These findings support the classic assumption that a flux rope still attached to the Sun plows outward through the ambient solar wind. This picture has been applied for decades to in-situ plasma and field measurements, heliospheric models, and geomagnetic storm predictions, the latter of which depend critically on the combination of the arriving ICME speed and an enhanced southward ($-B_Z$) component of the interplanetary magnetic field. However, the multipoint STEREO perspective also reveals a more complex picture in which the Sun-to-1 AU evolution and observer location both play a significant role in the outcome. Because STEREO provides the opportunity to regularly observe ICMEs at separated locations with a full complement of instruments including the multi-perspective imagers to characterize the associated coronal eruptions, we have the ability to determine how and where observed ICME properties – especially the key parameters of size, speed and sign of B_Z – are set.

Progress and Science Highlights. A number of papers written in the time period 2015-to date addressed various issues related to the evolution of ICMEs. When followed to 1 AU, this evolution has clear implications for space weather forecasting. Papers that include this aspect (e.g., Möstl et al 2015, Winslow et al 2015, 2016) are treated more fully under PSG 1-5. Vemareddy and Mishra (2015) present an investigation of an erupting CME magnetic flux rope from the source active region (AR) utilizing observations from SDO, STEREO, SOHO, and the Wind spacecraft. It is shown that the magnetic flux rope expanded self-similarly and the associated near-Earth magnetic cloud is found to retain source AR twist signatures. The kinematics of this CME propagation are found by employing a variety of stereoscopic as well as single-spacecraft reconstruction techniques. The signal contribution of STEREO comes from its ability to combine heliospheric imaging, allowing a CME to be tracked from Sun to 1 AU, with in situ observations at 1 AU. Comparing imaging and in situ data then gives us clues concerning its evolution and helps us associate remotely observed features and in situ observations near Earth. In this spirit, Mishra and Srivastava (2015) showed how simultaneous heliospheric tracking of different observed features of a CME can improve our understanding of the forces acting on these transients. Using time-elongation maps constructed from STEREO/SECCHI observations, the authors track continuously two density enhancements in the CME of 2010 October 6, one at the front and another at the rear edge. The estimated kinematics of the CMEs are used as inputs in the Drag Based Model to estimate the arrival time of the tracked features of the CME at L1. In situ plasma and compositional parameters suggest that the rear edge density structure may correspond to a filament associated with the CME, while the density enhancement at the front corresponds to the leading edge of the CME. The analysis suggests that the increasing separation between both features can be attributed to the expansion of the CME or unequal forces acting on them.

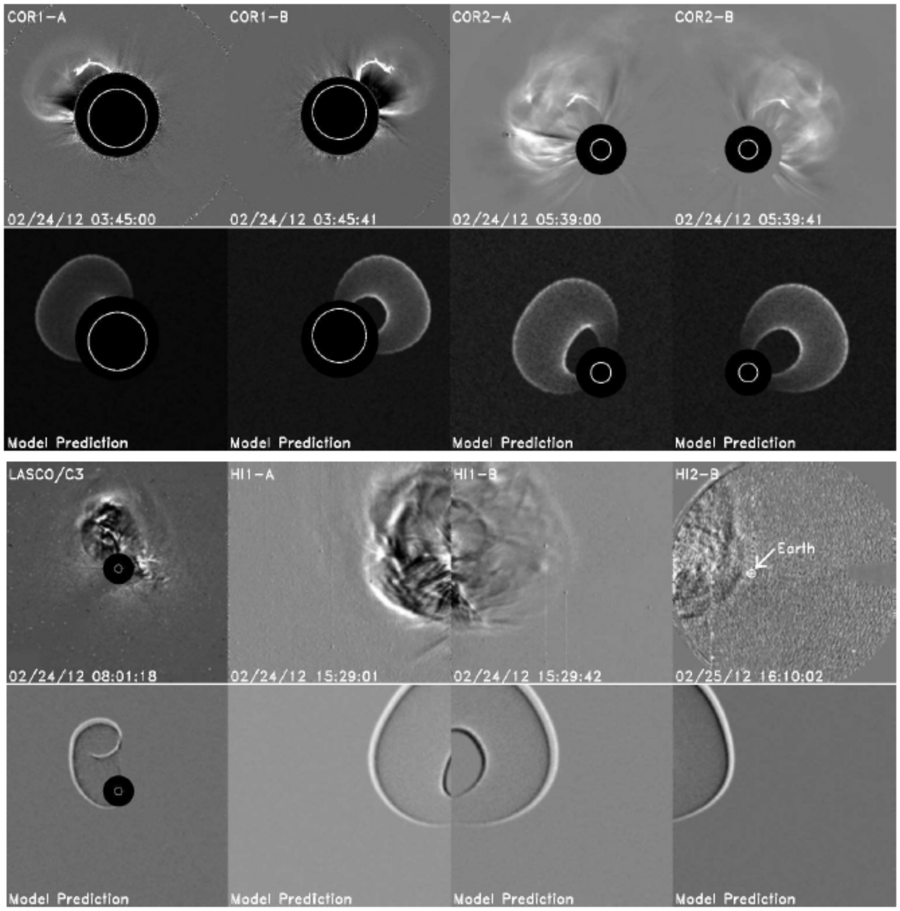


Figure 1: Complete coverage of a CME evolution demonstrated in a sequence of eight STEREO and SHOHO/LASCO images of a CME from 2012 February 24 in chronological order. In each case, full 3-D reconstruction is shown below. Such studies provide insight into how to improve predictions of the magnetic field orientation at 1 AU and thus the geoeffectiveness of the ICMEs (Wood et al. 2017).

Wood et al. (2017), taking advantage of the two STEREO spacecraft ideally positioned during 2008-2012 to view Earth-directed CMEs, completed the first in-depth STEREO survey of magnetic cloud (MC) events. A total of 31 (out of 48) MCs were successfully associated with erupting CMEs by tracking STEREO and LASCO imagery from the Sun to near 1 AU (see Figure 1) where in-situ observations of MCs are made with Wind. While the full 3-D kinematic and morphological analysis assuming a flux rope morphology revealed inconsistencies that reflect the challenges of modeling CME evolution, such unique Sun-to-Earth kinematic measurements can be used to provide CME arrival times at Earth and thus potential onset of geomagnetic storms. Such studies provide insight into how to improve predictions of the magnetic field orientation at 1 AU and thus the geoeffectiveness of the ICMEs.

STEREO observations also provide vital context for other heliospheric observations. CMEs are widely accepted as the source of transient modulation in the flux of galactic cosmic rays (GCRs), known as Forbush Decreases (FD). Occasionally, FDs occur for which there is no readily associated solar wind structure in near-Earth space, the so-called Phantom Forbush Decreases (PFDs). Thomas et al. (2015) recently used the unique locations of STEREO-A and B to identify large solar wind structures responsible for PFDs. The STEREO spacecraft allowed both in situ and coronagraph observations from well-separated points in the inner heliosphere to identify situations in which CMEs merge with pre-exiting Corotating Interaction Regions (CIRs) to create a magnetic barrier with a longitudinal extent to GCRs greater than just the remote CME itself.

Related work has compared STEREO ICMEs with their counterparts observed closer to the Sun (e.g., at MESSENGER at Mercury, or Venus Express at Venus) to investigate the evolution of the ICME structure as it propagates outward from the Sun, and in particular the field reorientations that affect its 1 AU B_Z (e.g., Winslow et al 2016; Good et al. 2015). These studies reinforce the message that forecasting ICME effects at 1 AU, even from an inner heliospheric beacon, depends on our ability to account for evolution and propagation effects. Experiments with such case studies and models are key to improving both our insights and forecast expectations.

Future prospects. STEREO observations continue to be regularly used in conjunction with global coronal and heliospheric models to determine which solar and interplanetary events are related, and how they are related. Realistic, 3D models of the solar wind structure obtained with ENLIL, SWMF, CORHEL, and now LFM-Helio, push the state of the art in describing ambient conditions, while various descriptions of injected coronal disturbances – some with increasingly detailed attributes – are being tested. The heliophysics community is at the threshold of being able to routinely fit CME structures to multiperspective coronal images, and to use these to simulate the launch of what become the ICMEs observed at 1 AU. The availability of STEREO data with its well-separated (relative to L1) perspective continues to both motivate this work and provide an observational basis for its validation. The ultimate goal is sufficient understanding to reproduce, with global models, the observed multipoint ICME attributes based on solar observations.

PSG 1-2 Physics of CME/ICME interactions (F2, W3)

Statement of Goal. CMEs interact with ambient flows of different origins as they propagate from the corona into the interplanetary medium. Interaction with large-scale structures close to the Sun, such as coronal holes and other CMEs, can severely alter the trajectories with serious consequences to space weather impact. Their ongoing interaction during propagation impacts the related SEP event(s) and the plasma and field parameters associated with the ICME disturbance(s). Our goal is to understand the physics of these interactions at different heliocentric distances, including their effects on particle acceleration and ICME geoeffectiveness, aided by STEREO data and STEREO informed theory and modeling.

Progress and Science Highlights. The physical details of the encounter between CMEs/ICMEs determines whether their interaction is constructive, destructive, or neutral from a potential space weather impacts standpoint. Mishra et al. (2016) study a case involving two interacting CMEs that occurred on 2013 October 25 (see Figure 2). They consider the propagation and expansion speeds, impact directions, angular sizes, and masses of the interacting CMEs using 3-D reconstruction techniques applied to SECCHI/COR and HI observations. They find that the higher expansion speed of the following CME compared to the preceding one may increase the

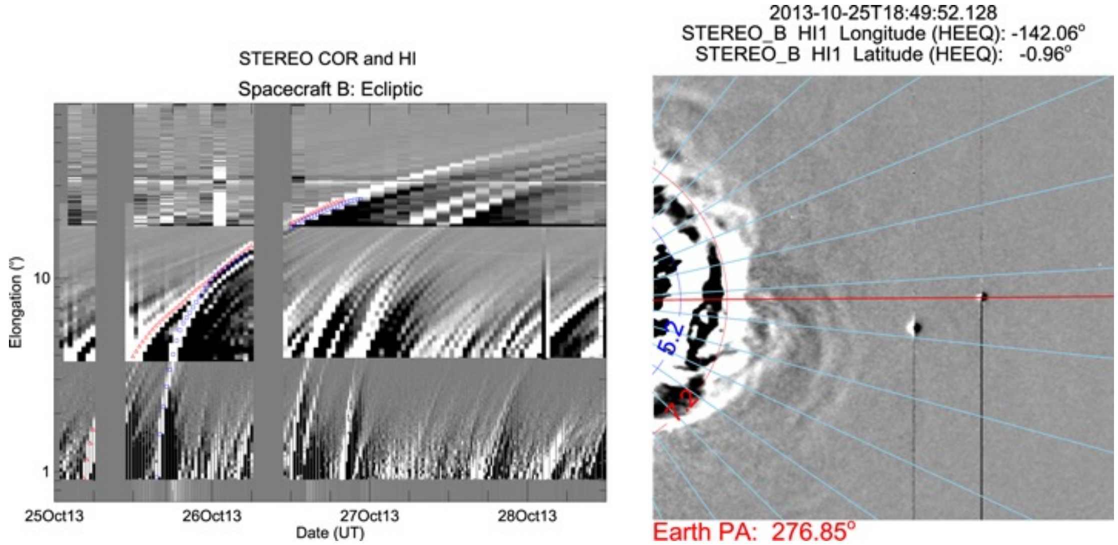


Figure 2: The colliding CMEs as seen in both STEREO SECCHI 'J maps' (plots of intensity as a function of time vs. angular position, left) and HI images (right). The collision in the J maps is inferred from the intersection of the topmost traces on October 26. The two curves (red and blue) in the HI image represent the CME fronts. The higher expansion speed of the following CME compared to the preceding CME may increase the probability of a super-elastic collision (Mishra et al. (2016).

probability of a super-elastic collision. Related simulations by Shen et al. (2016) show that super-elastic collisions occur when the approaching speed of two CMEs is relatively low.

In general, CME interactions can seriously affect the travel time of CMEs in the interplanetary medium. In particular, when there are many small CMEs ahead of a large CME that is potentially geoeffective, the arrival time of such a CME can be significantly delayed relative to the expected time based on coronal observations of the large CME. Niembro et al (2015) develop an analytical model to track the interaction region and its arrival time at Earth and validate their model using a number of observed interacting CMEs. It has been suggested that major Solar Energetic Particle (SEP) events may result from CME interactions close to the Sun, where the CME-driven shocks are the strongest. Mäkelä et al. (2016) are able to identify the location of the classical radio enhancement signature of acceleration using the direction finding technique from S/WAVES observations. The interacting CMEs on 2013 May 22 were observed by SOHO and STEREO and the radio-enhancement source was located exactly at the interface between the two interacting CMEs.

Future Prospects. In CME collision studies, the principal focus is the interactions between the driving ejecta. The interaction is complex given that CMEs are magnetic flux ropes, and that reconnection and associated heating and particle acceleration may be occurring. Further comparisons of STEREO (combined with ACE) observations with simulations of both CME/ICME interactions and ICME-solar wind stream interface (SIR/CIR) interactions will improve the basis for predicting related ICME magnetic field magnification and SEP event intensification (Gopalswamy et al. 2015; Lugaz et al. 2016). The upcoming solar minimum should provide additional cases, especially for the ICME-CIR interactions that will dominate space weather over the next ~4 years as the solar cycle declines.

PSG 1-3: Understand how solar energetic particles are accelerated and distributed so efficiently around the Sun *(F2, F5, H1, W1, W2, W3)*

Statement of Goal. From early in its mission, STEREO observations have renewed interest in the longitudinal extent of SEP events and its physical determinants. This topic is of interest for understanding both heliophysical and astrophysical particle acceleration and transport, and for its importance in predicting space weather effects of SEPs. However, in spite of advances in theory and modeling, there is still no validated capability for heliosphere-wide SEP event forecasting. The library of potential multipoint case studies provided by STEREO together with L1 observations is key to both understanding these events and being able to predict them.

Progress and Science Highlights. STEREO observations from the far side of the Sun have provided the first 360° view of SEP activity. STEREO observations, combined with near-Earth data, have shown that many SEP events contribute at multiple locations, indicating broad longitudinal SEP distributions. For example, in the 2011 November 3 event shock-accelerated SEPs were observed over a ~360° longitude span within ~1 hour (Gomez-Herrero et al. 2015). STEREO has been critical in revealing how SEP acceleration and transport mechanisms work together to distribute particles in longitude.

Using the Wang-Sheely-Arge WSA ENLIL + Cone model, Bain et al. (2016) conclude SEP activity at distant locations can be understood by mapping both local and remote magnetic field connections between the observer and shock source(s). Similarly, Lario et al. (2016) explain a broad event by showing the CME shock extended ≥190°in longitude. However, Laitenen et al. (2015) present a model in which particles instead access distant longitudes via turbulent field-line meandering, while Droege et al. (2016) show cross-field diffusion could explain three broad SEP electron events. Thus the physical picture of the energization and transport of SEPs is still actively evolving.

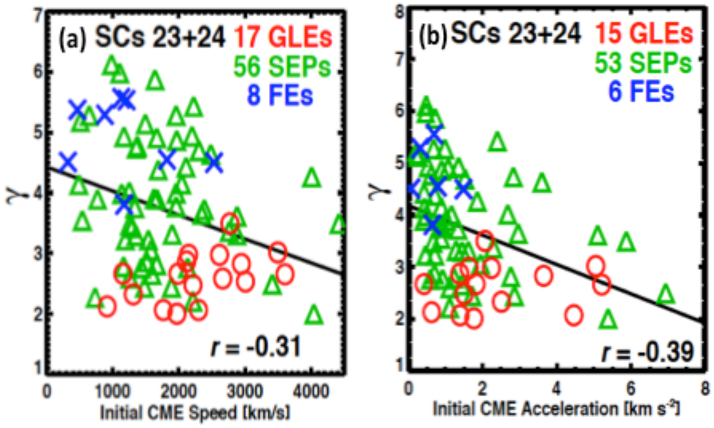


Figure 3: The SEP proton spectral index (ϒ) is plotted against (a) initial CME speed and (b) CME acceleration. Included are SEP events that have Ground Level Enhancements (GLEs), events associated with filament eruptions (FE), and typical SEP events. The hardest spectra (lowest spectral index events) are associated with higher initial speeds (≥1,000 km/s) or acceleration, indicating that low altitude acceleration is required for the highest energy SEPs (Gopalswamy et al. 2016).

Small ^{3}He-rich SEP events appear to be accelerated near active regions, often in association with EUV jets. Early single-point studies suggested their longitudinal spread was narrow. However, Nitta et al. (2015) using SDO/AIA and STEREO/ EUVI images find that 6 of 26 ^{3}He-rich events observed at L1 originated beyond the west limb. They conclude that the >100° wide distribution of ^{3}He sources is inconsistent with a simple Parker spiral or with a Parker spiral plus PFSS modeling of the coronal magnetic field. Recent work by Bučík et al. (2016) uses STEREO high-resolution EUV images to show very common (~60%) association of ^{3}He-rich SEPs with large-scale coronal EUV waves. They suggest that in some cases the ion-injection may be instigated by EUV wave expulsions.

It is well known that energy spectra of CME-shock accelerated particles exhibit spectral "breaks", above which the spectra suddenly steepen, and that the break locations (E_B in energy/nuc) depend on the charge-to-mass ratio of the ion. Thus, $E_B(Q/M) = E_B(\text{protons}) \times (Q/M)^b$. Li et al. (2009) predicted on theoretical grounds that *b* would range from ≈0.2 for a pure quasi-perpendicular shock to ≈1-2 for quasi-parallel shocks. Zhao et al. (2016) measure He, O, and Fe spectra in the 2013 November 3 event and found b = 1.12, 1.01, and 0.66 for STEREO-A, ACE, and STEREO-B, respectively. This first application of this approach at three separated locations suggests that STEREO-A and ACE were connected to the quasi-parallel portion of the shock and STEREO-B was connected to the quasi-perpendicular portion of the shock.

Gopalswamy et al. (2016) analyze 81 large SEP events from cycle-23 and 24 using STEREO, GOES, and SAMPEX data to compare the fluence spectral index, ϒ, with the initial CME speed (at less than or about 3 $R_\odot$) and subsequent CME acceleration (see Figure 3). They find that initial CME speed is a good proxy for initial CME acceleration, and that the hardest spectra (ϒ ≈ 2) were for GLE (Ground Level Enhancement) events (reported by neutron monitors) and large SEP events with the greatest initial CME speeds and acceleration. The weakest spectra (ϒ = 4-6) included CMEs with lower speeds and accelerations, many associated with filament eruptions. These data indicate that strong CME acceleration at low altitudes is required for hard SEP spectra, consistent with shock formation and SEP acceleration relatively close to the Sun.

The above result applies to protons. Dresing et al. (2016) find that electrons behave according to somewhat different rules. It appears that electron acceleration efficiency is much lower and declines more rapidly with distance from the Sun. Analysis of the comparative behaviors of SEP ions and electrons over large spatial scales is enabled by the STEREO multipoint observations.

Future Prospects. The launch of the Solar Probe Plus (SPP) and Solar Orbiter (SO) missions in 2018 will enable SEP studies ~6 times closer to the Sun than earlier missions, providing comprehensive measurements of the magnetic field, waves, shock properties, seed and accelerated particles in the region where CME-driven shocks accelerate ions and electrons to the highest energies. It will be essential to have particle and field measurements near 1 AU for the events that SPP and SO observe close to the Sun to place these measurements in the framework derived from previous SEP observations.

The 2018-2019 period, when solar activity is expected to be low, is especially favorable for observing events in isolation (at solar maximum it is difficult to match individual events to solar sources and to events at other spacecraft). Having both STEREO-A and near-Earth observations will increase the number of events observed at 1 AU and also provide 2-spacecraft events. With SPP and SO providing measurements much closer to the Sun, particle acceleration and transport models can become better constrained. In addition, solar wind stream interaction-related particle acceleration will return to dominance as solar activity declines, providing the prospect of comparing new STEREO-A and ACE observations to the previous solar minimum's results, and folding in new insights from SPP and SO. As stream interaction sources provide suprathermal seed populations that can penetrate into the inner heliosphere and experience further acceleration, we can investigate the extent of that penetration and its consequences.

PSG 1-4: Radio and in situ multi-spacecraft measurements of solar type III bursts (F2, W2, W3)

Statement of Goal. The radio burst signatures of solar eruptions are the fast-drifting type III radio bursts and slow drifting type II bursts that extend from near the eruption site outward beyond 1 AU. The radio emission is generated by a plasma wave process, in which energetic electrons accelerated at the shock or at the flare site cause the growth of Langmuir waves, which are converted to radio bursts. The radio bursts provide information on the flare, the CME, and the CME-driven shock. Important multiview observations from STEREO provide a complete picture of the solar disturbances as they propagate into the interplanetary medium, putting them in context with results from imaging and in-situ measurements.

Progress and Science Highlights. Recent observations from STEREO have substantially advanced our understanding of the solar radio bursts associated with flares and CMEs. The direction finding capability of the S/WAVES experiment has been extremely useful in understanding the dynamics of shocks and electron beams.

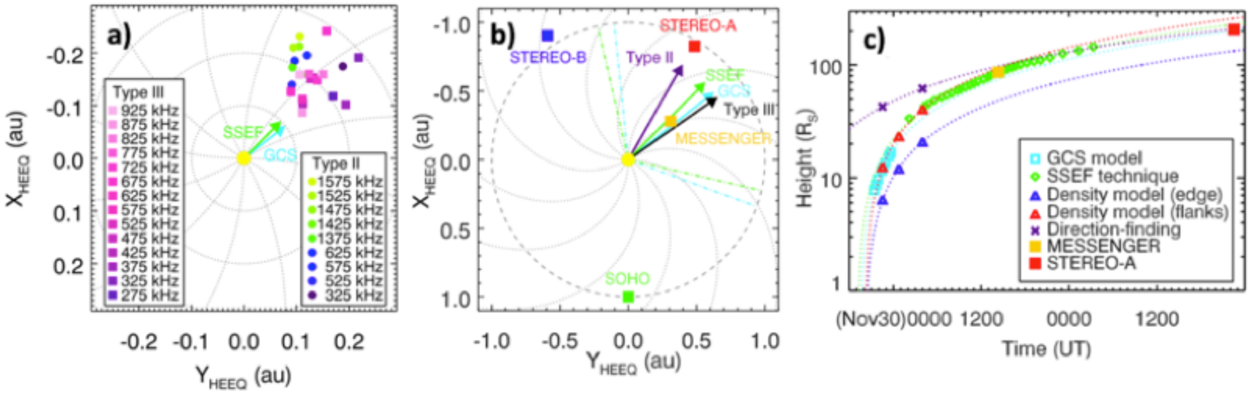


Figure 4: Multi-point radio observations are used to determine the locations of type III and type II bursts and direction of the CME. a) Radio source locations of type II (circles) and type III (squares) bursts for four time-frequency intervals in the XY_{HEEQ} (Heliocentric Earth Equatorial) plane. Colors denote frequencies. The cyan and green arrows indicate the CME propagation directions obtained by the GCS model and the SSEF technique, respectively. b) Positions of the spacecraft in the solar equatorial plane on 29 November 2013. The purple and black arrows indicate average directions of type II and type III bursts, respectively. c) Kinematics of the CME leading edge and radio sources between 2013 November 29 and December 1. Dotted lines are linear fits (Krupar et al. 2016).

Krupar et al. (2016) analyze both type III and type II bursts associated with a farside CME on 2013 November 29. They combine radio direction finding and CME forward modeling to understand the Sun-to-1 AU propagation of the CME along with its shock. Using a graduated cylindrical shell model to fit a flux rope to the multi-perspective CME images provided by STEREO and SOHO, they apply self-similar expansion fitting (SSEF) to model the ejecta kinematics in the heliosphere. The STEREO direction finding technique is then used to identify the location of the radio emission with respect to the CME. Figure 4 shows the CME was generally heading toward STEREO-A. The type III burst direction was consistent with the CME direction, indicating that the shock nose was above the eruption site. On the other hand, the type II burst was produced at the flank of the shock (Figure 4b). The derived kinematics of the CME in Figure 4c are confirmed from the shock arrival times at MESSENGER and STEREO-A. Schmidt and Cairns (2016) also study other aspects of this event using a combination of a data-driven, three-dimensional MHD simulation of the CME and plasma background with an analytic, quantitative kinetic model of the radio emission.

Type III bursts in the interplanetary medium allow us to study the behavior of electron beams injected at the Sun. Krupar et al. (2015) infer the speed of the electron beams from type III bursts to range from 0.02c to 0.35c. They also find that the median speed values decreased from 0.09c to 0.04c from near the Sun to the distant interplanetary medium, suggesting deceleration of the electron beams. These properties of type III exciter beams can be used as input parameters for numerical simulations of beam – plasma interactions in the interplanetary medium.

Future prospects. While type III and type II bursts continue to provide information that helps provide a complete picture of solar eruptive events, including their directions and their shocks, the number of such bursts is expected to diminish with solar activity. Nevertheless, some significant solar events have occurred at relatively quiet times, in which case the radio science capabilities described above will be marshaled to contribute to their analysis – including farside event diagnostics. Since radio bursts are due to accelerated electrons, multi-view observations of these bursts from STEREO and Wind will help us understand the difference between electron and proton accelerations near the Sun when combined with energetic particle and CME data from STEREO and missions near L1. Observations of type IV and type II bursts may tell us more about the changing heliosphere as new parametric regimes are encountered due to reduced activity. For instance, low-frequency type IV bursts, caused by electrons trapped in post-eruption arcades, may provide useful information concerning how reduced heliospheric pressure affects the heights of such arcades.

PSG 1-5: Characterize space weather throughout the solar system (F2, H2, W1, W3, W4)

Statement of Goal. Space Weather is usually associated with Earth's space environment, but it is, in its broader definition, solar system-wide. Flares, ICMEs, and SEPs affect each planet and solar system body in distinctive ways. Planetary missions, while sometimes tailored for observing the planet's response to external drivers, often do not have the capability to detect the sources of these drivers (e.g. solar inputs). The STEREO observations, when coupled to planetary observations, provide both a more complete picture of how space weather propagates within the heliosphere, and also critical input for properly modeling a planet's response to external drivers.

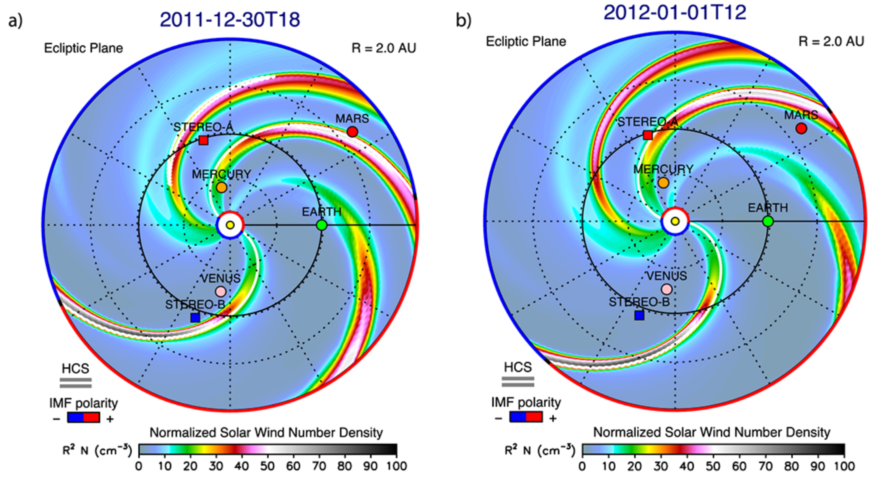


Figure 5: Snapshots showing the relative locations of STEREO-A and MESSENGER (at Mercury) for two ICME events studied by Winslow et al. (2016). These conjunction events allowed assessments of ICME complexity.

Progress and Science Highlights. Planetary scientists have made a wide variety of uses of STEREO observations in the period since the previous Senior Review. In particular, a number of investigations have focused on using STEREO to interpret the space weather conditions at Mercury, Venus, and Mars including radial evolution of transient structures. Winslow et al. (2015) use STEREO data together with MESSENGER observations to evaluate the statistical differences in ICME strengths between the orbital distances of Mercury and Earth. Their analysis shows a clear overall weakening of most leading shocks, consistent with an average deceleration of the ejecta drivers in that heliocentric distance range. In another study, Winslow et al. (2016) use conjunctions of STEREO-A and MESSENGER (Figure 5) to investigate the development of complexity during the propagation of several ICMEs between the two locations, although Good et al. (2015) had found that some events simply expand over this radial range. The ambient conditions, e.g., whether significant solar wind stream structure and/or the heliospheric current sheet are present, clearly influence the outcome.

Good and Forsyth (2016) assembled a large catalogue of MESSENGER and Venus Express (VEX) events, and together with STEREO and ACE data, identify multipoint detections enabling the evaluation of ICME widths versus their upstream shocks. They also identify 23 ICMEs observed by pairs of spacecraft in close radial alignment, providing a valuable resource to those seeking to analyze both the differences in space weather at terrestrial planets and the heliospheric distributions of events during the MESSENGER and VEX missions (2006-2013). The combination of five spacecraft vantage points offered unprecedented opportunities for multi-point ICME observations including STEREO data.

Möstl et al. 2015 use STEREO data in combination with measurements by the Radiation Assessment Detector (RAD) instrument on Mars Science Laboratory's (MSL) Curiosity rover, Mars Express, SOHO and SDO data to model the direction and expansion of a Sun-to-Mars event. RAD can detect the Martian equivalent of Forbush decreases, cosmic ray decreases marking the passage of ICMEs. Using this combined data set they characterize the elliptical shape of the CME-driven shock and infer significant non-radial propagation of the CME.

STEREO data have also played an instrumental role in a debate over whether MESSENGER detected solar neutrons in the vicinity of Mercury. Neutrons are produced by reactions similar to those that generate solar gamma-rays. They constitute the only efficient and direct neutral particle evidence of energetic ion interactions at the Sun from 50 to 300 MeV. STEREO-A energetic proton measurements were used by Share et al. (2015) to argue that the spacecraft was exposed to SEP fluxes at Mercury that produced instrument backgrounds, negating the interpretation by Lawrence et al. (2015) of a low energy solar neutron origin. This topic highlights the importance of multi-point observations of STEREO in interpreting sometimes controversial observation interpretations related to space weather effects on spacecraft throughout the heliosphere.

Harkening back to the original concept of comets as wind socks in the solar wind, DeForest et al. (2015) and coworkers used STEREO images to track over 200 tail features in Comet Encke's tail to explore turbulent motions in the solar wind. This work also relates to STEREO investigations of small solar wind transients described elsewhere, and has direct bearing on planned Solar Orbiter and Solar Probe Plus observations closer to the Sun.

Future prospects. Although MESSENGER and VEX are no longer in operation, MAVEN's ongoing measurements of plasma, field and energetic particles at Mars rely on STEREO observations for understanding solar activity impacts on the local space environment. Future opportunities include the alignment of Earth and Mars with STEREO-A in quadrature in 2018, providing an ideal opportunity for imaging with coronagraphs and HIs and relating these images to structures out to 1.5 AU. In 2018 October Mars and Earth are nearly along a Parker spiral interplanetary field line together with Venus, while STEREO-A's quadrature view persists. In 2019 March Mars and STEREO-A will be radially aligned with Earth and SOHO, providing further quadrature imaging capability. STEREO-A will help set the heliospheric context for BepiColombo cruise phase observations, including its first Venus flyby in 2019 July when particles and fields instruments may be turned on, and provide similar support for Solar Probe Plus and Solar Orbiter Venus flybys. Finally, STEREO-A will be in a position in the upcoming extended mission period to test the L5 concept of space weather monitoring and forecasting, on which we may someday depend. These observations will also allow us to determine the L5 location's usefulness in constraining the still-developing global heliospheric models of space weather. This PSG will continue as a key scientific driver for STEREO as a component of the greater HSO.

Goal Set 2: What Can We Learn from 360° Coverage of the Solar Corona?

PSG 2-1: Uncover the large-scale couplings in solar eruptive events (F1, F2, H1, W1, W2, W3)

Statement of Goal. STEREO far-side observations combined with Earth-side observations of SDO and SOHO provide essential views of the large scale, global properties of solar eruptions. This includes the connections between CMEs, flares, EUV waves, and shocks; interactions between different events; and the occurrence of sympathetic events in which one event appears to cause other homologous events.

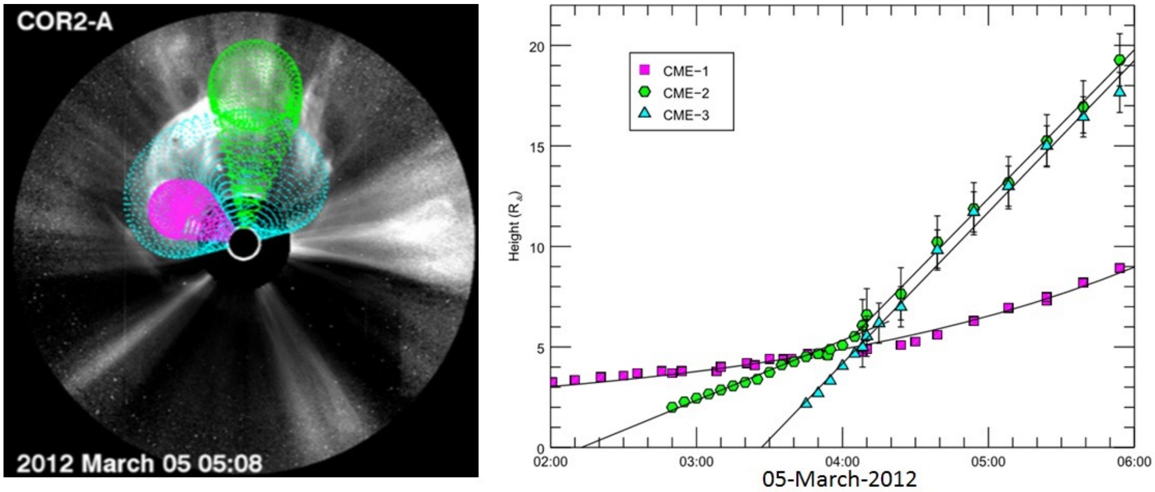


Figure 6: (left panel) Wire-frame models of three CMEs superposed on a coronal image taken by the COR2 on STEREO-A. The three CMEs interacted with one another in the space between Sun and Earth. CME1 was the slowest, which is least affected by the other two near the Sun. However, the shock from the third CME (CME3) passed through CME1 and heated it. CME2 was accelerated by CME3, so that it doubled its speed. CME2 was also deflected from its initial trajectory. It was possible to study the complex evolution of the three CMEs because of the availability of observations from multiple views from SOHO and STEREO. (right panel) Increase in the distance from Sun center of the three CMEs with time showing the effects of the interaction. The symbols represent the actual measurement of the apex distances of the wire frames in three dimensions. The lines through the symbols are the best fits to the data points (Colaninno & Vourlidas 2015).

Progress and Science highlights. The power of multiple viewpoints to disentangle complex solar activity is demonstrated by Colaninno & Vourlidas (2015). The authors are able to fit three CMEs simultaneously (a first for STEREO) despite their considerable overlap in the coronagraph images from STEREO COR2-A/B and SOHO LASCO C2-C3 (Figure 6). The availability of three viewpoints is crucial for disentangling the properties and particularly the size and propagation directions of the CMEs – one of them being Earth-directed. Due to the increased activity during that period, the arrival of CME-1 at Earth is unclear in the in-situ data from Wind. An intriguing magnetic structure corresponds to the projected time of arrival of CME-1 but has elevated proton temperatures. It is likely that the passage of the CME-3 shock through CME-1 heated the plasma leading to the observed signatures. CME-3 also accelerated and deflected CME-2 (see Figure 6). No evidence of CME 'cannibalism' is found. The study suggests that even coronagraph observations as complex as those in Figure 6 can be disentangled and the individual events analyzed properly if enough viewpoints are available. More importantly, these results are very encouraging in our efforts to understand the properties of Earth-directed CMEs in the presence of significant solar activity, which is also the time that the most intense Space Weather is expected.

Future prospects. This PSG reflects the unique achievement of NASA's Heliophysics Systems Observatory (HSO) to continuously observe the evolution of the solar corona over its full 360° extent. STEREO is the cornerstone for this accomplishment and remains so even with only one of the spacecraft. While the solar cycle will alter the number of eruptions in the corona, streamer blowout CMEs resulting from surface field evolution are still common, and provide the opportunity to analyze more 'controlled' multiple event examples. As such, STEREO observations are still key to understanding the complete signatures of large-scale eruptive events, which remains a high priority for the STEREO mission during the period covered by the current proposal.

PSG 2-2: Understand the lifetime of active regions, coronal holes, filaments, and filament channels (F1, F4, H1, H2, W1, W2)

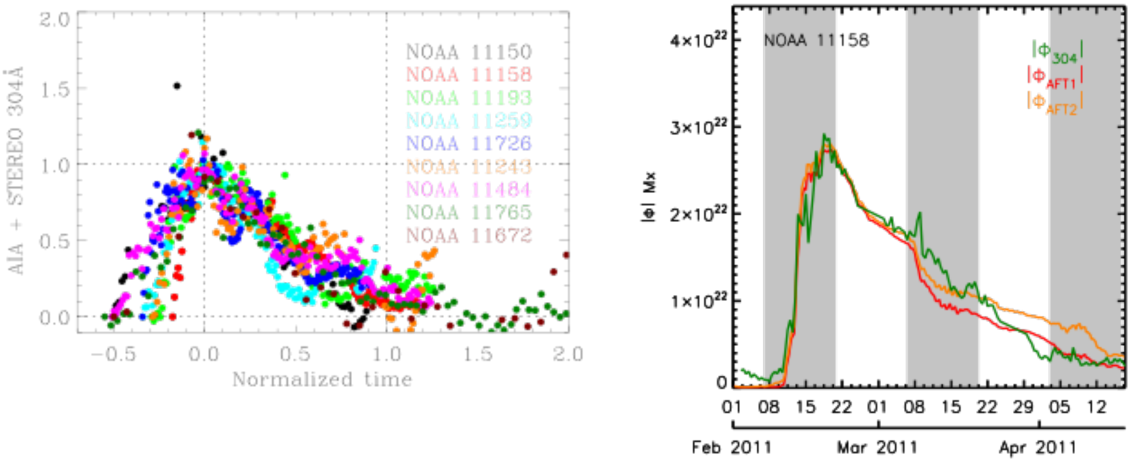


Figure 7: (left panel) 304 Å integrated light curves from nine NOAA active regions (ARs) measured with a combination of STEREO and SDO data. The common trends reflect the evolutionary histories of the active region magnetic field strengths. The light curves have been scaled to match at the peak intensity of NOAA 11158 (right panel), with the same intensity scaling factor also used to scale the duration, showing the homologous nature of the light curves. (right) Total unsigned magnetic flux in AR 11158 obtained from the 304 Å proxy (green) and the flux for two area integrations of the advective flux transport (AFT) model (red and orange). Gray areas mark the times when the active region is on the Earth side, when data from HMI magnetograms is being assimilated into the AFT model. This demonstrates the proxy value of the EUV measurements for farside magnetic field inference (Ugarte-Urra et al. 2015).

Statement of Goal Solar features including active regions, coronal holes, streamers, filaments and filament channels all evolve on time scales shorter than that of the solar rotation period. Thus, STEREO far-side coverage of the solar disk is vital to understanding the evolution of these features.

Progress and Science Highlights. Ugarte-Urra et al. (2015) using STEREO's 360° coverage of the EUV corona to study the lifetime of active regions (ARs) report two important findings: First, the study demonstrates that AR lifetimes are self-similar. Their light curves scale directly with their peak 304 Å emission (Figure 7, left). Therefore, the age and future evolution of a given AR can be estimated reliably by fitting a time series of its EUV light curve to the nominal curve in

Figure 7 (top). Second, they are able to evaluate the ability of flux transport models in predicting the magnetic evolution of ARs several weeks in the future using the STEREO/EUVI and SDO/AIA images in the 304 Å channel as a proxy for the unsigned photospheric magnetic flux (Figure 7, right). An advective flux transport (AFT) model was used to estimate the evolution of the magnetic flux in a given AR once the region crosses to the far side, where magnetic field observations are no longer possible. The paper demonstrates that an AFT model that assimilates nearside magnetic data with far side 304 Å measurements could provide a more complete picture of the magnetic field configuration of the entire Sun. This has significant implications for space weather predictions, such as solar irradiance, solar wind, and coronal field models.

Future prospects. STEREO continues to be the sole source of farside coverage in Heliophysics until SO and SPP become operational. As STEREO-A moves through its 'L5' orbital location, it will allow us to obtain observations of active region, coronal, and solar wind conditions and their evolution from this leading orbital perspective, and evaluate how useful these are for forecasting solar wind structure and eruptive activity at the Earth.

Goal Set 3: What can we learn from coverage of the full heliosphere?

PSG 3-1: Provide longitudinal coverage of the solar wind and transients that can affect the outer heliosphere (F2, F4, W1)

Statement of Goal. Near Earth and inner-heliosphere observatories combined with STEREO provide the extended longitudinal coverage needed to constrain the boundary conditions for solar wind and transients that affect the outer heliosphere. In particular, these observations are used to investigate the generation and evolution of global merged interaction regions, and the motion of the outer heliospheric boundaries (of particular interest to Voyager and IBEX).

Progress and Science Highlights. Intriligator et al. (2015) use the major events of 2012 July seen at STEREO-A as input to the 3-D HAFSS (Hakamada-Akasofu-Fry Source Surface) model and propagate the model to the outer heliosphere to compare with measurements at the two Voyager spacecraft (V2 at 102 AU and 30° S, V1 at 124 AU and 34°N). The authors conclude that the July 2012 solar events caused a solar system scale event, a metaphorical "tsunami," in the plasma and magnetic field throughout the heliosphere/heliosheath/interstellar medium.

Future prospects. Global heliospheric models will continue to be used to interpret observations of the outer heliosphere and its boundaries, including those from continuing Voyager and IBEX observations and upcoming IMAP. STEREO observations contribute essential information used in these through both unique perspective imaging that helps constrain the heliospheric model inner boundary conditions, and in-situ measurements that provide more widespread validation.

PSG 3-2: Characterize the Sources and Transport of Pickup Ions (F2, F3, H4, W1)

Statement of Goal. Source populations for pickup ions (PUIs) include the neutral component of the local interstellar medium (LISM) and an "inner source" of neutrals closer to the Sun (possibly generated by solar wind-dust interactions). Freshly made "pickup" ions provide information on processes such as solar wind mass loading and constitute a population of suprathermal heavy ions that can be further accelerated at heliospheric shocks.

Progress and Science Highlights. Efforts to answer the questions "What is the nature of the inner-source of pickup ions?" and "What are the processes responsible for the observed characteristics of PUIs" have previously been hindered due to a lack of suitable observations of PUI pitch-angle distributions. Such answers have become increasingly important, for example, in solving the mystery of the formation of the IBEX ribbon (McComas et al., 2012) which is closely connected to the scattering characteristics and transport of PUIs (Zirnstein et al., 2016).

STEREO PLASTIC's unique directional capabilities provide data that addresses these questions. Drews et al. (2015) present the first detailed He+ pickup ion velocity distribution function (VDF) observed at 1 AU. The data suggest that the He+ VDF consists of at least two contributions – a fairly isotropic shell distribution composed of particles with velocities close to the solar wind speed and a highly anisotropic torus signature that is composed of particles recently injected into interplanetary space and gyrating around the Interplanetary Magnetic Field (IMF). The transition between the two phases of the He+ VDF is gradual and allows one to infer valuable information on the scattering behavior and phase space transport characteristics of these ions.

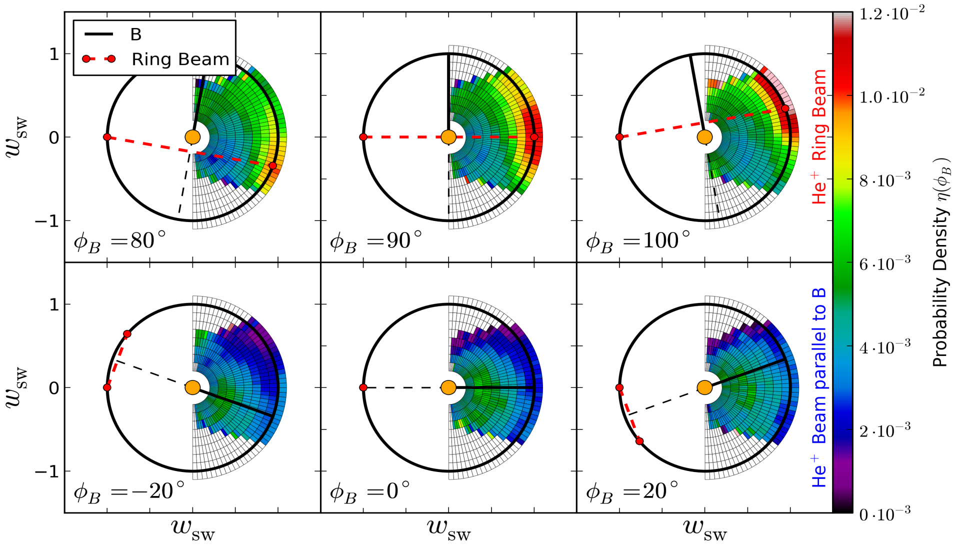


Figure 8: 2D VDFs for interstellar He+ show this ion to be highly anisotropic (contrary to most modeling assumptions based on 1D observations). Distinct signatures in the pitch angle distributions indicate two source populations: interstellar (top) and inner source (bottom) (Drews et al. 2015).

Recently the investigations on the PUI pitch-angle distribution with STEREO PLASTIC have been expanded to include heavy pickup ions, i.e. C+, N+, O+, Ne+ (Drews et al., 2016). The observations indicate that C+ pickup ions, previously thought to be exclusively produced close to the Sun as part of the inner-source of PUIs, show clear signatures of a torus shaped velocity distribution function, providing strong evidence that C+ pickup ions can be produced quite far away from the Sun. This observation challenges our current understanding of the characteristics of the inner-source of pickup ions. Furthermore, observations have shown that the pitch-angle distributions of He+, N+, O+, and Ne+ are missing a clear mass-per-charge dependence as would have been expected from standard theory of wave-particle interactions, believed to be the dominant process for the isotropization of the pickup ion velocity distribution function.

Recent analysis of the variation with ecliptic longitude of the He+ pickup ion cut-off speed, which reflects the radial interstellar neutral (ISN) flow speed at 1 AU (Möbius et al., 2015; Möbius et al., 2016), has obtained the ecliptic longitude of the ISN flow with high precision. The analysis is being evaluated for underlying systematic effects due to solar wind and interplanetary magnetic field variations.

Future Prospects. Together with past Ulysses GAS neutral and ACE SWICS pickup ion observations, the ongoing and future STEREO pickup ion and IBEX ISN flow observations will provide one hinge point of the plane established by the interstellar medium flow vector, V_{ISM}, and the interstellar medium magnetic field, B_{ISM}. The interstellar magnetic field is thought to control the shape of the heliosphere and thus will set a benchmark for the analysis of secondary neutral populations which provide a window on the heliospheric boundary region. The combination of long-term data sets from the STEREO and IBEX missions will enable searching for or constraining potential temporal variations, whether of heliospheric or interstellar origin (Frisch et al., 2013; Frisch et al., 2015). In addition, pickup ion fluxes are subject to solar cycle influences in, for example, the EUV and proton fluxes that affect ionization rates. PLASTIC's unique capabilities provide the missing link between the conceptual theory and modeling of processes that lead to the production of the inner source and strengthen future investigations on the solar-cycle dependent secondary ENA production mechanism. The Heavy Ion Sensor (HIS) instrument on Solar Orbiter (launch 2018) will also measure pickup ions in the same speed range as PLASTIC (one of its heritage instruments), but with an orbit extending down to 0.28 AU. The first perihelion will be reached about 3 years after launch. When both missions are operational, PLASTIC and HIS will provide an exceptional opportunity to study the radial evolution of interstellar and inner-source pickup ions from two or more vantage points.

PSG 3-3: Improve our understanding of dust in the inner heliosphere

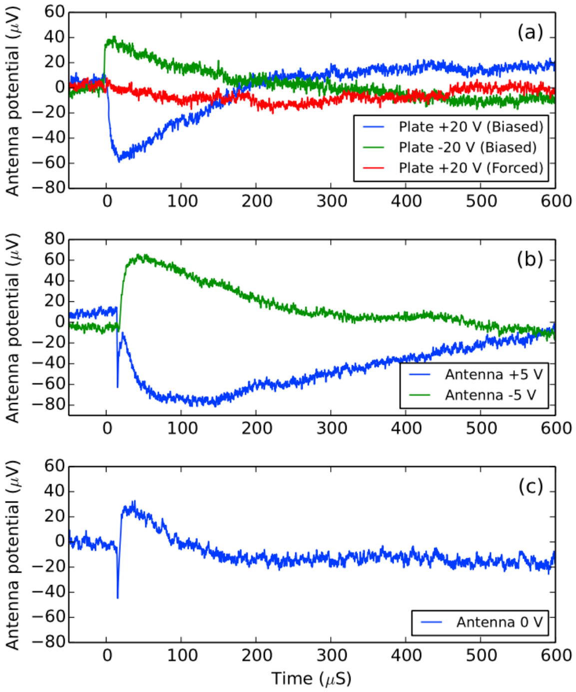


Figure 9: Dust impact plasma coupling with mock-up STEREO antenna/spacecraft system. Antenna signals from three laboratory configurations are shown: (a) Spacecraft is voltage biased, and antenna is hidden from impact. Signals are purely due to impact charge recollection by the spacecraft body. (b) Spacecraft is held at 0 V relative to chamber, and the antenna is biased. Long-timescale signals are due to antenna recollection of impact charge. (c) The short-timescale feature of panel (b) is not due to charge recollection, but instead caused by direct perturbation of the antenna by the rapidly expanding impact plasma cloud (Collette et al. 2015).

Statement of Goal. Dust detection on STEREO plays a key role in the still developing understanding of heliospheric dust flux variations with time and in space, as well as the nature of nanodust, with applications for planetary physics and astrophysics.

Progress and Science Highlights. Unique STEREO observations have detected three separate dust populations (Zaslavsky et al. 2012): (1) Micron-radius dust of interplanetary origin – these are particles generated by the collisional grinding of asteroids and comets; (2) Micron-radius dust of interstellar origin – the particles originate in the interstellar medium and travel through our solar system; and (3) dust particles with nanometer radii, generated near the Sun and entrained in solar wind flow by the Lorentz force. The last population has a flux that varies by orders of magnitude between spacecraft, even when the measuring spacecraft are close together. It is important to determine whether or not this third population is truly nanodust. If it is nanodust, then STEREO is detecting a component created in the inner heliosphere (~0.2 AU), where such dust significantly alters the dynamics of the solar wind through mass loading (Rasca et al. 2014) and heavy pickup ion creation (Taut et al. 2015). Nanodust also has a number of unique properties (Meyer-Vernet et al. 2015), such as its large surface-to-volume ratio, enhancing chemical activity at the surface. STEREO dust detections may be a critical tool to explore the numerous open questions surrounding these processes (Meyer-Vernet et al. 2014; Kellogg et al. 2016). A key question to resolve is the relative efficiencies of monopole (STEREO, Cassini) and dipole (Wind) antennas in detecting nanodust voltage pulses.

New work to determine if this third dust population is, indeed, nanodust is underway. Laboratory experiments using a model of a S/WAVES antenna and preamplifier have quantified our understanding of the response of S/WAVES to impacts of dust on the spacecraft (Collette et al. 2015, 2016). Researchers have begun to apply these advances to the interpretation of the STEREO spacecraft data. Malaspina et al. (2015) revisited the Zaslavsky et al. (2012) estimates for the flux and mass estimates for interplanetary and interstellar dust detected by STEREO, this time using laboratory-determined charge yields and antenna-coupling properties, suggesting for example, that STEREO observes primarily the β meteoroid component of interplanetary dust. Thayer et al. (2016) used the STEREO data to verify a relationship between the shape of dust impact voltage perturbation waveforms and spacecraft floating potential that was predicted by laboratory studies.

Other studies relate to the change in dust flux estimates around 2010. As noted by Malaspina et al (2015), “it is unclear whether this variation is caused by the disappearance of nanodust signals on STEREO-A or some other effect such as slow variation of spacecraft surface material properties due to long term exposure to the solar wind plasma and dust environment.” Furthermore, the narrow voltage spikes considered to be nanodust signatures, did not disappear on STEREO-B, prior to superior conjunction, which is still unexplained.

Future prospects. The dust populations identified in the S/WAVES data vary with the solar cycle in sometimes unexpected ways. Because the acquisition of new STEREO dust data comes as an automatic part of the S/WAVES measurements, the impact of a second weak solar cycle on the solar system dust populations at 1 AU will be evaluated as the cycle progresses. Work on understanding the mysterious third population continues, and will be enhanced by the new solar minimum measurements. We plan to produce and publish a database of dust detections by STEREO, similar to that produced for Wind/Waves by Malaspina and Wilson (2016), which will also enhance the utilization of the dust data.

Obtaining more STEREO-A data from the post-conjunction era will allow comparisons with pre-conjunction STEREO-B data that may answer questions about the different responses to dust by the two spacecraft due to spacecraft orientation. STEREO will also serve as an ideal 1 AU dust monitor for Solar Probe Plus and Solar Orbiter, given that their antenna systems are all similar.

IIIc. Scientific Impact of a One Spacecraft Mission

All PSGs can be achieved with regular STEREO synoptic data from STEREO-A. The loss of STEREO-B does not diminish the value of continuing observations with STEREO-A. The combination of SDO and SECCHI will continue to provide views of more than half the Sun in EUV and enable active region evolution diagnostics and the study of far side flares and CMEs. From 2018 October to about 2020 October, the angular separation of the STEREO spacecraft from the Earth-Sun line will decrease from 105° to 60°. The most severe impact of the absence of STEREO-B SECCHI data is the loss of EUV coverage of the western limb, as viewed from Earth, and an increased uncertainty in the 3D fitting of CMEs propagating in the far-side sector. Imagers on STEREO-A, however, will cover all CMEs propagating along the Earth-Sun line and 3D estimates of their size, direction, and speed will still be possible, provided the LASCO coronagraphs are operational. The analogy to the L-5 concept of a space weather monitor has been previously mentioned in this proposal and becomes increasingly relevant during this period. In addition, radio burst triangulation prospects will improve as STEREO-A approaches the Earth and its S/WAVES counterpart on Wind. Radio triangulation is optimized with spacecraft separations from approximately 30 to 90 degrees. Similarly, STEREO in-situ science objectives will still be achieved with various combinations of STEREO-A and other spacecraft near Earth (ACE, Wind, SOHO, DISCOVR) and elsewhere (MAVEN). After 2018, instrumentation on Solar Orbiter and Solar Probe Plus will cover, albeit intermittently, the solar far side and interplanetary conditions at large separations, providing opportunities for new coordination and investigations with STEREO observations. And there will even be enhancements to some of the science, for example with farside magnetograph and spectroscopic observations available from Solar Orbiter.

IIId. Scientific Productivity and Vitality

In the last two years, STEREO scientific productivity has continued at high levels, as measured by papers in refereed journals, theses, meeting presentations, and recognition of young researchers employing STEREO data to advance our understanding of solar and heliospheric phenomena. Since the launch of STEREO in 2006 October, some 1280 refereed publications have written use of STEREO data (see Appendix B for details). The 2016 SHINE Workshop in Santa Fe, New Mexico included three sessions involving STEREO observations. The 2016 EGU General Assembly in Vienna Austria included a special session on multipoint observations of the heliosphere in which STEREO was featured prominently. STEREO mission results are an important part of general conferences addressing the Sun and heliosphere, including the 2015 and 2016 AGU meetings, the 2016 EGU General Assembly, 2015 IAU General Assembly, and AAS/SPD.

At least seventeen theses using STEREO data were accepted in fulfillment of Ph.D. and master's degrees at universities in the US, Europe, and Japan. In addition, two young scientists received recognition in the form of prestigious awards for their work with STEREO data: The 2016 Arne Richter award for Outstanding Young Scientist was awarded by the European Geosciences Union to Dr. Christian Möstl for "his outstanding contributions to the understanding of coronal mass ejections, their 3D structure, their propagation in the heliosphere, and their effects at Earth." Dr. Möstl is affiliated with the Space Research Institute of Austrian Academy of Sciences. Also in 2016 Dr. Lan Jian was awarded COSPAR's Yakov B. Zeldovich Medal for young scientists for ``excellence and achievement for her important contribution to the study of interplanetary coronal mass ejections and stream interaction regions through the solar cycle". She is currently working for the University of Maryland and is funded in part by the STEREO/IMPACT team.

STEREO data has also been featured in the press and news media. NASA web releases connected to STEREO research have covered such topics as SEPs, CMEs, flares, and the solar wind. STEREO's 10th anniversary coverage included an event at the Smithsonian Air and Space Museum, together with articles and television and podcast interviews.

IIIe. Prioritized Science Goals, FY2018 - FY2022

The chief change to our Prioritized Science Goals is a refocusing of Goal Set 2 on the upcoming solar minimum. This time period presents an excellent opportunity to study the solar wind and the quiet corona at a time when the Sun is entering a new solar minimum (as in 2006, when STEREO was launched), but we are well-separated from Earth. We have refocused the PSG goal set on these topics, as described in more detail below. We also have an important opportunity to study variations in the Sun and heliosphere with STEREO capabilities over a second solar cycle.

Characterizing space weather, as described in Goal Set 1, is still a key STEREO mission focus. We have made small changes in emphasis in this goal set, expanding it to encompass the entire heliosphere, and expanding PSG 1-4 to encompass the more general range of heliospheric radio observations, from its earlier emphasis on Type III bursts. The study of large scale couplings in eruptions (PSG 2-1) will be folded into PSGs 1-1 and 1-2, while PSG 2-2 will be focused on the corona at solar minimum. Our previous PSG 3-1 concerning solar wind and transients in the outer heliosphere is now folded into PSG 1-5. We also describe below important opportunities related to the SPP and SO missions and STEREO L5 /quadrature that will open up in the FY2018-2020 period of this proposal.

STEREO Prioritized Science Goals FY2018-FY2022

Goal Set 1: Characterize space weather throughout the heliosphere

- PSG 1-1: Understand the large-scale structure of CMEs/ICMEs
- PSG 1-2: Understand the physics of ICME interactions
- PSG 1-3: Understand how solar energetic particles are accelerated and distributed so efficiently around the Sun
- PSG 1-4: Use measurements of radio bursts to study conditions in ICMEs and the solar wind.
- PSG 1-5: Characterize space weather throughout the solar system

Goal Set 2: Study the corona and solar wind at solar minimum *(New Goal Set)*

- PSG 2-1: Determine the structure of the quiescent solar wind
- PSG 2-2: Study the 360° minimum corona

Goal Set 3: What can we learn from coverage of the full heliosphere?

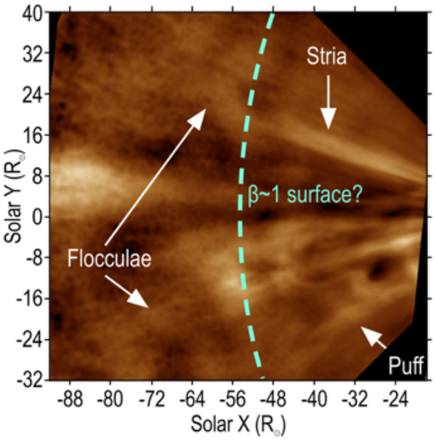
- PSG 3-1: Characterize the source and transport of pickup ions
- PSG 3-2: Improve our understanding of dust in the inner heliosphere

As in the past, STEREO team members will work to advance these goals. In addition, we are also reliant on the efforts of the many scientists funded by NASA and other science agencies in the US and abroad. It is a sign of the importance of STEREO data that it is used by a community of scientists much larger than just the STEREO team.

New Goal Set 2: Studying the corona and solar wind at solar minimum

PSG2-1: Determine the structure of the quiescent solar wind (F2,F5,H1,W1)

The multi-perspective, disk-to-1AU imaging and in-situ measurements on STEREO are ideal means to investigate long-standing questions about the source(s) of the solar wind affecting Earth. Advances in the image processing of the SECCHI heliospheric data combined with the reduction of solar activity as we approach the minimum of Cycle 24 offer a unique opportunity to study the structure and variability of the small-scale quiescent solar wind over the next 2-5 years. Several recent papers have demonstrated the capability to extract physical properties of the solar wind, such as speeds, spatial scales, and turbulence spectra, remotely from the SEC-



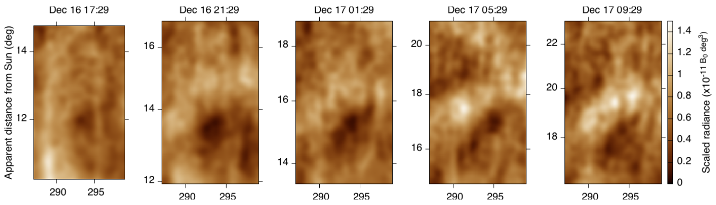


Figure 10: (left panel) The end of the solar corona is captured in this highly processed, radial-filtered HI-1 image from STEREO-A. The familiar radial striated corona fades out between 40-80 R⊙, marking a transition from low-beta to high-beta. (panel above): Growth of solar wind structures, called "flocculae" is captured in co-moving HI-1 time lapse movies of the solar wind. The flocculae cannot be explained by local compression alone, and may be a sign of growing hydrodynamic turbulence. Further study is necessary to reveal their cause and how they affect the solar wind itself. (DeForest et al. 2016)

CHI/HI-1 observations (Viall & Vourlidas 2015; DeForest et al. 2015, 2016; Tenerani, Velli & DeForest 2016), allowing us to follow its behavior from its origins in the corona to deep into the inner heliosphere. As CME activity wanes, the upcoming solar minimum presents a golden opportunity to study the small-scale structure of the slow solar wind and to test and extend results reached on two previous minima (e.g., Yu et al. 2016).

Recent Highlights. STEREO/HI-1 has captured the outer edge of the solar corona and the transition from the corona to the solar wind that fills the solar system. DeForest, et al. (2016) found a textural shift in images of the outer corona, from the familiar radial striated structure seen in coronagraphs, to a "flocculated", approximately isotropic structure that characterizes the slow solar wind throughout the solar system (Figure 10). They were able to demonstrate that the coronal striation breaks up between 10° – 20° ($40R_\odot$ – $80R_\odot$) from the Sun, signaling a shift from smoother, magnetically structured low-beta flow in the corona to more variable, turbulent high-beta flow in the solar wind. Further studies with HI-1 will yield insight into the cause of this transition and how it relates to familiar structures lower down in the corona.

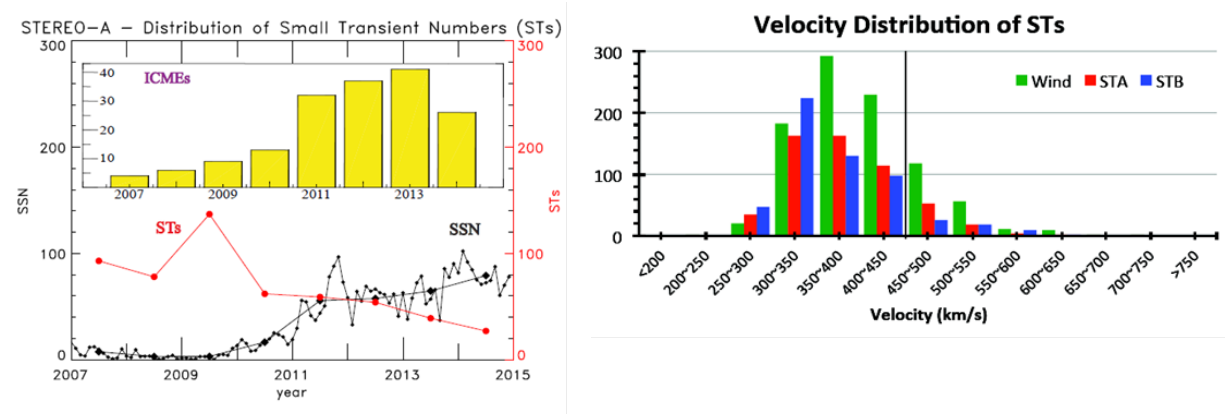


Figure 11: (left panel) Distribution of yearly numbers of small transients (STs) observed by STEREO-A (red) from year 2007 to 2014. The sunspot numbers (SSN) are shown in black. The top panel gives a histogram of ICMEs (yellow) observed in each year for comparison. (The STEREO ICMEs list is available on the web). (right panel) Distribution of ST frequency occurrence as a function of solar wind speed. (Yu et al., 2016)

On the in-situ side, Yu et al (2016) undertook an extensive statistical study of the occurrence and properties of small solar wind transients (STs) using the STEREO-A and B and the near-Earth spacecraft Wind. They find that the ST occurrence frequency follows the opposite trend to that of large transients. Figure 11 illustrates the clear anti-correlation with sunspot number. The ST number peaks in 2009, a solar minimum year. This trend is opposite to that of large ICMEs, shown by the histogram in yellow. The histogram on the left shows that the huge majority of STs are embedded in the slow wind.

STEREO will address several important questions. For example, what is the size and mass distribution of transient, small-scale structures? Are they an extension of the CME distribution or do they comprise a separate population? How do their properties compare to the statistics gathered in 2007-2009? Does the minimum 2007-2009 still stand out as unique?

Based on the values of the plasma beta, analytical modeling of flux rope-type small transients was also postulated to depend on solar cycle phase: While force-free modeling was suitable during solar maximum, it may be inappropriate during solar minimum. Is this still a valid conclusion? And if so, which non-force-free model should one use? What is the ejection mechanism and space weather role of the small slow CMEs trapped ahead of fast streams seen early in the STEREO mission (e.g., Rouillard et al. 2011)?

The near-quadrature location of STEREO-A relative to Earth enables studies of these transients as they head towards the in-situ spacecraft at L1. Moreover, the improvement in the processing and calibration of the SECCHI data should allow tracing the small intermittent coronal structure further inwards and possibly enhancing our understanding of the connection between coronal outflows seen in EUV imaging in the low corona (below 1.5 $R_\odot$) to the outflows imaged in white light in the outer corona (above 2.5 $R_\odot$). The in-situ data from STEREO-A meanwhile are a resource for comparison of structures observed at a separated location in the ecliptic at 1 AU, with those observed at L1. The measurements of plasma and magnetic field at the slowly evolving separation distance continues to provide a correlation length filter for studies that are of value for planning L5 missions, while the suprathermal electrons provide a measure of local structure magnetic topology, relevant to whether the source involves interchange reconnection or magnetic disconnection processes.

PSG 2-2: Study the 360° Minimum Corona (F4, H1,W1)

Solar Cycle 24 is on its declining phase with anticipated sunspot minimum in 2019-2020. Equatorial coronal holes have already made their appearance in the STEREO/EUVI images. STEREO was launched during a similar phase of the solar cycle in 2007 and studies of Stream Interface Regions (SIRs) and CIRs dominated the early STEREO science. However, those observations were taken when the STEREO spacecraft were at small elongation angles from Earth. This time around, STEREO-A provides a much wider longitudinal coverage both on the low corona (the EUVI plus AIA combination covers 2/3 of the total surface) and in-situ (at least 100° heliolongitude). Earth-directed CIRs are at optimal angles for detecting their Thomson-scattered emission while they evolve, and the equatorial coronal holes, can be followed much longer and over a larger longitude than was possible in 2007-2009. Hence, the next two years offer a prime opportunity to study the evolution of the solar corona towards its minimum state in 3D. What is the heliocentric distance of, and what are the solar wind properties at, the origin of SIRs? Which SIRs evolve into CIRs? Where does the particle acceleration in CIRs start? How accurate is the modeling of the background solar wind state and how can it be improved? STEREO can answer these questions.

Upcoming Opportunities

Opportunity: Solar Probe Plus and Solar Orbiter. The STEREO observations acquire an important new role during the extended mission phase discussed here. STEREO will provide support for two new Heliophysics missions, Solar Probe Plus (SPP), scheduled to launch in 2018 ,and Solar Orbiter (SO), scheduled for launch in early 2019. Both are encounter missions with brief periods of solar observations (30 days for SO, 10 days for SPP). They observe the Sun from within 0.28 AU orbits and from continuously varying vantage points mostly away from the Sun-Earth line. In other words, each perihelion passage will be a unique science target with high cost of science data return. To maximize the scientific return from these missions, their observations must be meticulously planned ahead of time. Therefore, knowledge of the three-dimensional status of the inner heliosphere before each orbit is absolutely required and STEREO is uniquely positioned to provide it. In the SPP case, the first perihelion (at 35 $R_\odot$) takes place in October 2018, barely 3 months from launch, leaving little room for trial and error in the observations. STEREO-A is at quadrature (~105 degrees from Earth) and has direct visibility of the corona surrounding SPP (the odd-numbered SPP perihelia occur behind the Sun-Earth line in 2018-19), providing optimal coverage of the solar corona and heliosphere. The STEREO contribution to the success of SO and SPP cannot be over-stated.

Opportunity: L5 testbed. A concept being actively developed on several fronts including international efforts envisions a space weather early warning mission featuring a spacecraft with imaging and in situ measurement capabilities parked at the L5 Lagrange point, 60° east of the Earth-Sun line. That vantage point allows active regions to be seen for several days before they rotate onto the hemisphere visible from Earth, as well as giving a "side" view that allows more accurate measurement of Earth-directed ICME propagation speeds than can be inferred from a single, Earth-Sun line view. From mid-2018, the STEREO-A-Earth angle will be within 45° of that separation, closing to zero by the summer of 2020, and should provide measurements that both address Goal Set 1 PSGs' science and determine whether an L5 view can provide improved space weather forecasting.

IIIf. Implementation

Implementation of the STEREO scientific goals for FY2018 - FY2022 is straightforward: We plan to continue the proven-value synoptic (essentially the same from day to day) measurements with STEREO-A that we have been obtaining since the spacecraft achieved heliocentric orbit in 2006 and 2007, while taking advantage of periods of higher than normal telemetry bandwidth to improve on temporal sampling, energy domain, polar angle range, and imaging spatial resolution and lossiness of compression as possible. Because we are only able to use the STEREO-A spacecraft for these measurements we are able to apply the DSN contact time previously allocated to the two STEREO spacecraft to achieve improvements earlier than the closing of the spacecraft-earth distance alone would allow.

Occasionally, STEREO has deviated from the synoptic plan for some hours per day for a limited time to capture unique scientific opportunities, such as imaging comets to search for disconnection events, but such campaigns are limited in duration to prevent disruption of the synoptic observations, and only carried out when operational risk is well understood and kept at a minimal level.

The PI team science operations staffing necessary to achieve these goals is minimal: the only expected changes are in the telemetry/sampling domain, as noted above, and occur infrequently. Pipeline processing is well understood and requires only fractional full-time equivalent support. The PI team budgets are balanced between operational requirements, data processing, and enough data analysis to maintain both the healthy interest in and use of STEREO data in the larger community, and the validation of the pipeline data products.

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IV. Technical Implementation

A. Mission management

STEREO mission operations are carried out by a dedicated STEREO team at the Johns Hopkins University Applied Physics Laboratory (APL), via a task on a contract between NASA Headquarters and APL. The Space Science Mission Operations (SSMO) office at NASA Goddard provides management and engineering oversight for contract operations, as well as DSN scheduling, flight dynamics (orbit), and NASA-rented tail circuits for communication with APL. The Project Scientist is the funds manager for STEREO, as well as providing scientific and Communications (the activities formerly known as public affairs) leadership for the mission; she is assisted in that work by two Deputy Project Scientists. All NASA personnel on STEREO, including a small number of Co-Investigators still funded for data processing and data-validating scientific research, charge only fractional FTEs to the project.

B. Science operations

Science commanding is carried out by the PI teams from workstations at their home institutions that communicate securely with the Mission Operations Center (MOC) at APL. Downlinked telemetry is flowed to the PI teams, as well as to the STEREO Science Center (SSC) at Goddard. The raw telemetry and the scientifically useful files reformatted by the PI teams are archived at the SSC, which also receives and rapidly publishes on the Web the space weather beacon data usually obtained by antenna partner sites organized though NOAA's Space Weather Prediction Center (SWPC). The SSC also provides the primary means of joint science planning and can act as single point of contact with the APL MOC for the science team. See Appendix A, below, for the Mission Archive Plan.

Science coordination is achieved through Science Working Team (SWT) meetings held either by telecon or in conjunction with scientific conferences. While the SWT meetings in the early years of the mission included scientific sessions as well, the feeling of the science team is that scientific progress is now better achieved through interaction with the larger scientific community, through workshops co-sponsored with other missions (e.g., the In-situ Science workshops and general scientific conferences (AGU, Cosmic Ray, SPD, etc.)).

C. Technical Risk

In our 2015 proposal we considered the following areas of technical risk: telemetry, spacecraft subsystem and ground system aging, and budget. Telemetry has been removed as a risk as the average STEREO-A data return has returned to the prime science level, i.e., 5 Gbits per day, in 2015 December. This was possible by revising the RF link analysis, decreasing spacecraft Earth range, and more frequent use of the 70m stations.

Spacecraft. As noted in Section II, the only known spacecraft degradation issues are in the Inertial Measurement Units and the star trackers on both spacecraft, and lower battery voltage on STEREO-B (see also Section II, above). The onboard software in STEREO-A has been patched to recognize situations in which any ring laser is faulty and react by marking data from the entire IMU as invalid; this would protect the spacecraft against anomalies of the kind that resulted in the loss of contact with STEREO-B. Obviously, when STEREO-B is recovered, its software would be patched as well.

The star trackers have slowly developed noise levels similar to the signal levels of fainter stars, often making for slow acquisition of guide stars; to counteract that, the mission operations team has commanded the operational temperature of the STEREO-A star tracker to a setting 30 degrees C lower than previously, and the noise appears to have been reduced. In 2013, the

STEREO-A spacecraft was transitioned to an attitude control law that depends on the star tracker (for roll attitude and rate information) and the SECCHI guide telescope (for pitch and yaw).

Fault protection will be enhanced on STEREO-B to account for the lower battery voltage after communications and attitude control are restored.

Ground System. The MOC Unix command and control workstations are in the process of being refreshed and the planning and assessment Unix workstations will be replaced afterwards. Similarly, the PI teams pipeline processing and commanding systems have been refreshed as needed (infrequently). The servers that process the raw, reformatted, and beacon mode telemetry at the STEREO Science Center, as well as those serving the STEREO public and SSC (data) Websites average over seven years in age, and will have to be replaced in the proposal period. Fortunately, small servers such as Mac minis or Intel Next Units of Computing (NUCs) are adequate for some of the tasks, and can be procured at extremely low cost.

Budget. For a discussion of the STEREO budget in one- and two-spacecraft scenarios, see Section V.

D. One and two spacecraft scenarios

At the time of writing, it is unclear whether and when communications can be restored with the STEREO-B spacecraft, and if so, to what extent the instrument suite will be able to resume its scientific operations. We therefore examine two extreme cases for the proposed mission extension: a single spacecraft (STEREO-A) and two spacecraft, the latter assuming a full return of the STEREO-B spacecraft and all its instruments to service before the start of the proposed extension period (2017 October 1).

Two spacecraft mission. This scenario would replicate the mission phase before the HGA thermal issue and superior conjunction, so we have a good baseline for planning. Costs for the PI teams and project management are unchanged except for inflation. In general, the scientific research carried out by the PI teams is sufficient to validate the continued quality of the data, and PI team members are focused on science operations, data pipeline processing, and validation of higher level data products as well as sufficient science analysis to make substantive progress toward the Prioritized Science Goals. Mission operations support will be less costly than in the two years before superior conjunction, when additional engineering support was needed to plan for superior conjunction operations, which involved contingencies not anticipated during the prime mission and first mission extension (2010).

We would propose to operate the two STEREO spacecraft in the same way we did prior to superior conjunction and the HGA thermal issue, with increasing data bandwidth and correspondingly higher daily data volume as the spacecraft-earth distance decreases. The higher telemetry would allow a return to higher sampling rates for the in situ instruments, a greater range of frequencies sample by S/WAVES, and more frequent images with less lossy compression for SECCHI.

Single spacecraft mission. This scenario envisions an unrecoverable STEREO-B spacecraft, or a recovery beyond the primary scope of this proposal (e.g., around inferior in 2022). In this scenario, as during the last year and a half, we would continue to use roughly the same number of hours of 34 m contact time we enjoyed per day for two spacecraft to double the contact time for a single spacecraft, or as close to that as is consistent with DSN loading. That would significantly accelerate the dates on which we could achieve higher data return and by 2017, we would be exceeding the maximum data return using 34 m stations in the earliest parts of the STEREO mission — but only for the STEREO-A spacecraft. By the spring of 2019, we could be achieving double that figure, as we did during a few weeks of the heliocentric phase of the mission in

2007, when we had dedicated 70 m support and 720 kbps downlink rates for true stereoscopic observations of the lower corona. Given the high contention for 70 m support, particularly during northern hemisphere winters, this would more reliably provide an increased downlink volume throughout the year.

With the additional telemetry, all the data originally provided by the instruments can be restored. For IMPACT, the primary effect of this on science would be the return by spring 2017 of full resolution (32 Hz) MAG burst data for high frequency waves and turbulence studies, and the collection of multiple bursts per day, as was done early in the mission. Other diagnostic products, such as burst criteria, and onboard pitch angle distributions (PADs) and moments products, which had been dropped to accommodate the lower telemetry rates, would be restored. The PLASTIC solar wind and pickup ion composition data, solar wind proton moments, and suprathermal rates would be restored, and the remaining ion rates, including solar wind protons, would be returned to their original cadence. PLASTIC would also recover housekeeping information used in tables. S/WAVES time and frequency resolutions would no longer be halved. By far the biggest impact of any increased telemetry volume would be on the SECCHI images, with significant improvements both in image quality from the use of lower compression ratios, but also in the image cadence needed to properly study solar activity. Only during two short “SECCHI campaign” periods early in the mission were such telemetry volumes achieved.

The increased telemetry would allow SECCHI to focus on 3D studies of the early phases of erupting events, such as the tantalizing evidence for a super-expansion phase (Patsourakos et al. 2010). They can reveal essential information for the 3D morphology of the erupting structures (e.g., Patsourakos et al. 2013) and will become increasingly important as STEREO-A nears quadrature configuration with SDO in 2018-19. Beyond 2019, the ‘campaign’-level telemetry opens up a whole new world of science objectives such as 3D studies of jets, and spicules (with SDO & IRIS) and the possibility to trace the origin of the solar wind via small-scale outflows from the inner to the outer corona---an important support for SO and SPP. These studies rely on high cadence, multi-view observations from SDO AIA and STEREO EUVI and detailed kinematic profiles from the COR1/COR2 telescopes. Increased telemetry during the SPP perihelion passes would allow STEREO to increase the resolution of in-situ data to improve the connections between the SPP in-situ measurements and lower the compression of the EUVI images and COR1 to enable higher fidelity off-limb observations for tracing small-scale structures to the SPP location. The in-situ option would be especially helpful for SPP perihelion passes in which SPP and STEREO are radially connected, while increased remote sensing data will be most useful when STEREO and SPP are in quadrature.

V. Budget

At the time of writing, it is unclear whether and when communications can be restored with the STEREO-B spacecraft, and if so, to what extent the instrument suite will be able to resume its scientific operations. We therefore, and ***with the agreement of Heliophysics MO&DA management***, examine two extreme cases for the proposed mission extension: a single spacecraft (STEREO-A) and two spacecraft, the latter assuming return to service and full scientific operation of all instruments before the start of the proposed extension period (2017 October 1).

Uncosted funds listed in the budget tables are funds obligated to grants and contracts for which the contractors have not yet submitted invoices. There are two varieties of uncosted funds in the STEREO budget. One is due to actual delays in spending by the instrument teams. The other is due to delays in invoicing for the grants funding the instrument teams and related delays in billing by subcontractors to those grants. This is a particular issue for STEREO because many of our team members are funded under grants, for which billing is not as regular as under contracts. We propose a cut in the budget for FY17 in the two-spacecraft budget and for FY17-19 in the one-spacecraft budget to reduce the uncosted funds due to actual delays in work done by the instrument and operations teams, leaving uncosted funds due to delays in invoicing, which we estimate to be about 2.4M and a cushion of about 10 weeks to allow for delays in getting funding to the PI institutions. Further cuts would affect the ability of the STEREO team institutions to perform necessary work.

In all budgets below (Tables V-1 to V-4) we have added a suggested guideline to show the reductions we propose related to reducing uncosted carryover from one fiscal year to the next. This reduced budget total and results of these reductions are highlighted in peach.

Two spacecraft mission. This scenario would replicate the mission phase before the HGA thermal issue and superior conjunction, so we have a good baseline for planning. Costs for the PI teams and project management are unchanged except for inflation. In general, the scientific research carried out by the PI teams is sufficient to validate the continued quality of the data, and PI team members are focused on science operations, data pipeline processing, and validation of higher level data products. Mission operations support will be less costly than in the two years before superior conjunction, when additional engineering support was required to design, implement, and test new onboard software and ground procedures for superior conjunction operations. That additional support was also used to deal with the HGA thermal issue and to modify the onboard anomaly response to prevent a repetition of the loss of communication with the STEREO-B spacecraft on STEREO-A. By contrast, barring new spacecraft hardware issues, we expect a much more familiar operational environment in the years FY2016 - FY2020. Even the changing downlink bandwidths and time to download the nominal data return volumes will simply mirror our experience before superior conjunction, with rates increasing and download times — and DSN contact requirements — correspondingly decreasing. ***The decrease in mission operations costs and uncosted funds allows us to propose an under-guide budget for this year, FY2017, but inflation causes us to exceed the guidelines for FY2019 - FY2022, despite holding the PI team budgets below inflation.***

An in-guide budget for a two-spacecraft mission showing the effects of cuts in FY18 onward is shown in Table V-1. In Table V-2 we show a proposed over-guide budget that would allow work of the instrument teams to continue at present levels.

Single spacecraft mission. This scenario is based on experience since the loss of contact with the STEREO-B spacecraft and the return to normal operations of STEREO-A after superior conjunction. Since data pipeline operations are extensively automated, and instrument planning and commanding involves little or no additional work for two spacecraft as opposed to one, none of the PI teams was able to identify significant cost savings for single spacecraft operations.

During the annual Heliophysics Program and Project Budget Exercise (PPBE) held in the spring of 2016, SSMO management was tasked with identifying mission operations savings in a single-spacecraft scenario. With the cooperation of the APL mission ops team SSMO was able to produce significant cost savings for single-spacecraft operations, as can be seen in Tables V-3 and V-4, where the single-spacecraft budget is presented.

In order to reduce the amounts of uncosted funds we propose an under-guide budget for FY17-19. ***After that time we can propose an in-guide budget by assuming cuts in the instrument budgets of 0.5-4%. This is shown in Table V-3. We also show, for comparison, in Table V-4 a one spacecraft overguide budget in which the instrument team budgets are flat.***

STEREO (2 Spacecraft) 619595 ($M) Inguide

	Prior	FY17	FY18	FY19	FY20	FY21	FY22	FY23	Total
N2 Guideline (Project Total)	522.741	8.250	8.250	8.250	8.250	8.250	8.250	8.250	580.491
N2 Suggested Guideline	522.741	6.500	8.250	8.250	8.250	8.250	8.250	8.250	578.74
Senior Review 2017 Submit (Project Total)	522.741	6.500	8.250	8.250	8.250	8.250	8.250	8.250	578.741
Labor	**14.817**	0.365	0.431	0.447	0.463	0.479	0.496	0.514	18.012
Travel	**1.133**	0.016	0.016	0.016	0.016	0.016	0.016	0.016	1.245
DA									
Taxes		0.130	0.146	0.142	0.137	0.136	0.132	0.133	0.956
FTE		2.1	2.1	1.8	1.7	1.7	1.7	1.7	
WYE		2.9	2.9	2.5	2.4	2.4	2.3	2.3	
IMPACT		0.918	1.270	1.241	1.196	1.184	1.150	1.161	8.119
PLASTIC		0.5	0.527	0.515	0.496	0.491	0.477	0.481	3.487
S/WAVES		0.46	0.497	0.485	0.468	0.463	0.450	0.454	3.278
SECCHI		1.2	1.579	1.543	1.487	1.472	1.431	1.443	10.156
SSC		0.417	0.410	0.352	0.339	0.336	0.326	0.329	2.508
Total DA	**377.675**	3.625	4.429	4.277	4.123	4.081	3.967	4.002	28.504
MO									
FTE		0.3	0.3	0.3	0.3	0.3	0.3	0.3	
WYE		9.6	9.6	9.6	9.6	9.6	9.6	9.6	
APL	**16.787**	2.265	3.140	3.270	3.400	3.420	3.510	3.450	39.242
FDF	**0.841**	0.107	0.110	0.113	0.117	0.120	0.124	0.128	1.660
DSN	**0.402**	0.112	0.114	0.117	0.121	0.124	0.127	0.130	1.247
Tail Circuits	**0.011**	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.081
Other Centers	**111.075**	0.000	0.000	0.000	0.000	0.000	0.000	0.000	111.075
Total									
Uncosted	**5.284**	5.746	5.591	4.829	3.797	2.719	1.525	0.364	0.000
Weeks of Uncosted	**33**	35	32	26	20	14	8	2	0.000
Burn Rate / month	**0.649**	0.649	0.700	0.751	0.773	0.777	0.787	0.784	0.000
Projected yearly costs		7.788	8.405	9.013	9.281	9.328	9.444	9.411	
Using Suggested NOA									
Total									
Uncosted	**5.284**	3.996	3.841	3.079	2.047	0.969	-0.225	-1.386	0.000
Weeks of Uncosted	**33**	25	22	16	11	5	-1	-7	0.000
Burn Rate / month	**0.649**	0.649	0.700	0.751	0.773	0.777	0.787	0.784	0.000
Projected yearly costs		7.788	8.405	9.013	9.281	9.328	9.444	9.411	
In-Kind costs to mission:		**0.043**	**0.044**	**0.046**	**0.047**	**0.048**	**0.050**	**0.051**	**0.329**
Space Communications Services		13.315	13.714	14.126	14.550	14.986	15.436	15.899	102.026
External (non-NASA) funding		0	0	0	0	0	0	0	0
Delta to Guideline (Project Total) (+over/-under)*	**0.000**	**-1.750**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**-1.750**

*** Excludes In-Kind contributions**

V-1: STEREO in-guide budget for a two-spacecraft mission. The budget is under guide for FY2017. If STEREO-B is recovered in the fall of 2017 the Guideline budget will not be sufficient to continue funding the instrument teams without significant cuts. The suggested guideline with an under-guide budget in FY17 and resulting calculations has been added and highlighted in peach.

STEREO (2 Spacecraft) 619595 ($M) Overguide

	Prior	FY17	FY18	FY19	FY20	FY21	FY22	FY23	Total
N2 Guideline (Project Total)	522.741	8.250	8.250	8.250	8.250	8.250	8.250	8.250	580.491
N2 Suggested Guideline	522.741	6.500	8.847	9.013	9.281	9.328	9.444	9.411	584.57
Senior Review 2017 Submit (Project Total)	522.741	6.500	8.847	9.013	9.281	9.328	9.444	9.411	584.566
Labor	**14.817**	0.365	0.431	0.447	0.463	0.479	0.496	0.514	18.012
Travel	**1.133**	0.016	0.016	0.016	0.016	0.016	0.016	0.016	1.245
DA									
Taxes		0.130	0.148	0.146	0.148	0.150	0.152	0.154	1.028
FTE		2.1	2.1	2.1	2.1	2.1	2.1	2.1	
WYE		2.9	2.9	2.9	2.9	2.9	2.9	2.9	
IMPACT		0.918	1.447	1.462	1.511	1.511	1.511	1.511	9.871
PLASTIC		0.5	0.600	0.621	0.643	0.643	0.643	0.643	4.293
S/WAVES		0.46	0.566	0.586	0.606	0.606	0.606	0.606	4.036
SECCHI		1.2	1.799	1.807	1.829	1.829	1.829	1.829	12.123
SSC		0.417	0.467	0.417	0.417	0.420	0.420	0.420	2.978
Total DA	**377.675**	3.625	5.026	5.040	5.154	5.159	5.161	5.163	34.329
MO									
FTE		0.3	0.3	0.3	0.3	0.3	0.3	0.3	
WYE		9.6	9.6	9.6	9.6	9.6	9.6	9.6	
APL	**16.787**	2.265	3.140	3.270	3.400	3.420	3.510	3.450	39.242
FDF	**0.841**	0.107	0.110	0.113	0.117	0.120	0.124	0.128	1.660
DSN	**0.402**	0.112	0.114	0.117	0.121	0.124	0.127	0.130	1.247
Tail Circuits	**0.011**	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.081
Other Centers	**111.075**	0.000	0.000	0.000	0.000	0.000	0.000	0.000	111.075
Total									
Uncosted	5.284	5.746	5.591	4.829	3.797	2.719	1.525	0.364	0.000
Weeks of Uncosted	33	35	32	26	20	14	8	2	0.000
Burn Rate / month	0.649	0.649	0.700	0.751	0.773	0.777	0.787	0.784	0.000
Projected yearly costs		7.788	8.405	9.013	9.281	9.328	9.444	9.411	
Using Suggested NOA									
Total Uncosted	5.284	3.996	4.438	4.438	4.438	4.438	4.438	4.438	0.000
Weeks of Uncosted	33	25	25	24	23	23	23	23	0.000
Burn Rate / month	0.649	0.649	0.700	0.751	0.773	0.777	0.787	0.784	0.000
Projected yearly costs		7.788	8.405	9.013	9.281	9.328	9.444	9.411	
In-Kind costs to mission:		**0.043**	**0.044**	**0.046**	**0.047**	**0.048**	**0.050**	**0.051**	**0.329**
Space Communications Services		13.315	13.714	14.126	14.550	14.986	15.436	15.899	102.026
External (non-NASA) funding		0	0	0	0	0	0	0	0
Delta to Guideline (Project Total) (+over/-under)*	**0.000**	**-1.750**	**0.597**	**0.763**	**1.031**	**1.078**	**1.194**	**1.161**	**4.075**

* Excludes In-Kind contributions

Table V-2: STEREO over-guide budget for a two-spacecraft mission. The budget is under guide for FY2017 to reduce uncosted carryover of funds, but overguide thereafter to allow for adequate funding of the STEREO instrument teams. The suggested guideline and resulting calculations has been added and highlighted in peach.

STEREO (1 Spacecraft) 619595 ($M) Inguide

	Prior	FY17	FY18	FY19	FY20	FY21	FY22	FY23	Total
N2 Guideline (Project Total)	522.741	8.250	8.250	8.250	8.250	8.250	8.250	8.250	580.491
N2 Suggested Guideline	522.741	6.500	7.800	8.100	8.250	8.250	8.250	8.250	578.14
Senior Review 2017 Submit (Project Total)	522.741	6.500	7.800	8.100	8.250	8.250	8.250	8.250	578.143
Labor	**14.817**	0.365	0.431	0.447	0.463	0.479	0.496	0.514	18.012
Travel	**1.133**	0.016	0.016	0.016	0.016	0.016	0.016	0.016	1.245
DA									
Taxes		0.130	0.148	0.146	0.148	0.150	0.152	0.154	1.028
FTE		2.1	2.1	2.1	2.1	2.1	2.1	2.1	
WYE		2.9	2.9	2.9	2.8	2.9	2.9	2.9	
IMPACT		0.918	1.331	1.434	1.456	1.449	1.441	1.433	9.462
PLASTIC		0.5	0.552	0.609	0.620	0.617	0.613	0.610	4.120
S/WAVES		0.46	0.521	0.575	0.584	0.581	0.578	0.575	3.873
SECCHI		1.2	1.784	1.772	1.763	1.754	1.745	1.735	11.754
SSC		0.417	0.430	0.409	0.402	0.400	0.398	0.396	2.851
Total DA	**377.675**	3.625	4.764	4.944	4.973	4.951	4.927	4.902	33.088
MO									
FTE		0.3	0.3	0.3	0.3	0.3	0.3	0.3	
WYE		9.6	9.6	9.6	9.6	9.6	9.6	9.6	
APL	**16.787**	2.265	2.355	2.453	2.550	2.550	2.550	2.550	34.060
FDF	**0.841**	0.107	0.110	0.113	0.117	0.120	0.124	0.128	1.660
DSN	**0.402**	0.112	0.114	0.117	0.121	0.124	0.127	0.130	1.247
Tail Circuits	**0.011**	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.081
Other Centers	**111.075**	0.000	0.000	0.000	0.000	0.000	0.000	0.000	111.075
Total									
Uncosted	5.284	5.746	6.136	6.394	6.424	6.430	6.412	6.370	0.000
Weeks of Uncosted	33	35	37	38	38	37	37	37	0.000
Burn Rate / month	0.649	0.649	0.655	0.666	0.685	0.687	0.689	0.691	0.000
Projected yearly costs		7.788	7.860	7.992	8.220	8.244	8.268	8.292	
Using Suggested NOA									
Total									
Uncosted	5.284	3.996	3.936	4.044	4.074	4.080	4.062	4.020	0.000
Weeks of Uncosted	33	25	24	24	24	24	24	23	0.000
Burn Rate / month	0.649	0.649	0.655	0.666	0.685	0.687	0.689	0.691	0.000
Projected yearly costs		7.788	7.860	7.992	8.220	8.244	8.268	8.292	
In-Kind costs to mission:		**0.043**	**0.044**	**0.046**	**0.047**	**0.048**	**0.050**	**0.051**	**0.329**
Space Communications Services		13.315	13.714	14.126	14.550	14.986	15.436	15.899	102.026
External (non-NASA) funding		0	0	0	0	0	0	0	0
Delta to Guideline (Project Total) (+over/-under)*	**0.000**	**-1.750**	**-0.450**	**-0.150**	**0.000**	**0.000**	**0.000**	**0.000**	**-2.348**

*** Excludes In-Kind contributions**

Table V-3: STEREO in-guide budget for a one-spacecraft mission. The budget is underguide for FY2017-19 to reduce uncosted carryover of funds. Small cuts below a flat funding profile are needed there after to keep the budget in-guide. The suggested guideline with an under-guide budget in FY17-19 and resulting calculations has been added and highlighted in peach.

STEREO (1 Spacecraft) 619595 ($M) Overguide

	Prior	FY17	FY18	FY19	FY20	FY21	FY22	FY23	Total
N2 Guideline (Project Total)	522.741	8.250	8.250	8.250	8.250	8.250	8.250	8.250	580.491
N2 Suggested Guideline	522.741	6.500	7.800	8.214	8.449	8.477	8.503	8.530	579.21
Senior Review 2017 Submit (Project Total)	522.741	6.500	7.800	8.214	8.449	8.477	8.503	8.530	579.214
Labor	**14.817**	0.365	0.431	0.447	0.463	0.479	0.496	0.514	18.012
Travel	**1.133**	0.016	0.016	0.016	0.016	0.016	0.016	0.016	1.245
DA									
Taxes		0.130	0.166	0.164	0.166	0.169	0.171	0.173	1.139
FTE		2.1	2.1	2.1	2.1	2.1	2.1	2.1	
WYE		2.9	2.9	2.9	2.9	2.9	2.9	2.9	
IMPACT		0.918	1.300	1.462	1.511	1.511	1.511	1.511	9.724
PLASTIC		0.5	0.600	0.621	0.643	0.643	0.643	0.643	4.293
S/WAVES		0.46	0.500	0.586	0.606	0.606	0.606	0.606	3.970
SECCHI		1.2	1.765	1.807	1.829	1.829	1.829	1.829	12.089
SSC		0.417	0.433	0.417	0.417	0.420	0.420	0.420	2.944
Total DA	**377.675**	3.625	4.764	5.058	5.172	5.178	5.180	5.182	34.159
MO									
FTE		0.3	0.3	0.3	0.3	0.3	0.3	0.3	
WYE		9.6	9.6	9.6	9.6	9.6	9.6	9.6	
APL	**16.787**	2.265	2.355	2.453	2.550	2.550	2.550	2.550	34.060
FDF	**0.841**	0.107	0.110	0.113	0.117	0.120	0.124	0.128	1.660
DSN	**0.402**	0.112	0.114	0.117	0.121	0.124	0.127	0.130	1.247
Tail Circuits	**0.011**	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.081
Other Centers	**111.075**	0.000	0.000	0.000	0.000	0.000	0.000	0.000	111.075
Total									
Uncosted	5.284	5.746	6.136	6.394	6.424	6.430	6.412	6.370	0.000
Weeks of Uncosted	33	35	37	38	38	37	37	37	0.000
Burn Rate / month	0.649	0.649	0.655	0.666	0.685	0.687	0.689	0.691	0.000
Projected yearly costs		7.788	7.860	7.992	8.220	8.244	8.268	8.292	
Using Suggested NOA									
Total									
Uncosted	5.284	3.996	3.936	4.158	4.387	4.620	4.855	5.093	0.000
Weeks of Uncosted	33	25	24	25	26	27	28	29	0.000
Burn Rate / month	0.649	0.649	0.655	0.666	0.685	0.687	0.689	0.691	0.000
Projected yearly costs		7.788	7.860	7.992	8.220	8.244	8.268	8.292	
In-Kind costs to mission:		**0.043**	**0.044**	**0.046**	**0.047**	**0.048**	**0.050**	**0.051**	**0.329**
Space Communications Services		13.315	13.714	14.126	14.550	14.986	15.436	15.899	102.026
External (non-NASA) funding		0	0	0	0	0	0	0	0
Delta to Guideline (Project Total) (+over/-under)*	**0.000**	**-1.750**	**-0.450**	**-0.036**	**0.199**	**0.227**	**0.253**	**0.280**	-1.277

*** Excludes In-Kind contributions**

Table V-4: STEREO over-guide budget for a one-spacecraft mission. The budget is under guide for FY2017-19 to reduce uncosted carryover of funds. The budget is over guide thereafter to maintain a flat funding profile for the instrument teams, which will still lead to an erosion of their budgets with inflation. The suggested guideline and resulting calculations has been added and highlighted in peach.

VI. Appendices

A. Mission Archive Plan

Mission-wide Data and Software

The STEREO Science Center (SSC), located at NASA Goddard, serves as the main archive for all STEREO data. The primary source of ancillary data products for the STEREO mission is the STEREO Data Server (SDS) maintained as part of the Mission Operations Center at the Johns Hopkins University Applied Physics Laboratory. These data, which include all operational and engineering data and reports shared between the operations and instrument teams, are mirrored over to the SSC several times per day for archiving. All the ancillary data products are made available online except for the telemetry dictionaries which are archived separately for security reasons, and the DSN Schedule Change reports which are not made public because they include email addresses; the information in them is included in the subsequent DSN schedule files. Event lists maintained by the PI teams and others are available at the SSC Website.

Telemetry, Ephemerides, and Attitude History. Final level-0 telemetry files are archived by the SSC for each of the instruments and spacecraft subsystems. All STEREO ephemerides and attitude history files are provided as SPICE kernels. SPICE is a standard ephemeris package provided by the Jet Propulsion Laboratory's Navigation and Ancillary Information Facility (NAIF), and used by many interplanetary and heliospheric missions. Information about SPICE and the SPICE software package can be obtained from the NAIF Website. The SPICE kernels archived by the SSC are in ASCII transfer format, which can then be compiled into machine-readable form for any supported platform.

SolarSoft. Data analysis software is distributed as part of the Solar Software Library, also known as SolarSoft. This multi-mission software library is used extensively within the solar physics community, and enables cross-mission data analysis. The primary emphasis is on Interactive Data Language (IDL) software, but source code for other languages is also distributed using the SolarSoft mechanism. Together with the large generic library supplied with SolarSoft, each instrument team provides software for analyzing their own data. Also provided are the most current ephemeris and attitude history files for the entire mission, and software to manipulate them in a large variety of standard coordinate systems.

Instrument resources. Resource pages are available for each of the STEREO instruments, using a standardized format first developed for the SOHO mission, and are accessible from the SSC Website.

Mission Documentation. A special issue (Volume 136) of Space Science Reviews (SSR) is devoted to the STEREO mission. In that issue are extensive descriptions of the spacecraft, instruments, and ground systems.

Data Distribution. The SSC resides within the Solar Data Analysis Center (SDAC) at the Goddard Space Flight Center. The SDAC is a multi-mission Resident Archive with extensive experience distributing data for a number of missions, including SOHO, TRACE, RHESSI, Hinode, SDO, and others, as well as archiving data for older missions such as the Solar Maximum Mission. The SDAC will act as the active Resident Archive for the lifetime of the mission and beyond. Ultimately, the data will be delivered to the Permanent Archive designated by NASA Heliophysics MO&DA management.

The remote sensing and *in situ* data being actively delivered to the SSC form the major core of what will become the STEREO long term archive, and many of the *in situ* data products are also being actively delivered to the Space Physics Data Facility (SPDF). SECCHI Level 1 and Level 2 products will be generated from the current Level 0.5 files using already existing software, after final validation of the calibration. The various levels of data from the IMPACT and PLASTIC instruments are already in archivable format, as are the CDF versions of the S/WAVES data in the SPDF, and only require revalidation of the calibration and completion of the most recent data. At the end of the STEREO mission, an additional year of work will be needed from the instrument teams to perform a last validation of the calibrations, and to complete any remaining data processing.

The Virtual Solar Observatory (VSO) 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. IMPACT magnetometer and particle data, as well as S/WAVES intensity spectra, are also available through the Virtual Heliospheric Observatory (VHO). An extensive list of all access sites, including those at the individual PI and Co-I institutions, is maintained on the SSC Website.

The Heliophysics Data Portal provides access to STEREO data from many different sources, including the VSO and VHO. SPASE descriptions for almost all STEREO science data products have been registered within the Space Physics Data Facility, as well as many of the browse data products for the *in situ* instruments. The instrument teams are in the process of reviewing the SPASE descriptions for accuracy and completeness. In addition, the SSC and SECCHI instrument teams have begun putting together SPASE descriptions for the various browse products and tools that are on their respective websites, and expect to have this process completed within the next few months.

IMPACT

Scientific Data Products. The IMPACT investigation provides several levels of science data products. The primary, “Level 1” science products include all science data at highest time resolution and in scientific units and coordinates. These products are produced at UC-Berkeley upon transfer of the Level 0 telemetry files from the SSC and validated by the IMPACT Co-Investigators within one month of generation. During this review period, the Co-Investigators responsible for data validation of the SIT and HET instruments retired, and their validation responsibilities were successfully transitioned to their successors. Once validated, these files are made publicly available (see below). Level 1 data files are in ISTP-compliant CDF format and intended to be self-documenting. The full complement of ISTP-required metadata is included within these files. All IMPACT Level 1 files are archived within the SSC. Appropriate metadata have been developed for each Level 1 data product, and incorporated into the VHO. In addition, a Level 1-like data product has been produced using the Solar Weather Beacon data for the period surrounding solar occultation. These data, for MAG and the SEP suite, are, for MAG, at a reduced cadence and, for SEP, include a subset of the data parameters available in the true SEP Level 1 data products due to the inherently compressed nature of the Solar Weather Beacon data. These data are intended to fill in data gaps during the period when true Level 0 and Level 1 IMPACT data was produced by APL and UC Berkeley only during periods of spacecraft contact.

Level 2 data are a merged data set, including data from the IMPACT and PLASTIC investigations, and averaged to ensure identical time cadences (1-minute, 1-hour and 1-day). These data are intended for quick browsing and are integrated with an online plotting and ASCII listing service hosted at UCLA. The same data in CDF format will also be available by the time of the Senior Review. Level 3 data are list-type data such as event lists compiled by the IMPACT team.

They are in PDF and Excel formats. Appropriate metadata have been incorporated into the VHO to enable searching on the data.

Currently, the IMPACT investigation provides Level 1 data for all instruments. Level 2 data including MAG and PLASTIC moments are being served at UCLA in ASCII format, and are archived within the SSC as CDF files. Level 2 data in ASCII format are also available for the SEP suite instruments through the Caltech and Kiel sites, with links for the latter on the UCLA site. CDF versions of these data are under active development. Level 3 event lists are served by UCLA, and archived within the SSC.

The STEREO Level 3 (ASCII) event lists of ICMEs, SIRs, shocks, and SEP events represent an unparalleled resource for the study of solar cycle evolution of space weather from a multipoint perspective. They include basic characteristics in addition to time interval, such as peak B field magnitude and peak pressure. STEREO-A continues to provide a basis for comparisons to ACE and Wind near-Earth observations. For STEREO-A, these lists have been updated to August 2014, or October 2016 for the SEP events; for STEREO-B, the lists are updated to the time when STEREO-B became lost in contact in September 2014.

During the periods surrounding solar conjunction, very little Level 1 and 2 data is available due to the fact that the spacecraft SSR was reallocated to record only Space Weather Beacon data. Therefore, the IMPACT Beacon data, processed and archived at the STEREO Science Center, should be used for studies requiring continuous data coverage. The IMPACT/MAG group has produced a MAG data product, newly calibrated, based on these Beacon data that are being served at UC Berkeley, UCLA, the STEREO Science Center and CDAWeb. This MAG product provides the highest quality continuous MAG data available for this period.

Documentation. The SSR special issue includes complete information regarding the IMPACT instruments and data products. In addition, documentation is served online through the IMPACT instrument resource page. Information about calibrations and software versions used in the production of Level 1 data products are listed on this website and included in the internal documentation of the CDF files themselves.

Analysis Tools. The IMPACT investigation provides data products in ISTP-compliant CDF and ASCII formats to ensure easy integration with users' native analysis environments. In addition, the IMPACT team provides custom software through the instrument resource page based on the UC-Berkeley TPLOT library. This is an IDL-based set of analysis routines designed specifically for *in situ* measurements.

Online browsers and plotters hosted by UCLA, UC-Berkeley, the University of Kiel, and the *Institut de Recherche en Astrophysique et Planétologie* (IRAP) provide tools on the web. At UC-Berkeley, a traditional browse-type, static plot tool is available. This tool links IMPACT and ACE plots and data with images and models. A real-time space weather tool has also been developed at UC-Berkeley that integrates STEREO Beacon, SDO and ACE plots.

Final Data Set. The IMPACT Level 1, 2 and 3 data sets are the "final" data products and are already being produced and archived at the STEREO Science Center. However, it is possible that instrument calibrations may be updated prior to the end of the mission necessitating reprocessing of some data products. Such reproduction will take place as soon as the new calibration factors are determined and incorporated in the data set archived at the STEREO Science Center.

Data Distribution. The IMPACT data sets are available through the main IMPACT UC-Berkeley instrument resource web site listed above. In addition, all data are mirrored by the SSC and available there. Data are also mirrored and available through CDAWeb. IMPACT data are being included in the VHO interface. Space Physics Archive Search and Extract (SPASE) descriptions of the IMPACT Level 1 data products have been written.

Together with the above, Caltech hosts a site specific to the Solar Energetic Particle (SEP) suite. This site provides SEP and some ancillary data (notably, orbit and attitude information) in ASCII format. A site hosted by the IRAP includes additional data products and analysis tools for the SWEA instrument.

The IMPACT team will review the data listings in the Heliophysics Data Portal for completeness and accuracy. The team will make changes to the SPASE descriptions of its data products as necessary and work to include additional data products as they come online.

PLASTIC

Scientific Data Products. Level 1 data are the highest-resolution, complete data set. They have the epoch time and instrument section decommutated, counts decompressed, and entries separated into meaningful products (solar wind proton moment array, reduced proton and alpha distributions, heavy ion species count rate arrays, pulse height data, housekeeping, etc.), but are not fully converted into physical units (such as flux) that require the incorporation of detection efficiencies which may change over the life of the mission (due to gain changes in the detectors). Level 1 data products are produced at UNH within 24 hours of receipt of Level 0 telemetry files. Software and calibration/efficiency files to convert the data into physical units, along with appropriate documentation, are delivered electronically to the SSC archive. Level 1 data products are in ISTP-compliant CDF files.

Level 2 data products include the most frequently used quantities from PLASTIC in physical units. These data products are accessible on the PLASTIC Website (menu link to “Resources”) and include both browse quality (typically available within 1 day of Level 1) and validated (updated monthly) products. Validated Level 2 products currently available on the UNH site as ASCII files include solar wind protons, alphas, and selected minor ions. Selected key parameters (such as solar wind bulk parameters, ion charge state distributions, and He+ intensities) are also provided on the UNH-hosted PLASTIC online browser as daily and/or monthly time series plots. Verified and validated products undergo both automatic and science personnel quality checks. These archival quality data are added to ISTP-compliant Level 2 CDFs and mirrored at the SSC. The validated PLASTIC proton moments are also included as a merged plasma plus magnetic field product courtesy of the IMPACT/MAG site at UCLA.

Level 3 data products typically result from directed scientific analysis, and include specific intervals (such as identified ICMEs) and other value-added products. He+ phase space densities are available for STEREO-A in 1 hour and 24 hour cadences, and He+ relative fluxes are available in a 24 hour cadence. Both He+ products are available in CDF and ASCII format through UNH, and also mirrored at the SSC website. A list of early mission suprathermal event periods is available through the SSC website in ASCII format.

Documentation. Full descriptions of the PLASTIC instruments and the Level 1 data products can be accessed through the Instrument Resource webpage at the UNH website. Metadata relevant to particular data products are also available within the CDF files. ASCII products either have the product information contained within the file header, or else a Readme file is provided. The instrument and data products are fully described in the PLASTIC instrument paper in the SSR special issue. This paper is available online, free-of-charge to the public, and is linked through the PLASTIC Resource page.

Analysis Tools. PLASTIC data are available in ISTP-compliant CDFs such that they can be easily integrated into existing analysis and search tools, such as the VHO and SolarSoft. In addition, the PLASTIC team has extended the UC-Berkeley TPLOT library (see IMPACT section, above) into the IDL-based SPLAT (Stereo PLastic Analysis Tool) that further enables integration of data sets. SPLAT and other IDL programs, including those that support composition analysis and those that create specialized ASCII files from the CDF files, are distributed through the SolarSoft library.

Data Distribution. PLASTIC Levels 1 and validated Level 2 and Level 3 data are available both via the UNH-hosted Website and at the mirrored SSC instrument data site. PLASTIC archival data is also available at the CDAWeb, the VSO, the VHO, and the Heliophysics Data Portal (HDP). In order to address comments from the last review, all SPASE descriptions in the HDP have been checked, and a SPASE description for the suprathermal event list has been added.

Final Data Set. Final PLASTIC data are created and mirrored by the archive on an on-going basis. There is the possibility that, with further scientific analysis, a product might be updated. If this happens, the data will be reprocessed and the new files distributed with an updated version number.

SECCHI

Scientific data products. All SECCHI image telemetry data are converted to FITS files upon receipt of version 02 of the Level-0 telemetry files, about 2 days from the date of observation. This processing is done at the SECCHI Payload Operations Center (POC), located at NRL. The FITS headers contain all instrument parameter and spacecraft pointing information. The images have been oriented to put the spacecraft north, which usually corresponds to ecliptic north, at the top of the image, but no interpolations are done at this Level-0.5 stage. The images may be converted to Level-1 by the user using a SolarSoft IDL procedure, SECCHI_PREP, which performs all of the calibration functions using the latest calibrations. Image header metadata are available in a database, accessible from the NRL SECCHI Website, which can be also used to query and download specific FITS files. In addition to the FITS data, the SECCHI Website serves a large number of Level-2+ data products for science and public use. These products currently include: (1) Browse images in PNG format (2) Javascript movies for user-defined intervals (1-36 hours) and (1-9 days). (3) Synoptic browse movies (individual or combined, 1, 2 or 4 weeks) in MPEG format. (4) PNG anaglyphs and stereo pairs of all EUVI data suitable for stereo viewing, (5) synoptic maps of EUVI, COR1, COR2 accessible in a variety of forms, and (6) auto-generated CACTus CME lists for SECCHI. Additional Level-2+ data products are readily available by request: (1) EUVI wavelet-enhanced dual-wavelength combined movies, and (2) COR2 total brightness and % polarization FITS files. New products on the SECCHI Website since the last Senior Review include: (1) Time-elongation plots ("J-maps"), and (2) cosmic-ray scrubbing results (link temporarily off line). In the near-term, a list of images affected by debris or other problems will also be added.

A new second SECCHI website is deployed at APL with additional data products. As of January 2017 the site mirrors all SECCHI data (except EUVI FITS files) in the GSFC and/or NRL sites. It also provides access to a range of Level2+ products: (1) A COR2 CME list with simultaneous identifications in STEREO-A & B and properties of the events. (2) EUVI and EUVI-AIA synchronic 360° maps in Carrington coordinates (195Å, 284Å, 304Å), (3) preprocessed EUVI wavelet-enhanced images, FITS and PNGs for the duration of the missions, and (4) EUVI wavelet-enhanced dual-wavelength movies. A CME list with 3D properties is available from the University of Göttingen. Several events catalogs (CME, CIRs) with en emphasis to the HI data are available through the HELCATS project.

Calibration activities for the SECCHI telescopes are now complete. Pointing and flat-fielding (including vignetting) calibrations have been established for all telescopes. Geometric distortion corrections have been implemented for all applicable telescopes (COR2, HI1, and HI2), as have the shutterless readout corrections for HI1 and HI2. Photometric calibrations have been implemented for all telescopes.

Housekeeping. Selected SECCHI instrument housekeeping telemetry is available via web interface to a database at NRL. Plots may be extracted from this database of various engineering parameters such as temperatures, currents, voltages, door position, guide telescope pointing and HK events. Table definitions and table structure are described on the NRL SECCHI web site.

Documentation. The NRL SECCHI Website serves: Science (FSW) Operations Manual, FSW documentation, image telemetry completeness data, instrument status, image scheduling details, various instrument and operations event logs, software user's guides, SECCHI FITS Keyword Definition, and the SECCHI Data Management Plan. A description of the instrument is given in the SSR special issue. SECCHI operations and data documentation are maintained on the NRL site. The pages are updated as information becomes available.

Analysis Tools. SECCHI analysis tools, and most of the pipeline software, are freely available through SolarSoft. The following tools are currently available via SolarSoft: data browsers, data calibration, movie generation and display, image enhancement and visualization, polarized image processing, star-removal, height-time plots, ray-tracing, CME detection, tomography. As these tools are improved and future tools developed, they will be added to the SolarSoft library. In addition, there are some stereographic visualization tools that currently require specialized hardware. At NRL all software is under Concurrent Versions System management.

Final Data Set. The SECCHI Level-0.5 data is "final" after the FITS files have been updated with any additional telemetry received in the final (+30-day) Level-0 telemetry from APL. Currently, the Level-1 (calibrated) product is the combination of the Level-0.5 FITS images and the SECCHI_PREP IDL routine and data files available in SolarSoft. This allows the user to take advantage of the evolving calibration of the various telescopes. At the end of the mission, the calibration files and parameters that are used in this package will be revalidated to ensure that they are up to date and able to generate Level-1 FITS files of calibrated images, polarized brightness, and brightness images. Calibration will include corrections for instrumental artifacts such as stray light, vignetting, shutterless readout, and conversion to physical units. (Geometric distortion is described by header keywords together with the World Coordinate System standard algorithms.) Complete documentation, transparent software code, and non-proprietary data formats ensure that calibration can be properly applied to Level-0.5 data into the foreseeable future. The final archive will contain both the calibrated Level-1 files and the final Level-0.5 files.

Data availability. The primary site for storage of Level-0.5 FITS image data is the NRL Solar Physics Branch (PI home institution). The primary means of querying data for analysis is by utilizing summary flat-files that are read by SolarSoft tools. Besides being available on-site, the data is freely available (in relatively small quantities) from NRL via database query at the SECCHI website. All of the data are also synchronized several times per day to the SSC. In addition, other partner institutions – LMSAL (California), APL (Maryland), RAL (UK), IAS (France), and MPS (Germany) – mirror STEREO data. These all serve as backups for the complete data set.

Virtual Observatory Access. The SSC is now serving SECCHI data through the VSO at GSFC/SDAC, which is intended to be the gateway to other Virtual Observatories. The SECCHI data are fully accessible to the wider VO community. VSO is committed to community interoperability efforts, such as the SPASE data model. The SECCHI team is working with representatives of the Heliophysics Data Portal to ensure proper descriptions of SECCHI data products.

S/WAVES

Scientific Data products. The S/WAVES investigation provides several levels of science data products. Access to the Level 0 data is achieved through a processing system called TMlib, based on a similar system (WindLib) successfully used since the early 1990s for the Wind/WAVES (W/WAVES) data. The TMlib can be downloaded from the University of Minnesota (send request to goetz@umn.edu).

Daily summary plots showing all frequency-domain receivers and summaries of the time domain receivers are available from the SSC and S/WAVES Webpage. Both of these sources also serve 1-minute averages in both ASCII and IDL save format of all frequency-domain receivers. These 1-minute averages are also served by the CDAWeb in CDF format. The CDAWeb site includes customized plotting capabilities. Both the daily summary plots and the 1-minute averages are produced automatically upon receipt of the data, so are available usually within 24-hours of real-time.

The French IRAP Plasma Physics Data Center (CDPP) also serves daily summary plots of the frequency domain receivers in a different format than those from the U.S sites. CDPP also serves the higher-level S/WAVES products associated with direction finding and wave polarization capability. This site requires a password (due to French security regulations), but this is freely given upon request.

Additional higher-level data includes the Type II/IV catalog maintained by the Wind/WAVES team and now including S/WAVES data. This site has been in existence since the late 1990s and is a valuable resource for solar researchers. The years covering the STEREO mission are archived on the SSC website.

Documentation. Three papers of importance to S/WAVES data processing are in the SSR special issue, one providing a complete description of the S/WAVES instrument, another discussing the antennas, and a third describing the direction finding technique used by S/WAVES. Pointers to these articles as well as to a description of the 1-minute average data are on the S/WAVES instrument resource page referenced by the SSC. The direction finding and wave polarization parameters are documented on the CDPP Web site mentioned above. The S/WAVES datasets have SPASE descriptions. We are currently reviewing the SPASE descriptions in the Heliophysics Data Portal (heliophysics.gsfc.nasa.gov) for accuracy and completeness.

Analysis tools. The customized plotting capability available at the CDAWeb is based on the same program used by the S/WAVES team. This original IDL program is available from the instrument resource site at the SSC.

Data Distribution. S/WAVES data, as mentioned above, are available directly from the team's US Web site, from the SSC, from CDAWeb, and from the CDPP. The S/WAVES event lists can be obtained from the Type II/IV catalog Web site, and from the SSC website.

Final Data Set. The S/WAVES data are "final" when they appear at ftp://solar-radio.gsfc.nasa.gov, given that updates occur for any additional telemetry received in the final (+30-day) Level-0 telemetry from APL. This FTP site provides the Level-1 (calibrated) products, which are ASCII and IDL saveset files for the HFR, LFR, and TDS. Plots of these data as dynamic spectra in Postscript, PDF, and PNG formats are also available on this FTP site.

B. STEREO Publication Record, 2015 - 2017

STEREO refereed journal (not conference proceedings) rates through the first few weeks of calendar year 2017 can be found in Table B-1.

Calendar Year	Refereed Journals and Theses Only
2006	**1**
2007	**12**
2008	**58**
2009	**129**
2010	**114**
2011	**125**
2012	**166**
2013	**169**
2014	**176**
2015	**190**
2016	**174**
2017 (through Feb. 24)	**25**
Total	**1339**

Table B-1: STEREO refereed papers and theses. Source: STEREO Publication Database.

Here, a "STEREO paper" is taken to mean any paper using STEREO data, or concerning models or theoretical interpretations of STEREO measurements. In 2015 and 2016 the mission continued with its high publication rate, with a total of 347 refereed journal articles. Since the beginning of 2015, STEREO data have been used for seventeen theses (13 PhD, 4 Masters).

Bibliography. A reverse time-ordered stand-alone list of STEREO publications accessible on line, as well as a searchable STEREO publication database. A list STEREO publications accessible by the NASA Astrophysics Data System (ADS), is available here.

C. Spacecraft and Instrument Status as of 2017 Feb. 24

Spacecraft

As discussed in Section IIc, contact with STEREO-B was lost in 2014. The operations team regained limited contact with it in August and September of 2016 and then lost contact again. We hope that we will be able to establish contact with it again when the spacecraft moves into a favorable configuration with respect to the direction of its solar panels. Efforts to contact it are still under way. Information gained during the contact period in 2016 indicates that 2 out of 11 pressurized battery cells were not functioning. While this degraded the main bus voltage by ~ 6 volts, there remains sufficient battery voltage to return the spacecraft and all instruments back to nominal daily science operations once attitude control is restored.

The Mission Ops team has made a number of changes to the spacecraft autonomy rules on STEREO-A to prevent a similar loss of attitude control. Among other changes, if even a single gyro within the IMU is producing bad data, only the solar presence detectors on all sides of the spacecraft will be used for attitude determination.

The STEREO-A spacecraft is healthy, aside from the loss of the primary IMU and the degradation of the backup IMU. All four reaction wheels and the sun sensors are nominal, and the propulsion system still retains ~ 50 years of fuel for momentum management. Solar panel performance remains nominal.

IMPACT

Flight hardware. During the review period, IMPACT relied on a software patch formulated and uplinked in 2014 to allow IMPACT IDPU to decimate science packets to lower data rates for the spacecraft offpoint conjunction modes. In addition, SWEA and STE-D were shut off upon entering the first sidelobe phase. This saved a large fraction of the available telemetry for the other IMPACT instruments, and more importantly minimized concerns about monitoring either instrument's state of health while we are not getting full instrument housekeeping. (Both SWEA and STE-D have had occasional SEUs that sometimes require intervention.) IMPACT boom suite instruments have otherwise been functioning nominally, with MAG obtaining low rate data through the sidelobe period for both reduced real time transmissions and continuous recording to the SSR. The SEP LET, SIT, and HET sensors continue normal operations when in contact. For the sidelobe periods a flexible packet decimation scheme was designed that provides broad energy and composition coverage (with reduced temporal resolution) based on in-flight particle identification, supplemented by limited pulse-height data. In-ecliptic particle flows are also monitored. The SEP-SEPT sensor dropped the N-S telescope data transmission as of the second sidelobe phase, leaving the ecliptic (E-W) telescope data intact.

During the period of solar occultation, the IMPACT team powered off the IMPACT suite because the mission would not have contact with the spacecraft and the IMPACT team, therefore, could not monitor the state of health of the instruments. After this period, the IMPACT instruments were successfully returned to normal (though decimated as described above) operational mode. All instruments were verified to have undergone no detectable degradation or other deleterious effects due to being powered off for the several months of occultation.

GSE. Screen magnification and reader software was installed on the UC-Berkeley POC GSE PC's to facilitate use of the machines by the IMPACT Operations Manager.

PLASTIC

During reduced telemetry periods, not all data products are available, and other remaining products have had reduced temporal resolution.

The STEREO-A PLASTIC instrument was off during the superior conjunction blackout period. STEREO-A PLASTIC was re-commissioned in July 2015, operating in a reduced telemetry mode due to downlink restrictions. Full instrument telemetry rates were restored in June 2016. Re-commissioning of STEREO-B PLASTIC is awaiting spacecraft recovery.

In September 2014, during an SEP event, a polar deflection high voltage power supply on STEREO-A began showing a gradual increase in its current draw, while maintaining its commanded voltage value. The power supply retained full operational capability (an examination of the data showed the polar angle measurement remained nominal), however the continuing current increase raised concerns about parts' stress and eventual tripping of hardwired current limiters. A yellow flag alert occurred in December 2014. Troubleshooting at that time was constrained by the limited availability of commanding windows during the approach to solar conjunction. As a safety precaution, the entrance system was on for only limited periods until a new table load was generated that included a change in the set point for the deflection voltages in the first step of the E/Q duty cycle (there are 128 steps in the cycle). After the table load, there was a 10 mA reduction in the current, which has only increased by one half mA in the past year. Solar wind measurements are not affected at all by the table change. Suprathermal measurements are only affected in a redundant energy step that is not used in routine analysis.

Post-launch analysis determined that the design of the contributed entrance system did not meet specifications, resulting in faster than anticipated gain decreases of the micro-channel plate detectors. The gain is routinely restored through increasing the MCP bias voltage. The spacecraft flip during solar conjunction meant the high-flux solar wind aberration direction shifted to a different, "fresher" section of the detector array (with slightly different gain). Calibration table changes on the flux and angle determinations are currently being incorporated into the routine processing.

GSE. The aging command computer for the STEREO-B PLASTIC instrument was replaced and ground tested for the much newer operating system.

SECCHI

All SECCHI instruments on STEREO-A were recovered successfully (2015/07/11) after their solar conjunction hibernation. Since then there have been five "Watchdog" resets on STEREO-A bringing the total to 23 (STEREO-B), 51 (STEREO-A) over the course of the mission. The resets are generated in the SECCHI Electronics Boxes (SEBs) and each results in a few hours' of lost observing time. One anomaly in the EUVI quadrant selector on STEREO-A (2016/06/02) was corrected by adjusting the encode timing delay. The COR1-A polarizer wheel showed some slippage that was addressed by adjusting the mechanism delay settings. Temperatures in some COR1 zones are rising, tripping autonomy rules but not otherwise affecting observations. The instrument team is investigating and will be updating the autonomy rules as required.

S/WAVES

The S/WAVES instrument on STEREO-A continues to function nominally now that we have emerged from behind the sun. During reduced telemetry periods, all data products were available at reduced temporal resolution. We expect that S/WAVES on STEREO-B is also capable of functioning nominally, if/when STEREO-B is recovered.

The STEREO-A S/WAVES instrument was on throughout the solar conjunction period with a small volume of data being recorded on the spacecraft solid-state recorder. Playback of the S/C SSR at the end of 2015 provided coverage of the entire conjunction period, though with much lower time and frequency resolution than typical for most of the mission. Loss of the STEREO B data has a significant effect on S/WAVES science but will be mitigated in the years to come with the use of the Wind/WAVES instrument for 3-D direction finding.

The University of Minnesota continues to maintain a Payload Operation Center (POC) at both APL and UMN. These are used sparingly but would be required in the case of an instrument contingency. They would also be used in the case of a flight software upload. The engineering model of the complete S/WAVES instrument is also maintained in Minnesota should it be required for any future reason.

D. Research Focus Areas, NASA Heliophysics Roadmap, 2014 – 2033 (annotated)

Understand the Sun and its Interactions with the Earth and the Solar System, including Space Weather

Solve the Fundamental Mysteries of Heliophysics

Explore the physical processes in the space environment from the Sun to the Earth and throughout the solar system

F1 • Understand magnetic reconnection
F2 • Understand the plasma processes that accelerate and transport particles
F3 • Understand ion-neutral interactions
F4 • Understand the creation and variability of solar and stellar magnetic dynamos
F5 • Understand the role of turbulence and waves in the transport of mass, momentum, and energy

Understand the Nature of Our Home in Space

Advance our understanding of the connections that link the Sun, the Earth, planetary space environments, and the outer reaches of our solar system

H1 • Understand the origin and dynamic evolution of solar plasmas and magnetic fields throughout the heliosphere
H2 • Understand the role of the sun and its variability in driving change in the Earth's atmosphere, the space environment, and planetary objects
H3 • Understand the coupling of the Earth's magnetosphere-ionosphere-atmosphere system, and its response to external and internal forcing
H4 • Understand the nature of the heliospheric boundary region, and the interactions between the solar wind and the local interstellar medium

Build the Knowledge to Forecast Space Weather Throughout the Heliosphere

Develop the knowledge and capability to detect and predict extreme conditions in space to protect life and society and to safeguard human and robotic explorers beyond Earth

W1 • Characterize the variability, extremes, and boundary conditions of the space environments that will be encountered by human and robotic explorers
W2 • Develop the capability to predict the origin, onset, and level of solar activity in order to identify potentially hazardous space weather events and all-clear intervals
W3 • Develop the capability to predict the propagation and evolution of solar disturbances to enable safe travel for human and robotic explorers
W4 • Understand, characterize, and model the space weather effects on and within terrestrial and planetary environments

2 | Heliophysics : Our Dynamic Space Environment

E. Acronyms and Other Abbreviations

AAS	American Astronomical Society
ACE	Advanced Composition Explorer
ADS	Astrophysics Data System
APL	Johns Hopkins University Applied Physics Laboratory
ASCII	American Standard Code for Information Interchange
AU	Astronomical Unit
CACTus	Computer Aided CME Tracking
CCMC	Community Coordinated Modeling Center
CDAWeb	Coordinated Data Analysis
CDF	Common Data Format
CDPP	Centre de Données de la Physique des Plasmas (France)
CIR	Co-rotating Interaction Region
CME	Coronal Mass Ejection
Co-I	Co-Investigator
COR1	SECCHI Inner Coronagraph
COR2	SECCHI Outer Coronagraph
CORHEL	CORonal-HELiosphere model
C&DH	Command & Data Handling
DISCOVR	Deep Space Climate Observatory
DSN	Deep Space Network
ENA	Energetic Neutral Atom
EUV	Extreme UltraViolet
EUVI	SECCHI Extreme UltraViolet Imager
FD	Forbush Decrease
FDF	Flight Dynamics Facility
FITS	Flexible Image Transport System
FSW	Flight SoftWare
FY	Fiscal Year
G&C	Guidance & Control
GAS	Ulysses Interstellar Neutral-Gas Experiment
GCS	Graduated Cylindrical Shell
GOES	Geostationary Operational Environmental Satellite
GONG	Global Oscillation Network Group
GSE	Ground support equipment
GSFC	Goddard Space Flight Center
HET	IMPACT High Energy Telescope
HEEQ	Heliocentric Earth Equatorial
HGA	High Gain Antenna
HI	SECCHI Heliospheric Imager
HIS	Solar Orbiter Heavy Ion Sensor
HSO	Heliophysics System Observatory
IAS	Institut d'Astrophysique Spatiale (France)
IBEX	Interstellar Boundary Explorer
ICME	Interplanetary coronal mass ejection
IDL	Interactive Data Language™
IMPACT	In-situ Measurements of Particles and CME Transients Investigation
IMU	Inertial Measurement Unit

IRIS	Interface region Imaging Spectrograph
ISTP	International Solar Terrestrial Physics program
kbps	Kilobits per second
L1	First Lagrangian Point
LASCO	SOHO Large Angle and Spectrometric Coronagraph
LET	IMPACT Low Energy Telescope
LFR	S/WAVES Low Frequency Receiver
LISM	Local Interstellar Medium
LMSAL	Lockheed Martin Solar and Astrophysics Laboratory
LWS	Living With a Star
MAG	IMPACT Magnetometer
MAVEN	Mars Atmosphere and Volatile EvolutioN
MESSENGER	MErcury Surface, Space ENvironment, GEochemistry, and Ranging
MHD	Magnetohydrodynamics
MO&DA	Mission Operations and Data Analysis
MOC	Mission Operations Center
MPS	Max Planck Institut für Sonnensystemforschung (Germany)
NAIF	Navigation and Ancillary Information Facility
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NRL	Naval Research Laboratory
NUC	Next Unit of Computing
PFD	Phantom Forbush Decrease
PAD	Pitch Angle Distribution
PI	Principal Investigator
POC	Payload Operations Center
PSG	Prioritized Science Goal
PLASTIC	PLAsma and SupraThermal Ion Composition Investigation
PUI	Pickup Ion
RAD	Radiation Assessment Detector
RAL	Rutherford Appleton Laboratory
RF	Radio frequency
RHESSI	Reuven Ramaty High Energy Solar Spectroscopic Imager
SCOSTEP	Scientific Committee On Solar-terrestrial Physics
SDAC	Solar Data Analysis Center
SDO	Solar Dynamics Observatory
SDS	STEREO Data Server
SECCHI	Sun Earth Connection Coronal and Heliospheric Investigation
SEP	Solar Energetic Particle
SEPT	IMPACT Solar Electron Proton Telescope
SEU	Single Event Upset
SIR	Stream Interface Region
SIT	IMPACT Suprathermal Ion Telescope
SO	Solar Orbiter
SOHO	Solar and Heliospheric Observatory
SPASE	Space Physics Archive Search and Extract
SPD	Solar Physics Division oft he American Astronomical Society
SPDF	NASA Space Physics Data Facility
SPICE	SO Spacecraft, Planet, Instrument, C-Matrix, Events

SPLAT	STEREO PLASTIC Analysis Tool
SPP	Solar Probe Plus
SSC	STEREO Science Center
SSMO	Space Science Mission Operations
SSR	Solid State Recorder
STA	STEREO-Ahead
STB	STEREO-Behind
STE	IMPACT Suprathermal Electron Telescope
STEREO	Solar TErrestrial RElations Observatory
S/WAVES	STEREO Waves Investigation
SWEA	IMPACT Solar Wind Electron Analyzer
SWICS	Solar Wind Ion Composition Spectrometer
SWMF	Space Weather Modeling Framework
SWPC	NOAA's Space Weather Prediction Center
SWT	Science Working Team
SXR	Soft X-Ray
TDS	S/WAVES Time Domain Sampler
TRACE	Transition Region and Coronal Explorer
UCB	University of California, Berkeley
UCLA	University of California, Los Angeles
UMN	University of Minnesota
UNH	University of New Hampshire
URL	Uniform Resource Locator
VDF	Velocity Distribution Function
VEX	Venus Express
VHO	Virtual Heliospheric Observatory
VSO	Virtual Solar Observatory
VSPO	Virtual Space Physics Observatory (now the Heliophysics Data Portal)
WSA	Wang-Sheely-Arge

STEREO instrument and instrument subsystem names are in blue.