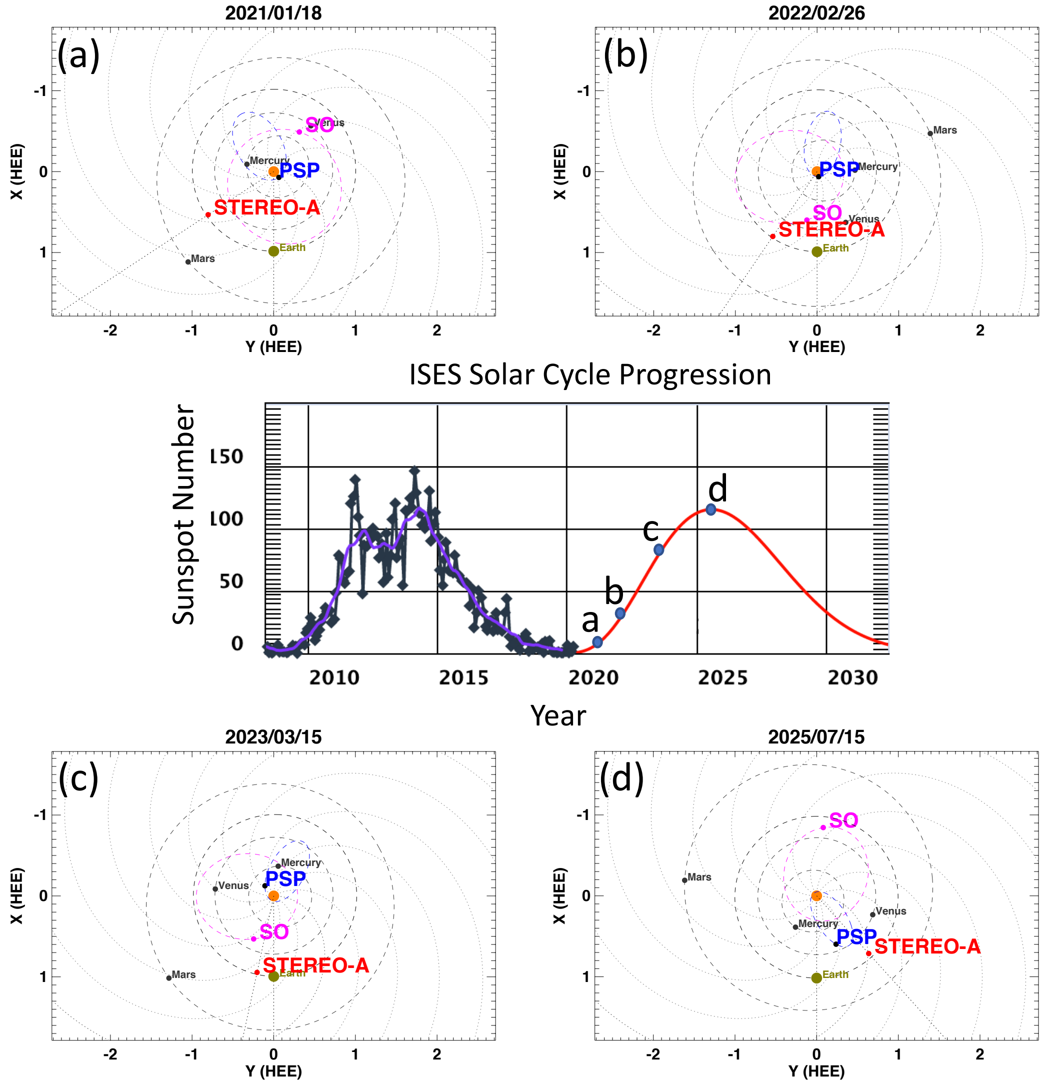
STEREO
A Proposal to the Senior Review of Operating Missions
June 2020



Orbital positions of STEREO-A, Earth (& L1), Parker Solar Probe (PSP) and Solar Orbiter (SO) at various times from 2020-2025. (a) STEREO-A near L5, (b) STEREO-A, SO, and PSP aligned along the Parker Spiral, (c) STEREO well positioned for stereoscopy, and (d) STEREO at solar maximum and headed for L4. Solar cycle chart from NOAA's SWPC. STEREO-A's location allows it to make unique contributions to the Heliosphere System Observatory.

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Solar TErrestrial RElations Observatory (*STEREO*)

I. Executive Summary

The vantage point of the *STEREO* mission beyond the Sun-Earth line and its combination of in situ and remote sensing instrumentation has led to key contributions to our understanding of the Sun and heliosphere and how they are linked. Now, with a combination of historical data from the last 13.5 years and new data resources inside 1 AU, *STEREO* is prepared to continue its contributions to understanding the corona, solar wind, eruptive events, and space weather.

The *STEREO* mission currently consists of the *STEREO-A* spacecraft, launched in 2006, which will be at a separation from Earth of 61° on Oct. 1, 2020. During the next five years it will swing through the Earth-Sun line and head back towards the L4 point. *STEREO* data are freely available at the *STEREO* Science Center and instrument team websites and used by scientists the world over, resulting in 1,871 *STEREO* based theses and publications in the refereed literature.

Over the last three years significant progress was made on the goals we set in the last senior review proposal. As described in Section III, these fell in three major groups: Characterizing space weather throughout the inner heliosphere, using 360-degree coverage of the Sun and heliosphere to study the solar corona and solar wind, and using coverage of the full heliosphere to improve our understanding of pick-up ions and dust. Highlights include collaborating with *Parker Solar Probe* to investigate the evolution of CME/ICMEs, multi-spacecraft studies of SEP acceleration, and the sources of density variations in the solar wind.

Over the next senior review period the *STEREO* team proposes to pursue a series of objectives. The first will combine ***STEREO-A*'s unique location with new opportunities presented by the recent launches of *Parker Solar Probe* (*PSP*) and *Solar Orbiter* (*SO*)** along with continued observations by the rest of the Heliophysics System Observatory to study CMEs, active regions and the solar wind from multiple points of view. The second takes advantage of *STEREO-A*'s passing through the Earth-Sun L5 point to explore that location's usefulness in space weather monitoring. The third will utilize the *STEREO* mission's data taken since 2007 to evaluate changes in the Sun and heliosphere over the last solar cycle and into the next.

In Section IV we describe technical implementation of the mission including status of the spacecraft, instruments and mission operations. In Section V we discuss Data and Code Management including *STEREO* plans to comply with new standards for the Project Data Management Plan and related documentation. Section VI discusses the proposed budget.

The following individuals were among those involved in the writing of this proposal as the STEREO Senior Review Working Group: J. Luhmann (UCB), R. Mewaldt (Caltech), N. Lugaz, A. Galvin, C. Farrugia (UNH), O. Dudley, A. Vourlidas, D. Wilson (JHU/APL), W. Thompson (Adnet), G. de Nolfo, N. Gopalswamy, T. Kucera, R. MacDowall, and N. Viall (GSFC). Numerous members of the Principal Investigator (PI) teams submitted early drafts.

Hyperlinks to locations on the web are underlined and highlighted in blue.
Note that Acronyms and Abbreviations are given in Appendix A.

II. Mission Summary

The *STEREO* spacecraft were launched on 2006 October 25 (October 26 UT) and inserted into heliocentric orbits in 2006 December (*STEREO-A*) and 2007 January (*STEREO-B*). Subsequently, the two spacecraft drifted in opposite directions from the Earth-Sun line by 22º per year. 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 far exceeded.

The primary science focus has been on the understanding of coronal mass ejections (CMEs), solar energetic particles (SEPs), and the solar wind, in particular with regards to their effects on space weather.

The mission instrumentation consists of the SECCHI remote imaging suite, imaging from the Sun to 1 AU with a combination of a solar EUV imager, two coronagraphs and two heliospheric imagers; the IMPACT suite, sampling the 3-D distribution of solar wind plasma electrons, the characteristics of SEP ions and electrons, and the local vector magnetic field; PLASTIC, measuring the properties of the bulk solar wind, in particular the plasma characteristics of protons, alpha particles and heavy ions; and S/WAVES, an interplanetary radio burst tracker that traces the generation and evolution of traveling radio disturbances from the Sun to the orbit of Earth.

The spacecraft subsystem failures in the thirteen years after launch were the loss/aging of the inertial measurement units (IMUs) and the loss of STEREO-B in 2014 (due to IMU failure) after nearly eight years of successful operation. Attempts were made to regain *STEREO-B*, including one period of contact with the spacecraft in 2016, however these were unsuccessful. The *STEREO* mission presently consists of the *STEREO-A* spacecraft. **Over the five-year period covered by this proposal *STEREO-A* will move from a separation angle from Earth of 61° on Oct. 2020, swing through the Earth-Sun line in Aug. 2023 and then move ahead of Earth again to a separation of 48° by the end of Sept. 2025. This range of locations will allow it to make unique contributions to heliophysics.**

III. Science and Science Implementation

IIIa. Scientific Productivity and Vitality

In the last three years, *STEREO* scientific productivity has continued at high levels, as measured by papers in refereed journals, theses, meeting presentations, and recognition of researchers employing *STEREO* data to advance our understanding of solar and heliospheric phenomena. Data from *STEREO* have been incorporated into many scientific investigations and also services using observations from multiple assets of the Heliophysics System Observatory (HSO). Since the start of the *STEREO* project some 1,871 refereed publications and theses have used *STEREO* data or described the mission and its instrumentation (1,856 since launch in Oct. 2006). A PDF format publication list of refereed journal papers and theses is available at the *STEREO* Science Center (SSC) (here). A database is also accessible through the SSC web site, but is not being updated at the time of submission because of COVID-19 related access issues. A list of refereed papers in the database of the Astrophysics Data System is available on line (see the STEREO ADS List). The ADS data base does not include many of the theses and also some of the more recent papers. See Appendix E for more information on publications.

At least 27 theses using *STEREO* data were accepted in fulfillment of Ph.D. and master's degrees at universities in the US, Europe, and Asia in 2017-2019. In 2018 *STEREO* Deputy-Project Scientist Nicholeen Viall was awarded both the American Astronomical Society/Solar Physics Division's Karen Harvey Prize and a NASA Early Career Achievement Medal for her work studying the solar corona and solar wind, including her analysis of *STEREO*/SECCHI data.

STEREO data have also been featured in the press and news media. NASA web releases connected to *STEREO* research have covered such topics as 3D modeling of CMEs, the structure of the outer corona, and circumsolar dust. Some of these stories are featured in the next section.

IIIb. Assessment of Scientific Progress, FY2017 - FY2020

Here in our assessment of scientific progress we report on only a small number of the many science results published in *STEREO*-based journal papers since the last senior review by the *STEREO* team and community at large. We organize them based on our Prioritized Science Goals as expressed in our last Senior Review Proposal. We also discuss *STEREO* progress in selected areas in the description of our future objectives (Section IIIc)

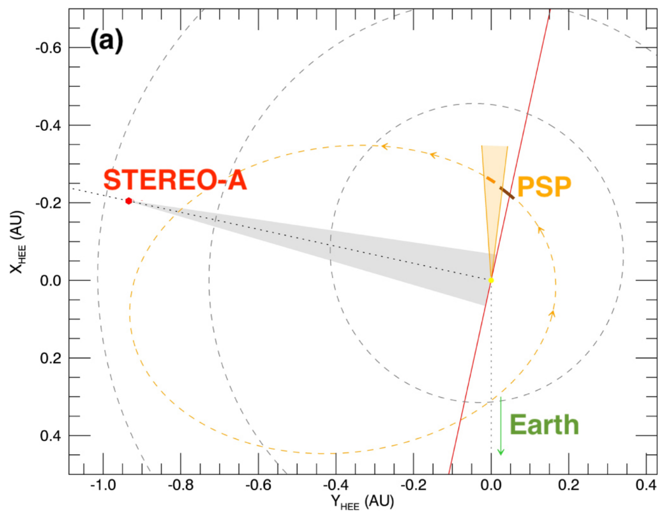
Goal Set 1: Characterize Space Weather Throughout the Inner Heliosphere

PSG 1-1: Understand the Large-scale Structure of CMEs/ICMEs

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. However, the multi-point *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 are set – especially the key parameters of size, speed and sign of B_Z.

Progress and Science Highlights. New opportunities for *STEREO* science are now enabled by the launch of *Parker Solar Probe* (*PSP*) in 2018, with *STEREO* observations proving to be crucial for the interpretation of *PSP* data. The Wide-field Imager for Solar Probe (WISPR) on *PSP* images solar transients from a location very close to the Sun. However, interpretation of WISPR images benefits greatly from 1-AU images, including those from *STEREO-A*. In addition, both radial and Parker Spiral alignments of *PSP* and *STEREO-A* allow studies of the propagation/transport of observed in situ features and particle populations.

An excellent example of the utility of *STEREO-A* imaging data in the *PSP* era occurred in the same perihelion period when *PSP* detected an apparent transient in situ structure passing through a heliospheric distance of 54.7 $R_\odot$. This structure has now been interpreted as the ICME resulting from a small streamer-blowout CME (Nieves-Chinchilla et al., 2020; Korreck et al., 2020). As this event was not visible by near-Earth imagers, the interpretation of these *PSP* in situ observations depended on SECCHI coronagraph and EUV imaging, while the non-observations of related in situ activities on *STEREO-A* provided additional information regarding the limited extent (or strength) of the ICME and any related SEP event at 1 AU. The relative geometry of the *PSP* and *STEREO-A* observations in Korreck et al. (2020) is reproduced in Figure 1 together with a STEREO-A/COR2 image from Nieves-Chinchilla et al. The lateral extent of the ICME measured at *PSP* is indicated by the brown segment of the *PSP* orbit. Inferred coronal speeds from the related time-height profile and J-map were ~245 km/s, while the in-situ plasma speeds of the ICME at *PSP* ranged between ~370 and 470 km/s. This implies continued acceleration and/or expansion of the ejecta between the COR2A field of view outer limit at ~15 $R_\odot$ and the ~55 $R_\odot$ location of the ICME detection, although the speeds remained sub-Alfvenic throughout and no related shock formed. **This "picture" of the first ICME ever encountered by a spacecraft at a distance this close to the Sun could not have been reconstructed without *STEREO-A*.**



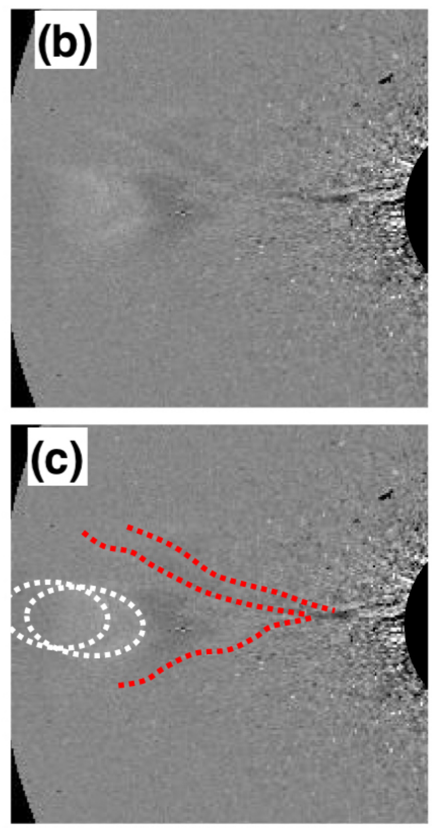


Figure 1: *Figure adapted from Korreck et al. (2020) (a) and Nieves Chinchilla et al. (2020) (b and c) illustrating how STEREO-A imaging provided crucial information used to interpret the spatial location, extent, direction (and speed, from timing) of a streamer blowout CME that was detected as an ICME on PSP's first perihelion. Panel (c) highlights double ring substructures in the CME (dotted white ovals) and a "V" shaped boundary to the flux rope structure (dotted red lines).*

PSG 1-2: Understand the Physics of ICME Interactions

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 of the resulting ICMEs with serious consequences for space weather impacts. Their ongoing interaction during propagation affects 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 interaction of multiple CMEs is known to be one of the essential ways to create long-duration and complex drivers of space weather at Earth and at other planets. However, in situ measurements by a single spacecraft do not usually provide enough information to understand how the succession and interaction of CMEs affect their properties and abilities to impact the global heliosphere. A series of two CMEs in July 2017 was measured in situ by *STEREO-A, Mars Atmosphere and Volatile EvolutioN* (*MAVEN*) and *Mars Science Lander* (*MSL)* and remotely by *STEREO-A* and *SOHO*/LASCO. The *STEREO-A* in situ measurements reveal the complex evolution and interaction of these two CMEs with each other and with a stream interaction region (SIR). This interaction resulted in ejecta with peak magnetic field of ~60 nT at *STEREO-A* and a decrease of the galactic cosmic ray flux (Forbush decrease) measured at the Martian surface by *MSL* of more than 15% with a perturbed period measured by *MAVEN* and *MSL* at Mars of >5 days. A detailed analysis by Dumbovic et al. (2019, see also Figure 2) suggested that the interaction of these two CMEs inhibited CME expansion along the Sun-*STEREO-A* line. This resulted in the extreme magnetic field values observed by *STEREO-A* together with a very long-duration event at Mars (hence the 5-day Forbush decrease).

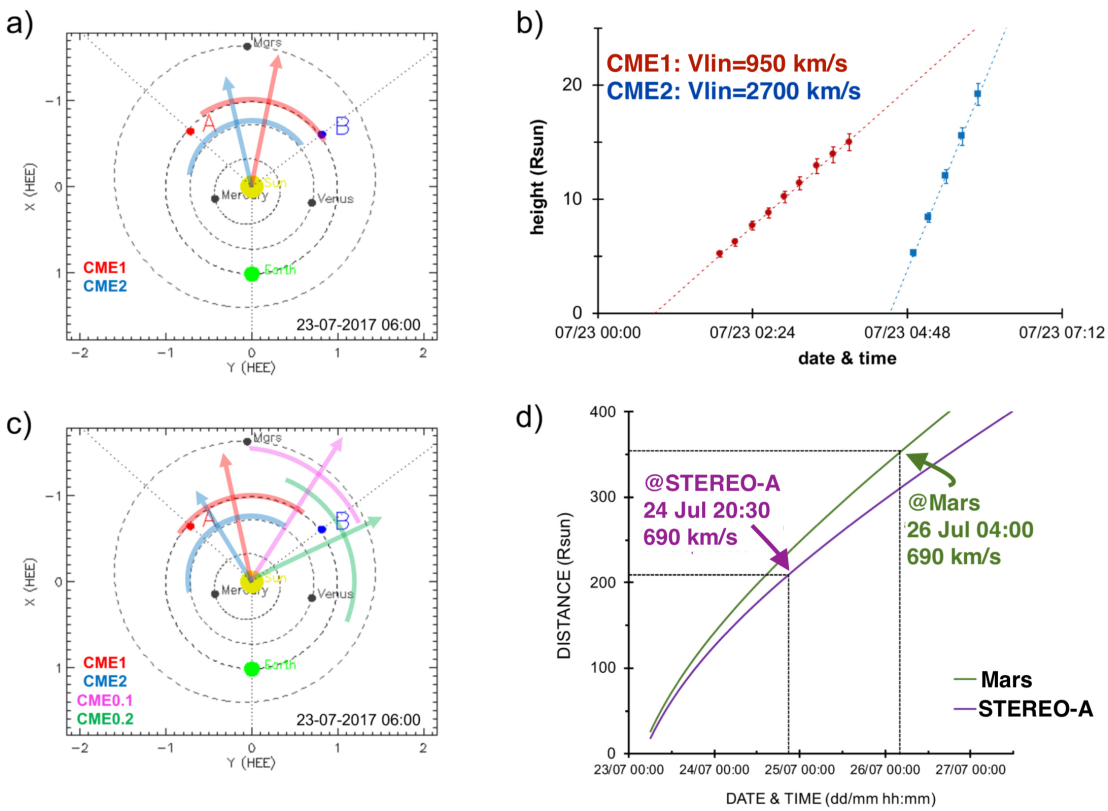
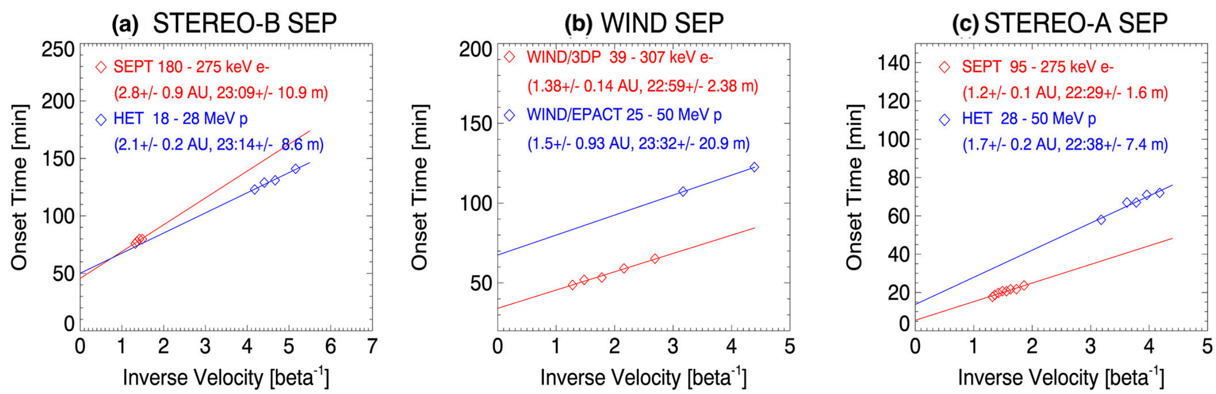


Figure 2: *(a)-(c**)** CME directions, size and kinematics obtained from STEREO-A and SOHO/LASCO remote observations (a, b and c) for two interacting CMEs (CME1 and CME2) as well as two earlier CME that may have been important for preconditioning interplanetary space. (d) A drag-based model of the merged CME structure in STEREO-A and Mars direction with arrival times at STEREO-A and Mars (adapted from Dumbovic et al., 2019). Data from multiple spacecraft, including STEREO-A, were needed to understand the trajectories and thus interactions of the two CMEs*

PSG 1-3: Understand How Solar Energetic Particles are Accelerated and Distributed so Efficiently Around the Sun

Statement of Goal. *STEREO* has provided important new observations on the longitudinal extent of SEP events. The underlying cause of SEP event width is of interest for understanding particle acceleration and transport, and for its importance in predicting space weather effects of SEPs. 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.



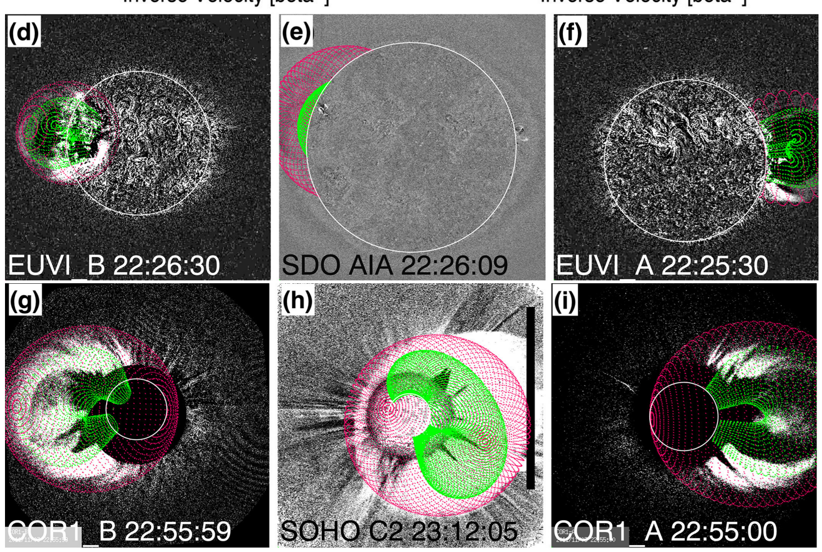


Figure 3: *A forward modeling technique constrained with multispacecraft observations allowed the determination of the location where the shock front intersects the magnetic field line connecting spacecraft observing in situ. (a)-(c): Proton fluxes of the SEP event from STEREO-B, Wind and STEREO-A. on 2011 Nov. 8. (d)-(i): Views from STEREO-B, SOHO and STEREO-A of the CME shock structures with the spheroid shock model (pink) and the flux-rope model (green) determined using EUV and white light data (adapted from Xie et al., 2017).*

Progress and Science Highlights. *STEREO* observations, together with near-Earth observations, provide important insight into the relationship between the longitudinal extent of SEPs and the role of magnetic connectivity to the solar source(s), whether flares or CMEs. In particular, its combined remote and in situ observations significantly advanced models that relate shock formation and evolution to particle acceleration. By comparing SEP onset delays from *STEREO-A*, *B*, and near-Earth spacecraft (*Wind*, *SOHO*) with estimated times for a shock wave to expand to magnetic fields connecting to these spacecraft, Xie et al. (2017) showed that SEPs observed at these spacecraft on 3 November 2011 are consistent with a direct connection to the CME shock source (see Figure 3). The notion that an observer's magnetic connection to a shock is essential for the occurrence of a local SEP event was applied to analysis of the late-cycle 24 July and September 2017 event cases by Luhmann et al. (2018), using coronagraph-based Wang-Sheeley-Arge (WSA)-Enlil cone model results to describe the shocks and field connection geometries at *STEREO-A*, L1, and Mars. However, Bruno et al. (2019) suggested that the ~10 hr delay between near-Earth and *STEREO* SEP observations at high energies, may be attributed to cross-field diffusion (see also Guo et al., 2018). ***STEREO-A* observations continue to play a central role in the ongoing debate about the relative importance of observer connection to extended shock sources versus transport in describing how widespread SEP events develop.** Combinations of *STEREO-A* data with that of other missions continues to provide unique and essential multi-point measurements.

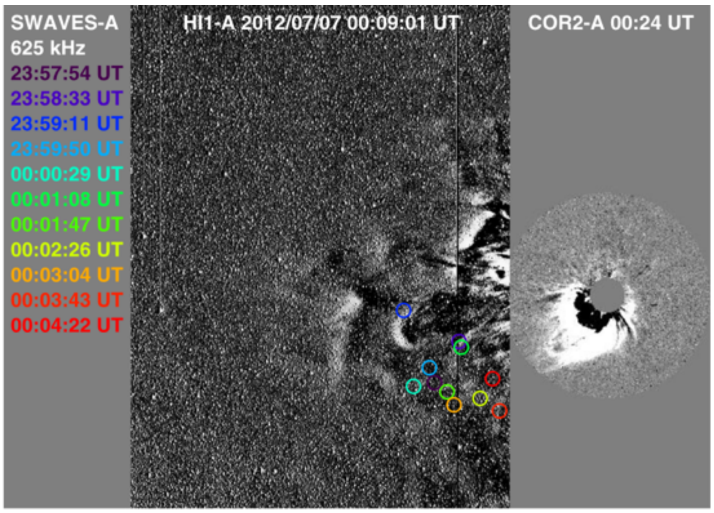


Figure 4: *STEREO data used to determine the location of shock-associated radio bursts. DH type II source locations at 0.625 MHz (colored circles correspond to various times) over-plotted on the combined SECCHI HI1-A (00:09 UT) and COR2-A (00:24 UT) running difference images. The radio sources are located above the nose of the CME heading in the southeast direction (Makela 2018).*

PSG 1-4: Use Measurements of Radio Bursts to Study Conditions in ICMEs and the Solar Wind.

Statement of Goal. The radio-burst signatures of solar eruptions are the fast-drifting type III radio bursts, slow-drifting type II bursts, occasional type IV bursts that extend down to a few MHz. The radio emission is generated by a plasma wave process, in which energetic electrons accelerated at the CME driven shock or at the flare site cause the growth of Langmuir waves, which get converted to radio bursts. Electrons are also energized in active regions by non-eruptive processes leading to type III storms. Radio bursts provide information on the flare, the CME, the CME-driven shock, and the source active region. **The additional-viewpoint observations from *STEREO* help obtain a complete picture of 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. *STEREO*/WAVES data in combination with *Wind*/WAVES, *STEREO*/SECCHI, *SOHO*/LASCO data have contributed to new discoveries on nonthermal processes in the inner heliosphere. Both shock nose and flanks have been proposed as sites of electron acceleration in CME-driven shocks (Gopalswamy 2018a,b; Krupar 2019). The direction-finding capability of S/WAVES provided important evidence for both sites during the 2012 July 6–7 event (Mäkelä 2018). The type II event has a high frequency component that starts in the metric domain (~80 MHz) and continues into the decameter-hectometric (DH) domain ending around 8 MHz; a low frequency component starts in the DH domain around 1 MHz and ends around 0.4 MHz. The S/WAVES-A direction-finding analysis places the radio sources close to the nose region of the associated CME as seen in the SECCHI COR2-A and HI1-A images (see Figure 4). However, the radio source locations were shifted away from the Sun and the leading edge of the associated CME, probably due to scattering of the radio waves.

STEREO has also led to the improved understanding of Langmuir wave physics. The S/WAVES Time Domain Sampler continues to collect bursts of plasma waves with resolutions as high as 250,000 samples/sec. Thejappa & MacDowall (2018a,b) used the S/WAVES data to suggest that strong turbulence processes, namely the oscillating two stream instability, formation of Langmuir solitons and spatial collapse of Langmuir waves play critical roles in stabilization of type III burst associated electron beams as well as conversion of Langmuir waves into electromagnetic waves at the fundamental and higher harmonics of the electron plasma frequency. Improved knowledge of Langmuir wave physics improves their utilization to identify the remote electron density distribution.

PSG 1-5: Characterize Space Weather Throughout the Solar System

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.

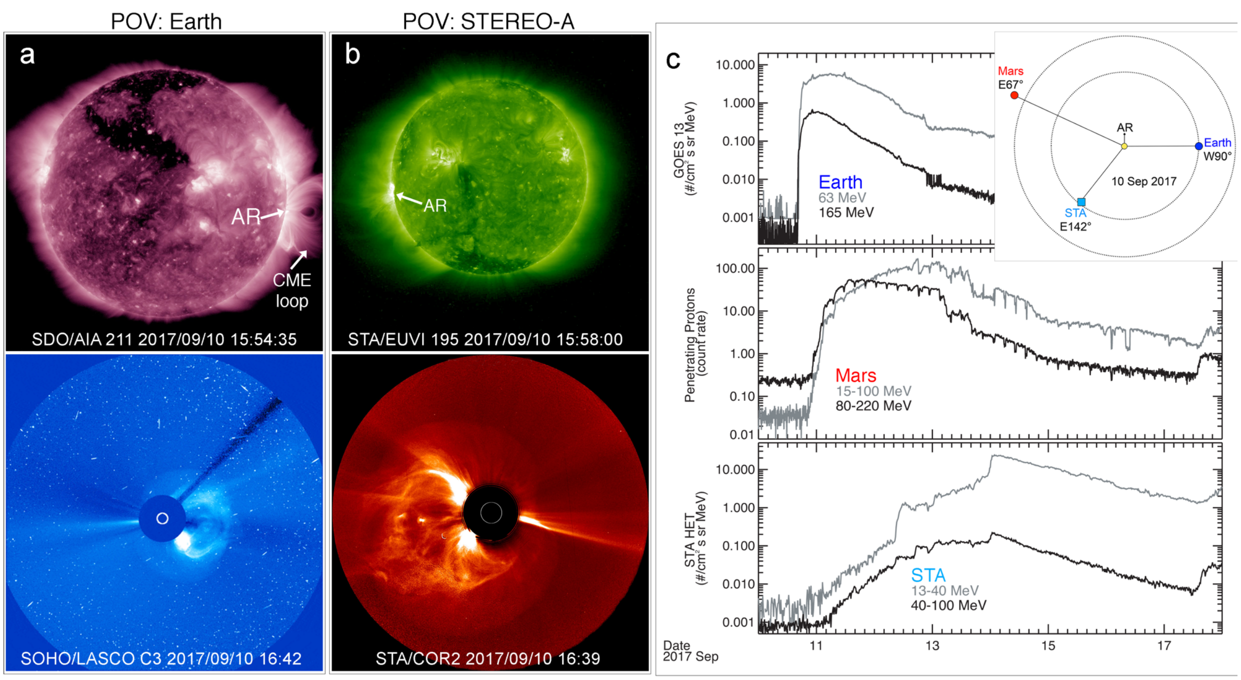
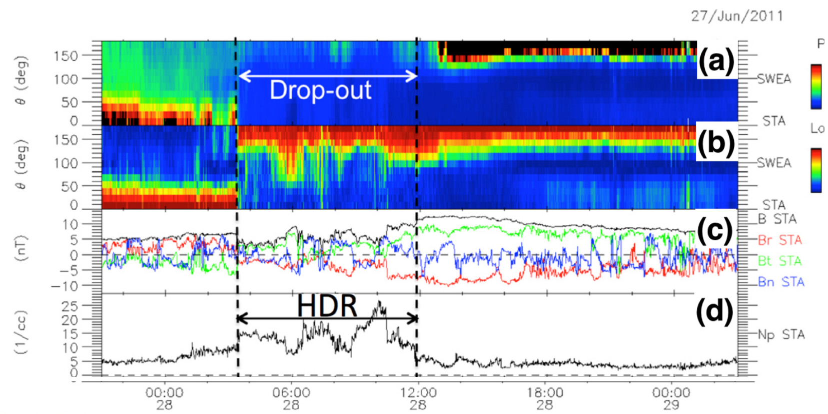


Figure 5: *STEREO images (column (b) and in situ data (bottom of column (c)) along with other data from near Earth and Mars. STEREO data were necessary to determine the spatial location, extent, direction (and speed, from timing) of the September 2017 major space weather event(s). (Lee et al., 2018)*

Progress and Science Highlights. The combination of *STEREO-A*'s off-Sun-Earth axis perspective for EUV and coronagraph imaging, coupled with in situ measurements, allowed interpretive reconstructions of major events impacting Mars. An X-class flare and a fast coronal mass ejection occurred in September 2017. The associated active region, AR2673, was on the farside solar disk facing Mars, where it impacted the local space weather. Figure 5 (Lee 2018) shows the multiperspective imaging of the Mars-bound CME, with *STEREO-A* in an almost quadrature configuration, and SEPs measured by *STEREO-A* on Parker Spiral field lines connected to the ICME shock. SEPs measured by the *MAVEN* spacecraft in orbit around Mars, and at Earth on the *GOES* spacecraft showed the great longitudinal influence of this activity. The most energetic of these SEPs reached the Mars atmosphere and surface (Guo et al., 2018), where they were observed by the *MSL*. They also produced a diffuse global UV aurora over Mars, seen by the *MAVEN* Ultraviolet Imaging Spectrometer (Schneider et al., 2018). Numerical results from the WSA-Enlil cone model for this event were used to analyze its broad heliospheric impacts. **This event provided an excellent example of the power of a distributed heliospheric observatory for diagnosing space weather events at remote locations in the solar system, including Mars where humans will one day travel**.



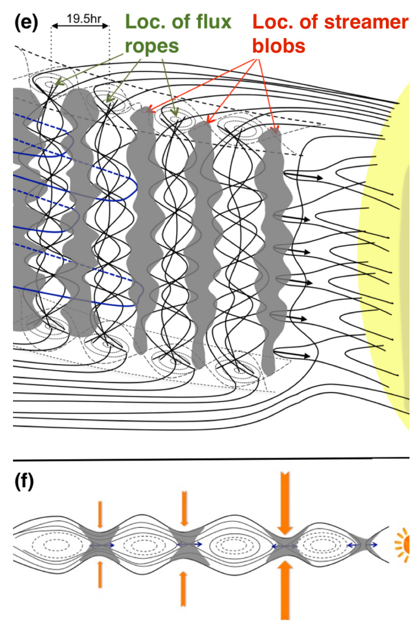


***Figure 6**: STEREO data have allowed new insights into the structure of the solar wind. Top: STEREO-A in situ measurements showing dense blobs that appear to be released from the tips of helmet streamers. From top to bottom: (a) pitch-angle distribution of supra-thermal electrons at ~250 eV, (b) normalized pitch-angle distribution of suprathermal electrons at ~250 eV, (c) magnetic field magnitude and components, (d) proton density. The vertical black dashed lines and the arrow above panel (a) mark the passage of the spacecraft through a high-density region (HDR) and associated drop-out of strahl electrons and change of magnetic field direction. These mark a change of magnetic sector Right: Sketch suggesting magnetic reconnection is the origin of the density enhancements (gray areas) (e) shows a plane containing the neutral line and (f) a plane perpendicular to the neutral line. (adapted from Sanchez- Diaz 2019).*

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

PSG 2-1: Determine the Structure of the Quiescent Solar Wind

Statement of Goal. The multi-perspective, Sun-to-1 AU 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, in particular the structure and variability of the small-scale quiescent solar wind.

Progress and Science Highlights. Two inter-related studies demonstrate how *STEREO*'s highly sensitive instruments and operational flexibility continue to lead to fresh insights into the solar wind structure. DeForest et al. (2018) uncovered radial structure with high density contrast at all observable scales down to the optical limit of the COR2 instrument via the detailed processing of images from a special deep-exposure (36 sec), high-cadence (5-min) campaign. The observations, taken close to solar activity maximum in April 2014, demonstrate that the quiescent solar wind is comprised of intermittent compact plasma parcels at all observable scales and position angles with far more structure and local dynamics than previously realized. Their detailed properties and origin remain to be understood.

A related study by Sanchez-Diaz et al. (2019) combining *STEREO-A* in situ measurements in the vicinity of the heliospheric plasma sheet (Figure 6, left) suggests that helmet streamers shed alternating bands of high-density regions separated by magnetic flux ropes that mostly remain connected to the Sun (Figure 6, right). Their picture may explain at least some of the structures seen by DeForest et al. (2018).

PSG 2-2: Study the 360° Minimum Corona

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

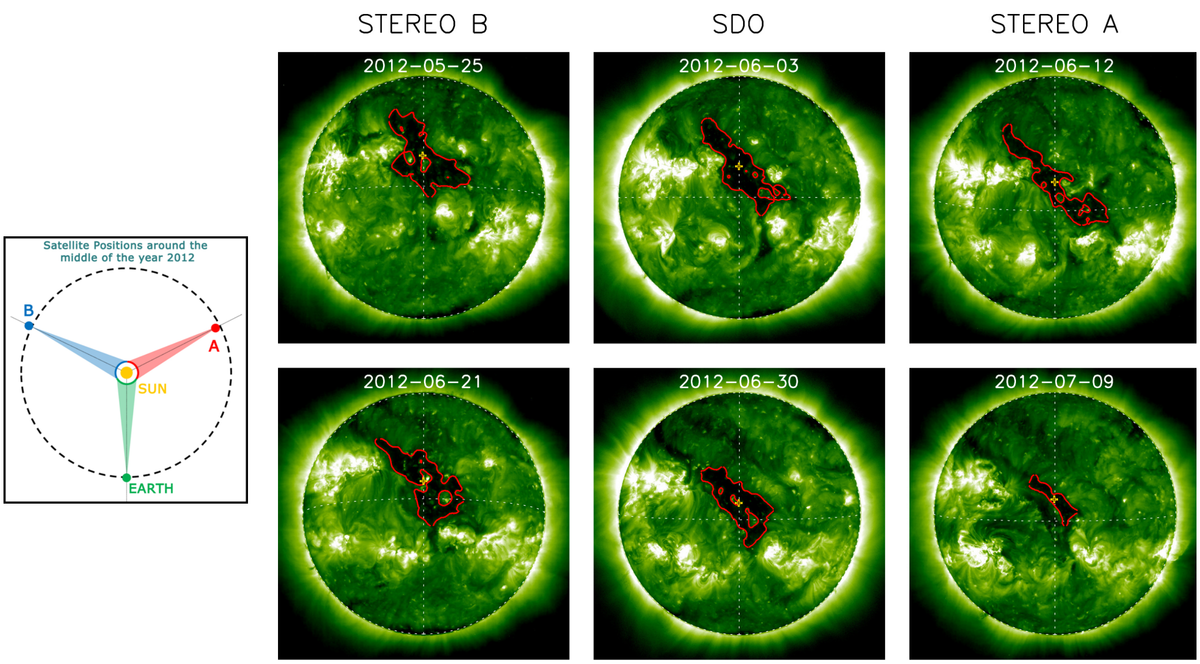


Figure 7: *Sequence of EUV images from STEREO-B, SDO, and STEREO-A, monitoring the evolution of a coronal hole from 2012, following it as the Sun rotates. This continuous monitoring is enabled by the advantageous viewing geometry in 2012 shown in the small figure on the left, illustrating how the three spacecraft could collectively monitor all parts of the Sun at all times (Heinemann 2018).*

Progress and Science Highlights. A recent study by Heinemann et al. (2018) demonstrates the power of 360° imaging of the EUV Corona. Studies of the evolution of coronal holes were previously frustrated by the inability to monitor coronal structures when they rotated behind the Sun as viewed from Earth. With *STEREO*, equatorial coronal holes (CHs) could be monitored continuously in EUV images (see Figure 7), while the high-speed wind streams from the CHs could be measured in situ at 1 AU. This monitoring revealed three phases of CH evolution: a growth phase, a maximum phase, and a decay phase, and quantified how the CH surface area and wind properties changed with phase. Wind speeds of 460-600 km/s, 600-720 km/s, and 350-550 km/s are observed respectively during the three phases.

Goal Set 3: What Can We Learn from Coverage of the Full Heliosphere?

PSG 3-1: Characterize the Source and Transport of Pickup Ions

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). *STEREO*/PLASTIC measures the ion distributions at uniquely high angular and energy resolution making possible new understanding of the acceleration and transport of PUIs, and related processes in the solar wind.

Progress and Science Highlights. Due to its motion relative to the Sun and solar gravity, the interstellar gas flow forms a pattern in the inner heliosphere that is symmetric about the interstellar flow direction. This modulates the pickup ion velocity distribution cut-off speed with ecliptic longitude in a way that can be used to determine the inflow longitude of the interstellar gas. However, a superposed epoch analysis performed by Bower et al. (2019) found that compressions and rarefactions associated with SIRs are also found to modify the pickup ion cut-off. While this interferes with the determination of the interstellar gas flow direction, it provides valuable information about the energization of pickup ions in a structured and dynamic solar wind. The study enabled valuable insight into PUI energization due to solar wind compressions, their evolution across the compression regions, and their dependence on the strength and presence of turbulent fluctuations. The knowledge of the effects of compressions on the pickup ion cut-off on interstellar flow longitude determination, complements other efforts to obtain the interstellar gas parameters with direct neutral atom imaging such as those from IBEX.

PSG 3-2: Improve Our Understanding of Dust in the Inner Heliosphere.

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. Dust has been studied both remotely by SECCHI imagers (see below) and via in situ dust impacts measured by the S/WAVES Time Domain Sampler (O'Shea et al. (2017) and references therein).

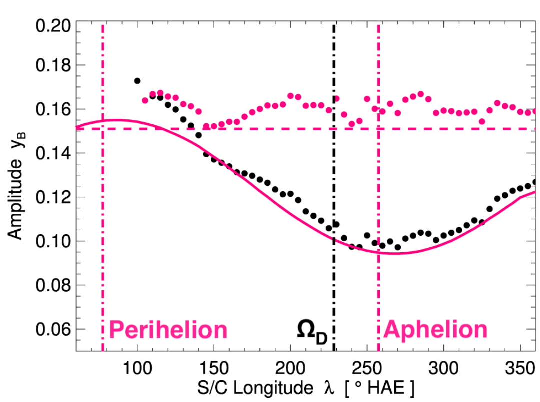


Figure 8: *STEREO based evidence for a dust ring along the orbit of Mercury. Shown are the maximum amplitude of the excess brightness gradient (in black) and detrended profile (in red) as a function of spacecraft longitude. The red solid line delineates the de-trending function. The dashed vertical lines show the aphelion, perihelion and descending node (Ω_D) of Mercury's orbit. Such a ring detected was not predicted theoretically before these observations. (Adapted from Stenborg et al., 2018b)*

Progress and Science Highlight. The raw images of the visible light corona and inner heliosphere from the SECCHI imagers are dominated by dust-scattered emission, the so-called F-corona. While this component is removed for most image uses, the analysis of the F-corona itself holds considerable interest for space and planetary physics as it is (currently) the only way to study circumsolar dust from different vantage points. In a series of papers, Stenborg & Howard (2017a, b); Stenborg et al. (2018a, b) and Stauffer et al. (2018) analyzed in-depth F-corona measurements from *STEREO-A*'s HI1 imager to better characterize the orbital dynamics of circumsolar dust. Their efforts resulted in the discovery of a dust ring near the orbit of Mercury. **Unlike the resonant dust rings near Earth and Venus' orbits, the Mercury ring was never predicted theoretically nor even considered by modelers.** Figure 8 shows the excess brightness beyond the expected trend, revealing the dust excess. The maximum brightness enhancement (~2%) corresponds to a 3-5% dust density enhancement relative to the background density at a projected radial distance of about 0.38 AU. The technique also serves as a novel remote-sensing detector of cometary dust trails as it revealed enhancements in the trails of comets 95P/Encke, 169P/NEAT, and 73P/Schwassmann-Wachmann 3.

IIIc. Goals and Objectives, FY2020-FY2025

STEREO's Science Objectives for the next 5 years address Key Science Goals 1 ("*Determine the origins of the Sun's activity*") and 4 ("*Discover and characterize fundamental physical processes…*") set forth in the **2013 Decadal Survey** (Baker et al 2013). Specifically, our Science Objectives flow down from Solar & Heliospheric Physics (SHP) Panel Challenges: SHP-1 *Determine how the Sun generates the quasi-cyclical variable magnetic field that extends throughout the heliosphere* (Sci Obj **C1, C2**), SHP-2 *Determine how the Sun's magnetism creates its dynamic atmosphere* (Sci Obj **A1, A2, B2, C2**) and SHP-3 *Determine how magnetic energy is stored and explosively released* (Sci Obj **A2, A3, B1, B2, B3, C3**). These in turn are clearly connected to the Heliophysics goals set forth in the NASA SMD Science Plan (2014). Another important consideration is *STEREO*'s contributions to the **Space Weather Action Plan (SWAP),** including "the creation of new capabilities to observe, model, and predict space weather phenomena." *STEREO* data and investigations, especially as related to *STEREO-A*'s location at L5 and eventually L4 will address important goals of SWAP related programs (Sci Obj **A1-3**, **B1-3**).

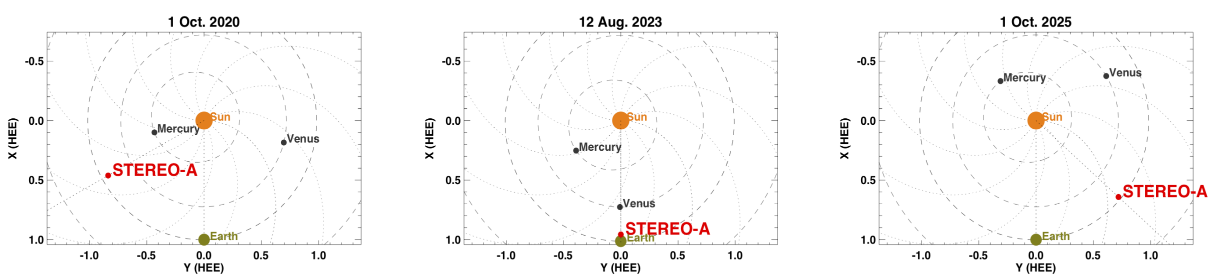


Figure 9: *During the 5-year period covered by this proposal STEREO-A will go from near the Earth-Sun L5 point to less than 0.047 AU from Earth and out again towards the L4 point. During this same time period we expect to go from solar minimum to solar maximum. This will allow STEREO to pursue a range of science objectives, including evaluating off-L1 locations for space weather research and analyzing features on the Sun and in the solar wind in conjunction with other observatories.*

Our objectives are optimized to take advantage of *STEREO*'s orbital configurations during the 5-year period covered by this senior review. We are currently at solar minimum, completing a solar cycle since launch. We expect to be in the waxing phase of the solar cycle, reaching solar maximum around the end of the 5-year period. *STEREO* will be making a 65º sweep past Earth moving from the approximate locations of the Earth-Sun L5 point, past Earth, and towards the L4 point by 2025 (see Figure 9). We expect to see much more solar activity during this time than was observed by STEREO immediately after it launched in the middle of a very quiet solar minimum. We also have at this time exciting new missions in the inner heliosphere for coordinated studies: *PSP, Solar Orbiter*, and *BepiColombo*. Based on these considerations, *STEREO* proposes objectives that fall in three main areas: (1) The structures of CMEs, active regions, and the solar wind as revealed by multi-point measurements (2) Applying *STEREO* observations toward evaluating off-L1 locations for space weather research, and (3) Understanding the effects of solar cycle variations on the corona and heliosphere. Although we are proposing for 5 years, we emphasize work that can be done in the next 3 years.

Sci. Obj. Set A: The Structure and Magnetic Morphology of CMEs, Active Regions, and the Solar Wind as Revealed by Multi-point Measurements

***Motivation*:** The three-dimensional structure and magnetic morphology of the solar wind and its transients is a central topic of Heliophysics, as they are the key agents of solar-terrestrial coupling. Work in the past decade has revealed that the evolution of CMEs and small transients may sometimes differ from self-similar expansion and radial propagation, with heliospheric deflection, rotation, reconnection, and deformation. These effects likely arise from their interaction with ambient structures (i.e., current sheets, dense or fast streams) or other transients. Meanwhile, the increased understanding of the behavior of small transients (streamer blobs, small flux ropes) from remote and in situ observations (e.g., Yu et al., 2018; Sanchez-Diaz et al., 2019) and simulations (Higginson et al., 2018) has uncovered their importance in creating the variability of the slow wind. Lastly, little is known about the radial evolution in the inner heliosphere of stream interaction regions (SIRs) with past studies focusing primarily on the evolution from Venus to Mars and beyond (Jian et al., 2008).

The unique vantage point of *STEREO-A*, as it passes through L5 and crosses over the Sun-Earth line in 2020-2023, combined with observations by the NASA HSO, gives us the needed multi-viewpoint measurements to advance our understanding of CMEs, small transients, solar wind streams and active regions. This will happen at a time of enhanced solar activity as compared to the previous period when *STEREO* was near-Earth in 2007-2009. All sub-objectives take advantage of these multi-point observations to go beyond past simplifications in our description of CMEs, active regions and solar wind streams. Together, they will improve our understanding of the magnetic morphology of the solar wind and transients, connecting active regions, heliospheric propagation and resulting morphology near 1 AU.

Science Objective A1: What is the 3D Morphology of Pre-eruptive Structures in Active Regions?

Previous Efforts. The key for understanding and eventually predicting solar eruptive activity is understanding the evolution of the magnetic configuration in active regions, particularly the buildup of free magnetic energy, currents, and helicity (e.g., Georgoulis et al., 2019). This remains a hard task, mostly because we lack the ability to measure the 3D coronal magnetic field and extrapolations from photospheric field measurements are uncertain in complex active regions, which are also the most likely to erupt. Malanushenko et al. (2014) used EUV images to constrain/validate magnetic field extrapolations before and after an eruptive flare and demonstrated the potential of robust 3D magnetic field reconstructions for assessing solar eruptivity. The validation of such extrapolations requires stereoscopy. STEREO was the first (and, so far, only) mission to image the corona stereoscopically, for a few months in 2007. The analyses focused on quiescent loops (**Figure 10** and Aschwanden 2011, for a review). However, these and the work of Malanushenko et al. were trailblazing studies and led to the inclusion in the COSPAR Road Map for Space Weather Research (Schrijver et al., 2015) of a EUV stereoscopy mission concept ("Binocular Vision for the Corona") as a high priority for advancing the science of space weather.

However, stereoscopic active region studies require a relatively small angular separation between spacecraft, and the low solar activity and scarcity of active regions in mid-2007 greatly limited the productivity of STEREO for these purposes, leaving much to be done in the near future when STEREO will once again be near Earth, but this time with the Sun in a more active state.

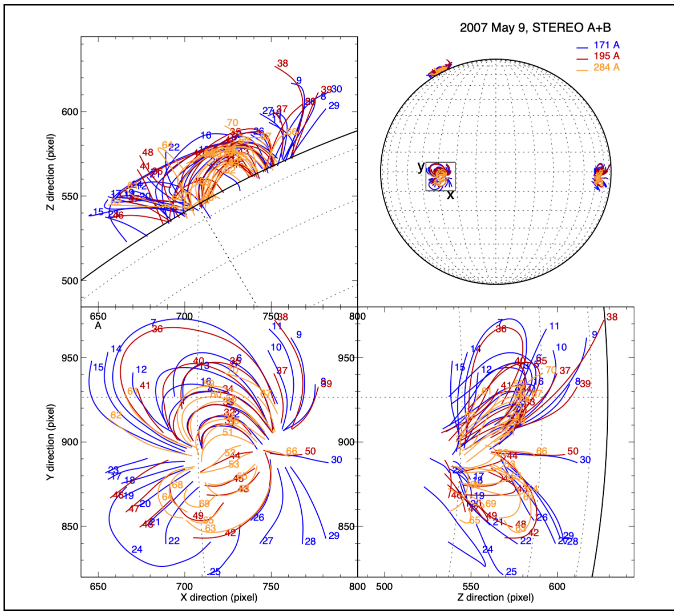


Figure 10: *STEREO-A's swing past Earth will result in sufficiently small separation angles with Earth-orbiting telescopes to allow further studies of the 3D structure in the solar corona. Here we see orthogonal projections of 70 stereoscopically triangulated coronal loops in AR 10955 shown from three different points of view, and made possible by observations from the STEREO-A and B/EUVI telescopes. The STEREO-A projection in the x-y image plane is shown in the bottom left panel, the projection into the x-z plane in the top panel left, and the projection into the y-z plane in the bottom right panel. The three orthogonal projections correspond to the positions indicated on the solar sphere in the top right (see Aschwanden 2011).*

Approach. EUV stereoscopy aided by simultaneous photospheric magnetic field measurements and coronagraphic imaging can lead to major insights in energy release processes. Between 08/2022 and 08/2024, *STEREO-A*/EUVI and *GOES*/SUVI meet the strawman requirements (angular separation of 10°-20°, multi-wavelength coverage at arc-second resolution) of the "Binocular Vision" concept. This period likely coincides with the rise to solar max for Cycle 25, creating a unique opportunity to validate the mission concept and investigate the value of EUV stereoscopy for Space Weather research. Based on the 2007 experience, the optimal periods for direct stereoscopy are at 5°-15° angular separations (12/2022 - 7/2023, 10/2023 - 6/2024). To prepare, we will reanalyze the 2007 EUVI-A/B data focusing on expanding the existing software to facilitate direct stereoscopic analysis and analyzing eruptive events. Then, during the 2022-2024 stereoscopy periods, we will embark on coordinated campaigns between EUVI-A and SUVI or *SDO*/AIA combined with middle corona in situ measurements from *PSP* (when appropriate), magnetic field measurements from *SDO*/HMI or ground-based observatories (GONG, DKIST). **These will create an unprecedented systems observatory for studying the fine-scale 3D structure and content of magnetic eruptions from active regions.** The science return would be increased greatly by extra DSN allocation to *STEREO* for specific intervals.

Science Objective A2: How Do Interplanetary Transients and Corotating Structures Evolve from the Sun to 1 AU?

Previous Efforts. Even with the advances of numerical simulations (e.g., Manchester et al., 2017) and observation-based reconstructions (e.g., Wood et al., 2017), we are still far from understanding how the near-Sun magnetic topology of ICMEs and small transients relates to the near-1AU measurements. The recent launches of *PSP* and *SO* missions enable multi-point in situ and remote-sensing observations throughout the innermost heliosphere. **When combined with *STEREO* and its off Sun-Earth line remote and in situ observing capabilities, the three spacecraft configurations provide crucial and unprecedented observations to address the evolution of CMEs and solar wind in the inner heliosphere.** Such synergies have already been demonstrated. Recent studies of CMEs with spacecraft in conjunction (Salman et al., 2020) and some of the first *PSP* investigations of CMEs (Wood et al., 2020, Figure 11) relied heavily on *STEREO* observations. Investigations of the evolution of fast and slow solar wind streams and SIRs, and the associated energetic population have similarly relied on joint *PSP/STEREO* studies (Allen et al., 2020, Leske et al., 2020; Rouillard et al., 2020).

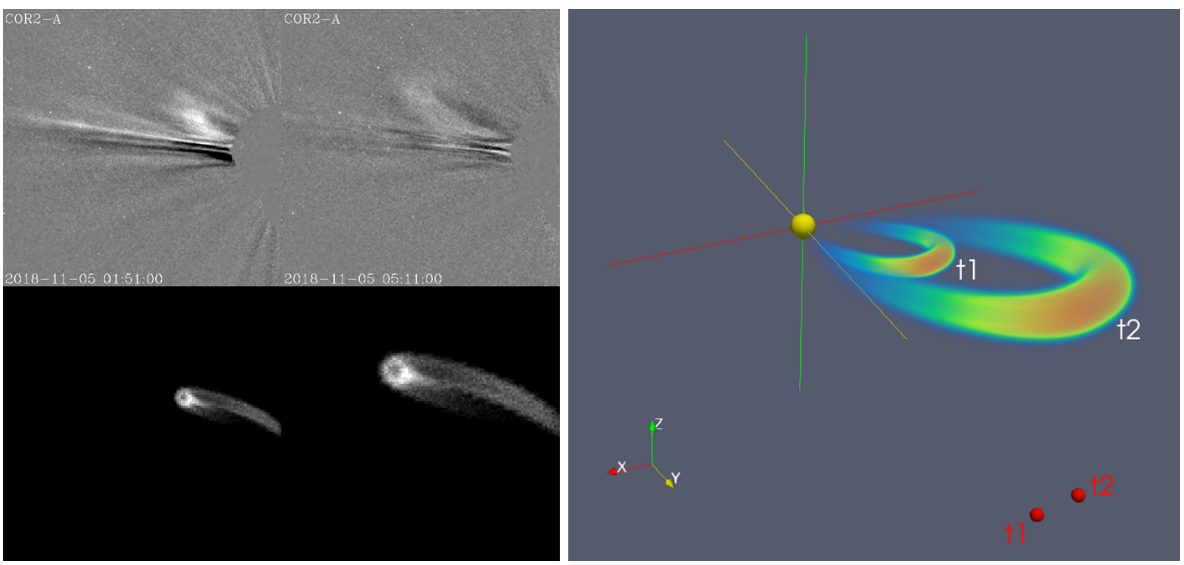


Figure 11: *On the upper left is a sequence of two STEREO/COR2-A images of a small CME from November 2018 that was also imaged by PSP/WISPR a day before PSP's first close perihelion passage, only 35.4* $R_{\odot}$ *from Sun-center, as well as by SOHO/LASCO near Earth. Consideration of the WISPR, LASCO, and COR2-A data allowed the reconstruction of the 3-D flux rope morphology of the event, shown on the right at two times (t1 and t2), with the red circles indicating the location of PSP at these times. Synthetic COR2-A images of the event based on this reconstruction are shown below the real images in the bottom left (Wood et al., 2020).*

Approach. The anticipated increase in solar activity over the next three years will provide more opportunities to address this objective by continuing the coordinated multipoint observations between *STEREO-A*, *PSP* and adding *SO* (in early 2022). Measurement of the same events/streams at *STEREO-A*, and *PSP* (or *SO*) will enable studies of how their properties change with distance due to interaction with various other structures.

Remote observations of streams and CMEs by *STEREO* will be combined with simultaneous *PSP/SO* in situ measurements to infer the global context necessary to interpret the measurements. Additionally, statistical analyses with dozens of events expected in the minimum and rising phase of solar cycle 25 will allow us to determine the typical ways ICMEs and small transients expand and accelerate/decelerate in the inner heliosphere, and how SIRs form and steepen.

Science Objective A3: What is the Magnetic Morphology of Heliospheric Transients?

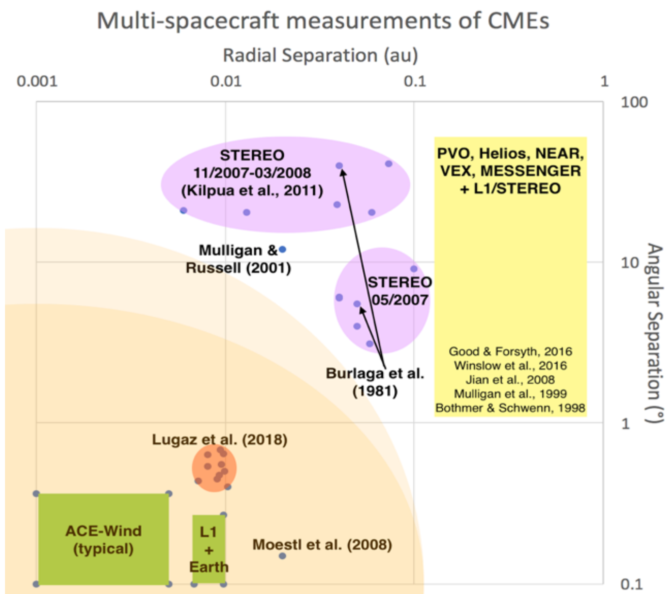


Figure 12: *Multi-spacecraft measurements of ICMEs and the expected magnetic cloud cross-section shape (orange). The only measurements below 0.1 AU at separations 1°-20° were made by STEREO, Helios (Burlaga et al., 1981) and NEAR (Mulligan 1999). There are < 12 such multi-s/c measurements. During its return to the Sun-Earth line near solar maximum in 2023,* ***STEREO-A combined with near-Earth assets is set to double or triple the number of multi-spacecraft measurements of ICMEs in this ideal range*** *(figure adapted from Lugaz et al., 2018).*

Previous Efforts. The 3D magnetic configuration of ICMEs, particularly their longitudinal and latitudinal components, are not known with certainty. Simultaneous multi-spacecraft measurements of the same ICME are exceedingly rare (in great part due to the low solar activity in 2007). As a result, neither the small-scale structure nor the variation in structure across the angular extent of ICMEs are well understood. STEREO spent 7 months within 10° of the Sun-Earth line during a deep solar minimum and captured only 2 ICMEs and no CME-driven shock or Energetic Storm Particle (ESP) event (Kilpua et al., 2011). *Wind*'s extended mission included several months of measurements away from the Sun-Earth line, recording 20 CMEs at longitudinal separations > 0.4°. Recent analysis of these data revealed significant differences between the magnetic field measurements from two spacecraft separated by less than 1° (Lugaz et al., 2018). This highlights the need for multi-spacecraft measurements 2-15° from the Sun-Earth line to understand ICME magnetic morphology (Figure 12).

Approach. The return of *STEREO-A* to the Earth's vicinity in 2022 offers an opportunity to measure a significant number of ICMEs and small transients from multiple closely spaced in situ payloads and thus investigate the fine-scale structure of the entrained magnetic field and plasma, robustly validate reconstruction algorithms, and understand in 3D the force balance within the structures. *STEREO-A*'s approach within 15° from assets on the Sun-Earth line in 11/2022 – 06/2024, could double the number of multi-spacecraft measurements of ICMEs, shocks and ESPs. This will create a unique system for resolving long-standing questions on the physics of ICMEs, with direct impact to Space Weather research. In 2011-2013, *ACE* measured ~30 CMEs/year and ~20 fast-forward shocks/year. Assuming a similar level of activity, we estimate that *STEREO-A* and near-Earth assets will jointly capture at least 40 CMEs and 25 shocks.

In addition to magnetic field measurements, suprathermal electrons are one of the clearest markers of magnetic topology and can therefore be used to study both ICMEs and solar wind structure and origins, with periods of counter-streaming electrons indicating closed loops or flux ropes still attached to the Sun at both ends. *STEREO* in situ data have the advantage of not being contaminated by sunward-streaming electrons from the Earth's bow shock and magnetosheath, allowing for a clearer identification of magnetic topology from suprathermal electron data. As shown by Shodhan et al. (2000), ICME topology near 1 AU inferred from their suprathermal electron anisotropies is often complex, exhibiting periods of counter-streaming interspersed (sometimes dominated by) unidirectional streaming. There are also occasional periods when the suprathermal electron fluxes are greatly diminished (dropouts). We will perform combined electron pitch angle distribution and spectrum analysis of time periods containing ICMEs and slow solar wind. This will tell us more about the sources and connectivity of the magnetic fields within and around ICMEs. For example, various portions of an ICME that are topologically distinct can have significantly different energy spectra. Similarly, the overall suprathermal electron characteristics of the slow solar wind have not generally been characterized in terms of magnetic structure/topology. While small flux ropes, false polarity reversals and heat flux dropouts (implying fields disconnected from the Sun) have been individually identified, comparisons of their different trends contain information. In particular, coronal field variations seen in models (PFSS or MHD) can tell us where source regions undergoing new field opening or closing, or interchanging fields, should map to *STEREO-A*. The full *STEREO* mission time series of slow wind topological features together with the readily available models can reveal in more detail the transient nature of the local solar wind. The insights gained will contribute to our understanding of the way coronal processes influence the structure and evolution of the interplanetary medium.

Sci. Obj. Set B: Applying *STEREO* Observations Toward Evaluating Off-L1 Location Space Weather Research

Motivation. The three subobjectives detailed in this section have a common motivation. NASA's participation in the Space Weather Action Plan includes "the creation of new capabilities to observe, model, and predict space weather phenomena." Because of its ability to provide solar "farside" information from beyond the visible disk in a near real-time mode, *STEREO-A* is a unique platform for evaluating the benefits of such resources. In particular, its near-real-time EUV and coronagraph images make it possible for forecasters to better locate and monitor major flares and eruptions that occur on or over the limbs but still affect Earth's environment. Both imaging and in situ-measurements at longitudes separated from the Earth-Sun line better-constrain global models of the solar wind, CMEs, and SEP events, especially when used in ensemble modes. **Over the rising phase period covered by this proposal, *STEREO-A* will drift from a roughly L5-like perspective to an L4-like perspective (Figure 9) providing real operational testing of the benefits of a second spacecraft at locations currently under serious consideration.**

Science Objective B1: How Do Coronal and Heliospheric Observations Obtained within ±60º Longitude of L1 Affect Space Weather Forecast Model Results?

Previous Efforts. *STEREO* coronal and heliospheric observations have been used extensively in developing and validating techniques and models for forecasting Time-of-Arrival (ToA), Bz, and other CME properties (Vourlidas et al., 2019 and references therein). The studies have shown that multi-viewpoint observations have increased the average forecasting accuracy for ToA to about 10 hours but several open questions remain. For example, the ToA error can be much higher than 10 hours even for events that can be followed all the way to 1 AU, and the benefit of three versus two viewpoints is not apparent (Wold et al., 2018), which is counterintuitive. Some of the reasons that prevent us from improving our forecasting accuracy were discussed by Vourlidas et al. (2019) and involve the small event numbers and the uncertainties in tracking features from the corona into the heliosphere. The return of *STEREO-A* to L5 offers an opportunity to improve the situation by increasing the number of events for study and for providing a comparison point with the previous cycle studies from the same locations.

Approach. The extensive experience gathered from applying an operational perspective in the analysis of CME kinematics will be used for CME ToA and other studies during the upcoming *STEREO-A* passage through L5. The analyses will benefit greatly (compared to the 2009 status of the field) by the increased sophistication of MHD models, the deployment of various empirical and semi-empirical models, the maturity of the 3D reconstruction software, and in particular the improved processing of the HI-1/2 images that may increase the accuracy of feature tracking in these images. The latter, in turn, could benefit Time-of-Arrival predictions and ease the validation of MHD modeling via comparison with synthesized images from these models. Neither of these strategies has received much attention so far. In addition, we will explore the utility of COR2 and HI1 observations in data assimilation schemes using Enlil or other models used within the *STEREO* team.

Beyond the near-term three-year plans, we switch our focus to topics relevant to the upcoming NASA Artemis program. Astronaut safety requires major improvements in forecasting and monitoring hazardous SEP events. The latter are best studied with observations over the West limb (i.e., from 'L4'), where solar flare and CME-driven shock sources are well-connected to the Earth vicinity by the heliospheric magnetic fields. *STEREO* will serve this function, starting in 2024 and beyond. In combination with *MAVEN*, it will quantify the advantage of routine, longitudinally separated space weather measurements for predicting such hazards at Mars.

Science Objective B2: How Accurate is the Assumption of Corotating Solar Wind Structure in the Face of Increasing Solar Magnetic Complexity?

Previous Efforts. Interplanetary field and solar wind plasma measurements made by *STEREO*, including transient and recurrent events, and suprathermal ion fluxes, provide a natural data resource for longitudinally separated measurements at 1 AU (see Simunac et al., 2009 and Jian et al., 2019 for discussions of *STEREO-A* and *STEREO-B* as a test bed for a L5 monitor). Turner & Li (2011) compared 2008-2009 solar wind observations from *STEREO-B* and *ACE*, when *STEREO-B* was trailing from Earth by ~60º. They found that the L1 solar wind speed was especially well-predicted by the *STEREO-B* measurements, while density and magnetic field strength showed positive correlations. Thomas et al. (2018) broadened this study, using various combinations of *STEREO* and *ACE* observations to evaluate equivalent solar wind predictions over a greater range of solar conditions (see Figure 13). The results showed good agreement between the spacecraft measurements including SIRs, with 'skill scores' reflecting the predictive quality for each parameter. However, the authors noted that transient structures like ICMEs are not captured with this approach, and that even high-speed streams and CIRs can be missed due to latitudinal separations of the spacecraft, and the often complex boundaries of coronal holes and the temporal evolution of the solar wind sources.

Approach. Of particular interest are comparisons between intervals when slow solar wind emanating from helmet streamers and pseudostreamers dominates at *STEREO* and at near-Earth assets. **The upcoming orbital and cycle phase circumstances present unique conditions for studying the persistence of solar**

wind parameters over various solar longitude separations during undisturbed solar conditions. Prior solar wind persistence studies during solar minimum estimated about 2-3 days robustness (e.g., Opitz et al., 2009 and references therein), although this result depended upon the type of solar wind being studied. At 60º longitude prior to Sun-Earth Line, solar wind at L5 will be sampled ~ 4 days prior to recurring structure arrival at the Sun-Earth line. Small transients are not expected to be observed by the separated spacecraft even as their separation diminishes. But how much are the slow solar wind characteristics determined by these features? And how much do they change as a function of this time and distance? The results have also space weather implications, as the accuracy of L5 monitor 'forecasts' depend on the persistence of solar wind structures.

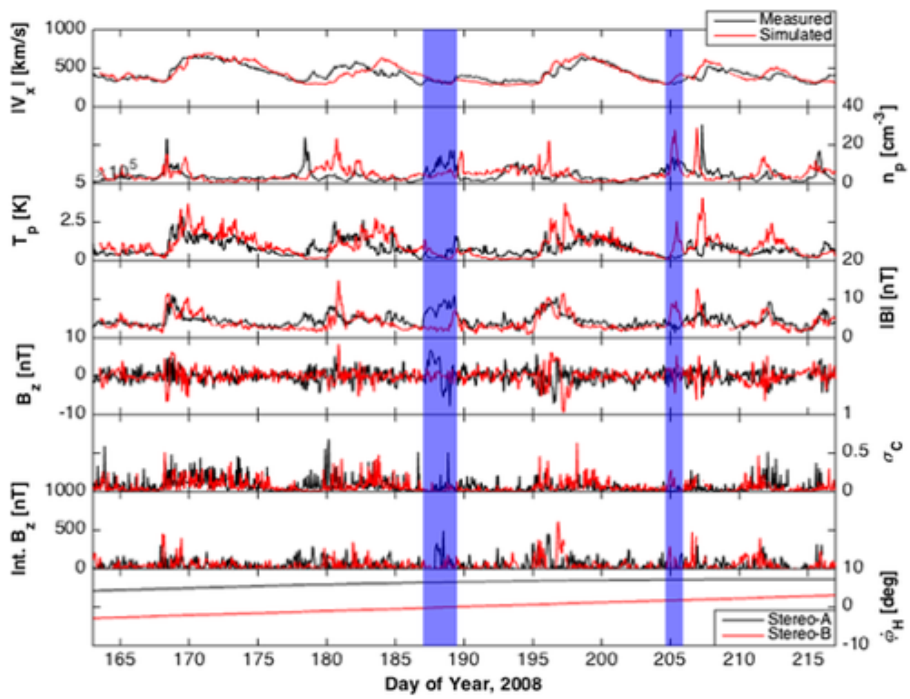


Figure 13: *Solar wind time series for STEREO-A (black) and its predicted behavior based on STEREO-B measurements (red). (From Thomas et al., 2018). The study showed good agreement between the spacecraft measurements including SIRs, but further work needs to be done to better predict other solar wind features like CMEs (marked by violet bands).*

Science Objective B3: Do High-energy SEP Events Originate at Low Coronal Shocks or Flares, and What Is the Best Indicator of Their Occurrence and Severity?

Current Status. While it is widely believed that shocks driven by CMEs are the dominant source of acceleration for large SEP events, the details are not well understood. Observations suggest that shock acceleration (Gopalswamy et al., 2013) low in the corona contribute to the highest-energy particles with particle injection corresponding to CME heights of ~3 $R_\odot$. Both the shock nose and flanks can play either a key or contributing role in particle acceleration (e.g., Lario et al., 2017, Gopalswamy et al., 2018b). Multi-point observations from the *STEREO* spacecraft and observations near Earth (e.g., *ACE*, *GOES*, PAMELA, *SOHO*, *Wind*), revealed how different magnetic connections to a shock affect SEP spectral features, onset times, and, when possible, composition (e.g., Xie et al., 2017, Bruno et al., 2019). Many factors contribute to the maximum energy such as the shock speed, geometry and age, the coronal magnetic field strength and configuration, the presence of suprathermal seed particle populations and pre-existing turbulence. Ground level enhancements (GLEs), though less frequent during solar minimum, occur throughout the solar cycle, making them of special concern to forecasters.

More recently, high-energy SEPs have been linked to the production of Long Duration Gamma-ray Flares (LDGRF) from back-precipitation of CME-driven shocks (e.g., Plotnikov et al., 2017, Jin et al., 2018), supported by the close relation between gamma-ray duration and the associated type II burst duration (Gopalswamy et al., 2018a). Others attribute LDGRF emission to stochastic acceleration within large coronal loops (de Nolfo et al., 2019) but it is debated whether these same high-energy particles escape flares directly as SEPs (e.g., Kocharov et al., 2020). *STEREO* observations were instrumental in comparing SEPs and the population of protons responsible for the production of LDGRF emission (Pesce-Rollins et al., 2015, de Nolfo et al., 2019, Gopalswamy et al., 2020).

Approach. Multipoint observations enabled with the *STEREO* mission are invaluable resources for piecing together the different processes responsible for accelerating particles to high energies. New insights will be gained from combined *PSP* and *SO* multipoint observations with *STEREO-A*. For instance, the *PSP* perihelia provide unique opportunities to detect the seed populations close to where CME shocks form, and to assess whether they provide a significant source for shock acceleration of extreme SEPs. The combination of *PSP* and *SO* and future and past observations of *STEREO* and *ACE* will contribute to a more detailed examination of gradual SEP events and associated shock characteristics, including the investigation of the radial dependence of ESPs. Already *PSP* has identified several small SEP events that were undetected by *STEREO* despite a good connection. As solar activity increases, we expect more such observations that will help strongly constrain transport modeling. We expect a strong variation of intensity with heliocentric radius for impulsive SEPs due to a combination of geometrical expansion and velocity dispersion. Measurement of the same impulsive SEP events at *STEREO-A*, *ACE*, and *PSP* will make it possible to test this expectation and investigate the possible role of solar wind turbulence and large-scale structures in altering the radial dependence of event characteristics. *STEREO-A*, combined with *PSP*'s sensitivity to gamma-rays in the IS⊙IS/HET neutral mode (McComas et al., 2016), are poised to further our understanding of the origin of LDGRFs and the possible connection to SEPs. SEPs heading back toward the Sun and into the solar atmosphere are a source, their partial reflection –which is included in current SEP event models- should produce characteristic time profiles both close to the Sun and at 1 AU that can be used as a remote diagnostic of that process.

Sci. Obj. Set C: Understanding the Effects of Solar Cycle Variations on the Corona and Heliosphere

Motivation: The Sun's activity cycle governs the radiation, particle, and magnetic flux in the heliosphere creating hazardous space weather. Investigation of solar cycle variations is important for long-term mission planning, the understanding of solar dynamo and the magnetic flux transport from the solar interior to surface, and the space-terrestrial climate relation. For instance, the sizes of the polar coronal holes and the locations and structure of the streamer belt were decidedly different in their details between solar cycles (SC) 23 and 24. The stronger SC23 had larger polar coronal holes and a streamer belt significantly more confined to the equatorial regions compared to the weaker SC24. The density and dynamic pressure of the solar wind decreased 17% and 22%, respectively, between SC23 to 24 (McComas, 2008), and the open magnetic flux during the SC23/24 minimum was about half that of the previous cycle (e.g., Lee et al., 2011).

In December 2019, the NASA/NOAA co-chaired international panel predicted solar cycle 25 (SC25) would start in April 2020 (±6 months) and reach its sunspot maximum in July 2025 (±8 months), with a smoothed sunspot number similar to SC24. If so, the next three years will fall in the rising phase of SC25. **With *STEREO* and near-Earth solar and solar wind monitors, which do not always observe the same events and conditions, we will be able to more fully evaluate how SC25 coronal and heliospheric conditions progress in comparison with previous cycles.**

Science Objective C1: How Do Coronal and Heliospheric Transients During the New Cycle 25 Rising Phase Compare to the Rising Phase for Cycles 23 and 24?

Previous Efforts. Hess & Colaninno (2017) compared multiple CME catalogs including the ones based on *STEREO* and concluded that there were fewer CMEs in SC24 than in SC23, proportional to the decrease in sunspot number. Jian et al. (2018, 2019) compiled *STEREO* Level 3 event lists of ICMEs, stream interaction regions (SIRs), shocks, and SEP events, representing an accumulating resource for the study of solar cycle evolution of solar wind, from a multipoint perspective. In contrast with the similar phases of SC23, based on *Wind*/*ACE* data and the same selection criteria, the *STEREO* ICMEs in SC24 occurred less often and were generally weaker and slower, although their magnetic field and internal pressure weakened less than the background solar wind. On the other hand, slightly more SIRs and higher recurrence rates were observed in years 2009-2016, with a lower association rate with the heliospheric current sheet, than for the corresponding phases of SC23. This is possibly due to persistent equatorial coronal holes and more pseudo-streamers in SC24. The solar wind speed, peak magnetic field and pressures of SIRs are all lower in this cycle but less so than for the comparable background solar wind parameters, similar to ICMEs (Jian et al., 2019).

Approach. We will survey solar eruptive and solar wind events in the upcoming years, including CMEs, ICMEs, SIRs, shocks, etc. for the purpose of investigating how the solar and heliospheric conditions vary during the ascending solar activity in SC25, and whether they are similar to the SC24 rising phase. There has been long-term north-south asymmetry in polar magnetic field and coronal structures, in terms of timing and strength. We will investigate how this asymmetry evolves in the new cycle and when there is a reversal of the trend. In addition, we will track the magnetic field polarity of ICME bipolar magnetic clouds which follow the Hale cycle of the solar magnetic field (e.g., Li et al., 2018). The ratio of bipolar magnetic clouds to unipolar magnetic clouds (purely north or south field) is higher in the rising phase of SC24 than in SC23 (Li et al., 2018). We will investigate whether conditions in the rising phase of SC25 will be similar to those in the weak SC24 or to SC23, which had same solar polar field polarity.

Science Objective C2: How Is the Corona Varying Over the Solar Cycle and How Does This Affect the Solar Wind?

Previous Efforts. STEREO observations have inspired the development of many image processing methods that bring out key features and information in white light and EUV coronal images – undetectable in the standard available output – thus improving their scientific utility (e.g., Stenborg et al., 2008; Morgan et al., 2012). A methodology to more accurately identify polar coronal hole boundaries developed by Kirk et al., (2009), applied to EUV images going back to the SOHO/EIT period and more recently to SDO/AIA and STEREO/EUVI, reveals polar coronal hole boundaries as a function of time together with measures of uncertainty. In a different effort, Wang et al. (2017, see Figure 14) generated 200 reconstructions (CRs 2054 – 2153) of 3D coronal electron density from 1.5-3.7 $R_\odot$ from COR1-A and -B full disk images.

Related new image based constraints can be used to optimize model parameters for adjusting the photospheric boundary conditions, enabling more reliable model reconstructions of the corona and solar wind conditions (Jones et al., 2016, 2017).

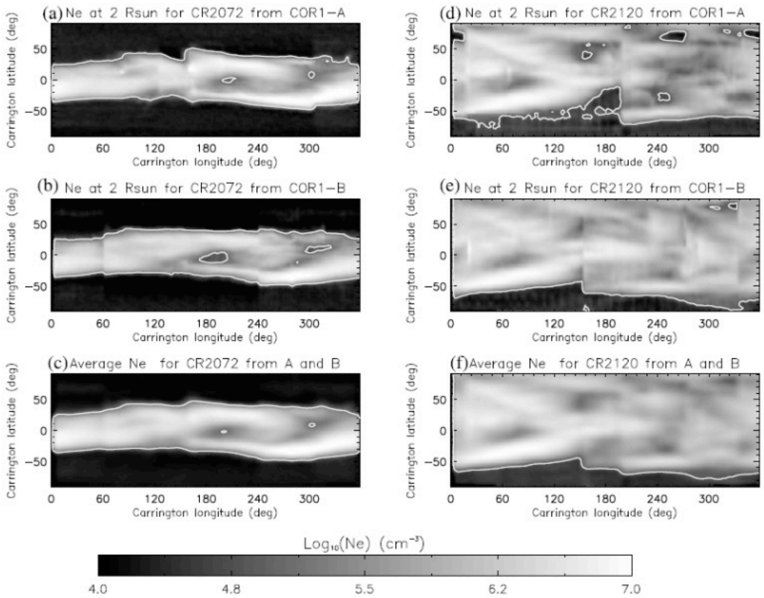


Figure 14: Two examples of the 3D coronal electron density reconstructed using the method of Wang et al. (2017). Left panels: for CR 2072 during solar minimum, showing a spherical cross-section of the density at 2.0 R from COR1-A (top), COR1-B (middle), and the mean of COR1-A and -B with 10°×10° smoothing (bottom). Right panels: same as the left panels, but for CR 2120 during solar maximum. The overlaid contours enclose regions with density $N_e >$ 3σ. (Wang 2017). Such density values can be used to validate solar wind models.

Approach. EUV and white light multi-perspective coronagraphic observations combined with multi-point in situ solar wind observations will allow us to infer, with the aid of magnetogram-based 3D models, developed by members of the *STEREO* team, how the corona and related solar wind structure are changing and evolving over time. The tools and methods mentioned above, as well as others, applied to existing and future *STEREO* EUV, white light, and in situ data (including, e.g., *STEREO-A*, *PSP*, *SO*, and L1 data) in conjunction with models are extremely powerful for both science and applications. For example, better 3D specification of the density and structure of the corona such as stream location and corona hole boundaries allow critical validation of coronal and solar wind models, ultimately leading to improvement in their physics and thus ability to accurately predict impacts. **Together, these data, tools and models improve our understanding of the nature and structure of the solar corona and wind, including how and why it is changing in the present solar cycle and implications for the next.**

Science Objective C3: How Are SEPs and Seed Populations Being Affected by Weakening Solar Cycles?

Previous Efforts. To reconcile puzzling SEP observations from Wind, ACE, and STEREO from 1995-2019 with the two-class SEP paradigm established during the early-1990's, Reames (2020) proposed that SEPs observed at 1 AU can be grouped into four sub-classes based on where, what, and how they are accelerated, namely: 1) Pure impulsive SEP events associated with solar jets; 2) Impulsive SEP events produced by narrow CME-driven shocks; 3) Weak gradual SEP events produced by weak, but wide CME shocks, and 4) Strong gradual SEP events produced by fast and wide CME shocks. The seed populations in these cases are: 1) ~3 MK coronal plasma; 2) and 3) left over ~3 MK coronal material mixed with ambient plasma; and 4) ambient coronal plasma that has distinct origin compared with the fast and slow solar wind (Reames 2019). Bucik et al. (2018a,b) combined in situ *STEREO-A* and *ACE* measurements with EUV imaging of solar source regions from *STEREO-A*/EUVI and *SDO*/AIA during numerous ^{3}He-rich SEPs (pure impulsive SEPs) to show that helical jets may be responsible for opening nearby closed field lines and releasing SEPs accelerated via reconnection processes into interplanetary space.

Approach. The significant increase expected in the occurrence rate of "pure" impulsive SEP events during the SC25 ascending phase will provide us with a larger database for confirming the Bucik et al. (2018a, b) results. Furthermore, according to the four sub-class scheme, solar flares without helical jets could provide a significant fraction of the seed population for CME shocks that produce event types (2) and (3), while type (4) events should have no relation with prior solar flares. We will use multi-spacecraft observations of the solar wind, suprathermal, and accelerated particle populations from *STEREO-A*, *ACE*, and *Wind* near 1 AU in combination with inner heliosphere in situ and remote sensing observations from *SO* and *PSP* during several individual SEP events to identify additional examples in support of or counter-examples for the Reames (2020) classification scheme, thereby **enabling us to significantly improve current understanding of the origins of the seed populations and how they affect the variability of SEP events.**

Implementation of Objectives

The FY2020-25 objectives can be addressed within the synoptic *STEREO* programs although we expect to continue SECCHI/COR2 (with additional SECCHI telescopes as required) deep exposure campaigns in conjunction with *PSP* and *SO*. For some objectives (e.g., A-3 and B-2/3) it would be helpful, although not required, to obtain extra DSN time (i.e., repeat the early mission campaigns in 05/2007 and 01/2008) which we would request if it is available.

STEREO functions as part of the Heliophysics System Observatory. As such most of our objectives involve data from other sources. In some of our objectives these are data already taken and freely available, including data from the first passes of *PSP.* Some objectives require data from other observatories. In most of those cases there is more than one possible source for data that would allow us to achieve our objectives. For instance, although optimally we would like both *PSP* and *SO* data to study the radial evolution of CMEs and solar wind, either data set would allow us to make some progress on our objective. Often multiple sources are available for data near Earth and L1. A particular source might be optimal, but other ones would still allow us to make progress. EUV imaging data can be obtained from both *SDO*/AIA and *GOES*/SUVI. Solar wind data can be obtained from *ACE*, *Wind, DSCOVR*, and eventually *IMAP* and *SWFO-L1*. None of our plans involve anything beyond the standard data products from these sources.

STEREO Contributions to the Heliophysics System Observatory

As in the past, we expect continued, broader community use of *STEREO* data outside of the *STEREO* team. ***STEREO* data is already being used extensively in conjunction with *PSP*** (e.g., Wood et al., 2020; Nieves Chinchilla et al., 2020; Krupar et al., 2020; Rouillard 2020 et al.; Leske 2020 et al. to name just a few of the initial *PSP*/*STEREO* papers). **and we expect this to be true for the recently launched *Solar Orbiter* as well.** *STEREO-A* is a key part of the Heliospheric System Observatory for studying the structure and trajectory of CMEs/ICMEs, structure and processes occurring in the solar wind, and acceleration and distribution of SEPs to name a few of the major topics for which STEREO provides highly important data.

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 a single point of contact with the APL MOC for the science team. See Section V, below, for more information on data archiving.

Science coordination is achieved through Science Working Team (SWT) meetings held either by telecon or in conjunction with scientific conferences. While the SWT meetings do sometimes include 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. Spacecraft, Instrument and Ground System Status

Spacecraft

As discussed in Section II, contact with *STEREO-B* was lost in 2014. The operations team re-gained limited contact with it in August and September of 2016 and then lost contact again. Per NASA directive, attempts to regain contact ceased, with the last support on October 17, 2018. 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. There remains a possibility of resuming recovery operations when *STEREO-B* approaches Earth again in the 2022-2023 timeframe, but that is not a focus of this proposal. 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 about 50 years of fuel for momentum management. Solar panel, battery, and High Gain Antenna performance remain nominal. *STEREO* is not contemplating any changes to the mission orbital parameters and will remain in its current orbit. As *STEREO* is not in Earth orbit there are no applicable requirements with respect to debris at the end of mission life (EOML), and the spacecraft will simply be left in their orbits. A letter concerning the EOML is in Appendix C

IMPACT

The IMPACT suite instruments continue to operate nominally. As remarked in previous Senior Reviews, STE-U is blinded by sunlight and no data is collected from it, however STE-D is unaffected and provides quality data. Likewise, SWEA's status is unchanged. As noted in previous Senior Review proposals, SWEA data are compromised below 45 eV but the instrument is fully functional in the suprathermal (45 eV-2 keV) range.

During the review period, the IMPACT suite was powered off by the spacecraft on Sep 23, 2018, due to the spacecraft's detection of excessive power consumption in the SWEA/STE power service. We believe this was due to a single event upset (SEU) of the type that has happened throughout the mission at the rate of roughly once a year. Restoration of science return for instruments except SIT occurred within 24 hours. SIT took several days to bring its high voltage supply back up, which is nominal for it as well.

PLASTIC

As reported in the previous Senior Review, one of the entrance system power supplies showed a current increase after an SEP event (September 2014) and a reduction in the upper voltage used for that power supply was introduced in 2015, and again in 2018. By using redundancy in the system, these changes had no impact on science products. As the PLASTIC is operated through the IMPACT DPU, the DPU instigated power off of September 2018 also powered off PLASTIC, which was then restored to operations.

PLASTIC continued to operate nominally until December 5, 2019, when a large out-gassing incident occurred. The origin of the out-gassing incident is not known at this time. The instrument suprathermal composition measurements have continued throughout and indicate the presence of water products. The position detectors measure the highest intensity of the out-gassing in a non-solar direction. The exceptionally large influx of background particles caused current increases in some of the high-voltage power supplies. On at least one occasion, the current limiter of the post-acceleration (PAC) power supply was triggered from the background-induced load, causing a reset of high voltages. Reduced high voltages are currently being employed and the solid state detector bias is currently off (energy measurement for mass determination is off), in order to inhibit triggering another current-limiter. The background rates contribution from the outgassing is being tracked and is reducing in an exponential fashion, but with continued sporadic (but lowering in intensity – factor x10) outbursts. The background level in the solar wind direction has dropped by two orders of magnitude and the signal-to-noise level is sufficient for determining solar wind protons except during minutes to hours with the larger background outbursts. At present power supply voltages and background signal levels, the retrievable science measurements include solar wind proton bulk parameters (Np, V, Temperature, N/S) in the solar direction and Time-of-flight

(M/Q) measurements of suprathermals in the non-solar direction. Time-of-flight measurement capability in the solar direction await higher PAC values. As the background levels decrease, the PAC level will be gradually increased, further increasing the signal-to-noise ratio and resolving TOF (M/Q) measurements.

At the time of submission uncalibrated solar wind proton data are now available. The PLASTIC team is working on new calibrations corresponding to the new voltage settings. Currently, the upper E/Q value of the instrument has been reduced from 80 keV/e to 45 keV/e, which impacts the suprathermal E/Q range, but not the solar wind ion E/Q range. The disabling of the SSDs has alleviated the current draw on the post acceleration (PAC) power supply, as the SSD power supply resides on top of the PAC supply. This disables the energy measurement used for mass determination. Mass information is not needed for solar wind protons and alphas, but may impact other species. We expect PLASTIC to be able to support all research activities presented in this proposal.

SECCHI

All SECCHI instruments on *STEREO-A* are operating nominally. Since the last Senior Review (February 24, 2017) there have been six "Watchdog" resets on *STEREO-A* bringing the total to 23 (*STEREO-B*), 52 (*STEREO-A*) over the course of the mission. The resets are generated in the SECCHI Electronics Boxes (SEBs) and each causes a few hours of lost observing time. Overshoot in the EUVI quadrant selector on *STEREO-A* since 2011 has been corrected by occasionally adjusting the mechanism delay setting. The COR1-A temperatures are gradually rising but this is generally not affecting observations. In 2017, after tripping during a momentum dump, autonomy rule limits had to be raised for various temperatures to match the limits for STEREO-B. Yellow/red high limits had to be adjusted for the COR1 detector temperature, which is increasing by ~0.5° C per year due to gradually degradation of the thermal blanketing at the front of the spacecraft. The only effect seen in the instrument is a small increase in CCD bias, which is automatically corrected for in the image processing. There is no effect on the COR1 data quality. The yellow/red high limits have been adjusted several times over the course of the mission to appropriate values to warn of any sudden changes in temperature that might occur. The rate of temperature increase is too low to pose a risk to the instrument or degrade the COR1 data quality. The SECCHI operations team continues to monitor the temperatures across all telescopes.

S/WAVES

The S/WAVES instrument on *STEREO-A* continues to function nominally. 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 for instrument contingency. They are also used for flight software uploads. The engineering model of the complete S/WAVES instrument is also maintained at UMN should it be required for any future reason.

Ground System

In May 2019, the Mission Operations team deployed new command and control workstations for the *STEREO* MOC to transition to a new Intel x86 platform with the Solaris 11.3 operating system, which Oracle will support until 2034. This upgrade also included software modifications required by the new hardware and by a transition to the CCSDS SLE bluebook version 4 protocol, which is required by the DSN. These changes have been in production/use since June 2019 and have been performing reliably. The Mission Operations team will upgrade the planning and assessment workstations to the same platform in 2020. The workstation and software upgrades have removed the ground system aging as a risk, paving the way for many years of smooth and reliable operation.

The Mission Operations team continues to work closely with NASA planners to schedule contacts with DSN and ESA ground stations. Despite heavy contention for ground station time, *STEREO*'s flexibility has enabled the mission to return consistently an average of > 5 Gbits of science telemetry every day. The Mission Operations team has improved the efficiency of the MOC planning system for RF downlink rate stepping during DSN contacts. Stepping the RF downlink rate higher leverages the increased received signal strength above 25° elevation for DSN contacts, which helps maintain higher science telemetry return daily.

***STEREO* Science Center**
As described in the Data and Code Management section, the *STEREO* Science Center (SSC) is the focal point for archiving data from the *STEREO* mission. The SSC resides within the Solar Data Analysis Center (SDAC), which is a multi-mission Resident Archive fully capable of archiving all *STEREO* data for the foreseeable future.

Space Weather Beacon
STEREO produces a near real-time stream of Space Weather (SpWx) Beacon data used extensively in SpWx forecasting by the NOAA Space Weather Prediction Center and other SpWx prediction organizations worldwide. *STEREO-A* provides coronagraph images of CMEs and in situ solar wind and SEP data, as well as, in its current location, advance warning of active regions rotating onto the Earth-facing side of the Sun. In addition, the *STEREO-A* coronagraphs serve as a backup for the *SOHO*/LASCO coronagraphs: *STEREO* provides data both during regular gaps in the *SOHO* telemetry stream and would become highly important should LASCO fail for any reason before new coronagraphs are launched (such a launch is not expected until at least 2025).

V. Data and Code Management

Data Management
The *STEREO* Science Center (SSC) is the focal point for archiving *STEREO* data, and resides within the Solar Data Analysis Center (SDAC) at the NASA 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.

As described in the *STEREO* Project Data Management Plan (PDMP), the remote sensing and in situ data 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 (FITS) 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.

An updated PDMP has been submitted with this proposal. Plans are underway to produce Calibration and Measurement Algorithm Documents (CMADs) for all the *STEREO* instruments. We expect that all work on CMADs will be completed by the end of 2021, if not sooner. Production of CMADs will be subject to limitations associated with the departure of personnel from the team over the life of the mission and time constraints on key team members, especially in cases in which assistance is needed from foreign partners.

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

In addition to the data for the long term archive, the SSC and the instrument teams provide the data in various formats and quicklook products to also ease use of *STEREO* data by the scientific community, data centers, space weather forecasting agencies and the public. These many resources are summarized at the SSC website. 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. The PLASTIC site includes preliminary versions of the solar wind proton data files and suprathermal event lists that are updated nightly, 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 (CDPP) 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.

UCLA's *STEREO* server was taken off-line in 2019 due to a security vulnerability discovered by UCLA IT personnel. This outage has slowed release of the Level 2 MAG/PLASTIC merged data set. UCLA now has a compliant network connection that can used for the STEREO system, and the needed staff are now in place. It is expected that the UCLA server will be back on line in the next few months.

Code Management

The primary source for *STEREO* data analysis software is the SolarSoft Library, which is openly available under the BSD-2 software license. SolarSoft is a multi-mission library and public repository that supports a large number of NASA missions, including *SOHO, STEREO, SDO, PSP*, and *Solar Orbiter*. All SECCHI analysis software is available through SolarSoft. PLASTIC analysis software is distributed as ZIP files embedded in the PLASTIC tree of the SolarSoft library. S/WAVES provides a sample routine for reading and display S/WAVES data. The IMPACT analysis software is designed to be used with the TDAS/SPEDAS library. The IMPACT routines can be found at http://stereo.ssl.berkeley.edu/stereo_idl/, while the TDAS library can be found at http://themis.ssl.berkeley.edu/software.shtml. The IMPACT team is considering distributing these also as ZIP files in SolarSoft, as is done for PLASTIC.

VI. Budget

The budget tables for *STEREO-A* mission operations and data analysis are in Appendix B. The NASA civil service science labor includes fractional Co-Investigator FTEs for S/WAVES, SECCHI, and IMPACT, as well as the project scientist, her deputies and a resource analyst. The civil service labor under mission operations represents the Mission Director. Note that the civil service labor figures do not include employees of the Naval Research Laboratory, who are considered contractors for the purposes of this budget. The Mission Operations (MO) portion of the budget includes work by the Mission Operations Center at APL and mission operations oversight and other MO related activities at GSFC. Instrument activities are divided between Science Operations and Science Data Analysis. A 3% rate of inflation is assumed. Mission and Science Instrument Operations increase with inflation, reducing the science data analysis budget over time.

Access to NASA High End Computational Facilities. All *STEREO* team access to NASA High End Computational Facilities is done through model runs at the CCMC. We expect the need for such services will be at the level of about 50,000 SBU/year.

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VII. Appendices

Appendix A: Acronyms and Other Abbreviations

3DP	Wind/3-D Plasma and Energetic Particle Investigation
ACE	Advanced Composition Explorer
AdSpR	Advances in Space Research
AGU	American Geophysical Union
AIA	SDO/Atmospheric Imaging Assembly
ApJ	Astrophysical Journal
ApJL	Astrophysical Journal Letters
ApJS	Astrophysical Journal Supplement
APL	Johns Hopkins University Applied Physics Laboratory
AU	Astronomical Unit
BSD-2	Berkeley Software Distribution -2
C3	SOHO/LASCO Coronagraph-3
CCSDS	Consultative Committee for Space Data Systems
CCMC	Community Coordinated Modeling Center
CDAWeb	Coordinated Data Analysis Web
CDF	Common Data Format
CDPP	Centre de Données de la Physique des Plasmas
CIR	Co-rotating Interaction Region
CMAD	Calibration and Measurement Algorithm Documents
CME	Coronal Mass Ejection
Co-I	Co-Investigator
CH	Coronal Hole
COR1	SECCHI Inner Coronagraph
COR2	SECCHI Outer Coronagraph
COSPAR	Committee On SPAce Research
COVID-19	COrona VIrus Disease 2019
DH	Decameter-Hectometric
CR	Carrington Rotation
DSCOVR	Deep Space Climate Observatory
DKIST	Daniel K. Inouye Solar Telescope
DPU	Digital Processing Unit
DSN	Deep Space Network
EIT	SOHO/ExtremeUltraviolet Imaging Telescope
EOML	End of Mission Life Plan
EPACT	Wind/Energetic Particles: Acceleration, Composition and Transport
ESA	European Space Agency
ESP	Energetic Storm Particle
EUV	Extreme UltraViolet
EUVI	SECCHI Extreme UltraViolet Imager

FITS	Flexible Image Transport System
FTE	Full Time Equivalent
FY	Fiscal Year
GLE	Ground Level Enhancements
GOES	Geostationary Operational Environmental Satellite
GONG	Global Oscillation Network Group
GRL	Geophysical Research Letters
GSFC	Goddard Space Flight Center
HET	IMPACT High Energy Telescope
HI	SECCHI Heliospheric Imager
HMI	SDO/Helioseismic and Magnetic Imager
HSO	Heliophysics System Observatory
IBEX	Interstellar Boundary Explorer
IT	Information Technology
ICME	Interplanetary Coronal Mass Ejection
IDL	Interactive Data Language™
IMAP	Interstellar Mapping and Acceleration Probe
IMPACT	In-situ Measurements of Particles and CME Transients Investigation
IMU	Inertial Measurement Unit
ISES	International Space Environment Service
IS⊙IS/HET	PSP/Integrated Science Investigation of the Sun /High Energy Telescope
JASTP	Journal of Atmospheric and Solar-Terrestrial Physics
JHU/APL	Johns Hopkins University Applied Physics Laboratory
L1	First Lagrangian Point
L4	Fourth Lagrangian Point
L5	Fifth Lagrangian Point
LASCO	SOHO Large Angle and Spectrometric Coronagraph
LDGRF	Long Duration Gamma-ray Flares
LISM	Local Interstellar Medium
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
M/Q	Mass to Charge ratio
MSL	Mars Science Laboratory
NASA	National Aeronautics and Space Administration
NEAR	Near Earth Asteroid Rendezvous
NOAA	National Oceanic and Atmospheric Administration
NRL	Naval Research Laboratory
PAC	Post-acceleration
PAD	Pitch Angle Distribution
PAMELA	Payload for Antimatter/Matter Exploration and Light-nuclei Astrophysics
PDF	Portable Document Format
PDMP	Project Data Management Plan

PI	Principal Investigator
PFSS	Potential Field Source Surface
POC	Payload Operations Center
PSG	Prioritized Science Goal
PSP	Parker Solar Probe
PLASTIC	PLAsma and SupraThermal Ion Composition Investigation
PUI	Pickup Ion
PVO	Pioneer Venus Orbiter
RHESSI	Reuven Ramaty High Energy Solar Spectroscopic Imager
SBU	Standard Billing Units
SC	Solar Cycle
S/C	Space Craft
SDAC	Solar Data Analysis Center
SDO	Solar Dynamics Observatory
SECCHI	Sun Earth Connection Coronal and Heliospheric Investigation
SEP	Solar Energetic Particle
SEPT	IMPACT/Solar Electron and Proton Telescope
SEU	Single Event Upset
SHP	Solar and Heliophysics
SLE	Space Link Extension
SIR	Stream Interface Region
SIT	IMPACT Suprathermal Ion Telescope
SMD	Science Mission Directorate
SO	Solar Orbiter
SOHO	Solar and Heliospheric Observatory
SPASE	Space Physics Archive Search and Extract
SPD	Solar Physics Division of the American Astronomical Society
SPDF	NASA Space Physics Data Facility
SPEDAS	Space Physics Environment Data Analysis Software
SpWx	Space Weather
STA	STEREO-Ahead
STB	STEREO-Behind
SSC	STEREO Science Center
SSD	Silicon Semiconductor Device
SSMO	Space Science Mission Operations
STE-D	IMPACT Suprathermal Electron Telescope Downstream
STE-U	IMPACT Suprathermal Electron Telescope Upstream
STEREO	Solar TErrestrial RElations Observatory
SUVI	Solar Ultraviolet Imager
SWAP	Space Weather Action Plan
S/WAVES	STEREO Waves Investigation
SWEA	IMPACT Solar Wind Electron Analyzer
SWFO-L1	Space Weather Follow-On at L1
SWPC	NOAA's Space Weather Prediction Center
SWT	Science Working Team
TDAS	THEMIS Data Analysis Software

THEMIS	Time History of Events and Macroscale Interactions During Substorms
ToA	Time of Arrival
TRACE	Transition Region and Coronal Explorer
UCB	University of California, Berkeley
UCLA	University of California Los Angeles
UMN	University of Minnesota
UT	Universal Time
UNH	University of New Hampshire
VEX	Venus EXpress
Wind/WAVES	*Wind* Radio and Plasma Wave Investigation
WISPR	Wide-field Imager for Solar Probe
WSA	Wang-Sheely-Arge
WYE	Work Year Equivalent

STEREO instrument and instrument subsystem names are in green.

Appendix B: Budget Spread Sheets

Project Name: STEREO

I. FY21 - FY25 NASA Full-cost Guidelines:

	FY21 Budget ($k)	FY22 Budget ($k)	FY23 Budget ($k)	FY24 Budget ($k)	FY25 Budget ($k)
Total	7,800.0	7,800.0	7,800.0	7,800.0	7,800.0

II. FY21 - FY25 '4-way' Functional Breakdown:

	FY21 Budget ($k)	FY22 Budget ($k)	FY23 Budget ($k)	FY24 Budget ($k)	FY25 Budget ($k)
1. Development	0.0	0.0	0.0	0.0	0.0
2.a Space Communications Services	1.1	1.2	1.2	1.2	1.3
2.b Mission Services	2,277.6	2,325.9	2,395.6	2,467.0	2,541.8
2.c Other Mission Operations	174.2	179.5	184.8	190.4	196.1
3. Science Operations Functions (Total)	3,038.0	3,119.8	3,173.9	3,254.9	3,333.4
4.a Science Data Analysis (Total)	2,309.0	2,173.8	2,044.4	1,886.4	1,727.5
4.b Guest Observer Funding	0.0	0.0	0.0	0.0	0.0
4.c Guest Observer administration costs	0.0	0.0	0.0	0.0	0.0
Total*	7,800.0	7,800.0	7,800.0	7,800.0	7,800.0

*Totals for Table II should be identical to totals in Table I.

IIa. FY21-FY25 Labor breakdown:	FTEs/WYEs	FTEs/WYEs	FTEs/WYEs	FTEs/WYEs	FTEs/WYEs
1. Mission Operations (Total)	**7.2**	**7.2**	**7.2**	**7.2**	**7.2**
1.a CS Labor	0.3	0.3	0.3	0.3	0.3
1.b WYE (Contractor) Labor	6.9	6.9	6.9	6.9	6.9
2. Science Operations (Total)	**10.6**	**10.5**	**10.5**	**10.5**	**10.4**
2.a CS Labor	1.1	1.1	1.1	1.0	1.0
2.b WYE (Contractor) Labor	9.6	9.5	9.5	9.5	9.5
3 Science Data Analysis (Total)	**10.3**	**9.5**	**8.7**	**7.9**	**7.1**
3.a CS Labor	0.9	0.8	0.8	0.7	0.7
3.b WYE (Contractor) Labor	9.4	8.7	7.9	7.1	6.4
4 GO Grants Administration (Total)	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
4.a CS Labor	0.0	0.0	0.0	0.0	0.0
4.b WYE (Contractor) Labor	0.0	0.0	0.0	0.0	0.0

III. FY21 - FY25 Instrument team breakdown

	FY21 Budget ($k)	FY22 Budget ($k)	FY23 Budget ($k)	FY24 Budget ($k)	FY25 Budget ($k)
SECCHI	2,063.5	2,022.0	1,993.5	1,966.5	1,930.6
IMPACT	1,661.4	1,654.1	1,607.5	1,577.0	1,556.7
PLASTIC	600.0	595.0	590.0	580.0	570.0
S/WAVES	597.0	592.0	587.0	577.0	567.0
Stereo Science Center (SSC)	425.1	430.5	440.3	440.8	436.5
Mission Operations	2,453.0	2,506.5	2,581.7	2,658.6	2,739.2
Total**	7,800.0	7,800.0	7,800.0	7,800.0	7,800.0

**Totals for Table III should be identical to totals in Table I.

IV. FY21 - FY25 '4-way' Breakdown for in-Kind contributions:

	FY21 Budget ($k)	FY22 Budget ($k)	FY23 Budget ($k)	FY24 Budget ($k)	FY25 Budget ($k)
1. Development	0.0	0.0	0.0	0.0	0.0
2.a Space Communications Services	3,801.3	3,915.3	4,032.8	4,153.8	4,278.4
2.b Mission Services	0.0	0.0	0.0	0.0	0.0
2.c Other Mission Operations	122.2	126.3	130.3	134.9	139.5
3. Science Operations Functions	0.0	0.0	0.0	0.0	0.0
4.a Science Data Analysis	0.0	0.0	0.0	0.0	0.0
4.b Guest Observer Funding	0.0	0.0	0.0	0.0	0.0
Total	3,923.5	4,041.6	4,163.1	4,288.7	4,417.9

V. FY21-FY25 Use of NASA High-end Computational Facilities (estimate, in-kind):

	FY21	FY22	FY23	FY24	FY25
Estimated Standard Billing Units (SBUs)	50,000	50,000	50,000	50,000	50,000

Definitions of the Four-Way Work Breakdown for NASA Science MO&DA Flight Missions

It is not possible to create a general functional breakdown that can apply to the work-breakdown structures of every flight project. This is intended as a guide for the purpose of identifying funding activities. Projects may modify the breakdown below to fit the project's particular situation.

1. **Development:**

   Development or re-engineering of post-launch flight software and ground systems.

   For science data centers: development or re-engineering of new capabilities, software tools, technology enhancements, improved services, etc.

2. **Mission Operations: "Control Center", communications and management funtions including:**

   2a. Space Communications Services:

   Antenna operations for

   - Prepass and postpass tracking operations
   - Spacecraft commanding and telemetry tracking, including radiometric data
   - TDRSS support

   Telecommunication services such as the use of dedicated circuits (tail circuits) or the use of local area networks.

   2b. Mission Services (i.e. satellite control centers and navigation):

   Command generation and telemetry monitoring

   Health and performance monitoring of the spacecraft, instruments, and ground system

   Spacecraft trajectory or orbit, and attitude planning and determination

   Resource constraints analysis (spacecraft power, data storage, telemetry rates, TDRSS, DSN, etc.)

   Mission analysis and planning/scheduling activities

   2c. Other mission operations including:

   Project management and accounting functions

   Mission system engineering

3. **Science Operations functions (e.g. sequence generation, science planning & data processing and distribution including:**

   Science events planning, integration, and optimization

   Science and engineering activity integration

   Instrument and observation performance analysis

   Mission and/or science operations centers

   Services for guest observers/guest investigators

   Science data calibration/physical unit conversion

   Validation and certification of processed data

   Data products distribution to investigators for analysis

   Science teams products for science data processing

   Generation of quick-look and common pool data sets

   Standard data processing

   Science data archiving

   Multi-mission data centers

4a. Science Data Analysis: "Science" functions:

   Customized Data Processing

   Analysis activities

   Writing and editing documentation

   Presentation and publication of scientific results

4b. Guest Observer Funding

Instructions for the Budget Spreadsheet

Note: All budget figures should be in terms of NOA: New Obligation Authority for that fiscal year. Do not include any unobligated nor uncosted carryover budget figures.

I. FY21-FY25 NASA In-Guideline budget.

Replicate your NASA budget guideline supplied to you by the Program Officer. If the budget guideline is zero for a given FY, and you propose to conduct MO&DA activities in that FY, then fill in a 'minimum acceptable' budget value consistent with the instructions in the "Call for Proposals".

II. FY21-FY25 '4-way' functional breakdown:

Break down the project's budget by function.

The rows in Table II correspond to the "Five-Way Work Breakdown" described below.

Totals for Table II should be identical to totals in Table I.

IIa.FY21-FY25 Labor breakdown:

This is a breakdown of the labor used by the project. The breakdown is essentially for 4 items, broken out in 2 way each: CS labor and WYE (Contractor) labor. For the latter these would be at a university, FFRDC, contractor, or other U.S. government agency. The breakout for whether this labor is used for mission operations, science planning operations, science data analysis/processing, which includess upgrades to piplelinea and software tools, and GO grants administration, where applicable for a mission.

III. FY21-FY25 Instrument team breakdown:

Break down the HQ guideline budget by instrument team. Identify the instrument budget line with the instrument's name.

Other Science Teams - The entries for 'Other Science Teams' are for the participation of scientists and investigators who are funded out of your project's account, but not assigned to a specific instrument team.

Other mission expenses - this should account for all other project expenses such as management, mission operations, mission-wide science or data analysis centers, etc.

Totals for Table III should be identical to totals in Table I.

IV. FY21-FY25 '4-way' breakdown for In-Kind contribution:

Show the 'cost' attributions for employing NASA tracking services such as the DSN, Ground Network, or TDRSS and other support not included in the 'full cost' representation of your budget.

This would included support from the JPL AMMOS project and any GSFC/SSMO multimission support not directly charged to your project's account.

Do not include any costs that would paid out of project accounts; those should tallied in the other tables.

Representations of direct or in-kind funding from international partners or from other US Government agencies should not be provided.

V. FY21-FY25 Estimates of amount of NASA High-End Computataional Facility resources will be needed:

Appendix C: End of Mission Life Plan

370 May 15, 2020

TO: 300/Director, Safety & Mission Assurance Directorate

FROM: 370/Quality & Reliability Division/Viens

SUBJECT: Code 300 Evaluation of End of Mission Plan for STERO Mission

REF: a) NASA-STD-8719.14B, Process for Limiting Orbital Debris

b) Call for Proposals, Rev 2a — Senior Review 2020 of the Mission Operations and Data Analysis Program for the Heliophysics operating missions, Revision 2b: January 21, 2020; NASA HQ / N. Fox / Director, Heliophysics Division, NASA HQ / J. Leisner / Senior Review, Program Scientist, NASA HQ / W. Stabnow / Senior Review, Program Executive

The STEREO mission has demonstrated full compliance with NASA-STD-8719.14B by virtue of its orbit. The spacecraft is in, and will remain in, a heliocentric orbit, and is not expected to reenter or interfere with the GEO protected region for the foreseeable future. Meaningful very long-term orbit propagations (on the order of a century) are not practical due to uncertainties in the conditions at the time of disposal. Due to the orbit that STEREO is in, none of the requirements of NASA-STD 8719.14B are applicable to the mission.

As there are no planned changes in orbital configuration, no additional EOMP analysis is required. Further details are documented in the End of Mission Plan (7381-9043), available from the Johns Hopkins University Applied Physics Laboratory. Please feel free to contact me (301-286-2505), if you have any questions or concerns.

Michael Viens

Cc: 370/Nowak, Sticka, JIRA,
380/Maggio
300/Leitner
592/Hull
HQ-SMD/H. Futrell
SSMO/R. Burns

1

Appendix D: Decadal Survey Goals

NASA Science Mission Directorate Heliophysics Goals

From the NASA Science Plan (2014)

- Explore the physical processes in the space environment from the Sun to the Earth and throughout the solar system
- Advance our understanding of the connections that link the Sun, the Earth, planetary space environments, and the outer reaches of our solar system
- 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

Decadal Survey Goals

Key Science Goals (p. 3) and Solar and Heliospheric Science Panel Goals (p. 264) from the 2013 Decadal Survey, Solar and Space Physics: A Science for a Technological Society by Baker et al.

Key Science Goal 1. Determine the origins of the Sun's activity and predict the variations in the space environment.
Key Science Goal 2. Determine the dynamics and coupling of Earth's magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs.
Key Science Goal 3. Determine the interaction of the Sun with the solar system and the interstellar medium.
Key Science Goal 4. Discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe.

Solar and Heliospheric Physics Panel's Major Science Goals

SHP1. Determine how the Sun generates the quasi-cyclical variable magnetic field that extends throughout the heliosphere.
a. Measure and model the near-surface polar mass flows and magnetic fields that seed variations in the solar cycle.
b. Measure and model the deep mass flows in the convection zone and tachocline that are believed to drive the solar dynamo.
c. Determine the role of small-scale magnetic fields in driving global-scale irradiance variability and activity in the solar atmosphere.
SHP2. Determine how the Sun's magnetism creates its dynamic atmosphere.
a. Determine whether chromospheric dynamics is the origin of heat and mass fluxes into the corona and solar wind.
b. Determine how magnetic free energy is transmitted from the photosphere to the corona.
c. Discover how the thermal structure of the closed-field corona is determined.
d. Discover the origin of the solar wind's dynamics and structure.

SHP3. Determine how magnetic energy is stored and explosively released.
a. Determine how the sudden release of magnetic energy enables both flares and coronal mass ejections to accelerate particles to high energies efficiently.
b. Identify the locations and mechanisms that operate in impulsive solar energetic-particle sites, and determine whether particle acceleration plays a role in coronal heating.
c. Determine the origin and variability of suprathermal electrons, protons, and heavy ions on timescales of minutes to hours.
d. Develop advanced methods for forecasting and nowcasting of solar eruptive events and space weather.
SHP4. Discover how the Sun interacts with the local galactic medium and protects Earth.
a. Determine the spatial-temporal evolution of heliospheric boundaries and their interactions.
b. Discover where and how anomalous cosmic rays are accelerated.
c. Explore the properties of the heliopause and surrounding interstellar medium

Appendix E: STEREO Publication Record

STEREO refereed journal (not conference proceedings) plus masters and PhD theses rates through May 2020 can be found in Table E-1.

Calendar Year	Refereed Journals and Theses Only
2001-2006	15
2007	11
2008	56
2009	129
2010	121
2011	124
2012	167
2013	188
2014	174
2015	184
2016	173
2017	175
2018	159
2019	119
2020 (through mid-May)	76
Total	**1871**

Table E-1. STEREO refereed papers and theses.

Here, a "STEREO paper" is taken to mean any paper using STEREO data, concerning models or theoretical interpretations of STEREO measurements, or describing the mission and its instrumentation. Since the beginning of 2017 STEREO data have been used for twenty-seven theses (17 PhD, 10 Masters).

Bibliography. A reverse time-ordered stand-alone list of STEREO publications accessible on line. There is also a searchable STEREO publication database, but is not being updated at the time of submission because of COVID-19 related access issues. A list of refereed STEREO publications in the database of the NASA Astrophysics Data System (ADS), is available here. The ADS database does not include many of the theses and some of the more recent journal articles.