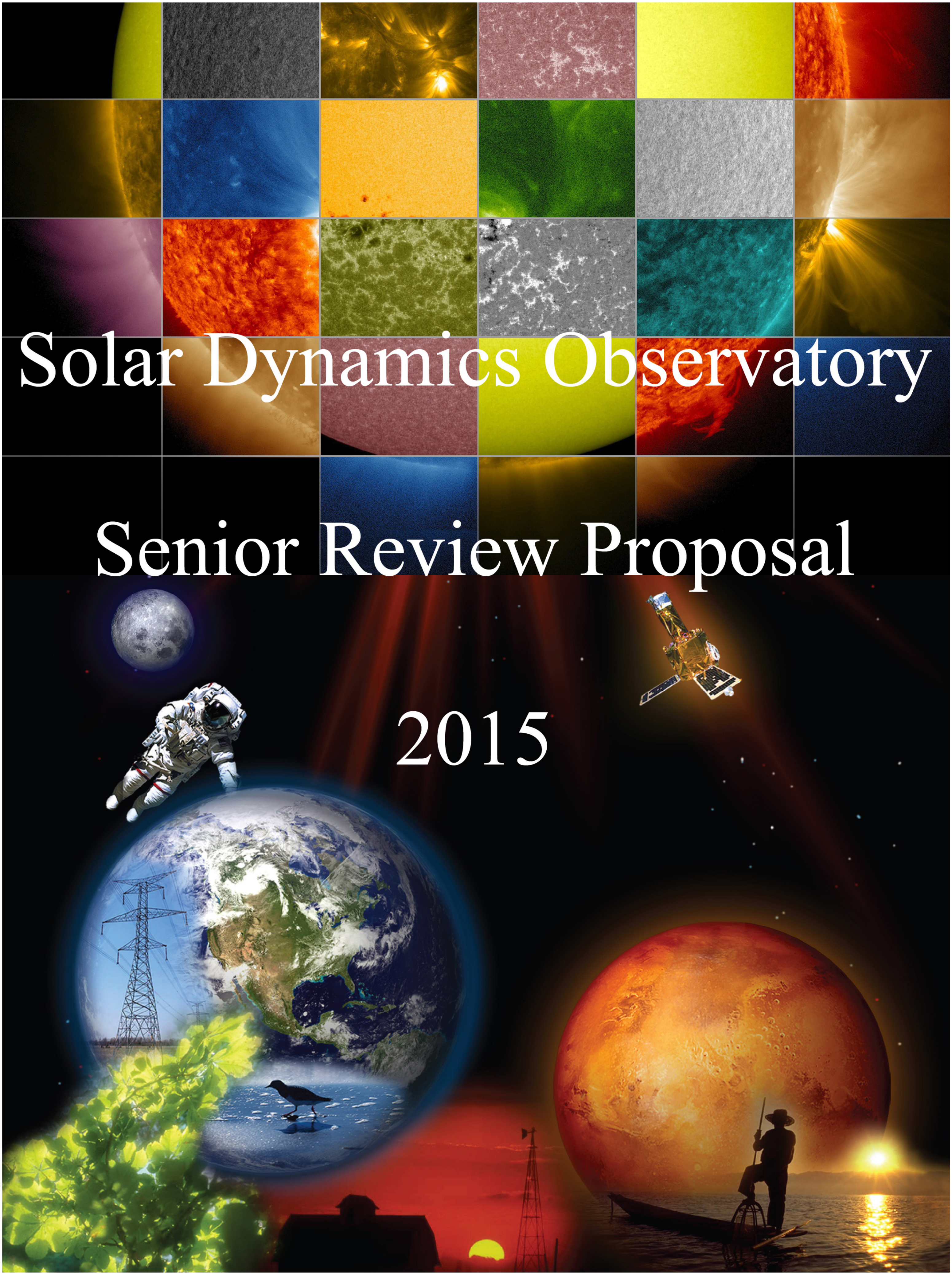
Solar Dynamics Observatory

Senior Review Proposal

2015



SDO: Our Eye on the Sun

Mission Fact Sheet

Name:		Solar Dynamics Observatory http://sdo.gsfc.nasa.gov
Launched:		February 11, 2010
Orbit:		Geosynchronous, 28° inclination
Data Downlink Rate		150 Mbps, continuous to dedicated ground station
Prime Mission		May 1, 2010 – April 30, 2012
Extended Prime Mission		May 1, 2012 – September 30, 2015
Proposed Mission		October 1, 2015 – September 30, 2017
Project Scientist		W. Dean Pesnell (NASA GSFC)
Science Investigation Team Principal Investigators		
AIA	Carolus Schrijver	Coronal images at many wavelengths and temperatures that capture the dynamics at multiple scales up to the full disk http://aia.lmsal.com
EVE	Thomas Woods	Extreme ultraviolet spectral irradiances at high cadence for flare energetics and ITM studies http://lasp.colorado.edu/home/eve/
HMI	Philip Scherrer	A continuous series of high-cadence, full-disk Dopplergrams and vector magnetograms http://hmi.stanford.edu

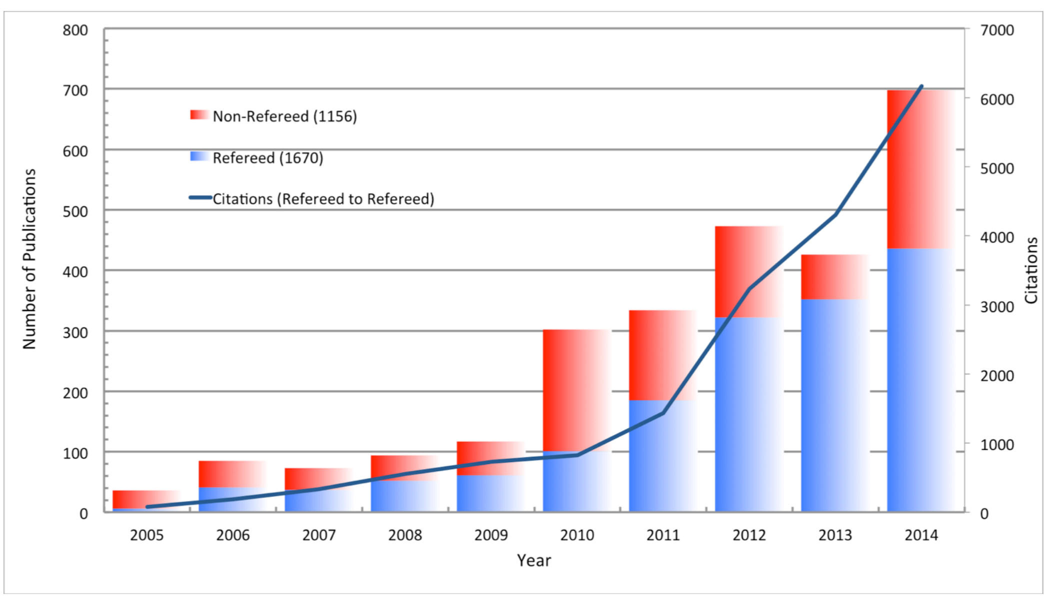


Figure 1.1: A graph showing the number of papers using SDO data in the NASA ADS database, along with the number of citations within the refereed literature.

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The Solar Dynamics Observatory

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Summary

The Solar Dynamics Observatory (SDO) will complete its five-year Prime Mission on April 30, 2015. The breadth of research topics enabled by SDO during its Prime Mission demonstrates the tremendous potential for the upcoming years. SDO comprises a suite of full-disk, high-resolution, high-sensitivity instruments that measures the solar interior flows, the surface magnetic field, and the outer atmospheric dynamics as the foundation of the Sun-Earth system. SDO has captured the rise from an unusually extended solar minimum to the peak of the cycle, and is now poised to address new challenges associated with the declining phase of the solar cycle. During its Prime and Extended Prime Missions, SDO has collected 24 times more data than obtained from all other space-based solar missions combined, while consistently giving top priority to its ever-expanding, increasingly diverse user community. With our over-guide proposal for an Extended Mission, SDO will carry out a high-priority research plan using current and future data and modeling assets to address emerging science topics most relevant to the Heliophysics research focus areas. The satellite, instruments, ground systems, and science team are ready to address the challenges associated with supporting the large number of external science investigations that are using SDO data products through its proposed extended mission, both in the US and abroad.

1. Science Plan and Implementation

1.1. Introduction

SDO delivers a diverse set of scientific research and data to discover and verify the many drivers and manifestations of solar variability and space weather. SDO is the first mission of NASA's Living With a Star (LWS) program that "improves our understanding of how and why the Sun varies, how the Earth and solar system respond, and how the variability and response affect humanity and space."

The physics of solar dynamics spans multiple scales: from the solar interior to the corona the Sun exhibits dramatic transitions across spatial, temporal, and energy regimes. The observational domain targeted by SDO spans nearly 20 orders of magnitude in density: from the tachocline – the engine of the solar cycle and where the Sun's magnetic variability begins – to the tenuous, magnetically-dominated corona that forms the base of our heliosphere. The key to understanding the drivers and manifestations of solar dynamics lies in the understanding of the interplay between these vastly different regimes.

To capture this range of scales, SDO produces low-latency data at a high cadence and with excellent signal to noise. This provides information needed by several classes of researchers. The low latency (or rapid access after observing) allows people to monitor solar conditions not only for space weather purposes but also for observation planning of other missions and launch decisions of sounding rockets. The high cadence means that changes previously missed by the strobing effect of lower cadences are more completely observed, allowing new discoveries as well as forcing the models to a more precise agreement with the solar conditions. The high signal to noise allows the data to be combined into more advanced products, such as vector magnetograms, coronal temperature maps, and to enhance weak wave signals that had been rare before but with SDO are produced on a regular cadence. *An example using all three is the passage of a sun-grazing comet through the corona. The high signal to noise makes the observation possible and permitted the development of a model of the comet tail. Comparing the comet tail emissions to coronal models allows the magnetic field high above the solar surface to be measured. The low latency enabled us to bring the excitement of scientific discovery to a large, and growing, public audience; the rapid delivery of these observations was a major reason "comet fever" took hold.*

SDO has been successful in reaching the public, media, and scientific community. The media, from the web to television to print, have used SDO images to illustrate space and solar stories. Scientists have published nearly 2000 refereed papers describing the science of SDO (Figure 1.1). They have used SDO data to see reconnection flows, large-scale readjustments of the corona far above the solar surface, a new class of flare activity, initiation of solar transients, and many other aspects of the Sun and solar magnetic activity.

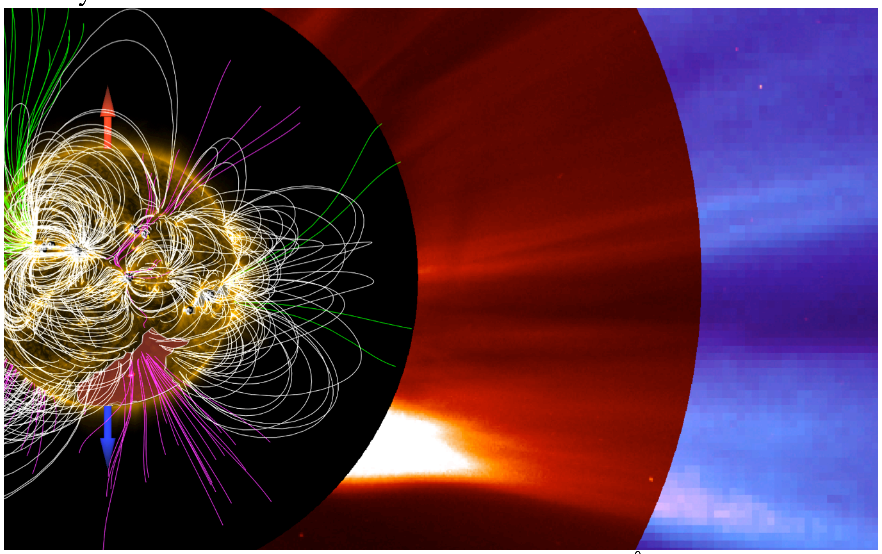

Figure 1.2. *A Helioviewer rendering combining AIA 171Å, with LASCO C2 and C3, showing the extrapolated magnetic field generated from HMI magnetograms, and selected HEK event listings, including coronal holes.*

There are many research topics that can be addressed by SDO data alone, but SDO's true potential emerges when its data are combined with that from other Heliophysics System Observatory (HSO) assets (Figure 1.2). The SDO mission has inspired a large, collaborative group of researchers, both professional and casual, that add value to our data far above the mission funding. To support these and other observing scenarios SDO observes "All the Sun All the Time." Researchers then "observe the archive" held and managed at the SDO instrument data centers, the EVE SOC and the AIA/HMI Joint SOC (JSOC).

This "observe the archive" strategy is fundamental to using SDO data because the data volume is too large for any researcher to download and analyze the full set. Some users require the highest temporal, spatial, and/or spectral resolution for a specific subset, and others study long-term variations that require data sampled over the entire length of the mission. The SOCs provide tools to allow researchers to select relevant events or time spans and to export the data needed for their particular studies. Most science data products are available within a few days of the initial acquisition, although some products require a few solar rotations to process. The "Sun Today," Helioviewer, and other browse products are available almost immediately, while many of the model and informatics products are available soon after to facilitate near-realtime (NRT) assessment for a variety of purposes.

NASA benefits from an SDO extended mission when the data continue to flow to this large and diverse group of researchers. No other mission has the high-cadence and low-latency solar data that space weather centers around the world rely on to forecast solar conditions and that other observatories with limited fields of view rely on to guide daily operations. Additionally, SDO will continue its support of the current fleet of satellites in the HSO. For example, during this extended mission the Sun will not only continue to produce eruptions that may impact geospace (see Figure 1.3), it will also develop large coronal holes, the source of the recurrent high-speed solar wind streams that energize the terrestrial magnetosphere. Relating these streams to the response measured by NASA's Van Allen Storm Probes and Magnetospheric MultiScale missions will provide new understanding of these complex interactions. The ICON and GOLD missions are planned for launch in 2017, and SDO is needed to interpret their observations of the driving source of energy into the ionosphere, thermosphere, and mesosphere. Soon after the end of this two-year extended mission, the Solar Probe Plus and Solar Orbiter missions are planned for launch, and SDO data will provide vital context for their observations.

This makes SDO a natural mission to extend for two years. SDO was designed from the outset to run with a high degree of automation, with a small core science team whose prime function is to perform data validation and forefront science, giving priority to supporting the larger research community. After the first two years of highly demanding development of the data infrastructure and the initial science investigation, the mission continued into what was essentially an Extended Mission phase, reducing the science-team funding by 30% for the past 3 years. The data stream of 1.3 TB/day requires continuous attention from scientists and engineers all along the path from the ground system through the production of crucial metadata to the data search and distribution systems. **At the in-guide budget level, the SDO teams cannot formulate a viable mission.** In our proposed Extended Mission, described below and supported by our over-guide request, we will keep the science data flowing, continue selected high-priority studies of solar dynamic phenomena, and maintain wide professional and public interest through the NRT data.

1.2. The Prime Mission of SDO: 2010-2015

SDO launched on February 11, 2010 and entered Phase E on May 1, 2010. Our five-year Prime /Extended Prime Mission ends April 30, 2015; we will continue operating SDO in a bridge phase to the end of FY2015. All instruments are operating in their nominal science mode, although EVE is operating in a degraded mode (described below). The dedicated ground station in New Mexico captures the continuous stream of science data and uplinks commands to the spacecraft. As a whole, SDO is operating exceptionally well and is expected to continue for many more years.

SDO was designed to meet a series of nested Level 1 requirements[1], demonstrating the soundness of design and construction of the observatory and the scientific utility of the data and research. Along with the instrument performance requirements, the observatory was designed to meet stringent data completeness and coverage requirements. These were phrased as a number of 72-day periods (these specific intervals of time were required by the solar interior studies) with appropriate completeness and coverage defined for each measurement. The Full Mission Success Criteria are listed in paragraphs 2.1.1-2.1.4 of the SDO Level 1 Requirements, as "The SDO shall obtain 22 72-day intervals of data from all instruments during the SDO Prime mission lifetime using the science instrument performance requirements for full success." SDO science data have been reported for all days since the beginning of Phase E, and there were no significant interruptions en route to Full Mission Success. AIA and HMI are now operating in the same mode as during the Prime Mission; EVE lost one of its CCD detectors in May 2014 (described below), but is still delivering high-quality science data from its remaining sensors.

HMI creates full-disk photospheric velocity measurements (Dopplergrams) every 45 seconds with the required resolution and noise level, data recovery of 98.4% and data completeness above 99% for each Dopplergram, needed for helioseismic studies. This exceeds the Full Mission Success requirements of a 50-second cadence, a data recovery of 95%, and 99% data completeness. HMI also creates full-disk longitudinal magnetic field measurements every 45 seconds and full-disk vector magnetic field maps every 12 minutes. Both satisfy the Full Mission Success requirements.

AIA obtains 8 images every 12 seconds: 7 EUV bands at full cadence, and two chromospheric bands alternating between 12 s cycles. A visible-light band is included at a very low cadence to monitor co-alignment with HMI. The images meet the spatial resolution and FOV requirements. The cadence of 8 images per 12 seconds satisfies the Full Mission Success requirement.

EVE measures the solar EUV spectral irradiance from 1-106 nm with a spectral resolution of 0.1 nm in the 5-106 nm range with its MEGS-A and B channels and in ~4 nm bands in the 0.1-37 nm range with its ESP channel. The high cadence EVE measurements include ESP bands at 0.25 s and MEGS-A 5-37 nm spectra at 10 s (requirement is 20 s). The MEGS-B 32-106 nm spectra were typically taken hourly, but occasionally at 10-s cadence for flare campaigns. The accuracy of the spectra at the bright spectral lines is about 10%, meeting the Full Mission Success requirements. EVE NRT data are being provided to NOAA and Air Force as a backup X-ray monitor to the GOES-15 X-Ray Sensor (XRS) for their space weather operations.

Unfortunately, on May 26, 2014 the EVE MEGS-A channel (5-37 nm) suffered a permanent short in one of the CCD electronics capacitors, and it now can only provide dark data (see Section 2.2.2). The failure occurred shortly after EVE met its data completeness requirement and reached the Full Success

[1] Program-Level Requirements For The Solar Dynamics Observatory, *http://sdo.gsfc.nasa.gov/assets/docs/AO-02-OSS-01.pdf*

criteria. EVE flight software is being changed in 2015 to address flare science with MEGS-B spectra.

All of SDO's measurement objectives are being met by the ongoing observation sequences on the three instruments. Even with the failure of MEGS-A, EVE's remaining sensor suite (ESP and MEGS-B) is sufficient to continue addressing the primary objectives. The vector magnetic fields were first published in December 2012 and the vector series is being calculated for all measurements since the beginning of Phase E. The other data streams were available soon after launch and remain so to this day.

1.3. Progress Toward Science Goals, Discoveries, and New Insights

The SDO investigations have enabled significant advances towards NASA Science Objective 1.4, "Understand the Sun and its interactions with Earth and the solar system, including space weather," specifically the 2014 NASA Science Plan's overarching science goals to "Explore the physical processes in the space environment from the Sun to the Earth and throughout the solar system" and to "Advance our understanding of the connections that link the Sun, the Earth, planetary space environments, and the outer reaches of our solar system."

The SDO mission was designed to use comprehensive measurements of the solar atmosphere and magnetic field to produce an understanding of the magnetic field that supports the corona and the internal dynamics that generate the magnetic field. The scientific goals of the SDO Prime Mission, detailed in the Report of the SDO Science Definition Team[2], were to improve the understanding of the following seven science questions:

1. What mechanisms drive the quasi-periodic 11-year cycle of solar activity?
2. How is active region magnetic flux synthesized, concentrated, and dispersed across the solar surface?
3. How does magnetic reconnection on small scales reorganize the large-scale field topology and current systems and how significant is it in heating the corona and accelerating the solar wind?
4. Where do the observed variations in the Sun's extreme ultraviolet (EUV) spectral irradiance arise, and how do they relate to the magnetic activity cycles?
5. What magnetic field configurations lead to the coronal mass ejections, filament eruptions, and flares that produce energetic particles and radiation?
6. Can the structure and dynamics of the solar wind near Earth be determined from the magnetic field configuration and atmospheric structure near the solar surface?
7. When will activity occur, and is it possible to make accurate and reliable forecasts of space weather and climate?

Addressing those key questions required measurements over a significant portion of Solar Cycle 24, which resulted in setting the SDO Prime Mission at five years instead of the typical two. After the first two years the budgets of the science teams were reduced by 50% (similar to the reduction to the extended mission, see Section 3.2), and we entered our Extended Prime Mission. The team enabled easy access to the data by developing tools for browsing, searching, and exporting subsets of data from the SDO Data Centers. This access is so ingrained into the SDO mission that we consider the Data Centers to be a "fourth instrument."

We have made significant progress on the science questions of the mission, and the SDO science investigations teams have achieved all of the measurement objectives of the mission. Studies related to SDO have led to the publication of nearly 2000 refereed papers (including 17 Ph. D. dissertations) and over 1000 conference papers (a complete publication list is on the SDO website *http://sdo.gsfc.nasa.gov*).

During the five-year Prime Mission we have watched solar activity change from very low to the peak of activity in Solar Cycle 24 (Figure 1.3). At the beginning of Phase E the monthly sunspot number was 8.5. The sunspot number peaked at 102 in February 2014, but an earlier peak of 97 in 2011 indicates multiple epochs of peak activity, similar to what happened in Solar Cycle 23. However, the curious delay in the solar cycle and its relatively low amplitude have only increased the community's interest in the solar interior and magnetic field studies that elucidate this seemingly anomalous behavior. During low

[2] SDO Science Definition Team Report, *http://sdo.gsfc.nasa.gov/assets/docs/sdo_sdt_report.pdf*

levels of solar activity, SDO scientists have been able to separate the radiant energy and impacts of individual flares and eruptions, which were sufficiently separated in time that they could be treated as isolated events. The interactions over large distances (the whole disk of the Sun) could be examined because of the complete full-disk coverage and the sparseness of the individual events and, which may not be the case if this cycle is prolific in declining phase activity similar to prior cycles.

The significance of SDO science to the Heliophysics Science Program is reflected in the 2014 Draft Roadmap for Heliophysics[3], which identifies SDO as important to 12 of the 13 Roadmap Research Focus Areas and 11 of 12 Decadal Survey Challenges[4]. SDO's full-disk, multi-domain, continuous coverage clearly supports a broad range of scientific areas in Heliophysics in general and in solar physics in particular. We now describe some of the science that has been accomplished by the SDO team during the Prime Mission.

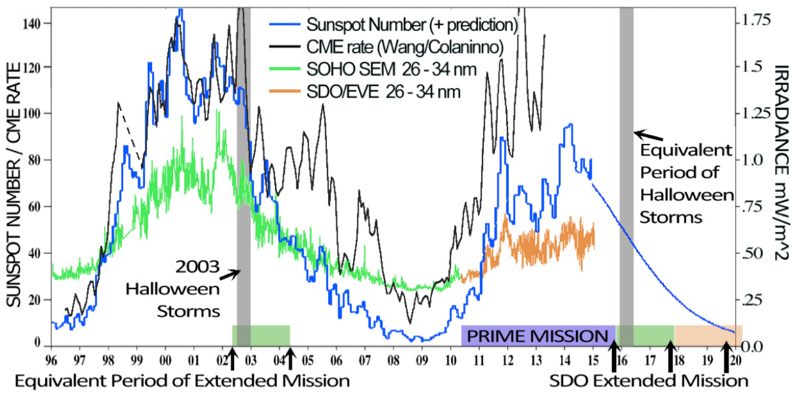

Figure 1.3 *Variation of monthly sunspot number (Schatten, 2005 for prediction) and CME occurrence rate (Wang & Colaninno, 2014) with time. Spectral irradiance in the 26-34 nm band is also plotted (SoHO SEM and SDO/EVE). The extended mission period is a very important time to study solar dynamics and geospace connections: The declining phase has historically produced more CMEs and high-speed streams relative to the irradiance. The period of the 2003 Halloween Storms during the declining phase of Solar Cycle 23 produced the strongest flare intensity ever recorded, intense CMEs, SEPs and geomagnetic storms. Relative to solar maximum, the equivalent period of the 2003 Halloween storms falls during the first year of the SDO extended mission.*

1.3.1. SDO Prime Mission Science Highlights

Breakthroughs in Coronal Seismology: SDO has produced a rapid expansion in the use of coronal seismology to understand the Sun's corona, because the high cadence and signal-to-noise ratio of AIA enable us to identify distinct coronal wave types. Among the discoveries that crucially depend on the high image cadence are waves interpreted as fast-mode magnetosonic wave trains that propagate at high speeds (up to some 2000 km/s; Liu *et al*. 2011; 2012b). Although the mode of these waves has been identified, their source has not yet: intriguingly, Liu *et al*. (2011, 2012b) find that the period of the fast-mode wave trains matches pulsations in the X-ray flare signal, but any causal connection remains elusive. Other wave types discovered or interpreted with crucial AIA observations include (a) transverse loop oscillations in hot (~10 MK) loops, observed off the limb (White *et al*. 2012); (b) standing slow-mode magneto-acoustic modes observed in combination of Nobeyama Radioheliograph microwave data (Kim *et al*. 2012); and (c) Large-amplitude (up to 25 Mm), low-frequency (of order 1 hour) oscillations in quiescent filaments (*e.g*. Li and Zhang, 2012). The latter waves are but one type of the many wave and wave-like phenomena excited by eruptive flares that can lead to rapid modifications of the outermost solar atmosphere. In such events, EUV Waves are often seen moving across the disk of the Sun, often in association with reflections and refraction phenomena (*e.g*. Liu *et al*. 2012b; Olmedo *et al*. 2012; Schrijver *et al*. 2013) as the expansion front excites quasi-resonant oscillations or as the wave fronts bounce off a region with modified propagation properties; models based on, or compared to AIA data have revealed the distinct behaviors of piston-driven waves and freely running fast magnetosonic waves, often in conjunction depending on coronal conditions that depend on height or direction (*e.g*. Schrijver *et al*. 2011a, and references therein). These waves have been used to measure the magnetic field and other properties of the

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[3] *http://sec.gsfc.nasa.gov/roadmap_2014_oct_draft.pdf*

[4] *http://www.nap.edu/catalog/13060/solar-and-space-physics-a-science-for-a-technological-society*

corona, by "sounding out" the structure through which the various wave modes propagate (see review by Liu & Ofman 2014).

Understanding The Solar Magnetic Field: Every observable change on the Sun, and subsequent effect felt by the heliosphere and geospace, originates in the Sun's evolving magnetic field. SDO observations have enabled significant progress towards one of the highest priority scientific goals of the LWS program: understanding the impulsive, eruptive nature of active regions that we see as energetic flares and coronal mass ejections (CMEs). The particles and fields expelled from the Sun by these events move though the heliosphere and strike planets. Extrapolating the coronal field from surface field measurements alone has proven problematic, but work by Malanushenko *et al.* (2014) shows that model fields based on SDO/HMI magnetic maps can be guided by the coronal loops imaged by SDO/AIA to map the 3D magnetic field and to quantify the embedded currents, thus enabling a more robust determination of the energy available for explosions. Gary *et al.* (2014) use another algorithm to combine HMI and AIA observations and derive the 3D coronal field over active regions, as a quantitative test of model fields. And Dudík *et al.* (2014) compared SDO/AIA observations with computer simulations to show that one candidate mechanism to destabilize the solar magnetic field (involving flux-rope currents) predicts features that match the observations for the event studied. These studies show that the combination of surface field measurements with coronal extreme-ultraviolet imaging enables us to measure the amount of energy that is available for flares and CMEs, and to advance our understanding of the destabilization of the Sun's magnetic field.

Turning the Sun Outside In: HMI Dopplergrams map the instantaneous line-of-sight motions over the solar disk once every 45 sec. The measured properties are used to probe the solar interior, including the dynamos that generate magnetic fields and fuel solar activity. Local surface motions result from two sources: the flows associated with turbulent convective cells near the surface, and the oscillations due to acoustic waves trapped within the solar interior and reflecting near the surface. Longer-lived turbulent cells identified in Dopplergrams may be used to directly trace the flows of the plasma in which they are embedded, just as magnetic and intensity features are used, but with the benefit that they are ubiquitous, covering all latitudes at all phases of the cycle. Hathaway *et al.* (2013) used these cells, known as supergranules, to show that there are also larger, deeper "giant cells" responsible for the faster rotation at the equator than at the poles. We have no *a priori* knowledge however of the depth to which the supergranules (or other surface features) penetrate nor how their surface motions may be affected by radial shears. Measured frequency and phase shifts of the acoustic waves (p-modes), which penetrate to the deep interior of the Sun, allow us to directly determine the plasma velocities below the surface. Zhao *et al.* (2013) for example discovered a meridional velocity profile with two cells within the sun, one overlying the other, rather than the single cell that had been assumed in earlier work. Hazra et al. (2014) found that their solar dynamo model is unable to reproduce solar behavior without a low-latitude equatorward flow at the bottom of the convection zone, as might be expected for the simple single-cell meridional flow. Chakraborty (2015) examined the center-to-limb effect that initially masked these discoveries in a Ph.D. dissertation. Other work has determined that the shape of the cells changes as solar activity comes and goes. Sometimes there is a single cell from equator to pole and other times there are several upwelling and downwelling regions (Zhao *et al.* 2014). The variation of the torsional oscillations has been examined for even longer-term predictions. Rings of slightly faster and slightly slower rotation gird the Sun and drift slowly from high latitudes toward the equator as the solar cycle progresses; Zhao *et al.* (2014) examined the motion of these rings and found that the timing of the maximum of Solar Cycle 24 inside the Sun agrees with the north-south difference in timing observed at the surface.

Space Weather in a Weak Solar Cycle: Although Solar Cycle 24 has proven to be below average in the sunspot number, numerous space weather effects, including strong flares and fast CMEs, are still observed (see Figure 1.3). EVE and AIA measurements quantified a new late phase of flares, a brightening of the Sun in EUV wavelengths that starts after the main X-ray bright phase, lasts up to several hours, and can emit *more* total energy than the X-ray phase. These EUV wavelengths are absorbed higher in the Earth's atmosphere, creating and modifying the F-region ionosphere. Because the late phase can last several hours, the atmospheric response becomes intertwined with the diurnal variations. A new set of flare classes that include the complexity of the flaring region and the late flare phase was part of one Ph. D. dissertation (Hock 2012), while another Ph. D. study (Mason *et al*. 2014) has demonstrated how EVE full-disk measurements of "coronal dimmings" may provide an early warning that a coronal mass ejection has occurred. Yet another Ph. D. dissertation (Krista 2012) mapped observations of coronal holes by the high-contrast AIA images to their space weather effects at the Earth. Coronal holes that develop during the decline of a solar cycle will emit high-speed streams that can be an important driver of geomagnetic storms, and they can also affect the propagation of CMEs through the heliosphere and modulate the geomagnetic impact.

As stated above, even a below-average solar cycle can have events with significant space weather effects. The first X-class flare of Solar Cycle 24 on 15 February 2011 was accompanied by a halo CME. Active Region 11158, the site of the February 2011 flare, was studied in great detail and in many wavelengths. Subsequent erupting region studies have formed the basis of new eruptive energetic models (see Section 1.4). EVE data are also being used by NOAA/SWPC as a proxy for X-rays as part of NOAA's space weather environment monitoring. The results of this research show success in providing national scientific capabilities through skilled researchers enhancing our knowledge base.

Rapid Changes in the Global Corona: Many examples have been observed where one part of the Sun's corona rapidly changes because something else changes far away. Observations with SDO have shown the entire corona can respond to an explosive eruption by a crowning of the magnetic field, much like a forest fire moving through the tops of trees. A model of these sympathetic eruptions has shown how they are triggered, even how the order of eruption is not necessarily determined by proximity alone (Schrijver *et al*. 2011a). Another example is material from a filament eruption falling back onto the Sun. The kinetic energy of the material falling back onto the Sun should be about the same as the energy emitted by that material as it stops (Gilbert *et al*. 2013). Models of the behavior of this material can be a basis for stellar accretion (Reale *et al*. 2014; 2015). Additionally, brightenings seen when a comet passes through the corona or when material from an eruption falls back onto the Sun may be very small in size but are important checks on our understanding of how the corona works. These observations help calibrate our models of the coronal magnetic field and add to our understanding of how the emissions are created. The heating of the ice evaporated from sun-grazing comets to the millions of degrees of the corona tests our understanding of the magnetic field deflecting the material and how cooler material is visible in the telescopes. Models of the solar magnetic field were improved to explain observations (Downs *et al*., 2013), and emission models of the corona were adjusted to allow for the input of new material (Bryans & Pesnell, 2012).

Solar Filaments and Their Eruptions: Solar filaments, large configurations of relatively cool material, are an integral part of the solar coronal field. In quiescence, that field suspends the filament plasma high above the surface of the Sun. Their presence and dynamics are often used as early indicators of coronal mass ejections that can eventually drive space weather. The continuous, high-cadence SDO observations have now enabled scientists to observe in detail how filaments are formed by tracing both the field patterns with HMI and the coronal evolution with AIA. The cool material responsible for the filament's appearance has been observed to cool down ("condense") from the surrounding coronal material (*e.g*. Berger *et al*. 2012). Observations also revealed that matter often drains out of a filament on a time scale of order one day, even as continuing condensation into the filament allows it to survive. (Liu *et al*. 2012a). The AIA observations also show how the filaments' field configurations destabilize, subject to the buildup of currents within them or the evolution of the surrounding field (*e.g*., Su & van Ballegooijen 2013). These results advance our scientific understanding of the physical processes governing the Sun and heliosphere and shed new light on a key question in Heliophysics: How filaments are maintained and why they erupt.

1.3.2.Public Involvement in SDO

SDO's media outreach activities have been extremely successful. The "Little SDO" Facebook page has over 900,000 followers and is one of the most popular NASA-related pages ever. Since launch, SDO images featured regularly in news stories, television shows, and documentaries about the Sun, space, and space weather. Media events organized by the SDO team include three SDO Data Events where the NRT data from a rare event was made available to the public through specially prepared websites and activities. All three involved special modes of spacecraft operation. The two comet events used spacecraft offpoints, while the 2012 Venus Transit reduced the compression ratio and spatial coverage of AIA images to improve the usefulness of those images for calibrations. Each SDO Data Event has required a special effort to handle the large data flows generated by the enormous public interest in the SDO images. SDO's Comet ISON Perihelion Data Event was the best-planned, and created the largest audience so far. We delivered 15 TB of data to over a million users during this Data Event. There were 33,000 RSVPs to the Google+ Hangout that ran during this event (500 was considered "exceptional" before), and 37,000 people participated in the Hangout (1000 had been considered "big"), as well as over 260,000 views on the SDO YouTube channel.

Other activities are ongoing and we hope to continue their support through the Extended Mission. For example, the SDO self-updating NRT movies are being adopted by more museums and public venues as an easy way to show up-to-date solar data with a minimum of effort. The Helioviewer tool, developed with partial support from SDO, has provided a window into the science data for citizen scientists to make and post movies of solar activity. Public users have created over 1.5 million SDO movies through the Helioviewer interfaces and have served as "SDO ambassadors" by sharing and publishing their efforts.

1.4. Science Plan and Prioritized Objectives in the Extended Mission of SDO

SDO has captured the rise from solar minimum to Cycle 24 maximum, and has in turn captivated the scientific community and the public with many exciting discoveries. The second half of the cycle presents new challenges and opportunities. As active regions migrate to ever-lower latitudes, magnetic interactions across the equator increase. As the poles start to accumulate flux for the next cycle, coronal holes and polar crown filaments become more common. These structural changes in the Sun motivate the following carefully selected Prioritized Science Goals (PSGs) for the next five years; these are only a small subset of the science that will be enabled by continued operation of SDO:

PSG 1: Subsurface Flows and Structure

PSG 2: Magnetic Variability and the Solar Cycle

PSG 3: Characterizing the Eruptive Potential of Active Regions

PSG 4: Collaborative Studies of Solar Eruptive Events (SEEs)

PSG 5: Global-Scale Coronal Dynamics Driving the Heliosphere and Magnetospheres

Table 1.1 (follows the PSGs on page 19) is a traceability matrix that relates each of the PSGs to the Focus Areas in the NASA 2014 Heliophysics Draft Roadmap and also the Challenges identified in the Heliophysics Decadal Survey. **At the over-guide funding level, PSG tasks identified as part of the "Two-year plan" form our primary validation effort and can be implemented.** Descriptions of the "Five-year plans" identify compelling investigations that could be addressed during additional extensions of SDO or can be carried out by external researchers. At the in-guide funding level, few of the science tasks detailed in the two- and five-year plans can be completed (see Section 3.2). Longitudinal and Stokes parameter maps will continue to be generated, but the SDO team will not be able to create vector magnetic maps for direct use in scientific studies, and will not be able to monitor or reduce systematic effects in the magnetic data. AIA images and EVE spectra would be produced, but the SDO team would not be able to maintain their calibration or play an active coordinating role within the larger research community, especially in the production of the metadata that eases the access to these images.

1.4.1. PSG 1: Subsurface Flows and Structure

Some of the SDO mission science goals involve understanding the structure and evolution of large-scale sub-surface flows and their relationship to the solar cycle; the subsurface structure and flows associated with local features and events such as active region emergence, flares, and atmospheric waves; and the physics of the internal acoustic waves. With high spatial resolution, continuity, and long-term stability, SDO observations are uniquely suited for the techniques of local helioseismology to make progress toward these goals.

PSG1 Task 1 – Extended measurements of the meridional cell structure. Significant new features of solar meridional circulation have been discovered with HMI data and await further data and analysis for confirmation and more complete characterization. These include the double-cell structure (Zhao *et al.* 2013), and a possible second pair of cells at very high latitudes in near-surface flows (Komm *et al.* 2013). Current noise levels prevent us from inferring the flow profile below 0.75 $R_\odot$, an important region close to the tachocline where the magnetic field is thought to be generated. Zhao *et al.* (2014) demonstrated that the subsurface meridional flow speed is anti-correlated with the poleward magnetic flux transport, meaning that a slower poleward flow may slow the magnetic polarity reversal (see also PSG2 Task 1).

Two-year plan: Extension of the data will reduce the noise level and allow the detection of the meridional flow speed nearer to the base of the convection zone. Five-year plan: This will allow us to complete the picture of the meridional circulation through the entire convection zone. Additional data will allow us to follow changes in the meridional flow between 0.75-1.0 $R_\odot$ over the course of a solar cycle.

PSG1 Task 2 – Measurement and analysis of localized flow structures. Analysis of the zonal flow fields observed with HMI has shown hemispheric asymmetries in the evolution of the torsional oscillation that seem to be correlated with hemispheric differences in the phasing of activity during the part of the current cycle that has been observed (Komm *et al.* 2014). They have also revealed ephemeral belts of anomalous zonal flows at high latitudes (Hathaway *et al.* 2013; Bogart *et al.* 2015; see also Fig 1.3). At least five such features lasting three to six months have been observed during the SDO mission with high-resolution ring-diagram analysis. Two-year plan: Detection and characterization of additional features during the declining phase of the cycle, and mapping of their 3-dimensional structure should give us a clearer understanding of their nature and their role in the torsional oscillation and the extended solar cycle. Beyond that, observations during the cycle minimum and polar field reversal may lead to some understanding of the patterns of active region emergence in preferred hemispheres or longitudes.

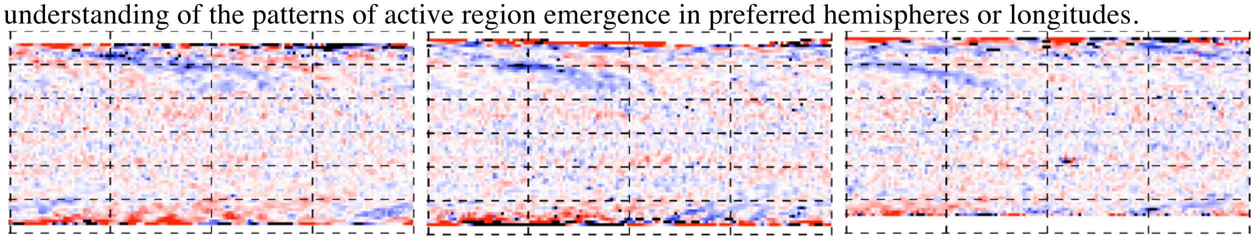

Figure 1.4 *Synoptic maps of the anomalous zonal flows inferred from ring-diagram analysis over the course of Carrington rotations 2097-2099 (19 May - 5 Sep 2010). Red areas have super-rotational flows relative to the mean for their latitudes, and blue opposite; the color scale ranges between ±0.5 m/s; lines of latitude are shown at intervals of 30^0 and of longitude at 90^0.*

PSG1 Task 3 – Implementation of new procedures for far-side imaging. Two-year plan: Monitoring of far-side active regions using helioseismic tools (Lindsey & Braun 2000) is very useful for global coronal field modeling, and leads to improvements in forecasting of space weather. Although the number of active regions is declining, large active regions with strong flaring activity are still likely to occur. Extended observation by HMI will enable continuous monitoring of far-side active regions. A new approach to far-side imaging based on time-distance techniques (Ilonidis *et al.* 2009; see also Liewer *et al.* 2015) will be implemented. This should improve the robustness of these data vital to space-weather forecasting and the planning of observations. Existing far-side maps need better calibration, which the proposed combination of different techniques will provide.

PSG1 Task 4 – Active region subsurface structure. Five-year plan: Although there are still uncertainties in the determination of the structure and evolution of large-scale flow fields, the general picture that has emerged is reasonably secure. The same cannot be said for the structure and dynamics associated with localized features and events. There are several problems: uncertainties in the physical interpretation of the measurements in areas of strong magnetic fields (Gizon *et al.* 2009; Moradi *et al.* 2010); incomplete understanding of the physics of wave generation, propagation, scattering, and absorption in such regions (*e.g.* Cally & Moradi 2013); and small samples of the events to be studied, especially the most extreme cases. Significant anomalies in subsurface flow fields and thermal structure in and near sunspot are observed, but to what extent these anomalies are symptomatic or results of the observation technique and analysis of the data is not really known. Additional data and improved modeling and analysis procedures will be required to sort out these issues.

PSG1 Task 5 – Mode physics. Five-year plan: Work is under way to learn more about the physics of the modes themselves. For example, there is evidence of cycle-dependent effects in the strength of high-frequency oscillations above the acoustic cutoff frequency in both HMI and AIA data (Howe *et al*. 2012). Study of these and other unusual phenomena, as well as solutions to the outstanding problems noted above will be facilitated by new data. Experience with the HMI data has led to a greater understanding of the best ways to compute and characterize the helioseismic data. Improved techniques are currently being implemented in both the measurement and the inversions of ring-diagram parameters.

PSG1 Task 6 – Sunquakes. Five-year plan: Flare-induced sunquake events (Fisher *et al*. 2012; Kosovichev & Zharkova 1998) provide unique opportunities to understand particle acceleration, energy transport, and shock waves caused by flares. However, these events are rare, and HMI has so far captured only about 20, insufficient to study this phenomenon statistically. Based on the behavior of the previous solar cycle, we expect more and stronger sunquake events during this declining phase.

1.4.2. PSG 2: Magnetic Variability and the Solar Cycle

Understanding the magnetic field is key to deciphering solar variability and the causes of space weather. Improved continuous full-disk measurement of the emergence, evolution, transport, and decay of the field by HMI during the start of the declining phase of Cycle 24 will enable the heliophysics community to gain that understanding by studying active regions and the field in less active regions, as well as the origins of disturbances observed at Earth and throughout the heliosphere. These research activities will continue inside the SDO science team and in the scientific community.

Solar Cycle 24 started with an extended minimum not seen before with advanced instrumentation able to record the Sun's magnetic fields, and the cycle continues to defy expectations and predictions by its irregular behavior with time, and its uncommonly weak polar cap field. Observing the unfolding of this phenomenon is of high interest and value to solar and stellar dynamo theorists because of its uniqueness, as well as to those interested in Sun-Earth couplings and galactic cosmic rays because they present extreme conditions to explore beyond the more common states of past decades.

PSG2 Task 1 – Magnetic field evolution over the solar cycle. Understanding the solar cycle is a fundamental goal of solar physics. Phenomenological magnetic flux transport models successfully reproduce the evolution of large-scale photospheric magnetic flux patterns based on observations of active regions and elsewhere, including the poles. As described in Section 1.3, combining HMI flow and magnetic field data led to the discovery of a difference in the meridional flow speed of near-photospheric plasma in regions of different magnetic polarity (Zhao *et al*. 2014). Areas dominated by trailing field move poleward more slowly than plasma in leading field regions. A quantitative relationship was found between flow speed and magnetic field (Sun *et al*. 2014, Figure 1.5).

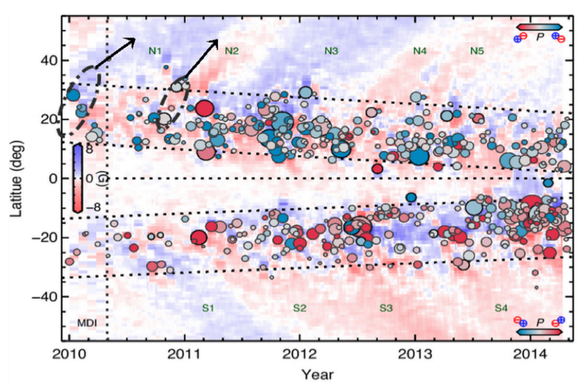

Figure 1.5 *"Butterfly diagram" showing flux from active regions (ARs) migrating poleward. Blue regions are positive flux, red regions are negative flux. Circles show individual ARs; size is proportional to umbral area and color is a proxy for the AR poloidal field. The black ovals identify ARs that initiated two of the poleward surges, which are indicated by arrows. This cycle, ARs in the north typically are blue. Sun et al. (2014) found that the leading polarity (red) surges move faster.*

Two-year plan: We will track the evolution of the photospheric magnetic field over the cycle identifying the contribution of each emerged active region to the decay and re-establishment of the new polar field. We will measure the flux that emerges and does not cancel or make its way to the poles, i.e. the flux that must cancel across the equator, as another measure of the flux that feeds the next cycle. While SDO measures magnetic field only on the disk, every visible patch of flux is tracked and cross-equatorial transport can be measured. Five-year plan: We will watch the development during the approach to solar minimum using the vector measurements; this will lead to a better understanding of (1) polar field reversal timing and strength; (2) solar activity cycle amplitude; and (3) north-south asymmetry in magnetic activity.

PSG2 Task 2 – Improving sensitivity of the HMI vector magnetic field observations. This will be a boon for studying the large-scale field. An ongoing effort is to reduce noise and better understand the systematic errors in HMI field measurements. The Q and U components of the Stokes polarization vector can be improved by combining filtergrams from the two HMI cameras, something we now know can be done successfully. Two-year plan: We will implement and validate a new observing program that uses the current circular polarization measurements from HMI's Doppler camera and additional linear polarization measurements from the Vector camera, without compromising the line-of-sight velocity or magnetic field sequence. This should increase our sensitivity in weaker-field regions by reducing photon noise by ~25%. Five-year plan: Most of the surface is covered by weak magnetic field, increasingly so as the declining phase continues. There is much to be learned by determining the characteristics of the ubiquitous horizontal component of field – its size scale and lifetime, as well as it spatial organization and dependence on location – outside of active regions.

PSG2 Task 3 – Active region twist. Magnetic twist is an inherent property of the field that can be inferred from series of vector magnetograms. Twist provides a window into the physical processes by which the field is generated in the solar interior, modified during its buoyant rise to the solar surface, and modified by surface dynamics. The build-up of twist must be closely tracked in emerging regions; and it is a key ingredient in triggering energetic events in the corona. Understanding twist is important for successfully forecasting space weather. Active region twist shows a hemispheric sign preference that depends strongly on the relative sign of magnetic twist and writhe, particularly in emerging active regions (Liu *et al*. 2014). The differences can distinguish multiple sources of twist and analysis suggests that at least some of the twist is generated by surface dynamics. Liu *et al*. (2013) discovered that subsurface flow gradients are different in simple and complex active regions. Two-year plan: We will investigate the extent to which near-surface processes are important and determine whether helioseismology can identify regions that will produce eruptions. The coupling of convective turbulence to rising flux tubes may change through the cycle or be associated with nests of solar activity. Five-year plan: Analysis of HMI and AIA observations of the solar surface and atmosphere will illuminate the coupled magnetic and kinematic processes acting in the solar interior and on the solar surface, and therefore of the solar dynamo and sources of helicity in active regions.

PSG2 Task 4 – Improving HMI science data by scattered light removal. Recently filtergrams corrected for the instrumental point spread function have been used to construct improved HMI observables, showing that sunspots are even darker and cooler than expected and that magnetic field measurements are most affected in plage regions (Norton *et al*. 2015). Though HMI does not have the highest spatial resolution, the consistent performance of the HMI instrument will allow us to study how sunspot parameters change during the course of this solar cycle. Two-year plan: We will determine how best to apply the scattered light correction to improve magnetic, intensity, and velocity measurements from HMI on the small scale that will enable better understanding of the nature of convection and how it changes over the cycle and with latitude. Five-year plan: We will observe convective changes during more of the cycle and apply the PSF correction to more of the data.

PSG2 Task 5 – MHD waves in the solar atmosphere. The presence of magnetic fields in the photosphere leads to conversion of acoustic waves to MHD modes. Couvidat (2013) compared converging and diverging waves at multiple heights and found that while sunspots are generally absorbers, for certain mode frequencies enhancements appear around sunspots. Likewise, wave phenomena in the chromosphere and corona are observed are probably associated with sub-photospheric oscillations (De Pontieu *et al*. 2015), but there is as yet insufficient correlative data to draw firm conclusions. Two-year plan: We will combine helioseismology and vector magnetic measurements from HMI and Hinode with IRIS and AIA observations in the chromosphere and atmosphere to determine how acoustic power couples to the corona under different magnetic field conditions. Five-year plan: Some MHD waves may contribute to shock heating in the chromospheric network, but we will investigate how energy in Alfvénic waves may reach the corona before dissipating, something that Solar Probe Plus may able to detect in future years.

PSG2 Task 6 – Flux rope and prominence formation. Flux ropes and prominences form over time via flux emergence and because of photospheric dynamics, but the process is not well understood, nor is it clear why some flux ropes erupt as CMEs while other CMEs form visible flux ropes only after eruption. HMI provides the long, uninterrupted time series of vector field measurements necessary to study formation and eruption of flux ropes. Two-year plan: We will work with modelers to make meaningful comparisons over the course of the solar cycle.

1.4.3. PSG 3: Characterizing the Eruptive Potential of Active Regions

Under what circumstances does the solar magnetic field explosively erupt? That question – at the core of several Heliophysics Roadmap RFAs (see Table 1.1) – continues to challenge solar physicists. Both empirical and modeling approaches are key to addressing this question and SDO provides critical input to both via its (vector-) magnetic field maps and the coronal images.

Before the SDO era, there was a large body of empirical work relating surface magnetic measurements to the probability of imminent flares and eruptions. More often than not, model inputs were heuristic quantities (*e.g*., unsigned flux content near inversion lines, see Schrijver 2007) computed from line-of-sight surface magnetograms. SDO has opened up new possibilities for this type of empirical analysis. Recently, Bobra & Couvidat (2015) trained a support vector machine (SVM) to forecast major flares (M1.0 and above) using a 25-dimensional feature space. The predictive skill (true skill statistic) of the SVM is a significant improvement over prior work. Although the study used 25 magnetic parameters, only four are found to be important. These are the total unsigned current helicity, magnitude of the Lorentz force, photospheric magnetic free energy density, and unsigned vertical current, all of which depend on all three components of the magnetic field.

While advances in forecasting based on statistical and machine learning algorithms is important for space weather operations, they do not directly teach us about the physics of flares and eruptions. For this we need 3D models of the magnetic field in the higher atmosphere. HMI surface field data provide the critical input needed for the boundary conditions of such models (e.g. Sun *et al*. 2012; Jing *et al*. 2012). Due to ambiguous results inherent in Non-linear Force Free (NLFF) extrapolations (DeRosa *et al*. 2009), AIA EUV and UV observations are essential for their model validation. Furthermore, the AIA team has successfully demonstrated a promising application of an entirely new method that combines HMI surface field measurements with AIA loop tracings so that observed loops are direct guides to the iterative process towards a NLFF field (Malanushenko *et al*. 2012).

The NLFF field models described above are constrained by instantaneous measurements and do not take into account the full time history of photospheric driving by flux emergence, submergence, shearing and diffusion. SDO has enabled a new class of models treating these effects. *Data-driven* models that use the photospheric electric field inferred from HMI vector magnetograms (*e.g*. method by Kazachenko *et al*. 2014) as time-dependent bottom boundary conditions have been applied to simulate ARs formation and destabilization (*e.g*. Cheung & DeRosa 2012). This type of modeling was also used to reveal the driver of homologous helical jets observed by IRIS, Hinode and AIA (Cheung *et al*. 2015). Such work illustrates how SDO provides more than just context imaging for other missions of the Heliophysics Systems Observatory. It demonstrates how SDO delivers unique science data to help us understand the physics of energetic events.

At least four Strategic Capability teams co-funded by NASA and NSF (with periods of performance between 2013 and 2018, *https://www.nas.nasa.gov/hms/2014program.html*) to model the Sun-Earth connection require HMI and AIA data, for model input and/or validation. As an example, the team led by G. Fisher at UC Berkeley is developing a data-driven model of the global coronal field with a commitment to deliver a module to NASA's Community Coordinated Modeling Center (CCMC). This model requires HMI vector fields for boundary conditions and AIA images for validation. Operation of SDO in the declining phase of Solar Cycle 24 will provide the essential data needed for modeling how low latitude ARs interact across the equator.

We propose the following science tasks pertaining for PSG 3:

PSG3 Task 1 – EUV-loop guided NLFF modeling. Two-year plan: The SDO team plans to develop the Malanushenko method into a tool for modeling large samples of ARs to quantify the free energy and relative helicity evolution leading up to, and following flares (NLFF fields cannot be used through the dynamic phase of eruptions). The team's ultimate goal for this project in the Extended Mission phase is to be able to create realistic model fields for (1) statistical analyses of free magnetic energy and helicity, and (2) providing initial conditions to MHD models by external investigations (to be supported through the NASA/SMD or NSF grants programs) to study which MHD instabilities lead to eruptions, and how magnetic reconnection permits abrupt energy release. Five-year plan: EUV-guided NLFF modeling will benefit from high-resolution stereoscopic observations, which will become a reality some time after the 2017 or 2018 launch of the Solar Orbiter, which carries EUV imaging instrumentation at comparable 174 Å and 304 Å channels at 1-arcsec resolution that are planned to be turned on for campaigns already during the early cruise phase.

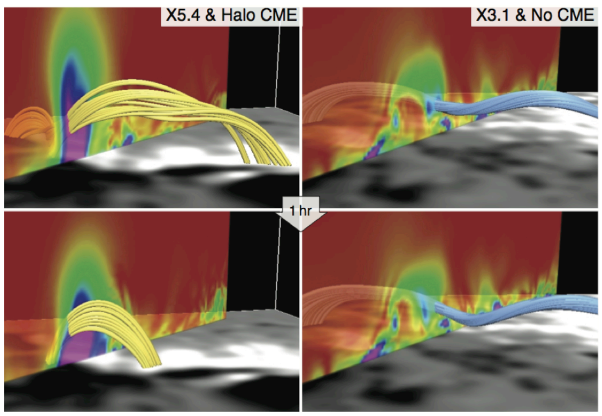

Figure 1.6 *Magnetic topology changes computed for two major flares, 7 Mar 2012 (left) and 24 Oct 2014 (right). Unlike most X-class flares, the 2014 event had no associated CME. Top panels show the pre-flare state; bottom panels show the post-flare state. In each panel, the lower monochrome boundary shows* B_z. *The semi-transparent vertical cross section shows the electric current density inferred from non-linear force-free field extrapolation, where red is the weakest and purple is the strongest. The topology change is large on the left (with CME) and small on the right (no CME).*

PSG3 Task 2 – Extension of SVMs for flare prediction. Two-year plan: The SDO team will further their analysis of flare prediction with machine learning algorithms. As in any prediction model, it is important to test whether the model has been overfitted. The training and validation data sets used by Bobra & Couvidat (2015) were limited to HMI AR patches taken during the first half of cycle 24, and it is important to find out whether the method has the same predictive skill for major flares produced by ARs at lower latitudes. Furthermore, the HMI and AIA teams will test whether the predictive skill of the method can be further improved by incorporating HEK events and EUV coronal features. Five-year plan: We will exploit novel machine learning techniques on a full cycle's worth of SDO data.

PSG3 Task 3 – Eruptive vs. non-eruptive events. Figure 1.6 shows the magnetic connections computed using HMI vector field before and after two X-class flares. The 2012 flare associated with a CME showed strong permanent changes in the horizontal field and field connections, whereas the CME-less 2014 flare associated with the largest sunspot group of Solar Cycle 24 was much less affected (Sun *et al*. 2015b). In this science task we will investigate what magnetic field configurations and topologies produce flares with and without CMEs (i.e., eruptive vs. non-eruptive). Two-year plan: We will characterize the changes in topologies of ARs before and after flares. We will test whether (1) the change in the photospheric horizontal field before and after a flare and (2) the change in magnetic topology in 3D field models are consistently smaller for non-eruptive flare events. Five-year plan: We will examine how magnetic topology/complexity determines whether flares of different sizes have associated CMEs using a full cycle's worth of SDO observations. PSG3 Task 3 is a joint effort with PSG4, which explicitly focuses on eruptive events.

1.4.4. PSG 4: Collaborative Studies of Solar Eruptive Events (SEEs)

There are many aspects of understanding the complex physics and processes of how magnetic reconnection can accelerate particles to high energies and lead to explosive eruptions that the 2012 HDS refers to as Solar Eruptive Events (SEEs). These events have long been studied in solar physics for their explosive release of energy in magnetized plasma, and studies often focus on the X-ray and EUV flares, CMEs, and solar energetic particles (SEPs). This SDO PSG, like PSG3, helps address a fundamental science question of the 2012 Heliophysics Decadal Survey: *Why does the solar magnetic field at times explosively erupt?* But different for PSG4 are tasks that require a broader collaboration between the SDO team and other HSO mission teams and ROSES investigators.

The HMI vector magnetic fields of active regions, AIA images of coronal structure, and EVE spectral EUV irradiance variations are critical for the PSG4 studies, along with collaborations with several other HSO missions, with a few key ones listed in the following tasks.

PSG4 Task 1 – SEE energetics. Two-year plan**:** A large, global energetics study was performed on 38 large SEEs (Emslie *et al.* 2012), but these events were from 2002 to 2006 - well before the SDO era - and only performed for the largest events. There have been more than 6000 SEEs observed by SDO with the X-ray flare magnitude of C1.0 or larger; a systematic analysis of SEE energetics, versus just the focus on a few events, is a rich area of research to pursue with the SDO data during the extended mission. The HMI fields can address the questions about how much magnetic free energy is available for SEEs. The combination of AIA corona images and EVE spectral EUV irradiance is providing information about particle acceleration, such as related to electron density increases in flare loops (Milligan *et al*. 2012), total flare radiated energy budgets in the EUV (Chamberlin *et al*. 2012), mass loss for CMEs (Mason *et al*. 2014), and post-eruption coronal cooling (Woods *et al.* 2011). The SDO observations, along with chromospheric measurements by IRIS, CME coronagraph observations by STEREO and SoHO, and hard X-ray observations by RHESSI, provide a more complete view of physical diagnostics addressing the energetics associated with the initiation and evolution of SEEs. For example, Milligan *et al*. (2014) provides a detailed study of the flare energetics combining SDO, RHESSI, and Hinode observations for understanding the acceleration and energy distribution of particles during the flare impulsive phase and their absorption depth into the chromosphere. Five-year plan: Some of the larger eruptive events have occurred during the declining phase (e.g. Halloween 2003 storms), so we anticipate new, and perhaps larger, events to study in the extended mission as cycle 24 declines towards the next minimum expected in 2018-2020. Longer term studies can build on these statistics from the early part of the SDO mission as well as start to look at SEEs and their changing energy evolutions and partitions throughout this solar cycle and with the future Solar Orbiter and Solar Probe Plus missions.

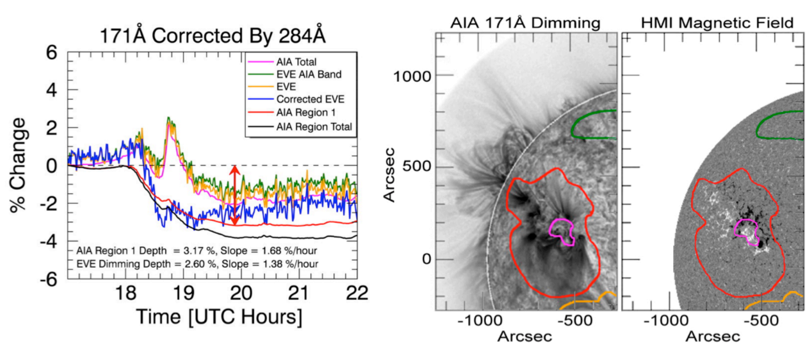

***Figure 1.7** Example of coronal dimming analysis with SDO data for the eruption on 7 Aug 2010. The coronal dimming region (red outline is region 1) is shown on the right for AIA and HMI images. The EVE Fe IX 171 Å irradiance decrease is consistent with the AIA region 1 dimming once the impulsive phase component is corrected using EVE Fe XV 284 Å (left: orange is uncorrected, blue is corrected).*

PSG4 Task 2 - On-disk CME detection. Two-year plan: The research community has relied on SDO's instrumentation to understand the origin and initiation of CMEs in collaboration with STEREO and SoHO observations. On October 1, 2015 STEREO-A/B will be at 170/175 degrees longitude separation from Earth. Small coronagraph separations make CME triangulation very difficult and unreliable; on-disk signatures are extremely important in understanding the 3D structure of CMEs. During this period in particular, the scientific community is heavily reliant on AIA coronal images to provide vital information regarding the 3D kinematics of eruptions. On October 1, 2017 the STEREO separations will be approaching 120 degrees apiece, which is much more advantageous for studying CMEs. However, if we do not recover STEREO-B, then we are facing a situation where there will be many CMEs that cannot be triangulated because of viewing geometries.

PSG4 Task 3 – Coronal dimming as CME proxy Two-year plan: One of the interesting discoveries of SDO is that evacuations of material due to solar eruptions, called "Coronal Dimmings," can be clearly observed and studied with the EVE full-disk irradiance observations. Figure 1.7 shows the synergy of the three SDO investigations when applied to the study of these phenomena as shown for the 7 Aug 2010 event (Mason *et al*., 2014). Following an eruption, EVE usually detects a decrease in irradiance for the cool coronal emissions (e.g. Fe IX – Fe XII). AIA is able to determine where the dimmings took place and identify which solar features are connected, and the combination of AIA and HMI allows us to understand the magnetic structure and evolution associated with the dimmings. The EVE coronal dimming observations, once corrected by removing the impulsive phase component, agrees very well with the AIA dimming observations as shown in Figure 1.7. The depth of the dimming is expected to be representative of the CME mass, thus more studies of the coronal dimming events, along with STEREO and SoHO CME coronagraph observations, during the extended mission are anticipated to improve the relationship of the coronal dimming properties to CME properties. Five-year plan: Our longer-term goal is to develop the capability for SDO data to be used as NRT early warning of CME mass and direction for space weather operations.

PSG4 Task 4 – SEE impacts at Earth. Two-year plan: An underlying motivation for understanding the SEE physics is to provide better measurements and models of the solar radiation and particles for studying and predicting impacts of solar storms on Earth's space environment. The EVE spectral EUV irradiance measurements are key for such studies. The EVE measurements are used for ionosphere research (e.g., Sojka *et al*. 2014), for realtime flare-related warnings at the NOAA SWPC, and by the US Air Force for daily satellite drag & tracking analysis (Hock *et al*. 2013). SDO EVE is providing much higher cadence, higher spectral resolution, and lower-latency solar EUV irradiance data products than ever provided before. Furthermore, the improved understanding of flare phases and energetics in the different phases has initiated new studies on the impacts of solar flares on Earth's ionosphere and thermosphere. One of the SDO discoveries is the EUV late phase whereby there are large, secondary EUV enhancements one to six hours after the X-ray flare peak and the initial EUV flare peak (Woods *et al*. 2011; Hock 2012). The HSO observations of SEEs, along with numerical modeling of such events, can trace the source of the energetic release of photon radiation, mass ejections, and energetic particles from the sun, through the heliosphere, into Earth's magnetosphere, and finally precipitation of energy into Earth's upper atmosphere. The LWS Grand Challenge Research program called RAISE is one example of a ROSES program that is modeling the impacts of solar events in Earth's atmosphere and will be using SDO observations for some of their studies. Similarly, the NASA MAVEN mission to Mars is studying similar impacts of solar events in Mars atmosphere. Five-year plan: New studies for this task will begin following launch of NASA's ICON and GOLD missions in 2017.

1.4.5. PSG 5: Global-Scale Coronal Dynamics Driving the Heliosphere and Magnetospheres

HMI's full-disk magnetograms are at the foundation of modeling the global field that drives the solar wind and its embedded heliospheric field. These magnetograms, assembled into full-sphere synoptic maps (including the high-latitude and polar fields observable that need special attention because they are only observable during part of the Earth's orbit around the Sun, and then with difficulty so close to the limb) are important to both the approximate but fast "potential field source surface" (PFSS, as shown in Figure 1.2) field models and to increasingly sophisticated MHD models developed by external teams (e.g., at U. Mich. and Predictive Sciences). As algorithms evolve, we expect to see advances from field relaxation models based on parameterized flows and heat input, to continuously-evolving assimilative models for which SDO's continuity and cadence are critical input. All such field models are used to understand and forecast, e.g., recurrent solar-wind streams, energetic particle pathways, and CME propagation.

AIA's full-sun, continuous data enable the study of coronal dynamics up to the global scale. This includes the quiescent evolution of the coronal field due to the emergence and displacement of flux. On time scales below a fraction of an hour, AIA revealed details of large-scale phenomena that were largely, or even entirely, inaccessible to previous generations of instruments. Events may be coupled through expansion-driven waves, field deformation by distant eruptions, modified reconnection as the disrupted large-scale field relaxes, and large high flux ropes that are at times just visible near the edge of the AIA field, or by a combination of these. One early detailed study of a series of coupled events (Schrijver *et al.* 2011b) revealed connections spanning almost a full hemisphere (including part of the far side, as observed by STEREO's SECCHI). A subsequent MHD experiment by the AIA Co-I group at Predictive Sciences (Török *et al.* 2011) demonstrated how field deformations by one eruption could destabilize other adjacent field configurations. Subsequently, more such coupled events were described (*e.g.* Schrijver *et al.* 2013) as we continue to assess their statistics.

The evolution of erupting flux rope configurations into fully developed CMEs remains one of the fundamental challenges for heliophysics. The combined perspectives from SDO, SoHO, and STEREO have provided many examples from surface into inner heliosphere that have advanced our quantitative insight into how these eruptions depend on, e.g., the profile of the field above the erupting structure and on properties of the field near the polarity inversion lines (Figure 1.6). They have also revealed rare surprises: the largest sunspot region in two decades (in October of 2014), exhibited 6 X-class flares, none of which was associated with a CME, whereas on average 90% of all other X-class flares are. Clearly, the processes that make a CME depend sensitively on the local field and on the embedding large-scale field; rare events, such as those in October of 2014, provide new insights – requiring an extended mission.

These processes drive heliospheric variability and space weather; the diversity of proposed interpretations shows that we need more observations to sort through the proposed processes because in order to uncover the most telling features, events have to be viewed under just the right conditions, from the right perspective, and covered by multiple instruments; the latter is particularly demanding for the small fields of view of high-resolution imagers and spectrographs (e.g., instruments on Hinode and IRIS). Moreover, changes in the global field throughout the cycle modify the environmental conditions for these processes. Hence, there is a unique opportunity to add information by continuing SDO into the decay phase of the cycle as cross-equatorial coupling and the polar caps increase in significance.

Another, related challenge is understanding the conditions under which the early phases of CMEs lead to SEP events in the heliosphere, in particularly those that propagate to geospace. The acceleration profile of the flux rope and the rope's interaction with the surrounding medium are both important to the formation of a shock front. Whether this shock front leads to SEPs depends at least on the angle between field and the direction of shock propagation, and probably on the plasma population within the shocked region. AIA's measurements can be combined with models infer where shocks occur and SEP generation is expected.

The extended mission coincides with the decline of the solar cycle into the next minimum (expected in 2018-2020), which is a time of prime importance in understanding solar dynamic phenomena and the solar cycle that drives these variations. That later period overlaps with the planned mission phases of Solar Orbiter and the Solar Probe Plus, which in combination with SDO and STEREO will provide unprecedented coverage of the evolving inner heliosphere.

PSG5 Task 1 – Global solar field. Two-year plan: The SDO team proposes to continue to assemble full-Sun field maps, including high-latitude and polar fields, and to compute PFSS field models and overlays of these on AIA images (as on the Sun Today pages, through SolarSoft IDL routines for detailed comparison, and in the options of Helioviewer) as quick-look guides to community researchers. Five-year plan: Calibration of the polar fields and development of assimilation-based MHD models will be essential to interpret Solar Probe Plus (SPP) observations. Solar Orbiter (SO) and HMI data together provide increased surface-field coverage.

PSG5 Task2 – Driving the heliosphere. Two-year plan: The SDO team proposes continued work on the large-scale connections in the corona because of its importance in understanding why the solar magnetic field destabilizes (see under PSG3) and how such events evolve into the heliosphere, including the evolution into CMEs and the generation and propagation of solar energetic particles. ***(a)*** The team plans continuation of multi-perspective views of the Sun by the SDO and STEREO (see the Sun Today web pages at *http://sdowww.lmsal.com/suntoday_v2*). ***(b)*** The team intends to continue to characterize events in the HEK database to guide the community to events of interest, and will complete a statistical analysis of events to quantify the importance of flare-eruption couplings. ***(c)*** Plans include collaboration with Meng Jin (LWS Jack Eddy Fellow at LMSAL at least through August 2016), using the AWSoM MHD code developed at U. Michigan, to assess how eruptions from one region may affect the stability of other regions. ***(d)*** Moreover, the SDO team will support external groups. For example, the AIA team plans to support an investigation led by colleagues in Graz, Austria, who were recently funded for three years to analyze how eruptions evolve from what can be observed by AIA into inner-heliospheric CMEs. Five-year plan: Combination of SDO data with SPP, SO, and STEREO remote-sensing and in-situ data will improve understanding of how heliospheric processes impact CMEs en route to Earth. On October 1, 2015 STEREO-A/B will be at 170/175 degrees longitude separation from Earth; their small coronagraph separations make CME triangulation unreliable. During this period in particular, the scientific community is heavily reliant on AIA disk images to provide vital information regarding the 3D kinematics of eruptions. On October 1, 2017 the STEREO separations will be approaching 120 degrees, which is much more advantageous for studying CMEs. However, if we do not recover STEREO-B, then we are facing a situation where there will be many CMEs that cannot be triangulated because of viewing geometries, unless AIA provides support.

1.4.6. Special Observing Opportunities and Rare Events

Continuous solar observing by SDO has yielded unique data sets because of SDO's all-seeing and ever-awake eyes. Among these are the first-ever observations of comets within the solar corona, which enabled a validation test of an MHD model of the Sun-to-heliosphere field configuration in a domain well above the EUV-bright corona yet below the range accessed by coronagraphs (Downs *et al*. 2013). Continued operation of SDO will add to these unique sets because the Sun itself offers new perspectives as the magnetic cycle proceeds, and in many cases because insufficient events have been recorded to date to appreciate what they tell us. For example, SDO observed a filament eruption that was so massive that matter falling back onto the Sun reached impact temperatures in excess of a million Kelvin; this proved to be an unprecedented opportunity to study in detailed images aspects of accretion processes that occur elsewhere in the universe (Reale *et al*. 2013; 2014). Another example is that, of the 43 X-class flares observed by SDO, many with quite distinct characteristics; only a handful were also observed with the high-resolution imaging and spectroscopy on Hinode and IRIS.

Among others, a solar eclipse visible across the USA in August 2017 will benefit from SDO when models of the corona are produced using SDO data and validated by the eclipse observations. Finally, we note that two transits of Mercury across the Sun will occur within the next five years, on Sep. 5, 2016 and Nov. 11, 2019. Such transits have proven to be excellent opportunities for public attention (see Section 1.3.2), apart from being useful for precise plate scale determination and coordinate system validation.

1.4.7. SDO Support of the Heliophysics System Observatory and the Research Community

The SDO science investigation fosters a collaborative research environment in which data from the mission is used to complement partner missions in the HSO. This collaborative environment is enabled by an open data policy, efficient mechanisms for data and meta-data exports, and SDO-sponsored science meetings. Proof of the open nature of the SDO data can be seen by the large number of nationalities of first authors of refereed papers using SDO data. Using data from the NASA ADS website, we determined that 46% of first authors were at institutions outside the United States. A better indication of the diversity of SDO's science is that there are almost 1000 different first authors of refereed papers using SDO data. The science results are heavily cited as well (Figure 1.1), showing they are significant to their subfields.

External researchers obtain their data from the SDO Data Centers. Some of the data exports are through a series of servers that provide data to users in Europe and Asia. The acceleration of science discovery is enabled by meta-data and summary data products and services, such as the HEK, that help researchers identify data sets relevant for their science goals. JPEG2000 summary images from the HMI and AIA instruments are readily available for browsing via the Helioviewer visualization tools, which can query the HEK for events and render Potential Field Source Surface (PFSS) models.

Many missions in the HSO benefit greatly from access to SDO data. Planning of several space-borne and ground-based observatories require NRT data from SDO. Studies of the coupling of small-scale structures to the larger-scale field require combining data from high-resolution imagers and spectrographs, such as on IRIS and Hinode, with the larger field of view from AIA and HMI. The field of view of IRIS, for example, typically covers only 60 arcseconds as it focuses on the UV emission from the chromosphere and transition region. Coverage of material moving up into, or down out of, the corona typically requires much larger fields of view that are routinely provided by AIA. Without such coverage, achieving the IRIS objectives of studying mass, energy, and field coupling from low to high atmosphere would be severely hampered or impossible. The STEREO spacecraft are currently in opposition, 2 AU from Earth on the far side of the Sun. Since launch, AIA has served as the "third eye" to STEREO's EUVI imager, and the three spacecraft have afforded the first-ever global view of our star. The importance of cross-cutting STEREO/SDO observations and models is described in PSG5.

The TIMED, AIM, and CINDI missions all use knowledge of the ionosphere and thermosphere to assist their data analysis. Access to contemporaneous SDO data makes the models underlying their inversions more accurate. Missions to study the radiation belts use SDO data to know when CMEs and high-speed solar wind streams, the sources of the variations those missions measure, are leaving the Sun.

Two new NASA missions are planned to launch during this extended mission of SDO. The Ionospheric Connections Explorer (ICON) mission, planned for launched in 2017, will explore the ionosphere to understand the physical connection between our world and the space environment around us. The ionosphere is where ionized plasma and neutral gas collide and react. The ionosphere has long been known to respond to "space weather" drivers from the sun, but recent NASA missions have surprised us in showing this variability often occurs in concert with weather on our planet. ICON will use SDO data to compare the impacts of these two drivers as they change the space environment that surrounds us. The Global-scale Observations of the Limb and Disk (GOLD) mission, also planned for launch in 2017, will use far-ultraviolet observations to image the ionosphere and thermosphere. It will also need SDO data to model and understand their observations of the Earth's outer atmosphere.

1.4.1. SDO and Cooperative Research with Astrophysics and Planetary Sciences

SDO observations support our understanding of activity of solar-like stars, because what can only be viewed as irradiances for stars can be imaged on the Sun (such as for the accretion analogy after a filament eruption described above). AIA images combined with EVE spectral irradiances aid the interpretation of observations of Sun-like stars through examples of flares, coronal dimmings, rotational modulation, and –on time scales that we hope to cover in the Extended Mission –cycle-related variability.

SDO science and data also supported astrophysics or planetary sciences when the AIA and EVE observations were, in part, responsible for advances in the CHIANTI spectral code where many spectral lines were added for the EVE/AIA wavelengths. Another example is when transit observations of Venus (in 2012) and Mercury (in 2016 and 2019) provide benchmark data to compare with exoplanet transits, including information on the background signals above which exoplanet signals are sought. The SDO observations are also important for the MAVEN mission to explore the solar impacts on the Martian atmosphere.

PSG1: Subsurface flows and structures	PSG2: Magnetic variability and the solar cycle	PSG3: Characterizing the eruptive potential of active regions	PSG4: Collaborative studies of Solar Eruptive Events (SEEs)	PSG5: Global-scale coronal dynamics driving the heliosphere and Earth's magnetosphere		**SDO Extended Mission Science Goals**
X	X	X	X	X	AIA	**SDO Data Sources**
		X	X	X	EVE	
X	X	X	X	X	HMI	
X	X	X	X	X	SDO Data Centers, JSOC-SDP, HEK, & EVE SOC	
					Roadmap Research Focus Area	**Decadal Survey Challenges**
		X	X	X	F1: Understand magnetic reconnection	SHP-3, SWMI-1
	X	X	X	X	F2: Understand the plasma processes that accelerate and transport particles	SHP-3, SHP-4, SWMI-2
				X	F3: Understand ion-neutral interactions	SHP-2, SHP-4, SWMI-3, AIMI-1, AIMI-2
X	X				F4: Understand the creation and variability of solar and stellar magnetic dynamos	SHP-1
X	X	X	X		F5: Understand the role of turbulence and waves in the transport of mass, momentum, and energy	SHP-2, SHP-4, SWMI-2, AIMI-3
X	X	X	X	X	H1: Understand the origin and dynamic evolution of solar plasmas and magnetic fields throughout the heliosphere	SHP-1, SHP-2, SHP-3, SWMI-3, AIMI-4
X	X	X	X	X	H2: Understand the role of the Sun and its variability in driving change in the Earth's atmosphere, the space environment, and planetary objects	SWMI-3, AIMI-4
	X	X		X	H3: Understand the coupling of the Earth's magnetosphere-ionosphere-atmosphere system, and its response to external and internal forcing	SWMI-3, SWMI-4, AIMI-1, AIMI-4
					H4: Understand the nature of the heliospheric boundary region, and the interactions between the solar wind and the local interstellar medium	*SHP-4*
X	X	X	X	X	W1: Characterize the variability, extremes, and boundary conditions of the environments that will be encountered by human and robotic explorers	SHP-1, SHP-3, SWMI-3, AIMI-4
X	X	X	X	X	W2: Develop the capability to predict the origin, onset, and level of solar activity in order to identify potentially hazardous space weather events and all-clear intervals	SHP-1, SHP-3
X	X			X	W3: Develop the capability to predict the propagation and evolution of solar disturbances to enable safe travel for human and robotic explorers	SHP-3, SWMI-2, SWMI-3
	X	X	X	X	W4: Understand, characterize, and model the space weather effects on and within terrestrial and planetary environments	SHP-3, SWMI-2, SWMI-3, SWMI-4, AIMI-1, AIMI-2

Table 1.1: A matrix tracing the SDO capabilities to the Heliophysics Roadmap Research Focus Areas and Decadal Survey Challenges.

2. Technical

2.1. Mission Operations, Spacecraft and Ground Systems Status and Performance

The SDO Spacecraft, the SDO Mission Operations Center (MOC) and Flight Operations Team (FOT) at GSFC, and the SDO Ground System (SDOGS) elements are all Green (see Figure 2.1).

SDO Subsystem Status

Subsystem	Status	Remaining Life	Comments
AIA		> 10 years	Original configuration
EVE		> 10 years	MEGS-A turned off, still meets original Level-1 Reqts. with MEGS-B and ESP
HMI		> 10 years	Original configuration
Data Centers		> 5 years	Some equipment needs to be refreshed, remaining life assumes regular maintenance
Command & Data Handling		> 5 years	Original configuration
Electrical Power System		> 10 years	Battery is in good shape, solar panels good to 2026
High-gain Antennas		> 10.5 years	Original configuration
Attitude Control System		At least 5 years	IRU-1 powered off, but powered on every 3 months. Reaction wheels are being run in a null-bias mode to avoid lingering near zero rpm.
Propulsion		> 5 years	Propellant is not a limiter on extended mission
S-band RF		> 5 years	Original configuration
Ka-band RF		> 5 years	Waveguide transfer switch will not be exercised unless there is a failure of a link from the transmitter to an antenna.
Thermal		> 5 years	Original configuration, all needed heaters working, all cooling is passive
DDS		> 5 years	Refresh completed and under test, remaining life assumes regular maintenance
SDOGS		> 5 years	Maintenance of aging components is a concern, remaining life assumes regular maintenance

	Fully Functional for proposed mission
	Degraded function but can be operated
	Dead or operationally useless

Figure 2.1: *The major subsystems of SDO are all green for the extended mission, with estimated remaining lifetimes exceeding five years.*

2.1.1. SDO Spacecraft Status

All SDO spacecraft subsystems are operating at nominal levels with two exceptions, neither of which interferes with SDO's ability to continue normal operations for at least the next five years.

One Inertial Reference Unit (IRU1) began drawing current above its yellow limit and is now powered off except for three days every three months. FOT and GSFC engineers removed IRU1 from the SDO attitude control loop. The two other IRUs are sufficient for complete pointing information; however, the SDO team is investigating gyro-less control modes. The SDO FOT and GSFC engineers solved an issue of ever-increasing torque being required for Reaction Wheel Assembly 4. Once a null bias modulation of the speeds was implemented all four wheels torque trends stabilized.

The spacecraft has used 1.65 kg of propellant for 10 station keeping and 21 momentum management maneuvers over the last five years. The 384 kg of remaining propellant suffice to maintain the SDO orbit and pointing as long as the spacecraft is operational in addition to raising the spacecraft into the final disposal orbit. A review of the on-orbit aging of the solar panels and battery indicates that there is sufficient margin to operate past 2026 with the current power system load.

2.1.2. Mission Operations Status

The FOT currently staffs the MOC 12 hours per day, Monday through Friday with personnel on call to support spacecraft and instrument issues. The FOT support for the SDO was designed to make effective use of automation to reduce labor costs. While the observatory provides a continuous flow of solar data to the users, the spacecraft, the MOC and SDOGS are largely autonomous. The robustness and redundancies in the SDOGS, including some critical computer refreshes, have reliably provided the high-rate SDO data with very few data losses over the 5-year Prime Mission. However, the number of activities the FOT must handle continues to increase as the observatory ages.

2.1.3. SDO Ground System Status

The SDOGS consists of a pair of 18-meter antenna dishes and the SDO Data Distribution System (DDS) located on the NASA White Sands Complex in New Mexico. With proper maintenance the SDOGS should operate reliably over the next five years.

The operation of the SDOGS has required several changes based on experience and lessons learned. The number of SDOGS anomalies has decreased from 67 in 2011 to 7 in 2013 and 2014. There are two primary contributions to this trend; a better understanding of the system and fixing the systemic problems that arose during the mission's infancy. The SDOGS anomalies in the last two years are primarily due to the aging of the SDOGS subsystems. The ground station computer hardware and software have been operating for almost eight years and are increasingly difficult to maintain. Some of the subsystems have already been replaced or upgraded. Three SDOGS subsystems should be replaced during the extended mission: The Frequency Conversion System, the Range Receive Command Processor, and the High Data-rate Receivers. All of these are essential for data processing and either have obsolete computer systems or are not supported by the original manufacturers.

2.2. Instruments and Science Operations Status and Performance

All SDO Instruments and Science Operations Centers (SOCs) have performed exceptionally well during the Prime Mission and are expected to perform well during the Extended Mission. However, there is the significant issue of obtaining enough funds above the in-guide budget in order to produce quality data products, versus just acquiring data as discussed later in the budget sections. The one significant instrument anomaly is a shorted capacitor in the EVE MEGS-A CCD electronics (May 2014 anomaly), which means there will be no MEGS-A science data during the extended mission. The EVE MEGS-B and ESP irradiance measurements will continue during the extended mission and can address all of the original Level 1 requirements for EVE observations without MEGS-A.

2.2.1. AIA Instrument Status and Performance

AIA instrument health and performance are excellent, and AIA is expected to continue to meet the needs set by the original science goals throughout the extended mission. None of the AIA subsystems show any sign of degraded performance, and because the instrument contains no consumables or limited-life items, we expect that AIA will continue to meet its science requirements for at least another decade.

In eight of the ten wavelength channels, sensitivity has degraded by less than 25% since being turned on, with degradation e-folding times exceeding 15 years. Only the 304 Å and 335 Å channels have shown larger sensitivity losses; both were consistent with expected degradation at longer EUV wavelengths. The 304 Å channel throughput fell rapidly early in the mission, but following a series of bakeouts of detector and mirrors in 2011 the rate of sensitivity loss decreased substantially; as of early 2015 the throughput is at approximately 20% of its initial value. The 335 Å channel sensitivity has fallen fairly steadily throughout the mission, and is now at 28% of its initial value. The 335 Å line generally targets emission from flares and hot active regions with a high emission measure, and the data from such regions remain excellent. Throughput in these two channels, now decreasing with an e-folding time of approximately 3.5 years, suffices amply for AIA to meet all of its science goals without a need to change the exposure durations or image cadence. Corrections to the response functions for all channels are regularly updated and are provided through SolarSoft.

Should instrument throughput become a concern during the Extended Mission, we could perform CCD bakeouts. We have not performed a bakeout since April 2012; the sensitivity in all channels is adequate such that it has been preferable to avoid complicating the instrument calibration by imposing discontinuous changes in sensitivity.

AIA uses 13 mechanisms (a shutter, filter wheel and focus mechanism on each of the four telescopes, and an aperture selector on one of them), each of which has performed approximately 26 million moves so far (well within the life cycle tests of 66 to 80 millions moves). The mechanisms have not changed their current draw, move time, or any other behavior while on orbit.

The image stabilization system (ISS) requires periodic calibration due to seasonal changes in the angular size of the Sun throughout the year and changing thermal loads, but the signal levels on the visible-light guide telescope have been steady and we have not had to retune the ISS for any degradation.

The transmission of the delicate thin-film entrance filters has gradually increased due to micrometeorite strikes; resulting in the appearance of stray light in the 4500 Å channel. However, this channel is not part of AIA's science program (used once per hour for alignment with other solar instruments). The nine EUV/UV channels use filter wheels behind the optics to reject visible light, and stray light remains at least three orders of magnitude below the threshold of detection in those channels. Finally, the CCD characteristics (dark current, bad pixels, and flat field pixel-to-pixel variation) have not shown significant changes since instrument commissioning.

Two classes of electronic upsets have caused brief interruptions in the steady flow of perfect data from AIA. Both are likely attributable to cosmic ray hits, although it is difficult to establish this definitively. The first affects the camera interface board, and causes corruption in the image data from the affected camera until a reset is performed. There have been five such upsets in total in three of the four AIA cameras (and two more on the two identical HMI cameras). The frequency is low and the recovery procedure is straightforward with full resets within three hours for all instances since 2012. There have been two occurrences of single-bit errors in the data compression tables that cause minor errors in the image data, but that are straightforward to clear. These infrequent anomalies have caused the loss or degradation of less than the equivalent of one day of data over the past five years.

2.2.2. EVE Instrument Status and Performance

EVE has been making solar SXR (0.1-10 nm) and EUV (10-122 nm) irradiance measurements since May 2010, continuously (24/7) and with high cadence (up to 0.25 sec) for some EVE channels and at least daily with the other channels. The EVE Multiple EUV Grating Spectrographs (MEGS) includes three moderate spectral resolution (0.1 nm) channels: MEGS-A1 covers the 5-20 nm range, MEGS-A2 17-38 nm, and MEGS-B 32-106 nm. The EVE broad band channels include the EUV SpectroPhotometer (ESP) with five bands in the 0.1-40 nm range, the MEGS photometer (MEGS-P) for Lyman-alpha measurements at 121.6 nm, and the Solar Aspect Monitor (SAM) that makes 0.1-7 nm SXR images of the Sun with low spatial resolution (~10 arc-sec).

The ESP remains operational and continues to provide accurate, high time-cadence (0.25-sec) irradiance data in four SXR-EUV bands. With its high reliability and the low latency of its Level 0C data product, ESP has proven useful for science investigations (e.g., Didkovsky *et al*., 2013). ESP NRT data serves as backup for the GOES XRS (Hock *et al*., 2013) and SoHO Solar EUV Monitor (SEM) 26-34 nm band in space weather operations at NOAA SWPC and Air Force Space Command.

The MEGS A1, A2, and SAM channels share a common CCD and made continuous (24/7) measurements with 10-sec cadence over the majority of the mission until one of the 24 V capacitors in its CCD electronics shorted in May 2014. This short happened over a few seconds, and protective current-limiting circuits in the EVE power supply prevented damage to any other system. Although MEGS-A is still functioning, this CCD can only provide background (noise) images, as the 24 V is needed as a bias for photon detection. The root cause for this capacitor short is considered to be bad ceramic material (cracked before or during manufacturing), and the most common solution to clear such a short is to power cycle the instrument. Despite over 500 power cycles of MEGS-A, the capacitor short has not been cleared, probably because the protective circuit limits the in-rush current. While this capacitor short might clear in the future, we do not plan for MEGS-A to provide solar irradiance data in this extended mission. The MEGS-A spectral coverage is 5–38 nm, but EVE ESP and AIA also cover this spectral range, albeit at lower spectral resolution. Figure 2.2 provides a summary of the important flare monitors in MEGS-A and how other SDO channels can provide the equivalent measurements to continue the flare science that MEGS-A had contributed. The SDO Level 1 and EVE science requirements, allowed for either MEGS-A or MEGS-B to be operational to meet the EVE science objectives. Therefore, the continuation of EVE observations with just ESP and MEGS-B during the extended mission will satisfy all of the original EVE science objectives.

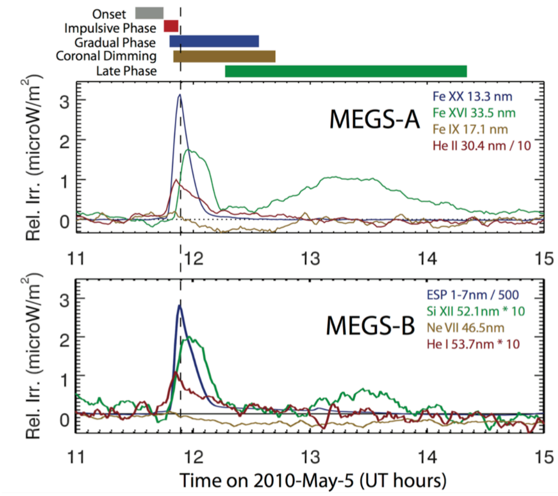

***Figure 2.2**: Flare phases during the C8.8 flare on May 5, 2010. The top panel shows the MEGS-A emission lines, and the bottom panel shows the MEGS-B and ESP emission lines that characterize the same flare phases.*

The MEGS-B channel continues to provide solar EUV irradiance data at 0.1-nm resolution for the 32-106 nm range and with 10-sec cadence. Because there was unexpected degradation for MEGS-B CCD at first light in April 2010, the MEGS-B observations have been limited to 3-6 hours per day since July 2010 in order to provide a long lifetime (> 10 years) for MEGS-B observations. Although most of the MEGS-B observations are limited to a few hours per day, there were continuous (24/7) 10 s cadence MEGS-B observations during May-June 2010 and during planned flare campaigns. The EVE team has developed new flight software to automatically activate the MEGS-B observations when the ESP measurements indicate that an M-1 or larger flare is starting. This autonomous flare detection algorithm has been tested with the Prime Mission data, and we anticipate that 95% of all future large (> M-1) flares will be captured by MEGS-B. The installation of this flight software revision in March 2015 will allow the maximum coverage for the larger flares while still limiting the MEGS-B exposure so that MEGS-B can be operational for many more years.

In addition to the solar eruptive event physics research that EVE data supports, the solar SXR and EUV irradiance data are used for studying the solar influence on Earth's ionosphere and thermosphere. For such studies, especially so for long-term (years) variations, it is critical to provide calibrated solar SXR-EUV irradiances from the EVE data. There are daily and weekly on-board calibrations for the EVE channels that include using redundant filters for tracking exposure-related degradation of the foil filters, dark filter position for tracking background drifts, and LED lamps for tracking CCD pixel-to-pixel variation such as bright solar lines locally degrading the CCDs. The ESP 0.1-7 nm band, MEGS-A1, and MEGS-SAM have almost no degradation over the mission. The other ESP bands and MEGS-A2 have a constant (almost linear) degradation of its Al/C foil filter that appears to be due to oxidation of the Al than to any hydrocarbon contamination. The MEGS-B does not have any foil filters, and its degradation is almost all at the CCD and is stronger at the bright emission lines.

These on-board calibrations track exposure-related degradation effects, but they don't necessarily track all degradation effects. So the EVE calibration plan includes underflight rocket calibration measurements using the prototype EVE. These underflight calibrations have been in May 2010, Mar. 2011, June 2012, Oct. 2013, and May 2015. This approach has achieved a calibration accuracy of about 10% for the EUV irradiance record over the life of the SDO mission. Without the underflight measurements, we estimate that the EVE irradiance data accuracy could degrade by 1-10% per year (wavelength dependent).

2.2.3. HMI Instrument Status and Performance

HMI has been operating almost continuously since the start of the science mission on 1 May 2010. Of the almost 80 million images taken up to 31 January 2015, only 0.05% have been partial images or lost due to data link issues. A better indication of the completeness of the HMI science data set is that 24 contiguous 72-day periods between 30 April 2010 and 21 Jan 2015 have a mean Dopplergram recovery rate of 98.43%. Approximately 80% of the gaps were expected due to eclipses or calibration maneuvers.

To monitor and maintain the HMI performance, a variety of calibration data are taken at regular intervals in addition to monitoring the instrument housekeeping parameters such as temperature, voltage, current, and observing sequence status. Twice daily, sets of images are taken to monitor the instrument throughput and image plate scale. Weekly and bi-weekly internal observing sequences are run to determine the optimal instrument focus and tunable filter settings and, updates to the small-scale image flat field. The large-scale image flat field is determined quarterly in conjunction with spacecraft offpoint maneuvers.

The HMI optics package has active thermal control that is monitored and adjusted to maintain an optimal operating environment. The thermal control was operated in a constant-duty-cycle mode until mid 2013 when it was modified to constant-temperature control in order to reduce the annual thermal variations. The HMI image focus is maintained at a roughly constant value by adjusting the thermal control of the HMI front window. Measurements of the instrument end-to-end optics transmission have shown a decrease of approximately 15% during the on-orbit operations due to expected radiation darkening of the optics. The decrease in transmission has been flattening out over the last 18 months. In order to maintain uniform signal intensity, the camera exposure times were increased by about 5% in July 2011 and January 2013. There is still sufficient margin in the to compensate for further throughput decreases. As with the Michelson Doppler Imager (MDI) on SoHO, there is a slow and decreasing drift in the optimal setting of the HMI Michelson interferometers due to aging of the optical components. This drift is corrected by adjusting the mechanism settings every 6 to 12 months. The current trending plots for the HMI instrument can be found at: *http://jsoc.stanford.edu/doc/data/hmi/trend_plots*

Two types of problems affecting the HMI instrument have interrupted science observing. The most serious was a reboot of the HMI flight software due to watchdog timer resets, which occurred twice on 24 April 2013 and 17 May 2014. The flight software and observing was restarted within 15 hours in the first instance and within 4 hours in the second instance. The other issue was the anomalous upsets described in Section 2.2.1. There is also an infrequent corruption of single images due to an error in the HMI camera interface electronics, which has affected approximately 200 images on the front camera and about 100 images on the side camera. The error rate is sufficiently low (4 images out of every 100,000 taken on average) that this error has no affect on the science observations.

Aside from these occasional problems, the HMI instrument has performed extremely well on-orbit. There is no indication that HMI will have any difficulty operating for an additional five to ten years.

2.3. Instrument Operations and Data Center Status

Data Products	Volume
AIA Level 1	1000 TB
AIA Level 1.5	1000 TB
AIA, higher level	75 TB
HMI Level 1	1600 TB
HMI Level 1.5 and higher	1500 TB
EVE Level 0b	33 TB
EVE higher level	2 TB

Table 2.1: Summary of data archived to date.

Table 2.1 provides a summary of the volume of SDO archived intermediate and final science data. The SDO Mission Archive Plan has additional details about the data volumes and status.

2.3.1. JSOC-IOC Operations

The operation of the SDO AIA and HMI instruments continue to run smoothly. The Joint Science Operations Center Instrument Operations Center (JSOC-IOC) team performs weekly calibrations of HMI and follows a bi-weekly calibration schedule for AIA. These calibrations include flatfields, long exposures, focal plan filter checks and entrance filter checks, as well as detunes for HMI. Monthly calibrations include AIA focus sweeps and AIA/HMI diagnostic data collection. In addition, a bi-monthly AIA guide telescope/PZT calibration is performed. The on-board clocks for both instruments need routine monitoring and adjustment. Eclipse seasons occur twice a year for SDO and require thermal adjustments for both AIA and HMI. The team meets before eclipse season starts to discuss strategy and after eclipse season ends to discuss lessons learned. The MOC and Alert Notification System (ANS) continue to function well and provide remote and continual monitoring for the instruments. In preparation for the extended mission, the JSOC EGSE workstations are being replaced.

The JSOC-IOC team conducts internal weekly planning meeting and participates in the weekly GSFC FOT telecon. The health of both AIA and HMI are closely monitored with twice-daily checks. The effort required for these checks has been cut in half since the beginning of the mission. In addition, the health and safety and the long-term trending websites have proven beneficial for not only monitoring the instruments but in helping to monitor the health of the SDO spacecraft as well. The JSOC team works closely with the FOT in monitoring the health of AIA and HMI by conducting semi-annual reviews of the trending data. The JSOC team monitors the instrument not only during normal working hours, but also on the weekends and provides emergency support 24/7 for both the AIA and HMI instruments. For the foreseeable future, the operation of HMI and AIA from the JSOC-IOC should continue to be a straightforward process. Web sites provide information on health and safety and on long-term trending:

http://jsocstatus.stanford.edu/hk/SDOStatus/index.jsp

http://jsocstatus.stanford.edu/hktest/long_term_trending/aia/temperatures.html

2.3.2. EVE Operations

The EVE operations includes weekly planning uploads, daily data processing, data distribution and archiving, and these are mostly automated at the EVE SOC at CU/LASP. The EVE public data products includes the photometer irradiance results with 0.25-sec cadence as Level-1 products, the MEGS spectra and extracted emission lines with 10-sec cadence as Level-2 products, and daily averages of these Level 1-2 products as the Level-3 products. The EVE team also provides NRT Level-0C products of ESP data and MEGS spectra with latency as low as 5 minutes for use in NASA, NOAA, and Air Force space weather operations. The current (version 5) EVE space weather products are released within 15 minutes, and within 48 hours for the research-quality products. For the extended mission we will continue the EVE operations, generating the EVE NRT (space weather) and research-quality data products, and improving the data processing algorithms such as corrections for instrument degradation trends. The EVE team is being significantly reduced for the extended mission to just the critical operations staff at CU/LASP and the instrument scientists at CU/LASP and USC.

2.3.3. JSOC-SDP Operations

The JSOC Science Data Processing (JSOC-SDP) center at Stanford University receives HMI and AIA raw telemetry from the DDS, and archives two copies to LTO4 tapes. The raw data is processed to reconstructed images (Level-0) then to corrected images (Level-1) for both HMI and AIA all of which is archived. The Level-1 data is the primary science data for AIA and is provided to the JSOC-AVC at LMSAL. HMI science data consists of magnetograms, Dopplergrams, etc., that are generated from the Level-1 and then archived. HMI science data are available for space-weather use 15 minutes after receipt and in final form within five days. Additional higher-level processing is required for some HMI science data products. These include helioseismic subsurface flow maps, global internal rotation, meridional flows, and vector field products including the detailed analysis of the disk passage of each emerging magnetic patch. Most higher-level products are available a day or so after the input data is available.

Altogether 45 computers including a 480-processor cluster are available for research computing by local and remote users and file servers totaling 2800 TB of on-line storage. The 9000 TB of archived data reside on 9,400 tapes with 2,200 LTO4/LTO6 tapes in an automated library and the rest on the shelf. There are an additional 2,500 telemetry tapes stored offsite. The tape archive grows at about 8 TB/day. The JSOC system stores the image and processing metadata in a PostGreSQL database The JSOC-SDP also houses the SoHO/MDI resident archive and IRIS mission archive (not supported with SDO funds).

The JSOC-SDP supports distribution of the HMI and AIA science data to the community. In 2014, the JSOC-SDP automated web services supported almost 300,000 data export requests totaling 145 TB (407 GB/day) with about 11% of these involving user-specified processing before export. The JSOC web portal supported requests from tens of thousands of distinct IP addresses in 2014. Remote clones of the JSOC system have been set up at twelve sites in six countries (USA, Germany, France, Belgium, UK, and S. Korea). The distribution to remote JSOC data systems runs at about 60 MB/s (5 TB/day), supporting typically three streams of AIA and HMI science data. The remote centers facilitate further distribution; one of them, NASA GSFC's Solar Data Analysis Center, serves as the Virtual Solar Observatory (VSO) interface to SDO data. The VSO fulfills about 125k requests for SDO data each month. AIA data images and movies and cutout are also available via web and SolarSoft services from the JSOC-AVC at LMSAL.

The staff needed to support the JSOC-SDP has been reduced from eleven at launch to seven. The computing hardware has been replaced as part of the ongoing maintenance plan that involves replacements as systems age. The various subsystems including the data capture system, main processing cluster, database machines, file servers, tape drives, web servers, and infrastructure are all near the beginning of life so should not need significant investments for the next 2 to 4 years. A system comprising hundreds of processors and 2700 TB of disk, managing more than 8 billion files in 9000 TB of storage will, however, need continuous care and support. Over the past five years we have had a number of file server failures, power outages, cooling outages, and other disruptions. While no data has been lost, the more severe events have resulted in processing delays of several hours to more than a week. These have required many nights and weekends of extra effort from the staff for quick recovery. At this point we are stretched so thin that overlapping vacations are sometimes difficult to manage. We have a number of tasks where only a single person has the critical skills such that the loss of another staff position will leave us vulnerable to longer downtimes if/when hardware failures happen.

2.3.4. JSOC-AVC Operations

The JSOC AIA Visualization Center (JSOC-AVC) helps researchers find data sets relevant to their topics of interest; to serve as an open forum where solar/heliospheric features and events can be reported and annotated; to facilitate discovery of statistical trends and relationships between different classes of features and events; and to avoid overloading the SDO data systems. To achieve these goals, the Heliophysics Events Knowledgebase (HEK) consists of registries to store metadata pertaining to observational sequences (Heliophysics Coverage Registry, or HCR), heliophysical events and informatics data products (Heliophysics Events Registry, or HER), and browse products such as movies. Interfaces for communications and querying between the different registries are also provided by web services. The Event Detection System (EDS) autonomously orchestrates a variety of feature and event detection modules in order to populate the HEK with events from SDO data. The AIA science team also inspects all AIA data to add additional events that are missed by the automated methods.

The Helioviewer tools at *http://www.helioviewer.org/* provide access to HMI and AIA data through the 36-second cadence jpeg2000 images generated at the JSOC-AVC and stored in the Helioviewer archive. These tools provide web and local Java tools to examine and combine solar data in a convenient form. They also have interfaces to query the HEK and display the solar events captured there. Some science and a great deal of public access are accomplished using these tools.

3. Budget

3.1. Plan for Requested Over-guide Scenario

Mission Operations: During the extended mission under the over-guide scenario, the data return requirement will be reduced to 90%. The minimum advisable level will be maintained for the FOT and system administration team that will staff the MOC one 8-hour shift each day. Another person will be on-site at the SDO ground station Monday through Friday. Nights and weekends will be supported in an unattended mode, the same as during the current mission, except that handovers and eclipses will also not be staffed.

SDO has been running in a robust and reliable unattended mode since soon after launch. The Alert Notification Service (ANS) has been used to notify essential people in the event of an anomaly within the observatory. Anomalies are assigned according to established and agreed-upon guidelines. Spacecraft anomalies will receive a more urgent response than ground-system anomalies.

The MOC will continue to produce mission support data products (e.g., orbital files, instrument and spacecraft timelines), and distribute those data products via the web. Routine health and status monitoring and trending of spacecraft housekeeping data will remain the same. Instrument commanding will continue to be restricted to Monday–Friday, as it is not supported in unattended mode. Engineering team support will be on an as-needed basis, as it has been during the primary mission.

Ground System: The SDO ground system will continue to provide the services and level of reliability needed to meet the SDO science objectives during the extended mission. The SDOGS and DDS will continue to provide primary ground station services; the cost of their services must be completely covered by the SDO budget. No significant changes are planned to the computer infrastructure used to operate the mission and process data; however, normal upgrades to disk space and tape backup capacity are planned to continue to provide a reliable system for the operations and science teams. System administration and ground software support are planned to provide ongoing maintenance for the operational systems. Maintenance contracts will be continued for critical hardware and software elements.

SDO Data Delivery System (DDS): During the extended mission, the DDS will continue to receive and forward telemetry files to the SOCs. We have recently refreshed the DDS core system with modern, VM-enabled, computers. This will allow continuing upgrades and replacements to be made with a minimal impact on operations and at lower cost.

Instrument Teams: The instrument teams will operate the instruments, accept the data from the DDS and continue the automated processing and distribution of SDO data products. Science data analysis will be supported to perform the science plan, concentrating on the PSGs described in Section 1.4. Funding for to replace computer systems over 5 years old and to buy more tapes and disks is included in the over-guide budget. A rocket underflight calibration with the prototype EVE will be flown in 2017 and the prototype EVE will have its NIST SURF calibrations in 2016.

SDO Science Data Archive: Final delivery of SDO science data to a long-term NASA archive will be conducted as part of the completion of the mission data analysis period and is described in the Mission Archive Plan submitted as part of this proposal.

3.2. In-guide Scenario and Impact Assessment

The science investigation described above is proposed for the over-guide mission scenario. Under the in-guide scenario, the science data quality will be detrimentally impacted, data products discontinued, science investigation personnel severely curtailed, and leave most PSGs unobtainable. Additionally, no NRT products from SDO will be produced. Focus will be on operating the spacecraft, instrument safety, and data collection. In particular, JSOC-SDP efforts would be reduced to data collection and archiving. Production of some Level 1 science data, such as vector magnetograms, would be deferred until additional sources of funding became available. These changes will especially affect any science using those data products. Without the PSG support, the routine validation of data would also cease in this scenario. The EVE calibration would suffer because the EVE rocket flights and SURF calibration runs would not happen.

One assumption of the Senior Review in-guide budget is that a 30% reduction from the Prime Mission budget would move the science analysis to external funding while maintaining the data collection and validation work. For SDO the reduction from early mission to minimal mission support already took place in 2012. This large reduction in science funding was imposed: Page 5 of the SDO AO states "*Less funding will be provided for the selected investigations for subsequent years; in particular proposers should reduce their Phase E budget by ~50% for years three to six. Additional science analyses using equivalent resources are expected to be competed in an LWS Guest Investigator program that will be advertised by NASA*." This corresponded to removing the science analysis support from the project and providing that support through another program. In essence SDO has already been operating in Extended Mission mode for three years. The in-guide Budget Scenario thus represents a total reduction of 50% from the initial Prime Mission budget. Our proposed over-guide budget is consistent with a one-third reduction from the initial Prime Mission budget.

The SDO team has considered how to make deep cuts from its already reduced operational mode, and we have serious concerns that SDO may be forced to consider ending mission operations from a spacecraft that currently produces high-quality research data and NRT data products.

The SDO data system has already proven to be effective and efficient, but it remains a relatively high cost to maintain because of its high data rate and large data volume. Some 1600 TB of raw and processed data products are brought into the archive each year with an additional 600 TB of not-archived NRT data which that are available within typically 15-30 minutes of having been recorded. The SDO data volume is already 24 times that for SoHO, STEREO, and all other previous space-based solar missions combined. Several hundred million solar images, solar spectra, magnetograms, and helioseismic measurements are available to the research community on demand essentially immediately.

The in-guide budget scenario can support taking and archiving the raw data, but there will have to be cuts in producing higher level data products and NRT products, and the calibration and validation efforts would have to be cut, that also includes the EVE calibration rocket flights. The heliospheric community has benefited with accurate solar measurements, but without on-going calibration and validation efforts, instrument degradation trending will have to be extrapolated and the accuracy uncertainty could grow to the order of 10% per year.

3.2.1. Mission Operations In-guide Impact

Because the mission operations team is reduced in size under the in-guide scenario, spacecraft maneuvers will be limited to those required to manage the orbit and angular momentum of the spacecraft. This will preclude any spacecraft maneuvers to support monthly and quarterly instrument calibration. The inability to conduct essential calibration will affect the science data quality if instrument performance is degraded. No special maneuvers, such as special modes requested by other missions or off-points for sungrazing comets, will be performed. The only way to make that magnitude of a cut is keep intact the most essential functions and to eliminate entirely several other essential functions that are not immediately fatal to the mission, but are in our judgment unwise to cut. Specifically we eliminate all Flight Software (FSW) support, allow all hardware and software maintenance licenses to lapse, defer needed replacement of critical aging SDOGS hardware, and eliminate FDF Orbit Determination. Eliminating FSW support risks permanent loss of institutional memory that would be impossible to recover once this highly specialized team is disbanded. Allowing maintenance to lapse increases the risk of loss of availability of support hardware and software systems. Deferring replacement of critical SDOGS hardware risks loss of communication with the spacecraft and data loss. Eliminating FDF Orbit Determination for SDO and relying instead on the free *space-track.org* two-line elements would be a clumsy approach to navigation, giving maneuver-planning accuracy that would likely increase the frequency of station keeping maneuvers and make the planning process more volatile. This would also make the Conjunction Avoidance and Risk Analysis (CARA) process far more problematic, with no high accuracy ephemeris available for SDO; conjunction analysis and collision avoidance ceases to be meaningful. The potential for losing the spacecraft to a collision increases in this scenario with a large risk of orbital debris left in GEO.

3.2.2. AIA In-guide Impact

At the in-guide budget, there will be (1) no AIA-team science investigation because there will be no science support in the budget, for either research or community collaboration. The SDO team will not be able to address PSG3 because vector-magnetic data will not exist; the team will not be able to address PSG5 because the assimilation-based full-sphere flux-transport model that takes in HMI magnetograms every six hours to update the field on the full sphere and its PFSS extrapolation will not be maintained. Moreover, at in-guide level to the AIA team there will be (2) no support to recover from any issues with the automated feature-event routines in the Event Detection System (which in that case should be anticipated to stop functioning within weeks of support ending); (3) no support for AIA data flow via SAO to provide AIA data to the VSO and our European partners; (4) no global PFSS models and image overlays (discontinuing a service provided since 1996); and (5) no support for on-orbit or data-system issues outside office hours. Moreover, because magnetograms are important to the annotation process, the absence of NRT magnetic data from HMI at the in-guide budget will delay the annotation by several days. Consequently, event identification and movie summaries would be delayed by several days.

At the in-guide budget, the AIA team can (a) minimally operate HMI and AIA (without special observing modes); (b) support the calibration of AIA data relative to EVE only (because EVE itself cannot support rocket underflights at in-guide funding); (c) validate AIA data by annotating observations in the form of HEK entries that will also support the community in locating data of interest (but with a delay of several days, as explained above); (d) respond to on-orbit instrument anomalies during office hours only (and provided that no more than about one such event occurs per year, as happened in recent years); (e) monitor for, and recover from, data-flow problems that are needed for instrument performance monitoring and event annotation; and (f) (during office hours only) maintain the SolarSoft IDL data "cutout" service, the jpeg2000 data stream used by Helioviewer and others, the SunToday website, and the production of daily and monthly movie summaries.

Included in the in-guide budget is only one full-time postdoc to work hands-on with the data and data system in order to help us identify any issues early on, and 1/3rd of the AIA PI's time for project management plus small fractions of engineer support for calibration, validation, and annotation activities.

3.2.3. EVE In-guide Impact

Funding the EVE investigation at the in-guide level would (1) remove support for the calibration rocket flights and associated NIST SURF calibrations; (2) eliminate the EVE NRT space weather products and related computer systems that require routine monitoring; (3) eliminate science analysis support for a graduate student and post-doc; (4) significantly reduce the data analysis checks for instrument trends and anomalies; and (5) significantly reduce the frequency for releasing new EVE data versions that correct for any new instrument trends or anomalies.

3.2.4. HMI In-guide Impact

The HMI budget covers three tasks: the JSOC-SDP task includes HMI instrument calibration, data collection, product generation, and distribution for both HMI and AIA; the helioseismology data analysis, validation and higher level product generation task; and the line-of-sight and vector magnetic field analysis, validation and higher level product generation task. The HMI team cannot accomplish all of these tasks with a reduction by 5 FTEs to reach the in-guide budget. For the JSOC-SDP a **reduction** in systems and hardware maintenance, disk and tape purchases and a **reduction** of technical staff will be required. This reduction will have **severe impacts** on the ability to generate higher-level products and to maintain a rapid response to anomalies of the spacecraft, instrument, or data system. The safe and secure collection and archiving of the telemetry and up to Level-1 products has high priority so these efforts will remain. We will **stop** the generation of NRT data products presently used for collaborative observation planning and space weather functions. This will relax the processing load and the need to provide quick response to most dataflow or computer problems. We will continue to operate the JSOC-SDP data export services, but at a lower priority. The damage to the JSOC distribution network with the loss of the remote data center at SAO (due to AIA in-guide budget limits) will shift the distribution load back to the JSOC. This will **severely impact** the availability of SDO data via the VSO**,** limiting the availability of SDO data in the US. For the helioseismology related task we will maintain some of the science staff and continue to produce higher-level local helioseismology products that are input to science analyses so PSG1 tasks will be possible but we will **not** continue to produce global helioseismology products. For the magnetic field task we will continue producing and archiving raw Stokes parameter data that are input to the vector magnetograms but with a **severely reduced** science staff we will **not** compute the vector magnetograms and higher-level products based on them and we will **not** implement the planned new observing sequence to improve vector field signal to noise. This will **eliminate** PSG2 Tasks 1–5 and will **severely impact** PSGs 3 and 4.

3.3. Budget Detail Explanation

This proposal is an over-guide submission. The workload analysis by the SDO team was unable to devise a workforce strategy capable of handling the data collection workload while still maintaining the scientific integrity of the data stream. We have detailed the impacts of the in-guide budget in Section 3.2. As shown in Table 3.1, we have asked for an over-guide of about 40% for the Extended Mission covered by this Senior Review. At that level, SDO will be run at just under two thirds of the budget in the first two years of its mission; after these first two years, SDO's budget was already cut to an equivalent that other missions would have in their extended phase.

		FY16	FY17	FY18	FY19	FY20
Budget ($1000)	In-guide	9,487.0	9,504.0	9,529.0	9,529.0	9,529.0
	Over-guide	13,303.3	13,458.7	13,324.5	13,902.2	14,372.5
	Difference	40%	41%	39%	45%	50%
Work Years	In-guide	30.41	30.26	29.96	29.86	29.86
	Over-guide	41.8	41.3	40.6	41	41

Table 3.1: *A comparison of the SDO In-guide and over-guide, both as budget and equivalent work years.*

SDO is unique in having its own ground system. Over 10% of the Mission Operations budget is for anticipated repairs of equipment related to the antennas and ground system at the WSC. All of these fixed costs and mission services can only be managed and are included in the budget.

Even after the budget reduction from the Prime Mission to the Extended Prime Mission in FY12, the SDO team collected, archived, and served one of the largest scientific datasets in the world. The team produced excellent research and supported research by scientists around the world. We believe this over-guide proposal will keep SDO producing world-class science for another two years.

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5. SDO ACRONYM AND ABBREVIATION LIST

See also http://sdo.gsfc.nasa.gov/resources/acronyms.php

ADS	Astrophysics Data System
AIA	Atmospheric Imaging Assembly
AIMI	Atmospheric-Ionospheric-Magnetospheric Interactions
AIM	Aeronomy of Ice in the Mesosphere
ANS	Alert Notification Service
AO	Announcement of Opportunity
API	Application Program Interface
ApID	Application Identification
AR	Active Region
AVC	AIA Visualization Center
AWSoM	Alfven-Wave driven SOlar wind Model
CARA	Conjunction Assessment Risk Analysis
CCB	Change Control Board
CCD	Charge Coupled Device
CCSDS	Consultative Committee for Space Data Standards
C&DH	Command and Data Handling
CI	Collaborative Investigator
CINDI	Coupled Ion-Neutral Dynamics Investigations
CME	Coronal Mass Ejection
Co-I	Co-investigator
CU	University of Colorado
DDS	Data Distribution System
DRMS	Data Record Management System
EDS	Event Detection System
EGSE	Electrical Ground Support Equipment
ESP	EUV SpectroPhotometer
EVE	Extreme ultraviolet Variability Experiment
EUV	Extreme Ultraviolet
EUVI	Extreme Ultraviolet Imager
FDF	Flight Dynamics Facility
FITS	Flexible Image Transport System
FOT	Flight Operations Team
FOV	Field of View
FTE	Full-time equivalent
FTP	File Transfer Protocol
GB	Gigabyte (10^9 bytes)
GOES	Geostationary Operational Environmental Satellite
GOLD	Global-scale Observations of the Limb and Disk
GSFC	Goddard Space Flight Center
HCR	Heliophysics Events Knowledgebase Coverage Registry
HDF5	Hierarchical Data Format, version 5
HDS	Heliophysics Decadal Survey
HEK	Heliophysics Events Knowledgebase
HER	Heliophysics Events Registry
HMI	Helioseismic and Magnetic Imager
HPA	High-Power Amplifier
HSO	Heliospheric System Observatory
I&T	Integration and Test
ICD	Interface Control Document

ICON	Ionospheric Connection Explorer
IDL	Interactive Data Language
IOC	Instrument Operations Center
IRIS	Interface Region Imaging Spectrograph
IRU	Inertial Reference Unit
ISON	International Scientific Optical Network
ISS	Image Stabilization System
JMD	JSOC Mirroring Daemon
JSD	JSOC Series Definition
JSOC	Joint Science Operations Center
LASP	Laboratory for Atmospheric and Space Research
LMSAL	Lockheed Martin Solar and Astrophysics Laboratory
LWS	Living With a Star
MA	Mission Archive
MAVEN	Mars Atmosphere and Volatile EvolutioN mission
MB	Megabyte (10^6 bytes)
Mbps	Megabits per second
MDI	Michelson Doppler Imager
MEGS	Multiple EUV Grating Spectrograph
MHD	Magnetohydrodynamics
MIL-STD	Military Standard
MK	MegaKelvin
MOC	Mission Operations Center
netCDF	network Common Data Form
NIST	National Institute of Standards and Technology
NLFF	Non-Linear Force Free model
NOAA	National Oceanic and Atmospheric Administration
NRT	Near-realtime
NSF	National Science Foundation
PB	Petabyte (10^{15} bytes)
PFSS	Potential Field Source Surface model
PI	Principal Investigator
PSF	Point Spread Function
PSG	Prioritized Science Goal
PZT	Piezoelectric Transducer
RA	Resident Archive
RAISE	Response of the Atmosphere to Impulsive Solar Events
RFA	Research Focus Area
RHESSI	Reuven Ramaty High Energy Solar Spectroscopic Imager
ROSES	Research Opportunities in Space and Earth Sciences
RWA	Reaction Wheel Assembly
SAM	Solar Aspect Monitor
SAO	Smithsonian Astrophysical Observatory
SCP	Secure Copy
SDAC	Solar Data Analysis Center
SDO	Solar Dynamics Observatory
SDOGS	SDO Ground System
SDP	Science Data Processing

SEE	Solar Eruptive Event
SEM	Solar EUV Monitor
SEP	Solar Energetic Particles
SMD	Science Mission Directorate
SO	Solar Orbiter mission
SOC	Science Operations Center
SoHO	Solar and Heliospheric Observatory
SPP	Solar Probe Plus mission
SQL	Structured Query Language
SSH	Secure Shell
STEREO	Solar TErrestrial RElations Observatory
SU	Storage Unit
SUMS	Storage Unit Management System
SURF	Synchotron Ultraviolet Radiation Facility
SVM	Support Vector Machine
SWG	Science Working Group
SWPC	Space Weather Prediction Center
SXR	Soft X-Ray
T&C	Telemetry & Control
TB	Terabyte (10^{12} bytes)
TBD	To Be Determined
TIMED	Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics mission
TLM	Telemetry
UC	University of California
USC	University of Southern California
UV	Ultraviolet
VC	Virtual Channel
VCDU	Virtual Channel Data Unit
VM	Virtual Memory
VSO	Virtual Solar Observatory
WSMR	White Sands Missile Range
XML	eXtensible Markup Language
XRS	X-Ray Sensor