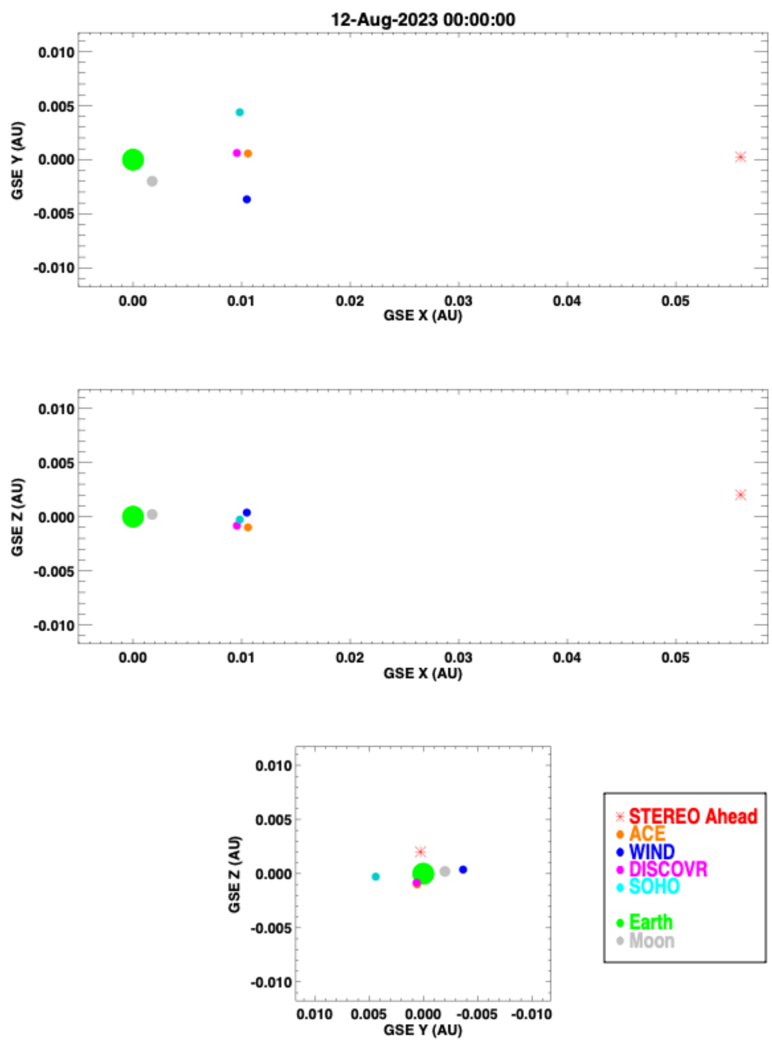
STEREO: Spending Solar Max Closer to Home
A Proposal to the Senior Review of Operating Missions
November 2022



The position of STEREO-A as is passes by the Sun-Earth Line in Aug 2023.

The top panel looks down on Earth's orbital plane with the Sun to the right. The Sun is to the left of this plot. The middle panel shows the elevation above or below the ecliptic plane. The last panel shows the view looking along the Earth-Sun line. This is the first time STEREO is on near-side of the Sun during solar maximum.

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I. Summary

The vantage point of the STEREO mission beyond the Sun-Earth line and its combination of in-situ and remote sensing instrumentation have 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 16 years and its unique place in the Heliophysics System Observatory (HSO), STEREO is prepared to continue its contributions to understanding the corona, solar wind, eruptive events, and space weather.

The two STEREO spacecraft, STEREO-A (STA) and STEREO-B (STB), were launched together in October of 2006 and inserted into heliospheric orbit. 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, with engineering sufficient to sustain an extended mission of up to five years' duration — which we have far exceeded. STB was lost in 2014 and the mission has continued since then with STA only, still providing a unique view of the Sun and Heliosphere. The primary science focus has been on the understanding of coronal mass ejections (CMEs), solar energetic particles (SEPs), and the solar wind, particularly 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 and alpha particles; 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.

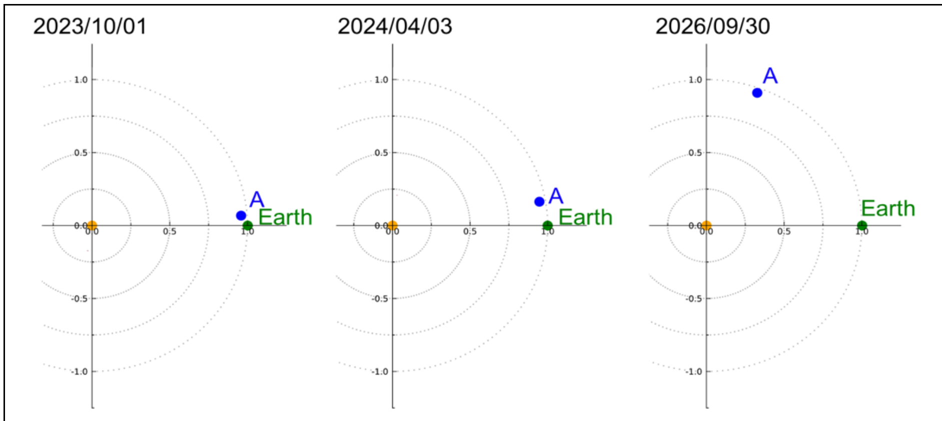

Fig. 1. The locations of STA over the proposal period. STA will go from near the Earth-Sun line through the Earth-Sun L4 point to a location 70 degrees from Earth. ***No other spacecraft provides this unique perspective on the Sun and heliosphere.***

Over the three-year period covered by this proposal, STA will cross the Sun-Earth line in Aug. 2023 and then move through the L4 Lagrangian point ahead of Earth, reaching a separation of 70° by Sept. 2026 (see Fig. 1). The near-Earth encounter provides opportunities for exciting new science involving collaborative observations of solar activity (e.g., CMEs, SEPs) with L1 spacecraft. The only other time STEREO was this close to Earth was shortly after launch, when the Sun was in a very deep minimum, providing little activity for study. In contrast, the next three years are near solar maximum, when the Sun should be significantly more active. Furthermore, the new missions Parker Solar Probe (PSP) and Solar Orbiter (SolO) will enhance still further the possibilities for research based on multi-point observations that can be done in conjunction with STEREO.

STEREO data and data analysis software are freely available at the STEREO Science Center and instrument team websites and used by scientists the world over, resulting in over 2,370 STEREO based theses and publications in the refereed literature.

Excellent progress has been made on the objectives we set in the last senior review proposal. These fell in three major groups (see Sec II.A): the structure and magnetic morphology of CMEs, active regions, and the solar wind as revealed by multi-point measurements; applying STEREO observations toward evaluating off-L1 location for space weather research; and understanding the effects of solar cycle variations on the corona and heliosphere. The team produced much important work on these topics.

Over the next senior review period the STEREO team proposes to pursue a series of objectives enabled by STA's unique location in the heliosphere combined with the upcoming solar maximum (Sec. II.B). The only previous time when STEREO was close to the Earth-Sun line was during a deep solar minimum. Now STA returns to the neighborhood of Earth as we approach solar maximum, enabling studies of solar transients by observatories with relatively close azimuthal separations that were not possible before. **Our sixteen-year database also makes possible important studies** of the evolution of the solar dipolar field and how that affects the heliosphere, along with studies of variations in solar wind features between and over solar cycles.

As is clear from our science objectives, STA's place in HSO is singular and vital (Sec. II.C). It is a key part of collaborative science being done to study the Sun and Heliosphere in conjunction with many different missions near Earth and L1 and throughout the solar system. This includes relatively recent missions like PSP and SolO and also upcoming missions like IMAP, PUNCH, and SunRISE.

In Section III we describe technical status of the mission, including status of the spacecraft, instruments and mission operations, and data and code management. Section IV presents responses to the findings of the 2020 Senior Review Panel. In Section V we describe our proposed overguide to produce multi-spacecraft machine learning data sets featuring STEREO/SECCHI remote sensing data. Section VI discusses mission management and the proposed budget.

The following individuals served on the STEREO Senior Review Working Group: J. Luhmann, Y. Li, C. Lee, J. Carlos Martinez (UCB), C. Cohen (Caltech), N. Lugaz, A. Galvin, (UNH), H. Wei (UCLA), B. Wood, P. Hess (NRL) C. Braga, O. Dudley, A. Vourlidas, D. Wilson (JHU/APL), W. Thompson (Adnet), M. Desai (SWRI), C. Cattell (U. Minn), S. Jones (CUA), G. de Nolfo, L. Jian, N. Gopalswamy, T. Kucera (GSFC). Numerous members of the Principal Investigator (PI) teams submitted early drafts.

II. Science and Science Implementation

A. Previous Science Objectives: Progress

In our last Senior Review Proposal, the STEREO team set itself nine objectives in three categories:
A. The Structure and Magnetic Morphology of CMEs, Active Regions, and the Solar Wind as Revealed by Multi-point Measurements
B. Applying STEREO Observations Toward Evaluating Off-L1 Location Space Weather Research
C. Understanding the Effects of Solar Cycle Variations on the Corona and Heliosphere.

As we show below, the team was able to make significant progress across the objectives despite the hurdles presented by the continuing COVID-19 pandemic and the relatively short turnaround of the senior review process. Although most of the works we are highlighting have STEREO team members as first authors, we are also including ones in which STEREO authors played important roles as co-authors. Such work supporting other community members or early-career scientists is absolutely essential for the scientific research done in Heliophysics and is especially critical for the sorts of multi-spacecraft studies in which STEREO team members are often involved.

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

Objective Summary: Investigations of the 3D morphology of pre-eruptive structures in active regions are needed to better understand the processes that lead to solar flares and CMEs. STEREO was explicitly designed to exploit the stereoscopic capability enabled only by closely-spaced (5°-15°) EUV imaging. The resulting 3D reconstructions reveal the coronal magnetic field configurations of structures observed to erupt. We are then able to assess whether the stereoscopic EUV observations can discriminate between sheared and twisted morphologies, thus elucidating a long-standing issue in CME eruption theories (*e.g.*, Patsourakos et al., 2020).

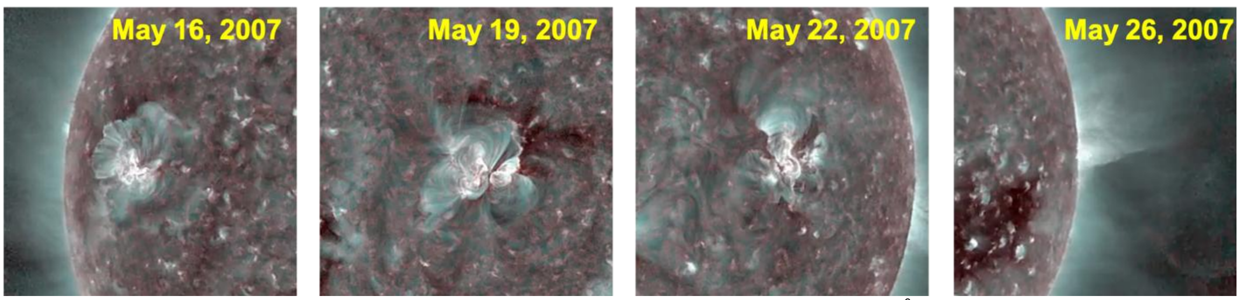

Fig. 2. Snapshots of the eruptions from AR 10956 in 195 (silver) /304 (red) Å channel composites from EUVI-A images as it rotates across the solar disk. Understanding the 3D morphology of such active regions is required to better understand eruptive events.

Progress: In 2021, we revisited the stereoscopic observations acquired in May – August 2007, which is the optimal period in the STEREO imaging data for stereoscopy, and identified isolated active regions with evidence of sheared magnetic field arcades or magnetic flux rope proxies (e.g., S-shaped hot loops). The regions had to be observed over a significant part of their passage across the visible disk (visible by both STA and STB), including their eruption. We identified two excellent candidates for analysis, AR 10953 (04/23 – 05/08) and AR10956 (05/13-23), that give rise to multiple eruptions as they cross the disk (See Fig. 2). This allows multiple views of their coronal morphology against an otherwise quiet coronal background. We compared Non-Linear Force-Free (NLFF) extrapolations of photospheric magnetic field observations from SOHO MDI directly with the stereoscopic observations to find out if the erupted structures were captured by those extrapolations.

This work serves as the steppingstone for extending the stereoscopic methodology to STA/EUVI and SDO/AIA pairs (for the 171 and 304 Å channels, initially) as STA is approaching Earth resulting in optimal configurations between December 2022 and June 2023. Further development of image processing and other necessary software is required for stereoscopy between STA/EUVI and Solar Orbiter/EUI because of the large difference in heliocentric distances between the two spacecraft. Although we have started planning for this activity under this objective, the actual effort will take place in the next mission extension phase to allow for collection of sufficient data and the completion of the in-flight calibrations of the EUI data products.

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

Objective Summary: In the last few years we have had the opportunity to study CMEs and the solar wind (including CIRs and SIRs) as they propagate away from the Sun, utilizing the unprecedented combination of new observations from STA, PSP, and other spacecraft. This allows us to obtain important new information about their structure and evolution.

Progress: With STEREO/SECCHI's ability to continuously image structures from the solar surface to 1 AU, combined with PSP/WISPR's ability to image CMEs near the Sun, a recent focus has been the study of events well observed by both STA and PSP/WISPR (Braga & Vourlidas 2021; Liewer et al. 2021; Wood et al. 2021). Of particular note is an event from 2019 April 2, with the PSP/WISPR-I images offering the opportunity to model the internal field structure of the event. STEREO provided crucial contextual information about the event, given that WISPR-I only saw it for about 6 hours while STA tracked it continuously over 4 days from the Sun to 1 AU (Wood et al. 2021). The STA images showed the presence of fast wind following the slow CME, resulting in a pile-up of material behind the flux rope ejecta, seen most clearly in STEREO/HI images far from the Sun. This interaction might be responsible for the time-dependent appearance of the CME's internal structure seen by PSP/WISPR.

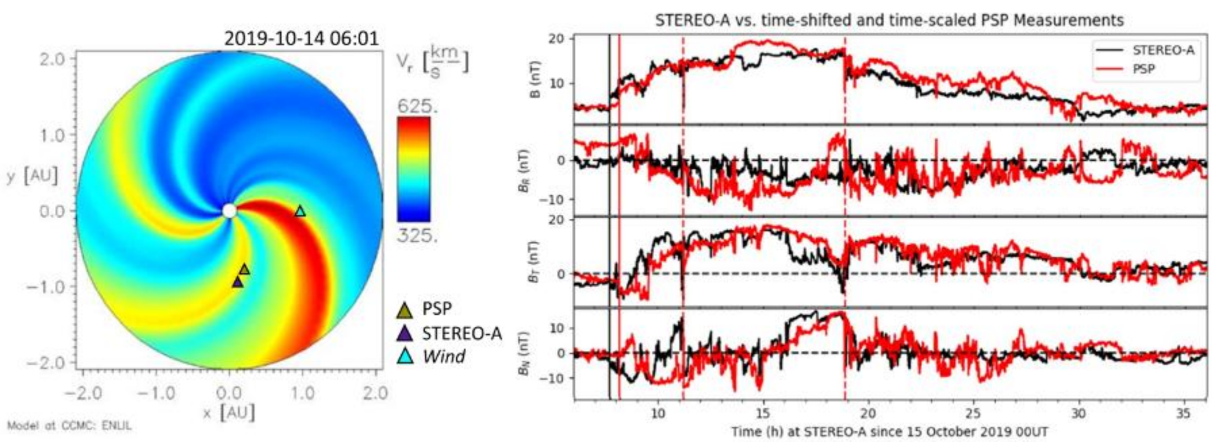

Fig. 3. Left: a WSA-ENLIL model of the inner heliosphere for 2019 October 14, indicating the relative positions of PSP and STA (0.15 AU apart radially). Right: a comparison of the in-situ measurements of a CME observed by STA (black) and PSP (red). The panels show, from top to bottom, the magnetic field strength, the radial (B_R), tangential (B_T) and normal (B_N) components of the field. The PSP data are scaled and shifted for time only to obtain the same duration of the event between the two dashed vertical red lines. The shock-like discontinuity at PSP is marked by the red vertical solid line, while the shock at STA is marked by the black vertical solid line. ***The combination of the data from the two spacecraft allowed us to determine that the structure of the CME was largely maintained from PSP to STA.*** *Winslow et al. (2021a).*

Cases where the inner heliosphere spacecraft line up radially with STA offered opportunities for the in-situ instruments on the spacecraft to study how CME plasma and magnetic field properties evolve. The first event observed in this manner by PSP and STA was reported by Winslow et al. (2021a). The encounter geometry is shown explicitly in the left panel of Fig. 3. A high-speed wind stream is compressing the CME flux rope from behind, leading to a speed profile that increases from front to back, in contrast to the decrease that is usually observed for expanding CMEs. As a consequence of the compression, the encounter time at STA is shorter than at PSP. However, despite the compression, the field structure of the CME is largely maintained, as shown in the right panel of Fig. 3. This consistency provides evidence in support of current approaches to space weather forecasting.

However, another CME studied by Winslow et al. (2021b) suggests that interactions with high-speed streams can result in significant alteration of CME internal structure, albeit over longer distances. Winslow et al. (2021b) studied two CMEs from 2013 observed by MESSENGER near Mercury that later encountered spacecraft at 1 AU, including STB. One event showed little change in internal structure between Mercury and ACE, but the one that hit STB did show significant alteration. A plausible interpretation is that a stream interaction region (SIR) between Mercury and 1 AU affected the CME structure.

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

Objective Summary: Multipoint measurements of CMEs and other heliospheric transients constrain our understanding of their 3D magnetic structure, informing us about their coronal connections, their propagation through the structured solar wind, and their potential space weather impacts. Such information also provides critical testing/validation of heliospheric models.

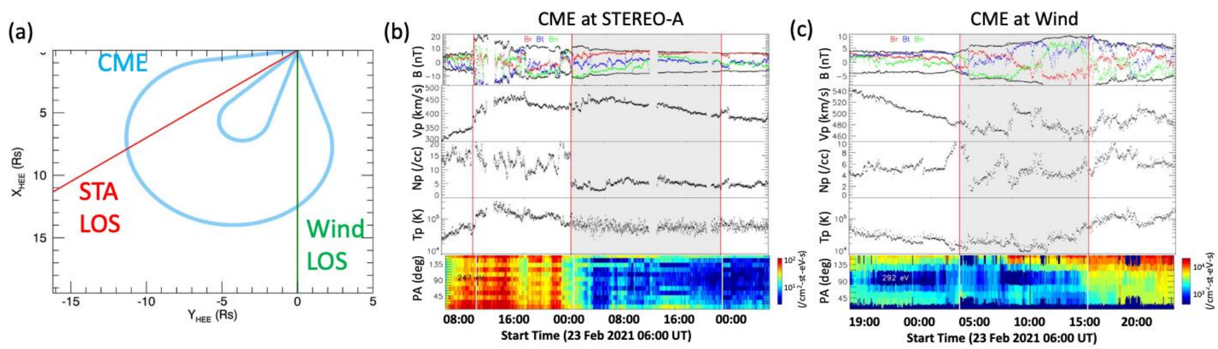

Fig. 4. (a) A reconstructed flux rope shape of a CME that erupted on 2021 February 20, which hit both STA (line of sight (LOS) shown by red line) and Wind near Earth (green line), separated by 55° (Lugaz et al 2022). In situ plasma and field measurements observed at these two locations are shown in panels (b) and (c), respectively. The panels show, from top to bottom, the three magnetic field components and the total field; the proton velocity, density, and temperature; and, finally, the pitch-angle distribution of suprathermal electrons at about 250 eV. The vertical lines show the shock (at STA), and the start and end times of the ME (at both spacecraft), which is also highlighted in gray. While the measurements at the two spacecraft have clear differences (presence of shock, CME expansion), ***analysis of LASCO and STEREO data revealed this is indeed the same CME, making this the widest confirmed multi-spacecraft CME ejecta measurement.***

Progress: As solar activity increases and STA moves closer to L1, we have the opportunity to observe the same transient with multiple spacecraft, to an extent greater than was possible when STEREO was launched during a deep solar minimum. Such proximate measurements are one of the best ways to determine the magnetic morphology of transients.

The first such CME observed during this recent time period was analyzed by Lugaz et al (2022). It erupted on 2021 February 20 and impacted both STA and Wind spacecraft, as shown explicitly in Fig. 4(a). The spacecraft were separated longitudinally by 55°, making this one of the widest multi-spacecraft magnetic ejecta (ME) detections ever reported. At STA, the measurements (see Fig. 4(b)) indicate the passage of a moderately fast (∼425 km/s) shock-driving ME, occurring 2–3 days after the end of a high-speed stream (HSS). At Wind (see Fig. 4(c)), the measurements show a faster (∼490 km/s) and much shorter ME, not preceded by a shock nor a sheath, and occurring inside the back portion of the HSS. The ME orientation measured at both spacecraft is consistent with a passage close to the legs of a curved flux rope. We expect many more proximate simultaneous multi-spacecraft measurements of ICMEs from 2022 to 2024 and extending into 2025 (with a maximum separation of 51°), *i.e.*, covering most of the solar maximum of solar cycle 25. These will provide a better understanding of the internal 3D structure of ICMEs and the time evolution of their structures and will provide constraints to models.

Using STA and SOHO quasi-quadrature measurements, Xie et al. (2021) performed a comprehensive statistical analysis comparing flux rope (FR) structures near the Sun and at 1 AU, to understand the physical connection of magnetic flux ropes among CME source regions, CMEs in the extended corona, and magnetic clouds (MCs) near Earth. The team confirmed that the hemispheric helicity rule held true for ~87% of their selected CMEs. For the 13 events that did not follow this rule, the FR axis directions and helicity signs could be inferred from SXT and EUV signatures as well as magnetogram data in the underlying source regions. Around 25% of the events had an axial rotation greater than 40º. In 56% of these rotation events, the FR rotation occurred during the early eruption or within the STEREO COR2 FOV, which could be predicted from the CME-FR tilt angles obtained from FR forward fitting models. In addition, Xie et al. (2021) found that for ~89% of the 19 "stealth" CMEs, they could use coronal neutral line locations and tilts to predict the FR helicity and its axial direction near Earth. These results improve our understanding of the magnetic structures of CMEs in the heliosphere.

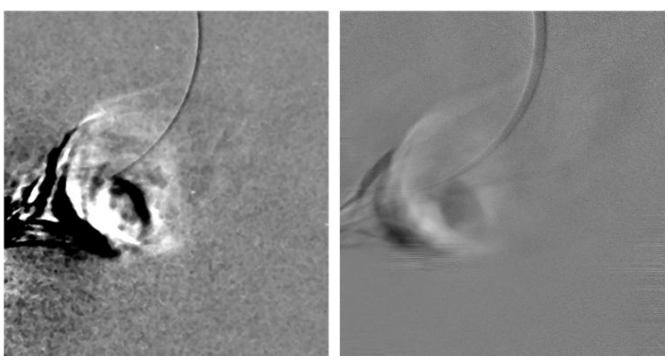

Fig. 5. Our team's new method of analyzing data from the Heliospheric Imagers by removing the dust contribution from the images. The dust contribution has dominated all HI observations since the beginning of the mission. Images are HI1-A data from 2021-Nov.20. Left: Earlier running-difference technique, Right: Image processed with new dust removal technique. ***The application of these new techniques results in a CME Time-of-Arrival (ToA) error reduction and allows us to study internal CME structure.***

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

Objective Summary: Over the period of the previous extended mission, STA was located close to 60° eastward of L1, and provided observations of multiple Earth-directed CMEs. These observations were used to validate and test models for forecasting Time-of-Arrival, Speed-on-Arrival (SoA) and magnetic field configuration of CMEs.

Progress: The team addressed the objective in two ways: (i) improving the image quality of the HI observations to increase the accuracy of CME tracking into the inner heliosphere and (ii) testing time-of-arrival forecasting methods with observations. We made significant improvements on the HI-1 images via a new methodology to remove the background emission from interplanetary dust (see Fig. 5). Braga et al. (2020) used the improved images to forecast the CME Time-of-Arrival and found lower errors than previous studies. The mean absolute error found was 6.9±3.9 h when compared to 9.8±2.0 h, which is the average among multiple previous studies reviewed by Vourlidas et al. (2017). Currently we are processing the full HI-1 A and B image database with the new background algorithm. The improved HI-1 data set will be made available to the public via the STEREO science center and the APL site by the end of CY2022.

Paouris et al. (2022) presented a data-assimilation prediction of CME's Time-of-Arrival using only observations from heliospheric imager and empirical methods. They found an average mean absolute error of 6.4 ±1.9 hours for the CME Time-of-Arrival among a set of events with 21 cases, one of the lowest to date. Among the CMEs, the authors found that events from a vantage point close to L5 had smaller errors than the remaining events. The results suggest that the proximity to L5/L4 is ideal for forecasting CMEs. This was also concluded by Palmerio et al. (2022a) in a multi-point observation and modeling study with significant STEREO team participation.

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

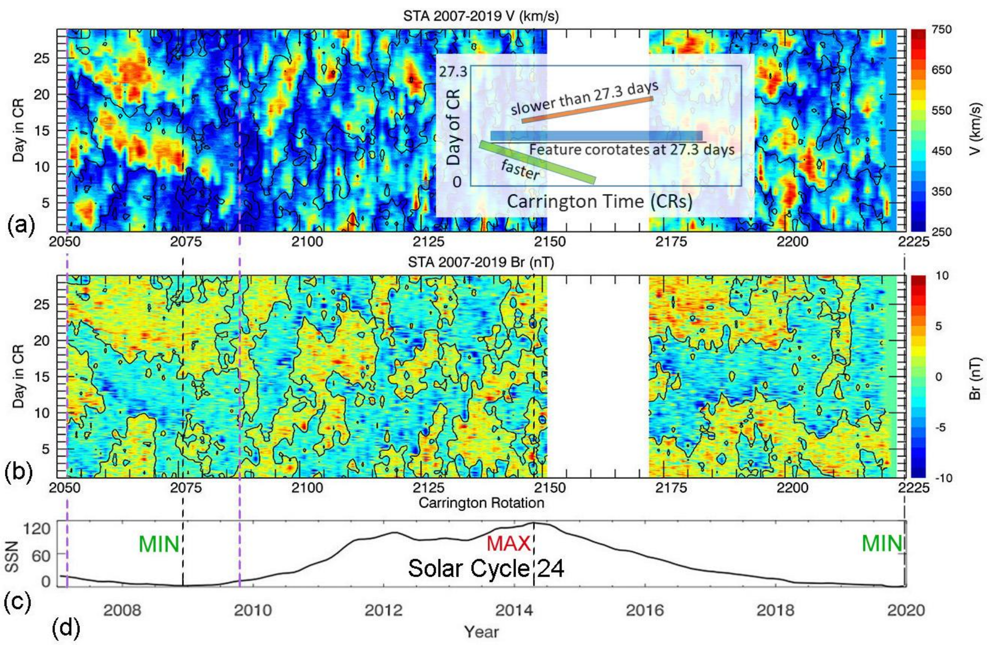

Fig. 6. A synoptic display of (a) solar wind speed and (b) radial magnetic field measured by PLASTIC and IMPACT, respectively, on STA throughout solar cycle 24. The plot is constructed by horizontally stacking strips representing successive 27.3-day solar rotations (the rotation number is along the bottom axis). Adapted from Li et al (2021). ***The downward-sloped structures indicate that features do not corotate but can return at a faster rate than the nominal Carrington period.***

Objective Summary: The extent to which the solar wind structure corotates with the Sun is of interest from both physics and forecasting perspectives. From a forecasting perspective, the question is whether the concept can be operationally useful, e.g., to using observations at L5 to predict what solar wind conditions are expected at Earth several days later. From a physics perspective, it relates to the evolution of coronal holes, and the extent to which streamers and transients contribute to the solar wind during the different phases of the solar cycle and during different cycles.

Progress: To make progress answering these questions, Li et al. (2021) examined the large-scale structure of the solar wind observed by STA IMPACT and PLASTIC for the years 2007 to 2019. As expected, the study found orderly recurrent stream structure during low solar activity, and more complex stream structure during high solar activity. However, the study also found that in the declining phase (2016-2019), after the STA solar conjunction data gap, the solar wind streams continued to show complex structure, although the magnetic field had returned to the simpler sector structure that characterized the earlier solar minimum phase.

The combined synoptic plots (See Fig. 6) and PFSS source mappings reveal that the concept of corotating solar wind streams is more complicated than that of a long-lived source that returns every Carrington Rotation (27.3 day) period. The most prominent high-speed streams (red contours in panel a) in the beginning of the observations exist for periods longer than most individual coronal hole lifetimes, and have downward slopes that indicate they returned at a faster rate than the nominal Carrington period. According to the model mapping, the source(s) of these high-speed streams include polar coronal hole extensions, while the more complex declining phase streams are still rooted in the low latitudes that had prevailed through the solar maximum. The implication for forecasting is that reappearance rates for CIRs are not necessarily at the nominal Carrington Rotation cadence. Rather, as shown by these STA data, cycle trends and source changes need to be taken into account.

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?

Objective Summary: Multipoint observations enabled with the STEREO mission are invaluable resources for piecing together the different processes responsible for accelerating particles to high energies, and where these processes occur.

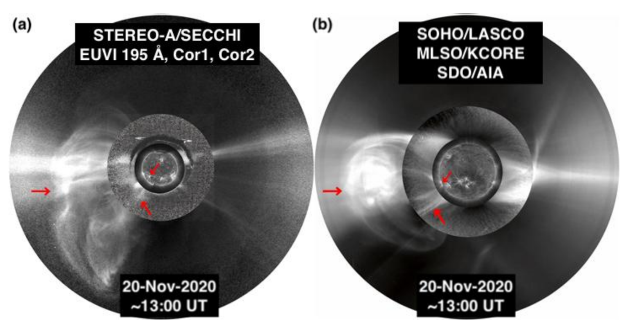

Fig. 7. Source locations and structures of one of the CMEs analyzed by Nieves-Chinchilla et al. (2022). (a) EUVI and Coronagraph data from STEREO. (b) Data from SDO, MLSO, and SOHO, all at Earth or along the Sun-Earth line. Red arrows in EUV images show the source locations, while in the Coronagraph images they show the CMEs. ***This combination of multiple points of view makes possible the extensive understanding of the geometry of these eruptions.***

Progress: The launch of STEREO in 2006 ushered in a new era of routinely studying SEP events from multiple vantage points. Such opportunities have grown with recently launched additional spacecraft (e.g., PSP, SolO), and STEREO's position at 1 AU, but separated from Earth, continues to be invaluable in these studies. A prime example is the study of SEP events on 29 November 2020 by Nieves-Chinchilla et al. (2022) in which data from multiple observatories, including STEREO (with SECCHI (see Fig. 7), IMPACT, PLASTIC and S/WAVES), PSP, GOES, MLSO and SoHO, combined with multiple models and techniques were used to extensively model two interacting CMEs and their associated shocks as they moved outward from the Sun. The second of these CMEs drove the first widespread solar energetic particle event of solar cycle 25. They measured type III bursts, a signature of accelerated electrons, associated with the interactions of the shock of CME2 with the leg of CME1.

STEREO co-authors also provided analysis of STA observations that were critical to multi-observatory studies headed by other authors. Such work with STA data was key to evaluating two possible scenarios for explaining the longitudinal extent of the 29 November 2020 event (Kollhoff et al., 2021). Additionally, the STEREO heavy ion analysis of the same event revealed that despite the exceptional width of the event, the composition and spectra were fairly typical of shock-accelerated events (Mason et al., 2021). While such studies often highlight the new mission observations, it is the significant analysis efforts and contributions made by the STEREO co-authors that make the high-impact results possible.

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?

Objective Summary: Investigation of solar cycle variations in transients is important for long-term mission planning, the understanding of solar dynamo and the magnetic flux evolution, and the space-terrestrial climate relation. Since early 2007, STA has conducted nearly continuous solar and solar wind monitoring for 15 years except for about one-year around the far-side super solar conjunction. This provides a critical vantage point to compare with the near-Earth solar and solar wind observations.

Progress: The STEREO team conducted a survey of all CMEs measured by STEREO from launch to 2016 with a focus on the difference in morphology between CME with shocks/sheaths and without shocks/sheaths (Salman et al., 2020b) and the different properties of the sheath regions of CMEs (Salman et al., 2021 and related PhD thesis 2021). This has shown that the magnetic field of the ejecta is a key parameter in determining the properties of the sheath regions, which are important to their space weather impacts. Statistical work based on the fifteen years of STEREO data also resulted in comprehensive evaluation of the expansion of CMEs (Al-Haddad et al., 2022). Additional work involved the creation of a database of about 50 events measured by two or more spacecraft (Salman et al., 2020a), which includes about 30 events measured by STEREO. We also investigated how these measurements can give information about the force-free nature of magnetic ejecta (Lugaz et al., 2020) and the change in orientation and magnetic complexity of CMEs as they propagate (Scolini et al., 2022). The same team members are currently investigating events from the rising phase of solar cycle 25 (2020-2022, see Lugaz et al., 2022) to further address this objective.

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

Objective Summary: Improving our ability to measure and model the solar corona is key to better understand its variation over the course of the solar cycle with the ultimate goal of improving models of the solar wind. To that end, the STEREO team has developed methods for comparing coronal observations with models using tomographic electron density reconstructions and multi-viewpoint EUV imaging.

Progress: Previous work by the team demonstrated that it was possible to use coronal rotation tomography of COR1 coronagraph images to reconstruct the coronal electron density (Wang et al. 2017). This density should be highest in regions well-confined by over-lying closed magnetic field, where the plasma is tightly confined, i.e., near the global magnetic neutral line separating regions of inward- and outward-directed magnetic field. Jones et al. (2022) developed a method for quantitatively comparing the location of the magnetic neutral line in coronal magnetic field models with local peaks in these coronal electron density reconstructions (Fig. 8). We demonstrated the application of this method to a Carrington

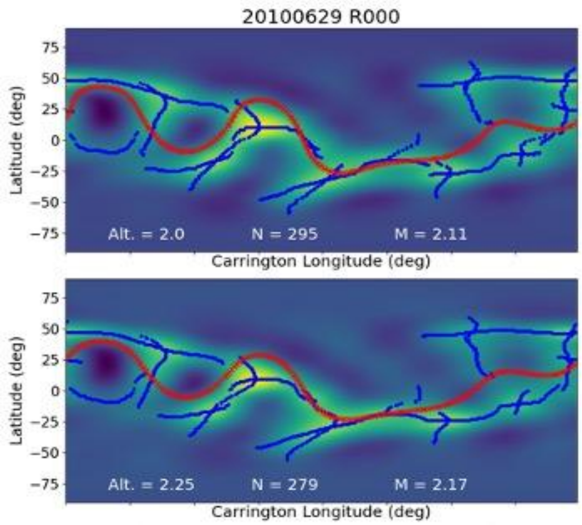

Fig. 8. Projection map of the coronal electron density around the entire Sun at different altitudes (color scale) based on STEREO/COR1 data. The blue lines show the derived location of magnetic neutral lines, and the red lines show a model magnetic neutral line. ***These comparesons can be used to select coronal models with more accurate magnetic neutral lines, resulting in more accurate prediction of the interplanetary magnetic field.***

rotation in which rapid, unobserved photospheric evolution on the far side of the Sun made coronal modeling particularly difficult. This method is important for accurately modeling the connection between the Sun and solar wind – essential for both basic research and space weather prediction.

Meanwhile, the work by Li et al. (2021) and Luhmann et al. (2022) emphasized the solar cycle changes in solar wind large scale structure, and its coronal connections (see Obj. B2). We postulate that the solar dipole field has begun to dominate, causing the heliospheric magnetic field to again approach a two-sector structure, but multiple solar wind streams contribute to the same magnetic polarity sector at this time. We further investigated this hypothesis by applying PFSS models to solar wind source mapping (Luhmann et al., 2022) for this period of observations, and found that the latitude distribution of the sources that map into the equator of the source surface is indeed different in the rising and declining phases.

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

Objective Summary: The aim of this objective is to study the behavior of candidate suprathermal seed populations as a function of solar cycle and longitude and to determine if these characteristics are manifested in solar energetic particles accelerated by CME-driven shocks using ACE and STEREO data.

Progress: The team studied energetic storm particle (ESP) heavy ion peak intensities relative to CME solar sources by examining the dependence of ESP heavy ion (He, O and Fe) peak intensities and energy spectra (~0.1 -1 MeV/nucleon) on the longitude of the observing spacecraft relative to the solar source of their associated CME, and the near-Sun CME speed. This study targeted ~90 ESP events observed in Solar Cycle 24 at the STA, STB, and/or ACE spacecraft. The key results are summarized as follows: ESP events driven by high-speed CMEs (> ~1300 km/s) show a more organized helio-longitudinal distribution in both the peak intensities and spectra. In particular, these events (1) are observed at a wider range of longitudes, (2) show, in general, larger heavy ion peak intensities near the nose of the shock and smaller peak intensities along the flanks and (3) have spectral indices that are smaller (harder) near the shock nose and larger (softer) near the flank. ESP events driven by slower CMEs (< ~1300 km/s) do not show such organization. A graduate student in the UTSA-SwRI space physics graduate program is leading this study, advised by STEREO team members and has one paper published in the Astrophysical Journal (Santa Fe-Duenas et al., 2022), and another in preparation.

In addition to energized SEP populations, we also investigated the energization of thermal and suprathermal electron populations using data collected by S/WAVES, IMPACT, and PLASTIC to study the role of whistler-mode waves in scattering and energization of solar wind electrons, finding that whistler waves interact strongly with strahl-energy electrons and may also heat core electrons (Cattell et al. 2020). Using particle tracing codes to model the interaction of solar wind electrons with whistler-mode waves, Cattell and Vo (2021) showed that the packet structure of the whistlers had a significant effect on the interactions.

B. Proposed Extended Mission Science Objectives

Our objectives for the next extension of the STEREO mission are divided into four themes, which leverage both STEREO's singular place in the HSO and the longevity of our data sets. STA is currently approaching the Earth's longitude and will cross the Earth-Sun line in August 2023 (Fig. 1), continuing on to 70° ahead of the Earth during the following three years covered by this proposal (Fig. 1). This provides unique, first-time opportunities for joint observations with Earth- and L1-based observatories at small longitudinal separations during solar maximum. The STEREO data, combined with those of the continuing PSP and SolO missions, allow us to further explore transient phenomena in the heliosphere. We also propose to continue our interest in space weather and take advantage of the wealth of our mission-long data for long-term solar corona, solar wind and solar energetic particle studies.

Research Theme A (RT-A): Leveraging the Inferior Conjunction of STA to Uncover the Multi-scale Nature of the Heliosphere at Solar Maximum

Motivation: Decades of remote and in-situ measurements of the solar wind led to a greater understanding of structures at the opposite ends of spatial/temporal scales (i.e., coronal holes and streams to energy cascade through turbulence). We know little about the intermediate scales, aka mesoscales (5-10,000 Mm; 10s - 7h), that result from the mixture of the solar wind plasma evolution in-transit and the solar driving (Viall et al. 2020). Yet, structures at these scales participate in driving the magnetosphere, determining

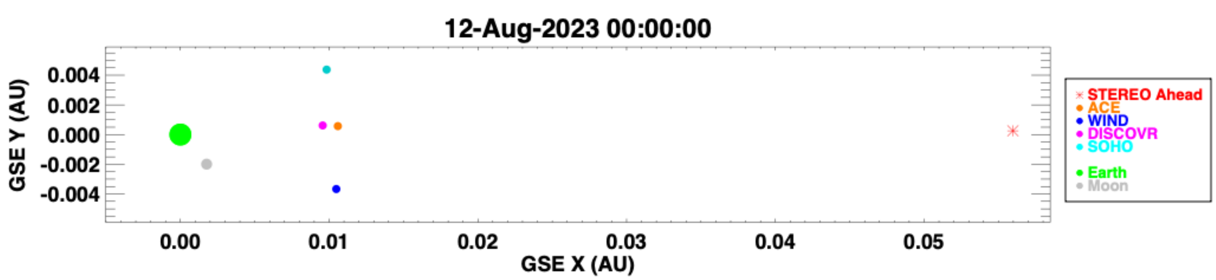

Fig. 9. View down on the orbital plane near the time of STEREO-A's pass through the Sun-Earth line. The Sun is towards the right. ***This time period will allow studies of the heliosphere on unique scales.***

the local magnetic geometry of CMEs and modulating SEP intensities, all key issues in fundamental heliophysics and Space Weather research. Our poor understanding of mesoscales results from the sparseness of in-situ measurements at these scales, together with the limited information about the responsible solar conditions. STEREO's attempt to address this knowledge gap during the early part of the mission (2007-2008) coincided with one of the weakest solar minima on record resulting in a small event sample of CMEs, SEPs, and shocks.

Approach: STA's inferior conjunction with Earth during the SC25 solar maximum (2023-2025) offers an excellent opportunity to attack this problem (Fig. 9). The STEREO instrument teams, operating as a unified Science team, will leverage the existing assets of the HSO at L1, cislunar space, and low Earth orbits to study the mesoscale properties of solar transients from loops to jets to CMEs, from the corona to their in-situ manifestations at 1 AU.

RT-A1: What is the multi-scale radial and longitudinal structure of CMEs, shocks and SEPs?

Over the next few years STA will approach and cross the Sun-Earth line at around 7 million km upstream of L1 and continue onwards at a rate of 22°/year all during solar maximum. This provides opportunities to explore the *mesoscale* (~1-30°) *longitudinal* structure of Earth-bound transients and also *fine-scale radial variations* by comparing data from STA to L1 probes (e.g., Wind, ACE, DSCOVR) and to observatories on or orbiting Earth. The STEREO team has begun identifying optimal events for study (e.g., 11/4/2021, 04/14/2022) leveraging the wide range of expertise available to our combined instrument teams.

The co-temporal in-situ measurements from the radially aligned STA and L1 spacecraft enable the investigation of the effects of magnetic reconnection (erosion) and pileup on the CME/shock dynamics and, by extension, on their geoeffectiveness. We will analyze magnetic field, plasma, and suprathermal electron data and combine them with imaging information to establish magnetic connectivity, topology, and dynamic properties at multiple points within the CME structure for all suitable events. Similarly-focused studies, but for angularly separated events in the 1-30° range, will reveal the physical origins of the meso-scale structures, the extent/importance of erosion across CME substructures (e.g., flux rope, coronal and heliospheric sheath regions) and enable high resolution modeling of the CME substructure.

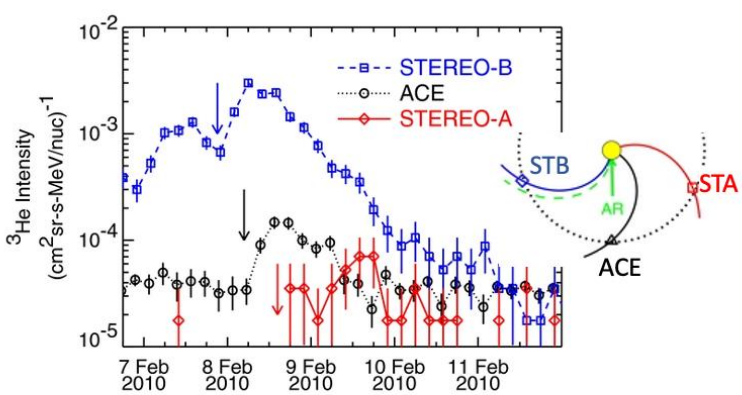

Fig. 10. The ^{3}He-rich event of 7 February 2010 (Wiedenbeck et al. 2013) was highly surprising in that it was observed by both STEREO spacecraft when they were separated by 136° in solar longitude (inset) when typically these events are only ~20° wide (yellow region, inset). ***STEREO data provide a unique probe into understanding the longitudinal structure of SEP events.***

The studies will be naturally augmented and extended to larger scales with the inclusion of serendipitous observations from the inner heliospheric probes at other locations (PSP, SolO, BepiColombo, MAVEN). Several such events have occurred since the last Senior Review and some are under study. STEREO team members will leverage their experienced systems approach in multi-point analyses (e.g., Lugaz et al. 2020; Nieves-Chinchilla et al. 2022) to lead studies pertaining to the objective discussed here. The successful completion of this work will improve our fundamental understanding of CMEs, which will in turn improve the characterization of the solar wind driving of the magnetosphere.

RT-A2: What process drives the longitudinal structure of ^{3}He events?

The longitudinal structure of ^{3}He-rich SEP events is considered to harbor particularly useful information about the contributions of near-Sun source populations (flare-accelerated) versus coronal/heliospheric sources (CME shocks). Previous STEREO observations revealed that the distribution of these flare-related particles could be spread over substantially larger longitudes than previously inferred from single spacecraft data (Wiedenbeck et al. 2013, Dresing et al. 2014). However, the extremely quiet solar minimum period early in the STEREO mission resulted in no suitable ^{3}He-rich SEP events for study when the spacecraft separations (including ACE at L1) were smaller. The upcoming near-Earth passage during solar maximum will allow us to constrain their solar activity associations and mesoscale variations over separation ranges that were previously missed. The science team will investigate how long a single source can accelerate ^{3}He-rich particles, why they are so widespread when they seem to originate from a compact source region, and how magnetic connectivity and suprathermal populations modulate their flux distributions.

RT-A3: What is the magnetic topology of pre-eruptive structures in active regions?

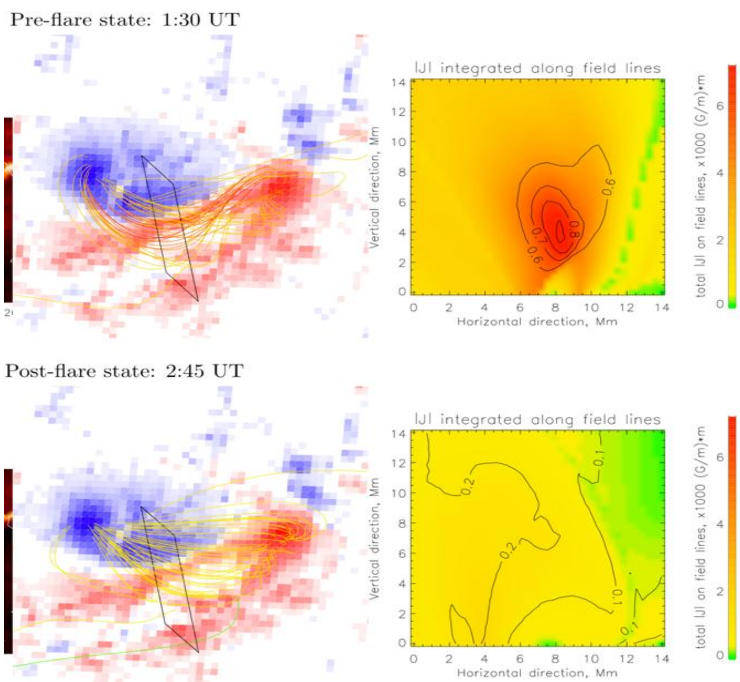

Fig. 11. Close-up of an active region before and after a flare, showing drastic change in the field structure along the polarity inversion line. Left column: close-up of field lines in the Malanushenko et al. model viewed along the LOS. The field lines, colored by total current along them, were initiated from the rectangular vertical slice. Right column: electric current magnitude, integrated along field lines. The contours represent the twist, $Tw = \alpha L/4\pi$. Clearly a highly twisted structure, with $Tw \approx 0.9$ total turns, disappears after the flare (from Malanushenko et al. 2014). ***Stereoscopic studies between STA and SDO/AIA or GOES/SUVI will allow us to study the evolution of active regions in the times before and after eruptions.***

The proximity to Earth in 2023-2025 will enable once more the stereoscopic reconstruction of EUV loops using SECCHI/EUVI-A and GOES/SUVI, which share four common channels (and SDO/AIA 171Å). The stereoscopic studies will focus on the evolution of active region structures towards eruption by comparing 3D reconstructions of loops with coronal magnetic field extrapolations (Fig. 11). EUV stereoscopy has already been applied during the early mission phase (Aschwanden 2011) to quiescent loop systems. Improved algorithms have been developed that allow applications in eruptive conditions (Malanushenko et al. 2014) and the use of EUV observations from different instruments (EUVI and AIA; McCarthy et al. 2021). This is an opportunity to extend these techniques to GOES/SUVI and even to SolO/EUI and use SDO/HMI and DKIST to investigate in detail the 3D topology and magnetic content of loop systems during active region evolution in an attempt to quantify the buildup of magnetic energy in the corona---a key parameter for understanding solar eruptions (e.g., Patsourakos et al. 2020). In preparation of this objective, the STEREO team is designing dedicated 2-day EUVI-EUI campaigns for

December 6-8, 2022 and March 25-26, 2023. In addition, the team is requesting an increase in the SECCHI telemetry allocation (2x) to repeat the high cadence stereoscopic campaign of May 4-17, 2007 with SDO/AIA and GOES/SUVI in June or October 2023, when the separation angle is optimal (~5 deg).

Research Theme B (RT-B): Multi-dimensional Studies for the New Multi-Spacecraft Era

Motivation: The heliosphere inside of 1 AU is a large and dynamic region, where the solar wind, magnetic structures, and suprathermal and energetic particles are accelerated, formed and evolve. Given that most observational data are single-point in-situ measurements near 1 AU combined with remote sensing observations of the Sun and near-Sun region, it has been necessary to rely on modeling to attempt to fill the large observational gap (e.g., Odstrcil, 2003; Luhmann et al 2007, 2010). With the launch of near-Sun missions, it is now possible to constrain the parameters of these models with observations made in the inner heliosphere and to study the evolving conditions in the inner heliosphere directly.

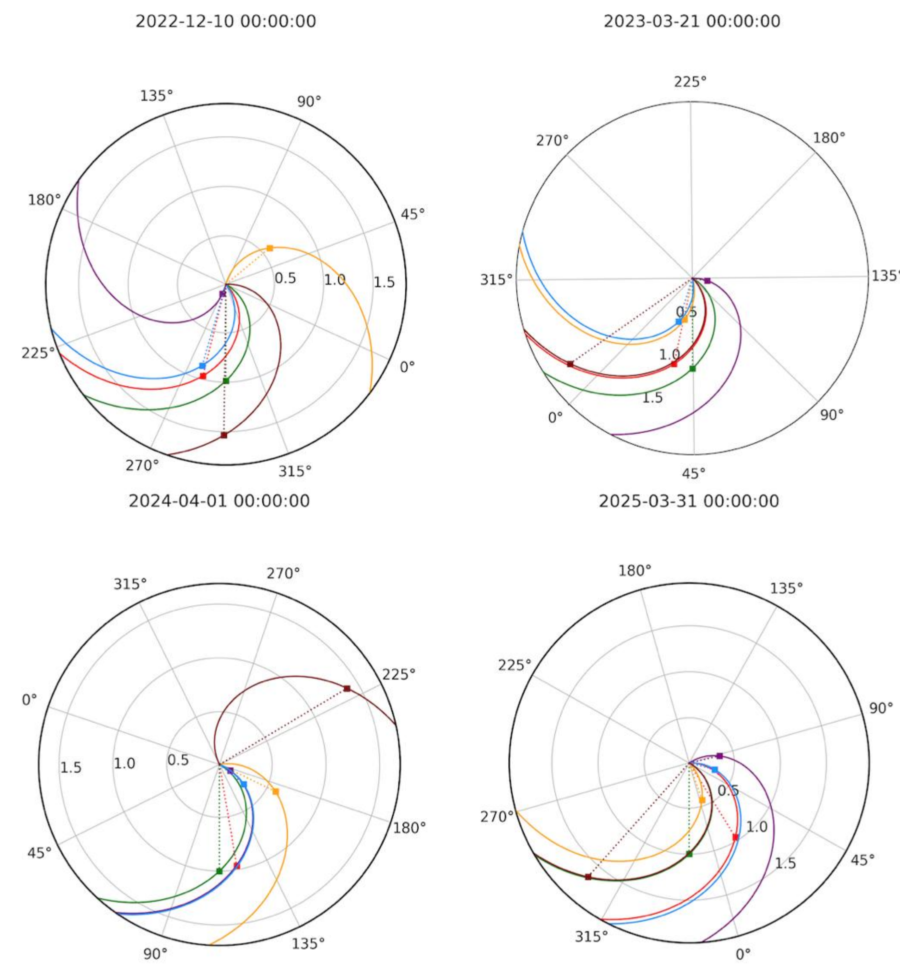

Fig. 12. Examples of specific multi-spacecraft alignments with STA: (top left) radial with PSP and SolO; (top right): rough radial alignment with both SolO and Bepi-Columbo and Parker spiral alignment with Mars; (bottom-left) along a nominal Parker spiral with PSP and SolO; (bottom right) along a Parker spiral with SolO and nearly radial with Bepi-Columbo. ***Multi-mission configurations like these will make possible new measurements of evolution and structure of helio-spheric transients.***

Approach: Solar cycle 25 will be near maximum during the time period 2023-2025 and with the current inner and outer-heliospheric assets (e.g., PSP, SolO, Bepi-Columbo, MAVEN, MSL) it will be possible to study the radial evolution of solar wind structures and SEPs in greater detail than ever before. At various times there will be alignments such as the examples shown in Fig. 12, where STA and two other spacecraft will be nearly aligned radially at several distances, or distributed along the same nominal Parker spiral, or combinations such as STA and another spacecraft aligned nearly radially with STA and the third spacecraft positioned along the same Parker spiral. In addition, there will be numerous opport-unities involving alignments of STA and one other spacecraft. STEREO data will be combined with that from other observatories to understand SEP events, investigate a possible source of seed particles, and to determine the effects of microphysics on the evolution structures in the solar wind.

RT-B1: How does heavy ion composition vary in SEP events?

A number of studies have looked at the variation of SEP event characteristics as a function of longitude (e.g., Cohen et al 2017; Lario et al 2017), with STEREO observations being a critical component of the investigations. The studies often show substantial dependence on longitude, including the relative abundances of elements such as H, He, O, and Fe. Prior to the recent launches of PSP and SolO, there were few opportunities to examine the radial dependence of SEP distributions, but now examinations of both radial and longitudinal variability are increasingly possible. One example occurred on 28 October 2021, when the first ground level enhancement (GLE) event of solar cycle 25 was observed at 1 AU by near-Earth spacecraft and STA. Observations well inside 1 AU were also made by instrumentation on PSP and SolO. Although ACE, STA, and PSP were separated by ~60° in longitude and 0.4 AU in distance from the Sun, the event-integrated fluences revealed near spatial independence in the O and Fe spectral shapes and the Fe/O abundance ratio over more than a decade in energy. Work is ongoing to understand the conditions which led to the unexpected uniformity in composition and spectra. As solar

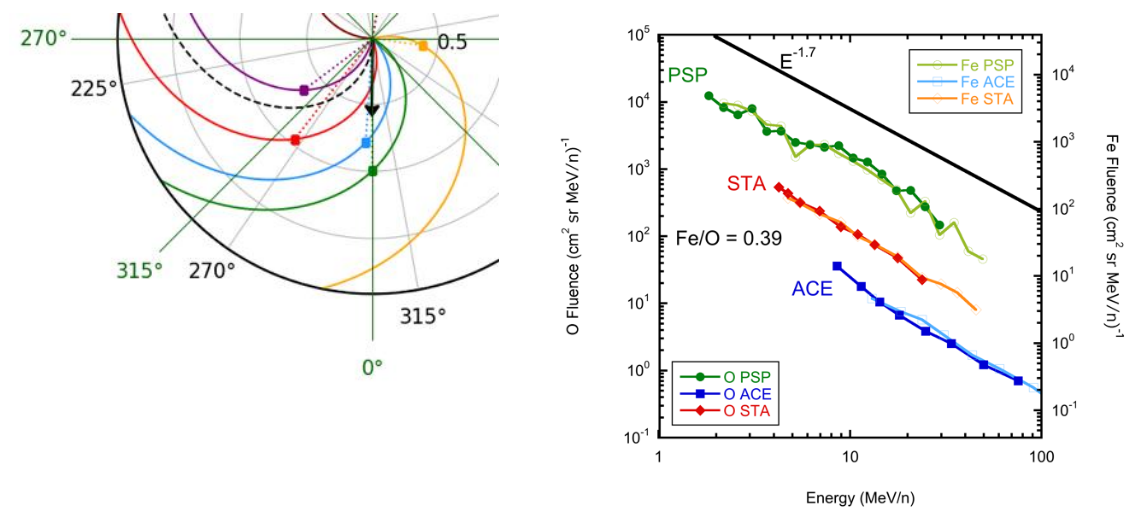

Fig. 13. Left: The 28 Oct 2021 event was observed by STA and other spacecraft distributed over 60° in longitude and 0.4 AU. Right: At STA the event integrated Fe spectra (right axis) closely matches that of O (left axis) when scaled by a Fe/O ratio of 0.39, indicating an energy-independent, enhanced Fe/O abundance. Very surprisingly, this scaling also applies to PSP and ACE observations, revealing an SEP event with uniform heavy ion characteristics over a substantial region of the inner heliosphere. ***STA observations combined with similar observations from other spacecraft are an essential way of understanding variations in SEPs.***

cycle 25 continues to develop, it is expected that SEP event activity will continue to rise leading to additional opportunities to study the spatial dependence of SEP composition, spectra, and time profiles. Opportunistic alignments with multiple spacecraft may also allow the radial and longitudinal dependences to be somewhat disentangled; e.g., during the October 2021 GLE event, SolO was radially aligned with ACE, yet longitudinally separated from STEREO.

RT-B2: What is the role of microphysics in radial evolution?

The importance of wave-particle interactions in the evolution of solar wind particles and structures has long been recognized (Gary et al., 1975, Kennel et al., 1985). The new views provided by the waveform capture data from S/WAVES yielded unexpected results suggesting that waves in the frequency range from the lower hybrid frequency to the ion plasma and electron cyclotron frequencies play a more significant role than previously thought. For example, whistler-mode waves have amplitudes 1 to 3 orders of magnitude larger than traditional spectral instruments could observe and often propagate at highly oblique angles (Breneman et al., 2010; Cattell et al, 2020); both features result in much stronger interactions with electrons over a wider energy range (Cattell and Vo, 2021; Vo et al., 2022). The waves

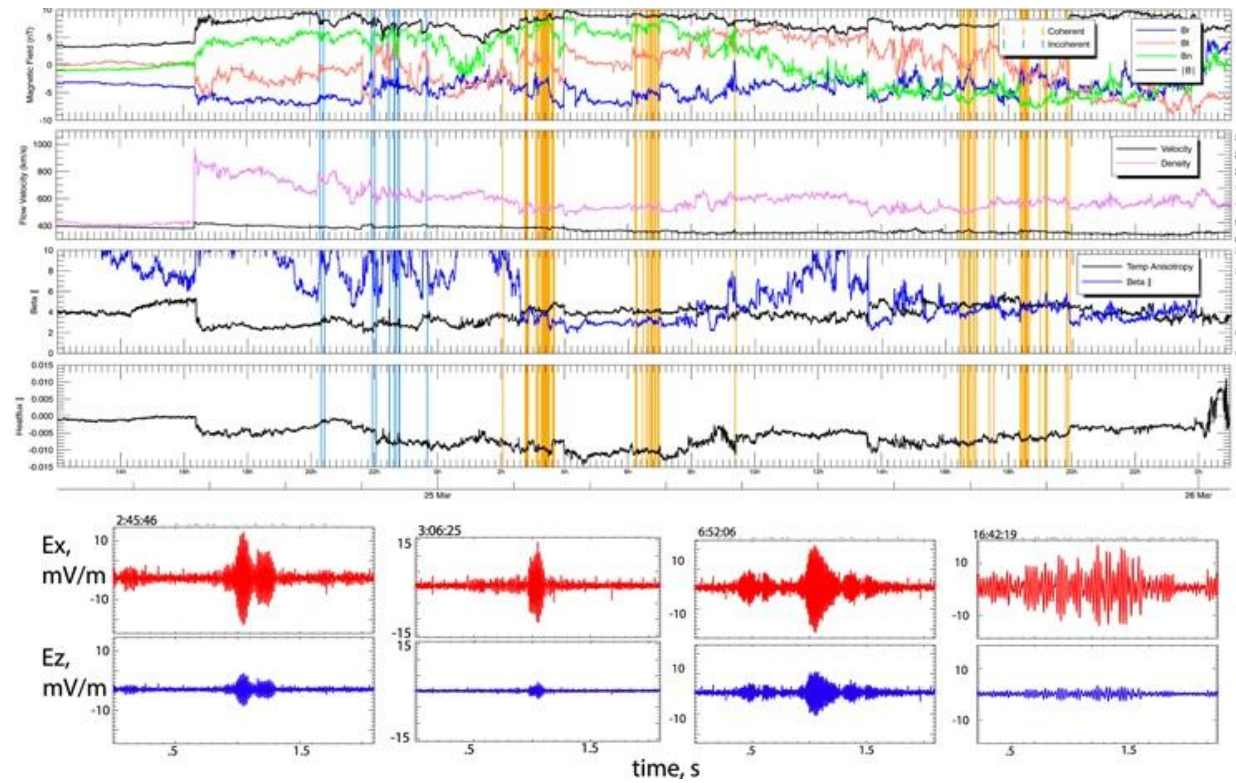

Fig. 14. Large amplitude narrowband whistler-mode waves (see lower waveform snapshots from STA/WAVES of one perpendicular component and the parallel electric field) are commonly observed in CMEs and shocks (example CME and shock properties from STA/IMPACT are plotted in the top 4 panels), as well as SIRs. Because the waves are obliquely propagating they interact strongly with electrons over a wide energy range. ***The waves may, therefore, impact the radial evolution of solar wind structures****. Data from 2017-Mar-24 12:00 to 2017-Mar-26 01:00 UT. Cattel & Vo (2021).*

control electron heat flux and scatter strahl to form the halo, thus modifying solar wind energetics. The wave occurrence is strongly correlated with CMEs (see Fig. 14**)** SIRs and shocks. The upcoming STA-PSP radial alignments occurring as solar activity increases will help determine the radial dependence of these waves and explicitly determine their influence on SIRs, CMEs and shocks. We will compare electron distributions and wave measurements to study wave scattering of strahl and determine whether the core is significantly heated. In addition, the obliquely propagating whistlers can interact with solar energetic electrons (SEEs). We will compare observations of SEEs and waves during conjunctions between inner heliospheric probes and STA to examine whether these obliquely propagating whistlers are important for understanding electron propagation.

RT-B3 Can Type III Radio Storms be a Source of Seed Particles in the Acceleration Sites of the Inner Heliosphere?

The variability of solar energetic particle properties is caused by many factors. One of them is the presence of superthermal particles in the particle acceleration regions. Such seed particles are often attributed to flares and CMEs occurring prior to an eruption. We will investigate an obvious source of suprathermal particles that has not been considered - the type III radio storms produced by nonthermal electrons accelerated in solar active regions. Most accelerators such as shocks and current sheets in flares are known to accelerate both electrons and ions, so we expect the type III storm sources accelerate ions as well. There are two particle accelerators in the inner heliosphere that can access these storm superthermals: CIRs and CMEs (see Desai & Giacalone 2016). Storm type III bursts occur in the boundary between an open field (OF) region adjacent to an active region (AR), but not all such regions produce type III bursts. In order to produce the type III bursts a particular OF-AR configuration needs to be conducive for interchange reconnection with the polarity of the open field adjacent to the opposite polarity in the AR. The interchange reconnection can accelerate electrons responsible for the storm type III bursts and also, most likely, protons. The accelerated particles propagate along open field lines that end up in CIRs. Therefore, the superthermals accompanying the type III storms can act as seed particles for the CIR accelerator. It is also possible that type III bursts from such configurations provide seed particles for SEPs produced by CME shocks.

Preliminary work by Gopalwamy et al. (2022a) compared a CIR accompanied by a type III storm to one not accompanied by a type III storm and found the former to have a higher particle flux (electrons and ions). They also performed an initial statistical study and found that the proton and electron fluences are higher in the storm associated CIRs by factor of about 6 and 8, respectively than those in the storm-free CIRs. If the active region in the OFAR configuration erupts and launches a shock-driving CME, the shock is highly likely to access the storm superthermals close to the Sun, so it is also possible that type III storm sources from such configurations provide seed particles for SEPs produced by CME shocks (Gopalswamy et al. 2020b).

We will follow up on this initial study with a further statistical analysis, identifying sets of solar energetic particle (SEP) events from storm-hosting and storm-free active regions and comparing the energetic particle properties between the two sets along with the characteristics of the OF/AR configuration associated with the region, considering (separately) energetic particles produced by CIRs and CMEs. This study will reveal effects of seed particles from the type III storm source on the SEP intensity. Such a study requires a range of points of view to obtain enough events and to adequately characterize the particle fluxes and source regions. We will identify type III storms using STEREO/WAVES, Wind/WAVES and PSP/FIELDS, verify the OFAR configuration using EUV images from SECCHI and SDO, and obtain particle fluxes from L1 monitors and STEREO.

Research Theme C (RT-C): Space Weather Research During Solar Cycle 25 Maximum

Motivation: In contrast to the previous two solar cycle maxima, we now have the NASA Artemis program that is setting up the infrastructure via a series of missions for sending humans back to the Moon, with the long-term goal of establishing the Moon as a basecamp for human explorers en route to Mars. In addition, NASA Goddard recently established the Moon to Mars (M2M) Space Weather Analysis Office which partners with CCMC to support the NASA Space Radiation Analysis Group (SRAG) by providing predictive capabilities of the space radiation environment (e.g., from SEPs) beyond low Earth orbit, and to support NASA robotic missions with assessments of space weather conditions and analyses of related anomalies. Given our current endeavors to revisit the Moon – and one day to visit Mars, NASA needs to engage in space weather forecasting more broadly throughout the solar system. With the approach of maximum solar activity of Cycle 25, we will have new opportunities to demonstrate the importance and benefits of having continuous coverage of the interplanetary conditions from STEREO along the 1 AU orbit and from various, off-SEL vantage points, for both scientific research and forecasting of space weather impacts and effects at Earth and also at the Moon and Mars.

Approach: The recent and upcoming positions of STA with respect to the helio-longitudinal locations of Earth/Moon and Mars together with the current and upcoming missions at these interplanetary locations will provide opportunities to carry out a variety of investigations that are relevant for understanding and forecasting space weather impacts and effects at these interplanetary bodies by solar flares, CMEs, SIRs/CIRs, high speed streams, heliospheric current sheet crossings, and SEPs.

RT-C1 How do space weather forecasting capabilities change between L5 and L1?

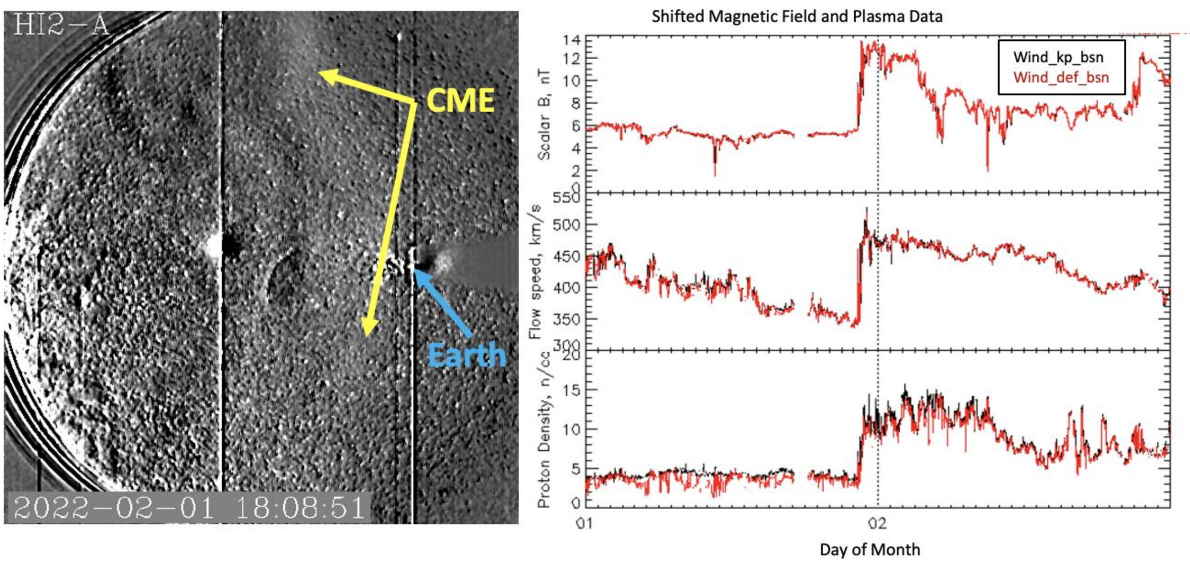

Fig. 15. An example of a CME that HI2-A is imaging as it passes over Earth. The CME erupted late on 2022 Jan. 29. The left panel shows the CME front just before it arrives at Earth late on 2022 Feb. 1, with the arrival explicitly illustrated in the right panel, which plots plasma field, flow speed, and proton density from the Wind spacecraft near Earth. ***STEREO's Heliospheric imagers continue to provide a unique Sun-to-Earth view of CME propagation.***

Many conceptualizations of the future of operational space weather forecasting envision a spacecraft at or near L5 (60° trailing Earth) for space weather monitoring purposes. Such a vantage point is advantageous for viewing Earth-directed CMEs from a lateral perspective, allowing more accurate kinematic measurements of the events for Earth arrival time prediction (e.g., Rodriguez et al. 2020, Vourlidas et al. 2020). The STEREO spacecraft were the first to image and track Earth-directed CMEs from the L5 vantage point. Thus, STEREO observations are the ideal datasets for testing and validating L5-based space weather forecasting methodologies. Here, we propose to study CMEs observed along the Sun-Earth line, not only while STA was around the L5 point but also while it approaches Earth. Our objective is to investigate whether the L5 viewpoint offers a concrete advantage over smaller angular separations in improving the arrival time predictions for Earth-directed CMEs. Note that STB's L5 passage occurred during the extended solar minimum of 2009 resulting in an insufficient number of energetic CMEs for analysis. The STA L5 passage in October 2020, and the subsequent approach to Earth, is already providing a much better set of events for this objective (see Fig. 15 for an example). To close on this objective, we will survey the observations of Earth-directed CMEs from mid-2020 to the present and connect the STEREO remote sensing observations with L1 in-situ measurements. We will then compare Earth arrival time predictions based on the STA imagery using existing techniques (Wood et al. 2017, Braga et al 2020) with the actual arrival times and quantify the effect of angular separation on the time of arrival accuracy using various forecasting metrics

RT-C2 What is the CME shock-source direction of observed >300 MeV SEP protons?

It is well known that gamma-ray emission from solar eruptive events results from the precipitation of >300 MeV protons accelerated in the corona (see Cliver 2022). While the impulsive gamma-ray emission is due to protons accelerated in the flare reconnection region, the origin of protons responsible for the emission occurring beyond the flare impulsive phase has been controversial. Storage and release of the particles accelerated in the flare site and the shock-accelerated particles transported back to the Sun are the two competing scenarios. The extended emission is also known as sustained gamma-ray emission (SGRE), which emphasizes the shock as the sustainer of >300 MeV protons. The same shock is also responsible for the acceleration of solar energetic particles to high energies (up to GeV) and ~10 keV electrons responsible for interplanetary type II radio bursts. In this scenario, the shock accelerates the high energy protons, so the SEP spectrum is expected to be hard. However, some SRGE-associated SEP events have a soft spectrum, which Gopalswamy et al. (2018; 2021) attributed to the poor latitudinal connectivity. Soft-spectrum events have their shock nose typically at large angles from the ecliptic. If the highest-energy particles are accelerated near the shock nose, these particles do not reach an ecliptic observer and hence the observer sees a soft spectrum. The close correlation between SGRE and interplanetary type II bursts (Gopalswamy et al. 2018) suggests that the high-energy protons and electrons are energized at the nose region of CME-driven shocks. Direction finding using S/WAVES data can locate the type II burst source relative to the shock nose (Makela et al. 2018). Using the direction finding, we will estimate the source direction with respect to CME/shock nose from SECCHI observations and hence test the nose-region hypothesis. We will also use 3D shock propagation models that provide the distribution of shock properties over the entire shock surface.

RT-C3 What are the Impacts & Effects of Significant Space Weather Phenomena at Mars?

Mars is weakly shielded by its "hybrid magnetosphere" with both induced and intrinsic magnetospheric features resulting from the planet's tenuous atmosphere and inhomogeneous crustal magnetic fields (DiBraccio et al. 2018). Thus, the space weather impacts and effects on human explorers and supporting infrastructure, both in orbit around and at the surface of Mars, will be different from the terrestrial experience in many aspects. Without a L1 upstream monitor like ACE at Earth's L1, our current understanding of the interplanetary conditions at Mars heliocentric distances rely on observations obtained at Earth or STA for periods when Mars is in opposition or Parker spiral alignment with either observer locations – which occurs about every two years (See Fig. 12 and papers by, e.g., Thampi et al. 2021; Palmerio et al. 2021b, 2022) and on serendipitous space weather measurements by planetary science missions (e.g., Crider et al. 2005; Jakosky et al. 2015; Lee et al. 2018; Delory et al. 2012).

The upcoming alignments of Mars with STA during the 2023-2025 solar maximum are uniquely timed to investigate space weather phenomena near Mars and their impacts on the Mars system (magnetosphere, ionosphere, surface). Observations from current Mars missions (MAVEN, Mars Express, MSL) together with those by STA will help to address important questions, such as, "How efficiently do SIR-related compression regions transition to shocks from 1 AU to ~1.5 AU?'', "Under what conditions can SIRs be more impactful than CMEs in driving magnetospheric (e.g., Gruesbeck et al. 2017) and ionospheric disturbances?", and "What is the nature of the evolution of CMEs, CME-driven shocks, and the associated SEPs as they propagate from the Sun out to ~1.5 AU?". Answering these questions will provide better insights on how Mars responds to space weather drivers (e.g., solar flares, CMEs, high speed streams, SIRs, SEPs, heliospheric current sheet, nominal solar wind) and how they may impact human exploration infrastructure in orbit and at the surface.

Research Theme D (RT-D): Solar Cycle Science

Motivation: STEREO's extended mission observations through solar cycle 24 led to many insights into the transformative effects of the activity cycle on the heliosphere. Attempts to model the changing 3D coronal hole and loop structures in the EUV images, and to map from 1 AU back to the sources of the observed solar wind, highlighted the challenges produced by solar field evolution on time scales shorter than a solar rotation (e.g., Arge et al., 2013). They also highlighted the importance (and poor knowledge) of the solar polar fields in making accurate models. Research on the contributions and role(s) of pseudostreamers in both coronal structure and solar wind sources led to revised solar cycle paradigms beyond the traditional tilted dipole field descriptions (e.g., Riley & Luhmann 2012). Overall, STEREO has shown us how ecliptic plane conditions at 1 AU fit into the global context of the heliosphere. But while trends and patterns have been revealed using the coronal images and in-situ data (e.g. Jian et al., 2018, 2019; Li et al., 2021) over the ~1.5 solar cycles covered by the STEREO mission so far, the existence of cycle-to-cycle differences (e.g. the weakness of cycle 24), the known 'lottery' of solar events and event sampling, and open questions raised in the course of the research, make the value of observing the SC25 solar maximum (~2023-2025) clear.

Approach: We propose to use STEREO's well-understood instrumentation and team experience to attack outstanding questions related to solar cycle effects. Two studies will provide insight into connections between 3D solar/coronal attributes and their 1 AU in-situ consequences, taking full advantage of the combined STEREO investigations from the start of the mission up to the present new maximum. Together, these provide the opportunity to shed new light on both the poorly-observed solar polar magnetic fields, and the effects of the polar field reversals on the heliosphere. A third study will utilize our long-term data base to understand small scale structures in the solar wind and how they vary.

RT-D1. How does the solar dipole component evolve over time?

The polar photospheric magnetic flux is poorly measured due to both the weakness of the magnetic field in these regions and the observing geometry of existing magnetographs in the ecliptic plane. Many members of the coronal magnetic field modeling community have theorized that the measured magnetic flux in the polar regions must be systematically too low, based on comparisons between IMF observations and heliospheric magnetic field models (see Petrie 2015). Our team has developed a technique for perturbing synoptic photospheric magnetic flux maps by quantitatively comparing coronal magnetic field models with STEREO COR1 coronagraph images (Jones et al., 2017). A preliminary study based on MLSO K-COR data from May of 2016 showed that our optimization consistently resulted in a stronger dipole component during that time. We will extend this study to determine whether this general pattern holds throughout the solar cycle.

COR1 data are ideal for this comparison because it has a field of view that extends below the canonical source surface height of 2.5 solar radii, and the data are available daily for more than a decade, independent of terrestrial weather conditions. Comparisons with COR2 data toward applying a similar approach out to larger radial distances will be explored. This work is expected to impact both the manner in which the solar polar magnetic fields are handled in creating coronal model boundary conditions, and the interpretation of the apparent open flux 'deficit' in the heliosphere. The results will contribute to the current broad community interest in observing the poles and modeling the corona, which is essential for forecast models.

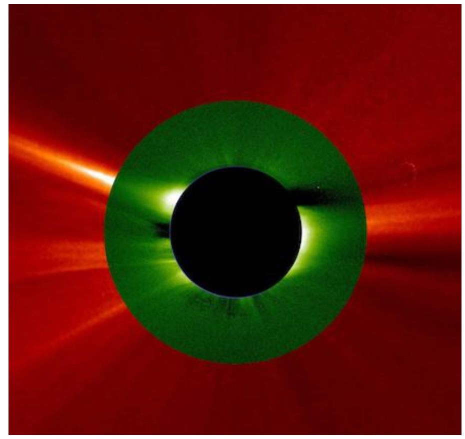

Fig. 16. STA COR1 (green) and COR2 (red) images showing coronal structures that will be used to determine how to modify the magnetic fields used in the coronal models. ***COR1 is ideal for coronal field modeling because its field of view extends below the canonical source surface height of 2.5 Rs, and the data are available daily for more than a solar cycle.***

RT-D2. How does the Sun's polar field reversal affect the solar wind?

An intrinsic part of the passage through solar maximum is the reversal of the Sun's polar magnetic field polarities. Solar wind source mapping studies indicate that the polar hole solar wind largely vanishes at the time of field reversals, while outflows and transients from mid and low latitude coronal holes and streamers become dominant (e.g., Luhmann et al., 2022). Although the polar field reversal is merged with the higher activity levels from CMEs in the corona and solar wind, it may produce unique features. For example, it has been suggested that the coronal field observed during the reversal produces multiple heliospheric current sheet structures (e.g., Wang, 2014) that must propagate into and through the heliosphere. In addition, some coronal field models during reversals indicate the traditional 'polar' coronal holes and their equatorward extensions are replaced by large areas occupied by pseudostreamers. We propose to investigate the in-situ consequences of this still poorly understood aspect of the solar maximum solar wind. During the previous solar polar reversal, STEREO was in the process of going through solar conjunction. The new reversal will be both more completely observed, and better supported from the viewpoint of Earth-perspective observations used for inferring the prevailing coronal structure. Recent observations of the solar magnetic field, combined with coronal models, suggest a new cycle maximum polar field reversal is already underway (Fig. 17). This effort will focus on the use of the EUV images of the coronal structure to validate the corona magnetic configuration

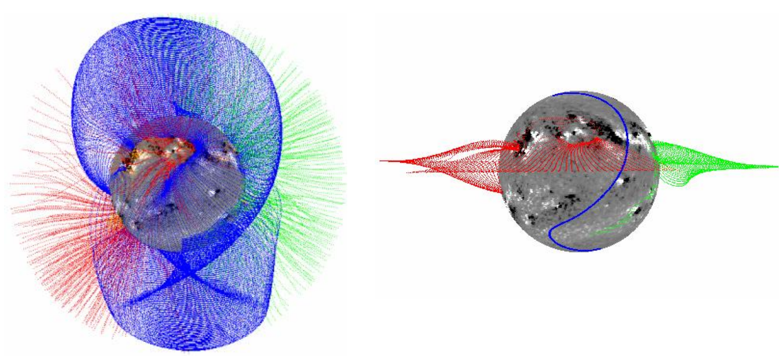

Fig. 17. PSFS model of Sun showing the coronal magnetic field on 7 Nov. 2022, suggesting the new solar maximum polar field reversal has already started. ***STEREO data will allow us to study the effects of such changes in the corona and solar wind.*** *Red and Green lines show open field regions of opposite polarity, while blue lines show closed field lines associated with the main helmet streamer belt. Courtesy: [GONG]*

(e.g., by comparing with available PFSS models) together with interplanetary magnetic topology information available from MAG and from SWEA suprathermal electrons (e.g., see Li et al., 2021) that are minimally affected by Earth's foreshock.

RT-D3. How do small-scale solar wind sub-structures vary between and over solar cycles?

The expanding variety of heliospheric structures and their plasma and magnetic field signatures is garnering new attention in part because of the interest in the contributions of reconnection and turbulence to the solar wind at 1 AU, and in part in preparation for the PUNCH mission that highlights the solar source aspects. Applying newer, automated techniques, we will incorporate machine learning techniques to search for solar cycle patterns and features in the in-situ data not previously identified via targeted examination, and for differences between the cycles. In particular, the interplanetary field enhancement (IFE) is a unique solar wind structure, characterized by cusp-like symmetrical enhancements in the magnetic field, which may provide important insights on solar wind sources or evolution. They highly resemble entangled flux rope structures identified at Earth's magnetopause in MMS data (Russell & Qi, 2020). In addition to their sharp peaks in field magnitude, they are distinguished by nearly central current sheets that exhibit a range of orientations. Entangled flux ropes in the heliosphere may arise at solar wind stream boundaries where adjacent streams originate from source regions with large spatial separations, or as the aftermath of reconnection across heliospheric current sheets. We will use machine learning techniques to examine the full record of STEREO data from 2007 up to the current date to identify IFEs and obtain a more complete statistical picture of IFE occurrence and correlations with solar wind properties at 1 AU, and associations with other structures throughout the solar cycle. These statistical results will allow us to investigate the IFE generation mechanisms and conditions for their development, toward defining their context and contributions to the broadening spectrum of solar wind solar wind features.

C. Contributions to Heliophysics System Observatory

STEREO is an essential and unique part of the Heliophysics System Observatory, providing a perspective not available from any other source. The Heliophysics Observatory Science is so central to the STEREO mission that HSO science figures prominently in most of the objectives described in Section IV, but we revisit some of these topics here as well as further ways STEREO will support HSO efforts through 2026.

As described earlier in this proposal, over the next few years STA is passing close to and through the Earth-Sun line. This will be during the ramp-up to solar maximum, making possible exciting research that was difficult the first time STEREO was this close to the Sun-Earth line, during a deep solar minimum. During this time STEREO will be a key contributor to studies of variations of heliospheric phenomena over relatively short distances in conjunction with L1 missions Wind, ACE, and DSCOVR. As also discussed in our objective section, small angular separations are ideal for active region tomography and also triangulation of eruptions near the solar surface. As STA comes close to Earth, its coronagraphs will have some redundancy with SOHO/LASCO. However, that is not true for its heliospheric imagers, which will continue to provide a unique view of the inner heliosphere. This could be crucial for PSP and SolO science in particular. For example, STA/HI will have a perfect view of SolO during its 2023 April perihelion, and the HI1-A and HI2-A imagers will have a unique perspective on any ICME front passing over SolO. Likewise, STA/HI will have an excellent view of PSP during approach to its 16th perihelion passage in 2023 June.

Once STA passes the Sun-Earth line in 2023 it will continue on towards the Earth-Sun L4, which it will reach in June of 2026. This location is especially important for measurements of upstream SEP characteristics and imaging of active regions near and beyond the western solar limb as seen from Earth.

As it separates from Earth it will again provide a unique perspective of the Sun and measurements of in-situ conditions in a region of the solar system otherwise unsampled by operational spacecraft. STEREO in-situ measurements and EUV images from this vantage point will also be valuable for heliospheric model selection and model validation, and such models are used for understanding observations through the HSO. This location is important for coordinating space weather studies for other planets.

STEREO provides key supporting data sets for many of the SolO mission goals, especially those concerning solar transients and SEPs (Müller et al 2020) and the PSP goals to explore mechanisms that accelerate and transport energetic particles (Fox et al. 2016). Coordination with the PSP and SolO missions over the next few years will be enhanced by the fact that both missions will be in their prime phase, and with PSP achieving some of the lowest perihelia of the mission. Solar cycle 25 also appears to be cooperating with a faster increase in activity than predicted. As of mid 2022, there have been several large SEP events observed by multiple spacecraft, and over 100 fast (>500 km/s) CMEs We expect many more over the next few years. Obtaining simultaneous observations of solar radio bursts close to the Sun with PSP, intermediate distances with SolO, and at 1 AU with STEREO will provide us with new data to understand the generation and propagation of these waves that are so important for understanding acceleration of electrons in flares and CME shocks.

STEREO data will also be a highly important resource for upcoming heliophysics missions. Launching in February 2025, the NOAA Space Weather Follow-On at L1 Mission (SWFO-L1) and the NASA Interstellar Mapping and Acceleration Probe Mission (IMAP) carry both plasma and magnetic field instruments, as well as energetic particle detectors with energy ranges overlapping those of IMPACT. Moreover, like STEREO and ACE, the new missions will provide science-level data products along with beacon data for space weather forecast applications. This combination of new measurements at L1, the rising solar activity cycle, and the observations by IMPACT and PLASTIC during this time (when STEREO is relatively near the sun-earth line) will provide opportunities to obtain multipoint diagnostics of the causes behind the strongest space weather activity of the new cycle maximum, including major shocks with their associated plasma and field drivers, and the upstream counterparts of ground level enhancement (GLE) SEP events. They will also provide inputs for high-interest space weather model development and forecasting. Of note is the fact that the IMAP energetic particle detector, High-energy Ion Telescope (HIT), is heavily based on the STEREO IMPACT Low Energy Telescope (LET). Thus, the energetic particle events observed by IMPACT LET can be almost directly compared with those by IMAP for both science and measurement cross-calibration and validation. STEREO beacon data at L4 together with those from IMAP I-ALiRT and SWFO-L1 at L1 can be used simultaneously during a SEP event to develop, test, and improve SEP now-casting and forecasting techniques – critical information for strategic planning of future L4 missions.

SunRISE, scheduled to be launched in 2024, will determine the location of radio bursts from 0.1 MHz to 25 MHz, to provide data on electron acceleration mechanisms associated with CMEs and the magnetic field topology from active regions into interplanetary space. STA will provide important complementary information with regards to the trajectories of CMEs and SEP events.

In addition, the Polarimeter to UNify the Corona and Heliosphere Mission (PUNCH) will launch in April 2025 and will produce continuous 3D images of the inner heliosphere from a constellation of satellites in a sun-synchronous, low-Earth orbit. One of the PUNCH science goals is to understand the structure and evolution of CMEs and CME-driven shock fronts, the latter of which is the major source of SEP acceleration. While PUNCH will capture the details of shock evolution, interactions, and instabilities, this mission does not include a particle detector for measuring SEPs. Thus, STEREO will provide off-Sun-Earth-line in-situ and imaging observations to compliment PUNCH images. This will include SEP observations from L4 for interpreting the 3D CME and shock structure information from PUNCH.

STEREO data are freely available and are used extensively beyond the STEREO team, resulting in 473 refereed papers from 2020 to present, many of which utilize data from multiple spacecraft. **The contributions of STEREO to the achievement of science goals of existing and future HSO missions illustrates the centrality of the HSO concept in the advancement of heliophysics.**

D. STEREO Objectives and HSO Contributions Fulfill NASA Goals

STEREO's science objectives for the next 3 years address the 2013 Decadal Survey Key Science Goals 1 ("Determine the origins of the Sun's activity") and 4 ("Discover and characterize fundamental physical processes…"). 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" (RT-D1 and D2);
SHP-2 "Determine how the Sun's magnetism creates its dynamic atmosphere" (RT-A3); and
SHP-3 "Determine how magnetic energy is stored and explosively released" (All Objectives in RT A, B, C, and RT-D3).
These in turn are clearly connected to the Heliophysics goals set forth in the NASA SMD Science Plan (2020). 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 STA's recent location at L5 and eventual location at L4 will address important goals of SWAP related programs (RT-C).

Our contributions to the HSO address these goals as well. Additionally, STEREO's role in space weather prediction connect it to the Strategies of the NASA's 2020 SMD Science Plan: 1.2: "Participate as a key partner and enabler in the agency's exploration initiative, focusing on scientific research of and from the Moon, lunar orbit, Mars, and beyond", and 1.4: "Develop a Directorate-wide, target-user focused approach to applied programs, including Earth Science Applications, Space Weather, Planetary Defense, and Space Situational Awareness."

III. Technical Status

A. Spacecraft, Instrument and Ground System Status

Spacecraft
The STA spacecraft is healthy, aside from the loss of the primary IMU and the degradation of the backup IMU. In February 2022, the engineering team conducted a successful telemetry assessment review and reported all spacecraft subsystems as healthy. All four reaction wheels, the sun sensors, Guide Telescope, and star tracker are nominal, and the propulsion system still retains ~50 years of fuel for momentum management. Solar panel, battery, and High Gain Antenna performance remain nominal.

The Mission Operations team at JHU/APL has made a number of configuration changes to STA to prevent a loss of attitude control, as happened on STB in October 2014, and to permit continued science operations without further degradation of the remaining IMU. STA pointing performance continues to meet and exceed its original requirements by utilizing the Star Tracker and the SECCHI Guide Telescope as the only attitude sensors. The remaining IMU is kept powered off and held in reserve for very rare fault scenarios (none have happened in the last 7 years).

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. MAG continues to perform nominally. MAG's offsets drift slowly with time, but this is corrected in our data products.

On Aug 31, 2022, the SEP-Central processor reset. The HET team had begun to send commands to update their low gain thresholds and the reset occurred upon receipt of the first command packet by the SEP-Central processor. Since this was not a power-cycle the rest of the SEP instrument suite continued to operate, and the suite was brought back to normal science operations on Sep 2, 2022. The SEP team is working to understand what happened, but the investigation is ongoing. This was the first commanding of the SEP suite since March 2019, and it is suspected that corruption of the portion of SRAM devoted to the command interpreter occurred during the more than three years of continuous operation since that time.

PLASTIC
As reported in the last Senior Review, 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; however, the composition measurements indicated the presence of water ions. The background flux appears most affected at higher voltages within the entrance system. Some of the high voltages were reduced accordingly and the energy detector bias is currently off. The background rates contribution from the outgassing is being tracked and has decreased in an exponential fashion by several orders of magnitude since the previous Senior Review. The signal-to-noise level is sufficient for determining solar wind protons. 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.

The solar wind proton speed coverage range in the current entrance system voltage configuration is 210 – 1650 km/s. (Solar wind speeds above 1200 km/s are extremely rare.) We expect PLASTIC to be able to support all research activities presented in this proposal.

SECCHI
All SECCHI instruments on STA are operating nominally. Since the last Senior Review (November 18, 2020) there have been ten "Watchdog" resets bringing the total to 62 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. The instrument was rebooted three additional times, one to fix IP processing errors and twice to reset the image counter. The bugs have been recorded and are being investigated. Overshoot in the EUVI quadrant selector on STA since 2011 has been corrected by occasionally adjusting the mechanism delay setting. No such correction was necessary since the last Senior Review. Yellow/red high limits had to be adjusted for the COR1 detector temperature, which is increasing by ~0.5° C per year due to gradual 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 automati-cally 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 moni-tor the temperatures across all telescopes. The COR1 observing sequence was modified in mid-February 2021 to co-add two exposures at each polarization step, with the effect of doubling the effective exposure time, and thus significantly improving the signal-to-noise.

S/WAVES
The S/WAVES instrument on STA 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 engineerng model of the complete S/WAVES instrument is also maintained at UMN should it be required for any future reason.

Ground System
In December 2021 and June 2022, the Mission Operations team completed the final STEREO MOC upgrades of the planning and assessment workstations to transition to a new Intel x86 platform with the Solaris 11.3 operating system, which Oracle will support until 2034. The MOC command and control workstations had the same platform upgrade in May 2019. These changes have been in production use from June 2019 through June 2022 and have been performing reliably.

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 on average more than 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 a 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. STA 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 STA coronagraphs serve as a backup for the SOHO/LASCO coronagraphs: STEREO provides data 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).

B. Anticipated Mission Operations

The STA spacecraft continuously adjusts its roll angle to keep the high gain antenna pointed toward Earth. In the early years of the mission, after leaving the near-Earth environment, the nominal spacecraft roll kept the spacecraft +Z axis within a few degrees of solar north. This changed after the spacecraft passed behind the Sun in 2014, after which the nominal roll was close to ±180° from solar north. When STA passes close to Earth in August 2023, the nominal roll angle will change again, back to its original configuration. This will take place gradually, with most of the change occurring during a one week period between 9-15 August 2023. All the instruments will continue to be able to operate and collect science data during this period. At the end of this process, those IMPACT detectors designed to look along the Parker spiral will be optimally aligned again, and the roll will allow SECCHI/HI to continue pointing at the Sun-Earth line.

The STEREO team is not contemplating any changes to the mission orbital parameters, and it 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 STA and STB spacecraft will simply be left in their orbits.

C. 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. 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 and archiving.

An updated PDMP has been submitted with this proposal. Since the last Senior Review, Calibration and Measurement Algorithm Documents (CMADs) have been produced for all the STEREO instruments and are also submitted with this proposal. They are also available on the STEREO website and are archived in the SPDF.

SPASE descriptions for almost all STEREO science data products have been registered within the Heliophysics Digital Resource Library (HDRL), as well as most browse data products. SPASE descriptions for the handful of remaining products are underway. Adherence to format and metadata standards has allowed STEREO data to be easily incorporated into several 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 data products.

In addition to the data for the long-term archives, 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 proton event lists that are updated nightly. Additional S/WAVES data are available from the Centre de Données de la Physique des Plasmas (CDPP) in France. The SECCHI/COR1, SECCHI/COR2, 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 interaction regions, and SEP events, and a validated suprathermal proton event list is provided by the PLASTIC team. These latter lists are archived on the SSC website as Level 3 data products. We are also working with the SDAC and Heliocloud to make STEREO data available in the cloud as part of the NASA Transform to Open Science (TOPS) initiative.

The STEREO team continues to work towards providing important new data products to the heliophysics community. The IMPACT team is investigating the possibility that data concerning heavy ions (He-Fe) can be recovered from the IMPACT/HET instrument, which has thus far only been used to study electrons and protons. If successful, this would make possible new IMPACT-based SEP data products allowing the study of heavy ion SEP data three decades in energy. STEREO team members are also working to expand existing STEREO ICME catalogs to include more detailed information about the ICMEs and to synchronize the catalog with all space observatories to create more synergies among missions.

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 displaying S/WAVES data. The IMPACT analysis software is designed to be used with the TDAS/SPEDAS library. Berkely publicly hosts both IMPACT the IDL routines and TDAS library. Both are also archived in the IMPACT Software pages at the SSC, along with IMPACT pipeline processing software.

The SSC has been working on archiving all instrument documentation and software. Archiving of the documentation is complete and accessible in the /instruments/documentation/ directory on the SSC website. Extensive work has also been done on the parallel /instruments/software/ directory for archiving the instrument software. Along with the analysis software, the goal is to archive software used to produce the instrument FITS and CDF data archived within the SSC, including those which start from the Level 0 telemetry files. Some parts of the software, such as that provided by the Hammers Company for SECCHI telemetry processing, are proprietary and the source code cannot be archived. In those cases, links are provided explaining how to contact the software providers. Links are also provided for software in the SolarSoft Library, which is archived within the SDAC. At the end of the mission the SDAC will be provided with the complete software and documentation archive along with the then current version of SolarSoft.

IV. Responses to findings from 2020 Senior Review

We have attempted to address the finding from the 2020 Senior Review panel in this proposal. Here are our specific responses to the particular points raised:
The Science Objectives listed in the proposal are broad in nature, which leads to difficulty in assessing how science closure will be achieved and demonstrated in the next Senior Review. We feel we have made significant research progress in most of our objectives given the relatively short time (about 2.5 years) since we submitted our last SR. Part of the broad focus of our objectives necessarily arises from addressing the interests of the science team, which is larger and more diverse that the typical teams in grant proposals. We also desire to contribute to research on some of the large, long-term problems that

STEREO is best suited for, such as the evolution of solar transients in the inner heliosphere or improving our ability to forecast space weather. This time, however, we endeavored to be more focused in our objectives.

Ensuring maximum scientific and operational use of the STEREO PLASTIC, the instrument's science and beacon data should be corrected to as high quality as possible.

Although PLASTIC data is still not of its previous quality, the team has been working on this and PLASTIC data quality has improved since the last SR (Sec PLASTIC status).

There is no CMAD document currently in place. While the proposal asserts that a CMAD document should be available by 2021, the plan for creating this document is not clearly described.

The CMAD was submitted in Nov. 2021, and the latest version of has been provided with this proposal.

The proposal does not present a clear documentation or mission code or a clear open-source plan. There is no strategy for the long-term archiving of SSWIDL routines. Key documentation for the software such as the SECCHI Data User Guide is not currently available in a NASA archive. The mission code for processing from raw data to higher levels is not well documented on the mission website or NASA archives.

A discussion of how we have addressed these issues is in the Code Management Section.

V. Overguide Request: ML Ready SECCHI Data

Responding to the fast growing interest of the community and NASA HPD in machine learning/artificial intelligence (ML/AI) applications in Heliophysics, the SECCHI instrument team is proposing the construction and public release of ML/AI-ready datasets, starting with the EUVI. The team will leverage the recent STEREO-funded project within the Frontier Development Lab (FDL) workshop, which developed an ML/AI-based framework to cross-calibrate EUV images from different instruments (in this case, EUVI-A, -B, and AIA) and seamlessly combine them to create a 4π representation of the EUV atmosphere. This product can be used for improving spectral irradiance (and subsequently thermospheric density) forecasting, investigating long-range interactions across the solar corona, and validating global magnetic field models, among other studies. However, the FDL effort was based on a single month of EUVI/AIA data due to the limited duration of the FDL effort (8 weeks) and the lack of an ML/AI-ready EUVI dataset.

We propose to create ML/AI datasets for the duration of the STEREO mission (2007 onwards). We will start with the EUVI data given the existing FDL development. The effort requires identification and removal of 'bad' images (i.e., corrupted, rolled, or otherwise non-standard images), validation of header information, update of calibration factors and other corrections, documentation describing the dataset to both experts and non-experts in solar physics, and finally production of a dedicated ML/AI Level-1 dataset to be served by the SSC. The project will be completed within the first two years of the next extended mission phase. In the 2nd year, we will start the ML/AI preparation of the coronagraph data. In year 3, we will use those data to create synchronic and near-synchronic SECCHI-LASCO Carrington maps of the corona at a set of heights between 2.5-15 Rs, in an effort to minimize the effects of temporal evolution on global descriptions of the corona by exploiting the expanded coverage provided by STEREO. The methodology and a possible science application are described in Sasso et al (2019, see their Fig. 5 for an example of a near-synchronic map). We will expand and streamline the maps construction using the ML/AI dataset only. Maps will be constructed at 6 heights (2.5, 4, 6, 8, 10, and 15 Rs) to capture the closed/open magnetic field transition and the Alfvènic region and start from 2008 onwards to provide a continuous (and ML/AI-compatible) dataset for the duration of the STEREO mission through cycles 24-25. All data sets will be made available from SSC by the end of the extend phase. This project involves significant additional effort to produce and maintain the ML/AI sets and accompanying documentation. We plan on hiring a junior scientist with ML/AI background to lead this effort fulltime.

VI. Management and Budget

A. Management Plan

STEREO mission operations are carried out by a dedicated STEREO team at JHU/APL, via a task on a contract between NASA Headquarters and APL. The Space Science Mission Operations (SSMO) office at NASA Goddard, including the STEREO Mission Director, 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 science and Communications (formerly known as public affairs) leadership for the mission; she is assisted by a Deputy Project Scientist. 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. The SECCHI instrument suite is headed by the Naval Research Laboratory, the IMPACT suite by University of California Berkeley. PLASTIC is headed by University of New Hampshire. The S/WAVES instrument has Co-PI-s at the Observatoire de Paris and University of California Berkeley. Most of the PI teams also have active team members at other institutions

With the goal of establishing continuity of leadership of the investigation teams, we have commenced nominating mid-career scientists as new Co-I's. These individuals will become deputy-team leads, with the expectation that they will be taking over the management duties as the senior personnel step down. The IMPACT investigation (PI J. Luhmann) has already submitted the required requests and supporting documents to HQ, while Brian Wood has already succeeded the original PI, Russ Howard, on SECCHI.

B. Budget Narrative

The budget tables for STA 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 deputy, 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. Amounts listed are total burn rates including both new funding and uncosted earlier funding. Our science funding is based on this uncosted carryover. We note that our science funding is expected to decrease by FY25 and to be essentially gone by FY26. In addition to the in-guide budget we are also requesting an overguide as described in Section V.

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.

VII. Appendices

The Project Data Management Plan (PDMP), and Calibration and Measurement Algorithms Document (CMAD) will be submitted separately from this document.

A. Acronyms and Other Abbreviations

3DP	Wind/3-D Plasma and Energetic Particle Investigation
ACE	Advanced Composition Explorer
ADS	Astrophysics Data System
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	The Johns Hopkins University Applied Physics Laboratory
AR	Active Region
AU	Astronomical Unit
BSD-2	Berkeley Software Distribution -2
C3	SOHO/LASCO Coronagraph-3
CCMC	Community Coordinated Modeling Center
CDAWeb	Coordinated Data Analysis Web
CCD	Charged Coupled Device
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
COR1	SECCHI Inner Coronagraph
COR2	SECCHI Outer Coronagraph
COVID-19	COrona VIrus Disease 2019
CR	Carrington Rotation
DSCOVR	Deep Space Climate Observatory
DKIST	Daniel K. Inouye Solar Telescope
DSN	Deep Space Network
EIT	SOHO/ExtremeUltraviolet Imaging Telescope
EOML	End of Mission Life Plan
ESA	European Space Agency
ESP	Energetic Storm Particle
EUI	Extreme Ultraviolet Imager
EUV	Extreme UltraViolet
EUVI	SECCHI Extreme UltraViolet Imager
FDL	Frontier Development Lab
FITS	Flexible Image Transport System
FR	Flux Rope
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
HCS	Heliospheric Current Sheet
HDRL	Heliophysics Digital Resource Library
HET	IMPACT High Energy Telescope
HI	SECCHI Heliospheric Imager
HIT	High-energy Ion Telescope
HMI	SDO/Helioseismic and Magnetic Imager
HPD	Heliophyics Division
HSO	Heliophysics System Observatory
HQ	Headquarters
IBEX	Interstellar Boundary Explorer
IDL	Interactive Data Language
IFE	Interplanetary Field Enhancement
IT	Information Technology
ICME	Interplanetary Coronal Mass Ejection
IDL	Interactive Data Language™
IMAP	Interstellar Mapping and Acceleration Probe
IMF	Interplanetary Magnetic Field
IMPACT	In-situ Measurements of Particles and CME Transients Investigation
IMU	Inertial Measurement Unit
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
LET	Low Energy Telescope
MAG	IMPACT MAGnetometer
MAVEN	Mars Atmosphere and Volatile EvolutioN
MC	Magnetic Cloud
MDI	Michelson Doppler Imager
MESSENGER	Mercury Surface, Space Environment, Geochemistry and Ranging
ML	Machine Learning
MLSO	Mauna Loa Solar Observatory
MMS	Magnetospheric Multiscale Mission
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
NLFF	Non Linear Force Field
NOAA	National Oceanic and Atmospheric Administration
NRL	Naval Research Laboratory
OF	Open Field
iPATH	improved Particle Acceleration and Transport in the Heliosphere
PDF	Portable Document Format

PDMP	Project Data Management Plan
PI	Principal Investigator
PFSS	Potential Field Source Surface
POC	Payload Operations Center
PSP	Parker Solar Probe
PLASTIC	PLAsma and SupraThermal Ion Composition Investigation
PUI	Pickup Ion
PUNCH	Polarimeter to UNify the Corona and Heliosphere Mission
RHESSI	Reuven Ramaty High Energy Solar Spectroscopic Imager
SBU	Standard Billing Units
SC	Solar Cycle
SDAC	Solar Data Analysis Center
SDO	Solar Dynamics Observatory
SEC	SECCHI Electronics Boxes
SECCHI	Sun Earth Connection Coronal and Heliospheric Investigation
SEE	Solar Energetic Electrons
SEP	Solar Energetic Particle
SEPT	IMPACT/Solar Electron and Proton Telescope
SHP	Solar and Heliophysics
SIR	Stream Interface Region
SIT	IMPACT Suprathermal Ion Telescope
SMD	Science Mission Directorate
SoA	Speed-on-Arrival
SolO	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
SR	Senior ReviewSSC STEREO Science Center
SSMO	Space Science Mission Operations
STA	STEREO-Ahead
STB	STEREO-Behind
STE-D	IMPACT Suprathermal Electron Telescope Downstream
STE-U	IMPACT Suprathermal Electron Telescope Upstream
STEREO	Solar TErrestrial RElations Observatory
SUVI	Solar Ultraviolet Imager
SunRISE	Sun Radio Interferometer Space Experiment
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
SXT	Soft X-ray Telescope
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
UTSA	University of Texas, San Antonio
UNH	University of New Hampshire
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.

B. References

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