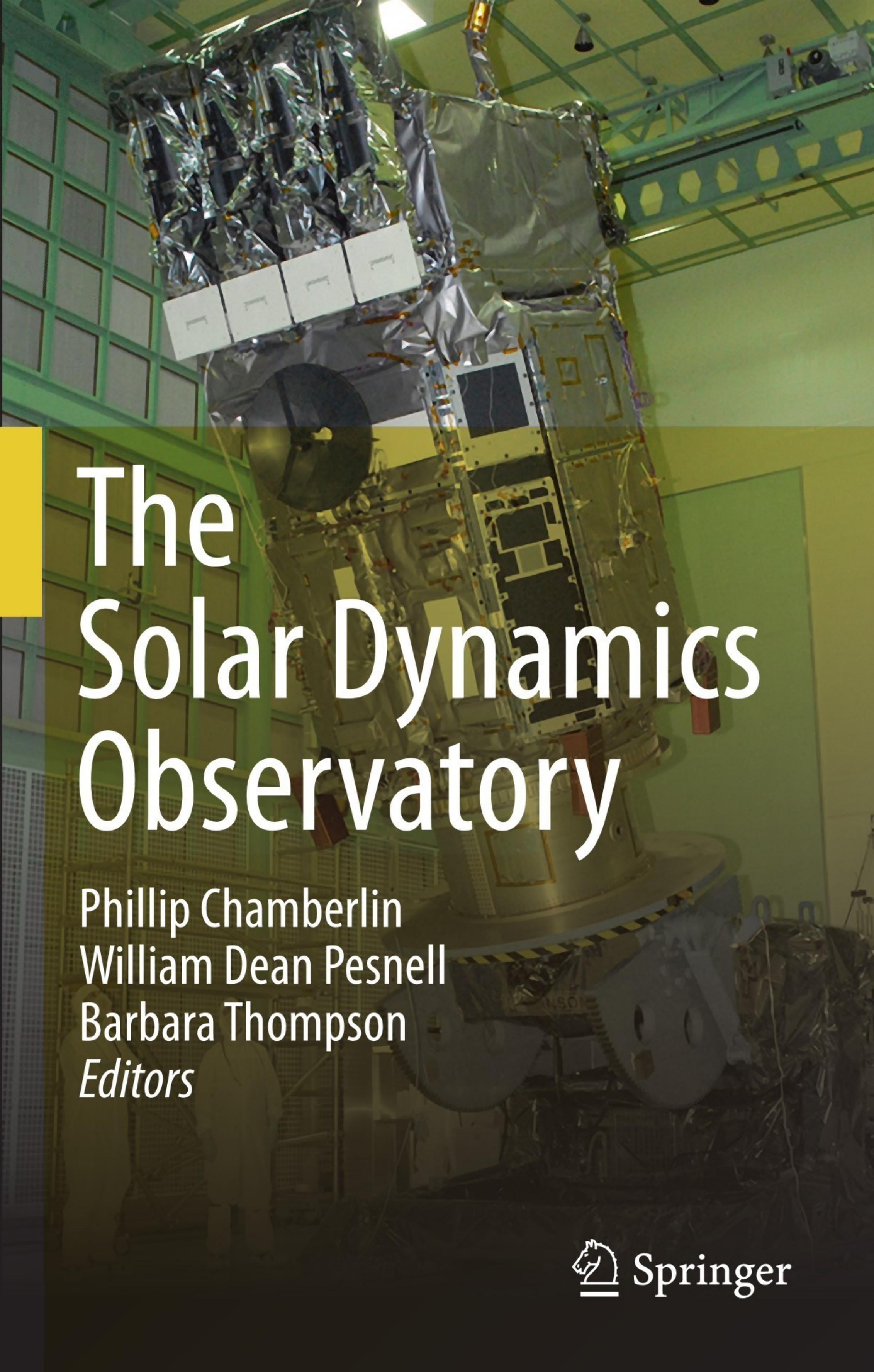

The Solar Dynamics Observatory

Phillip Chamberlin
William Dean Pesnell
Barbara Thompson
Editors

Springer

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Cover illustration: The cover image shows the Solar Dynamics Observatory in the cleanroom at Goddard Space Flight Center undergoing final tests and preparation just prior to shipping to Florida for launch. Credit: NASA/B. Lambert

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Preface

R.R. Fisher

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My initial exposure to early data from the *Solar Dynamics Observatory* (SDO) took place late one morning in the Spring of 2010 and eventually ended in the early evening. As night fell, I found myself feeling excited, a little relieved, and hugely impressed by the scientific and technical contributions of those who developed the SDO systems. I was also confounded by what I had seen.

The data were so rich! The temporal and spatial content of the imagery was overwhelming. It took until the next morning for me to realize that the new data were, in fact, revolutionary. In half a day, my understanding of the dynamic Sun had been swept away by the SDO systems. The mission's quest for new observing capability was wildly successful! I could only speculate on the SDO's future impact on scientific research.

In its first year SDO has given us unprecedented views of filament eruptions, measured the total energy emitted by flares, and started watching for active regions before they erupt through the solar surface. Each is a vital piece in our understanding of solar activity and of how that activity creates space weather. Filament eruptions are the source of coronal mass ejections, while solar flares increase satellite drag and disrupt communications. Prediction of solar activity is a goal of SDO and knowing where they will erupt is a major step toward short-term prediction.

SDO is the first space-based mission of NASA's Living With a Star program. It carries three instruments dedicated to improving our understanding of the production, evolution, and destruction of the solar magnetic field. The SDO science investigation teams are committed to rapidly providing their data to scientists, space-weather organizations, and the public.

SDO provides full-disk images of the Sun in many wavelengths, starting in the soft X-ray and moving though the UV into the visible. Magnetic-field maps and Doppler-velocity maps

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are now obtained at cadences never before achieved. The EUV spectral irradiance is measured at an unprecedented rate allowing the estimation of the total energy radiated by even small, C-class flares. This irradiance is also used to calibrate the EUV images, so that the radiance from coronal loops can be measured and converted into temperature maps. By revealing global changes in the solar atmosphere over spatial scales ranging from the resolution limit to fractions of a solar diameter, SDO is writing a new chapter in our understanding of the Sun and of how space weather is created by solar activity.

This volume on the *Solar Dynamics Observatory* (SDO) mission continues a tradition of *Solar Physics* to dedicate topical issues to major space science missions. I encourage you to read the articles, use SDO data in your research, and simply enjoy looking at the Sun in the splendor that SDO is revealing.

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The *Solar Dynamics Observatory* (SDO)

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Abstract The *Solar Dynamics Observatory* (SDO) was launched on 11 February 2010 at 15:23 UT from Kennedy Space Center aboard an Atlas V 401 (AV-021) launch vehicle. A series of apogee-motor firings lifted SDO from an initial geosynchronous transfer orbit into a circular geosynchronous orbit inclined by 28° about the longitude of the SDO-dedicated ground station in New Mexico. SDO began returning science data on 1 May 2010. SDO is the first space-weather mission in NASA's *Living With a Star* (LWS) Program. SDO's main goal is to understand, driving toward a predictive capability, those solar variations that influence life on Earth and humanity's technological systems. The SDO science investigations will determine how the Sun's magnetic field is generated and structured, how this stored magnetic energy is released into the heliosphere and geospace as the solar wind, energetic particles, and variations in the solar irradiance. Insights gained from SDO investigations will also lead to an increased understanding of the role that solar variability plays in changes in Earth's atmospheric chemistry and climate. The SDO mission includes three scientific investigations (the *Atmospheric Imaging Assembly* (AIA), *Extreme Ultraviolet Variability Experiment* (EVE), and *Helioseismic and Magnetic Imager* (HMI)), a spacecraft bus, and a dedicated ground station to handle the telemetry. The Goddard Space Flight Center built and will operate the spacecraft during its planned five-year mission life; this includes: commanding the spacecraft, receiving the science data, and forwarding that data to the science teams. The science investigations teams at Stanford University, Lockheed Martin Solar Astrophysics Laboratory (LMSAL), and University of Colorado Laboratory for Atmospheric and Space Physics (LASP) will process, analyze, distribute, and archive the science data. We will describe the building of SDO and the science that it will provide to NASA.

The Solar Dynamics Observatory
Guest Editors: W. Dean Pesnell, Phillip C. Chamberlin, and Barbara J. Thompson

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Keywords SDO · Solar cycle · Helioseismology · Coronal · Space weather

1. Preface: *Living with a Star* and the *Solar Dynamics Observatory*

The goal of NASA's *Living With a Star* (LWS) Program is to provide the scientific understanding needed to address those aspects of heliophysics science that may affect life and society, where heliophysics is the study of the Sun and how it influences and drives changes in all objects within its reach. The ultimate goal is to develop the ability to predict conditions at Earth and in the interplanetary medium due to the Sun's ever-changing output, a subject called space weather.

LWS is designed to give us a better understanding of the causes of space weather, whose effects can disable satellites, cause power-grid failures, and disrupt global positioning system and other communications signals. The LWS program includes coordinated strategic missions, missions of opportunity, a targeted research and technology program, a space-environment testbed flight opportunity, and partnerships with other agencies and nations. Each LWS mission is designed to answer specific science questions needed to understand the interconnected systems that impact us.

Radiation Belt Storm Probes (RBSP), the second LWS mission, will be launched in 2012 to study the acceleration to high energies of electrons in the Earth's radiation belts. *Balloon Array for Radiation Belt Relativistic Electron Losses* (BARREL) is a multiple-balloon investigation of the Earth's radiation belts that will fly from Antarctic stations during the southern Summers of 2012 and 2013. Two solar missions, *Solar Probe Plus* and *Solar Orbiter* (a joint mission with ESA), are planned for launch later this decade. They will study the coronal heating and solar-wind acceleration problems from platforms flying close to the Sun and out of the Ecliptic.

LWS is a part of the *International Living With a Star* (ILWS) Program, an organization bringing together researchers and space-weather operators to further develop our ability to understand and predict space weather.

2. Introduction

The *Solar Dynamics Observatory* (SDO) is designed to provide the data and scientific understanding necessary to predict solar activity, from anticipating whether flares and CMEs will occur the next day to the level of solar activity in future solar cycles. Monitoring the topology of magnetic fields as they are formed within the Sun itself through the outer atmosphere, or corona, by high-resolution images may provide the precursors for predicting flares and CMEs. A key insight that SDO hopes to provide is the topological configuration that is needed to drive reconnection and reorganization in these built-up and stressed magnetic fields – the energy release and source that drives the solar eruptive events.

Longer timescales require a knowledge of how magnetic field is transported, amplified, and destroyed inside the Sun and ultimately ejected from the interior – the solar dynamo. Between these limiting timescales another goal of SDO is to predict where and when active regions will emerge, how those magnetic fields erupt and decay, and how the host of other phenomena related to the solar magnetic field come and go.

Solar Cycle 24 started in December 2008 and is predicted to rise to a below-average peak in 2013. This affords an excellent laboratory for SDO. All previous space-based missions with significant duration sampled Solar Cycles 20 – 23, which had above-average levels of activity. The latter half of the 20th century is estimated to have the highest levels of solar activity in the past 10 000 years (Solanki *et al.*, 2004). Solar Cycle 23 was well-measured by the still-operating SOHO and *Hinode* missions, with STEREO starting at the beginning of the extended solar-minimum period.

Two instruments on SDO concentrate on the energy radiated in the extreme ultraviolet. Solar Extreme Ultraviolet (EUV: 1 – 122 nm) photons are the dominant cooling radiation of the solar corona and are also the dominant source of heating for Earth's upper atmosphere. When the Sun is active, EUV emissions can rise and fall by factors of hundreds (and X-rays by factors of thousands) in just a matter of seconds. These surges heat the Earth's upper atmosphere, inflating it and increasing the drag on satellites. EUV photons also can break the bonds of atmospheric atoms and molecules, creating a layer of ions that alters and sometimes severely disturbs radio communications and global positioning system navigation.

SDO will also measure variations inside the Sun, providing the information needed to understand the internal motions that generate the magnetic field, and then the magnetic field as it emerges through the solar surface. The combination of the various measurements allows SDO to study the lifecycle of the solar magnetic field.

To achieve its goals SDO will transmit approximately 150 000 high-resolution full-Sun images and 9000 EUV spectra, or 1.5 terabyte of science data, to the ground each day during the prime mission. This will be converted into images, Dopplergrams, magnetograms, and spectra. Over the five-year prime mission, SDO will return roughly 3 – 4 petabytes of raw data.

The rapid cadence and improved spatial resolution of the SDO instruments is already providing new science results. Images from AIA quickly showed how the global magnetic field of the Sun must relax after even a modest flare and filament (Schrijver and Title, 2011). The low level of flaring during the first year of SDO science operations allowed the discovery that the energy released in many flares is poorly estimated by the GOES X-ray radiometers (Woods *et al.*, 2011b). Energy is radiated at longer wavelengths and for a longer time – a significant finding for people modeling the response of the terrestrial atmosphere to flares.

3. History

The *Solar Dynamics Observatory* is a flagship mission that represents a substantial enhancement of capabilities demonstrated by earlier NASA missions and other science projects. Those earlier measurements revealed new details about the solar interior and the mechanisms driving the solar dynamo. Unlike the line-of-sight (LOS) magnetographs flown on earlier missions, SDO carries a full-disk imaging vector magnetograph with a data cadence sufficient to see changes in the magnetic-field strength and direction that could be related to flares or CMEs. Another needed capability was rapid-cadence images of the solar corona with wavelength coverage to span temperatures from the chromosphere (10 000 K) to flares (2×10^7 K). Full-disk images with spatial resolution of $\approx 1''$ are needed to both resolve known spatial scales and to sample the variations across the disk. The solar images from *Yohkoh*, SOHO, and *Skylab* were used by solar physicists to understand solar activity and by space-weather forecasters to monitor solar activity. Additional bandpasses to better estimate the plasma temperature and higher cadence were both required to understand the response of the corona to the injected magnetic field.

One direct connection between solar activity and the Earth is through the emissions at extreme ultraviolet wavelengths (1 – 122 nm). The utility of these measurements was demonstrated by the SEE instrument on the TIMED satellite (Woods *et al.*, 2005). An instrument with higher duty cycle and cadence would measure the total-energy content in flares while also providing the data to calibrate the coronal images and measuring the radiant energy output of the Sun that creates the ionosphere.

Enhancing the helioseismic and LOS magnetic-field capabilities demonstrated by the MDI instrument on SOHO and the ground-based GONG network was part of a proposal to NASA entitled SONAR (or Hale). This mission had advanced sufficiently far toward realization that it was moved to the LWS program and revised to become SDO. The initial organization of the LWS program by the LWS Science Architecture Team occurred in parallel with the development of SDO.

A Science Definition Team for SDO was formed in November 2000 with David Hathaway (NASA/MSFC) as the chair and Barbara Thompson (NASA/GSFC) as the Study Scientist. The team met several times until July 2001, when the SDT Report (Hathaway *et al.*, 2001) that codified all of the measurement and science requirements was released. This report formed the basis for the NASA Announcement of Opportunity AO 02-OSS-01 soliciting science investigations, which was released 18 January 2002.

The HMI and EVE Science Investigation Teams (SITs) were selected on 19 August 2002 while the AIA SIT was selected on 7 November 2003. The observatory was built and completed testing by September 2008, when delays in the Atlas V launcher line caused it to be left in storage until June 2009. At that time SDO was moved to Florida for launch preparations and launched on 11 February 2010. Science operations began on 1 May 2010 and will continue for the baseline lifetime of five years. There are no consumables on the spacecraft that will limit the useful life of the mission. It is estimated that over 100 years of propellant is left in the tanks.

SDO has several features unique to a NASA science mission:

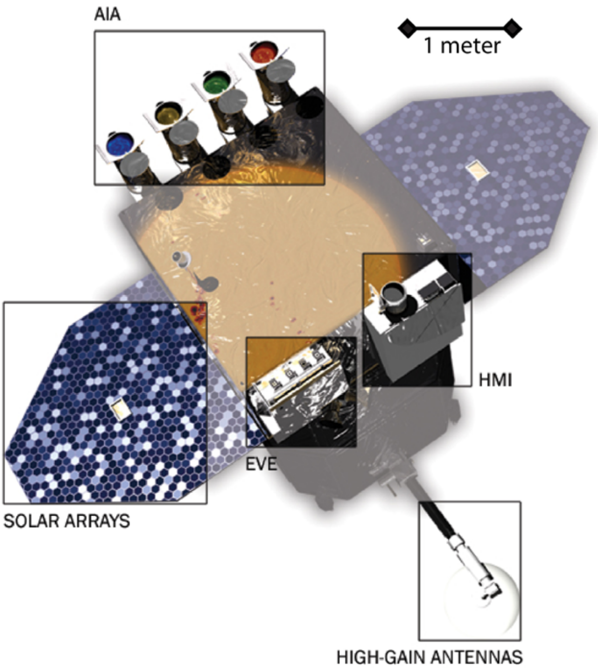
i) A sustained high rate of science-data production and the movement of those data within the spacecraft. This requires reliable electronics that are robust against radiation-induced effects while maintaining timing tolerances better than 1 ns.
ii) The continuous downlink of science data, using a highly automated data pipeline to process the data for immediate use by the space-weather community as well as SDO science investigations.
iii) The extremely accurate pointing and stability required of the spacecraft to allow registration of successive images.
iv) The long (five years) mission life with high-duty cycle instruments.

To date all of these features but the fourth are working and only the long lifetime has yet to be proven.

Because SDO was designed to measure high-resolution data for a five-year mission, the science data resolve the eruptive events, such as flares and coronal mass ejections, while building a well-characterized database for long-term studies. By combining SDO data with those of other missions, such as SOHO, TRACE, *Hinode*, and TIMED, we will be able to construct a picture of the Sun over an entire 22-year magnetic cycle. It is these long-term research projects that should solve the puzzle of the solar cycle and the space weather it creates at Earth.

SDO was built by a team made up of the Goddard Space Flight Center, Stanford University, in Palo Alto, California, the Lockheed Martin Solar Astrophysics Laboratory (LMSAL), also in Palo Alto, California, and the Laboratory for Atmospheric and Space Physics (LASP), University of Colorado in Boulder, Colorado. Goddard was responsible for designing and building the spacecraft and many of the components of the spacecraft. The other team members are the Science Investigation Teams, who are responsible for designing and

Figure 1 The SDO spacecraft with the instruments, high-gain antennas, and solar arrays highlighted. The thrusters and main engine are located on the opposite face of the satellite.



building their instrument, for running the instruments after launch, and performing science investigations related to the data produced by the instruments.

4. The Spacecraft Summary

The SDO spacecraft is shown in Figure 1. A summary of relevant information is:

Satellite: Three-axis stabilized and fully redundant spacecraft.
Duration: Five-year science mission and sufficient propellant to operate for an additional five years.
Mass: Total mass at launch was 3000 kg: instruments 300 kg, spacecraft 1300 kg, and fuel 1400 kg.
Dimensions: The overall length of the spacecraft along the Sun-pointing axis is 4.7 m, and each side is 2.2 m. The span of the spacecraft is 6.1 m along the extended solar panels and 6.0 m along the deployed high-gain antennas.
Solar Array: The 6.6 m^2 of solar panels produce 1500 W of power with an estimated efficiency of 16% after five years on orbit. The "homeplate" shape prevents the solar panel from blocking the high-gain antennas.
High-gain Antennas: The high-gain antennas rotate once each orbit to track the ground station.
Maximum Downlink Rate: The spacecraft has a continuous, high-rate science-data downlink rate of 150 Mbps at a Ka-Band frequency of about 26 GHz; includes 130 Mbps of data and 20 Mbps of encoding overhead.
Mission Operations Center: Located at Goddard Space Flight Center in Maryland.
SDO Ground Station: Located at White Sands Complex in New Mexico.

Table 1 The SDO Level 1 science requirements.

Scientific Questions
What mechanisms drive the quasi-periodic 11-year cycle of solar activity?
How is active region magnetic flux synthesized, concentrated, and dispersed across the solar surface?
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?
Where do the observed variations in the Sun's extreme ultraviolet spectral irradiance arise, and how do they relate to the magnetic-activity cycles?
What magnetic-field configurations lead to the coronal mass ejections, filament eruptions, and flares that produce energetic particles and radiation?
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?
When will activity occur, and is it possible to make accurate and reliable forecasts of space weather and climate?

Table 2 The instrument science objectives.

Gauge the energy from solar activity that is input into the Earth's atmosphere and near-Earth space
Probe the dynamics of the near-surface shear layer of the Sun to observe the local strong-flux regions before they reach the photosphere
Probe the internal processes that govern the solar cycle
Observe the initiation and progression of dynamic processes in the chromosphere and corona to understand their connection to the Sun's magnetic field.

Table 3 SDO measurement objectives.

Make measurements over a significant portion of a solar cycle to capture the solar variations that exist on all time scales from seconds (solar eruptive events) to months (active region evolution, solar rotation) to years (solar cycle)
Measure the extreme ultraviolet spectral irradiance of the Sun at a rapid cadence
Measure the Doppler shifts due to oscillation velocities over the entire visible disk
Make high-resolution measurements of the longitudinal and vector magnetic field over the entire visible disk
Make images of the chromosphere and inner corona at several temperatures at a rapid cadence.

5. Science Goals

The scientific goals of the SDO project, which were first posed in the SDO Science Definition Team report (Hathaway *et al.*, 2001), are to improve our understanding of the seven science questions listed in Table 1. The instruments must be designed to meet the instrument science objectives listed in Table 2 using the measurements listed in Table 3. All of the questions are related to developing an understanding of the solar magnetic field. Three of the science questions emphasize predicting solar activity.

To satisfy these science goals, the Science Investigation Teams described next have created specific research topics and goals.

Table 4 The SDO science investigations.

Investigation	Abbrev.	Returned Data
Heliospheric and Magnetic Imager	HMI	Full-disk Dopplergrams
		Full-disk LOS magnetograms
		Full-disk vector magneograms
Atmospheric Imaging Assembly	AIA	Rapid-cadence, full-disk EUV solar images
Extreme Ultraviolet Variability Experiment	EVE	Rapid-cadence EUV spectral irradiance

6. Science Investigation Teams

The science payload of SDO comprises three instrument suites built by the Science Investigation Teams (SIT). The SITs are summarized in Table 4. The instrument suites are described in detail in other articles in this Topical Issue, so we provide only a brief summary of each.

6.1. *Atmospheric Imaging Assembly*

The *Atmospheric Imaging Assembly* (AIA) is an array of four telescopes that observes the surface and atmosphere of the Sun. The AIA Principal Investigator is Alan Title of LMSAL. AIA was built to obtain full-disk images of the solar atmosphere with a field of view of at least 40′ and a two-pixel resolution of 1.2″. Filters on the telescopes cover ten different wavelength bands that include seven extreme ultraviolet, two ultraviolet, and one visible-light band to reveal key aspects of solar activity. The wavelength bands were chosen to yield diagnostics over the range of 6000 K to 3×10^6 K. AIA uses multilayer coatings combined with foil filters to isolate the desired spectral bandpasses for each telescope. AIA was built by LMSAL, Palo Alto, California. A detailed description of AIA can be found in Lemen *et al.* (2011).

6.2. *Extreme Ultraviolet Variability Experiment*

The *Extreme ultraviolet Variability Experiment* (EVE) measures fluctuations in the Sun's ultraviolet output. Tom Woods of LASP is the Principal Investigator. EVE will measure the solar spectral irradiance in the most variable and unpredictable part of the solar spectrum from 0.1 to 105 nm as well as 121.6 nm. EVE has three parts: MEGS, ESP, and SAM. MEGS combines grating spectrometers with two CCDs to create images of the spectral irradiance in various wavelength ranges. These individual sections are then combined to give the spectrum between 6.5 to 105 nm at 0.1 nm spectral resolution. A silicon photodiode strategically placed inside the MEGS-B channel measures the irradiance of Lyman-α at 121.6 nm, the single brightest line in the EUV. ESP is a series of radiometers placed behind a transmission grating that measures the irradiance in several wavelength bands (0.1 – 5.9, 17.2 – 20.6, 23.1 – 27.6, 28.0 – 31.6, and 34.0 – 38.1 nm). It is similar to the SEM instrument on SOHO. SAM is a pinhole camera used with the MEGS-A CCD to measure individual X-ray photons in the wavelength range 0.1 – 7 nm.

This design will allow solar scientists to continuously monitor EUV emissions at a ten-second cadence. EVE was built by LASP at the University of Colorado. A detailed description of the EVE instrument and science investigation can be found in Woods *et al.* (2011a).

6.3. *Helioseismic and Magnetic Imager*

The *Helioseismic and Magnetic Imager* (HMI) will map magnetic and velocity fields at the surface of the Sun. A key goal of this experiment is to decipher the physics of the solar magnetic dynamo. The Principal Investigator for HMI is Phil Scherrer of Stanford University. HMI was built by LMSAL, Palo Alto, California. A detailed description of the HMI science investigation is given in Schou *et al.* (2011).

HMI measures the Doppler shift of the Fe I 617.3 nm spectral line to determine the photospheric surface velocity over the Sun's entire visible disk. HMI creates a full-disk photospheric velocity measurement (or Dopplergram) every 45 seconds with a two-pixel resolution of $1''$, a noise level $\approx 25\ \mathrm{m\,s^{-1}}$, a data recovery of 95% of the Dopplergrams, and a data completeness of 99% for each Dopplergram. These Dopplergrams are then used to study the inside of the Sun.

HMI uses the Zeeman effect of the same spectral line to measure the Stokes parameters required to create full-disk longitudinal magnetic-field measurements (LOS magnetogram) and full-disk vector photospheric magnetic-field maps (vector magnetogram). The LOS magnetograms have a cadence of 45 seconds with a two-pixel resolution of $1''$ resolution, a noise level of 17 G, and a dynamic range of ± 3 kG. The vector magnetograms have a 12-minute cadence with a polarization accuracy of no less than 0.3%. HMI thus provides the first rapid-cadence measurements of the strength and direction of the solar magnetic field over the visible disk of the Sun.

7. Science Data Capture Requirement

An important consideration during the post-launch science phase, or Phase E, is the science data-capture requirement, driven primarily by the needs of the helioseismic studies. Long, uninterrupted periods of continuous observation provide the best data for the helioseismology algorithms that are used to study the internal structure of the convection zone. The development of predictive models for short-term phenomena such as flares and CMEs also relies on a low-latency, continuous dataset. SDO is designed to return science data for at least 22 individual 72-day periods over the five-year mission. For one 72-day period to be considered complete, the ground system must capture 95% of all possible observation time. The remaining 5% is covered in the SDO Science Data Capture Budget, which accounts for science-data outages and interruptions expected during the mission. These outages and interruptions include:

- Planned operations, such as thruster-based, station-keeping maneuvers, and high-gain antenna (HGA) handovers. SDO uses thrusters to maintain the longitude and inclination of its orbit and to control the momentum in the reaction wheels. HGA handovers occur near eclipses when a single antenna cannot maintain contact with SDOGS while keeping the observatory oriented along the solar-rotation axis (solar North).
- Instrument calibration, roll, and off-point maneuvers. Each instrument has a set of calibration maneuvers that are performed on a regular basis. Some, such as daily flatfields and internal calibrations, affect only a single instrument. Others, such as roll maneuvers, affect all of the instruments.
- Eclipses of the Sun by the Earth and transits of the Moon across the Sun. For several weeks around the Equinoxes, SDO will experience eclipses when the Earth passes between the satellite and the Sun. This causes a loss of 44 hours each year. Lunar transits

occur at least once per year and a maximum of four times a year during the SDO mission. Transits of Mercury (on 9 May 2016 and 11 November 2019) and Venus (on 6 June 2012) across the solar disks are counted toward good science data as they are used for calibration purposes (100 hours per year).
- Random interruptions caused by energetic charged particles (Single Event Upsets and Solar Energetic Electrons: 34 hours per year).
- Unplanned interruptions at SDOGS include signal attenuation due to rain, interference of direct solar radio emissions when SDO is directly in line with the Sun and the ground station, and equipment problems (112.5 hours per year).

Whenever a maneuver moves the instruments off of the Sun, it is necessary to include time for thermal and alignment recovery.

The Flight Operations Team (FOT) and instrument operations teams are jointly responsible for tracking science data losses. Planned events causing data loss will be scheduled in order to satisfy the requirements for data capture and completeness. For data to be considered complete, the ground system must forward sufficient downlinked HMI data to the JSOC to allow HMI to construct 95% of anticipated Dopplergrams with 99% of the pixels containing science data. The AIA and EVE instruments have less stringent data-capture requirements of 90%. In the event that more than 5% (HMI) or 10% (AIA and EVE) of the data are lost before a 72-day period is completed, the PIs may jointly elect to start a new 72-day period during which the data-capture requirement will be enforced. After one year of science operations, we have completed five 72-day observation periods without an interruption. As of 1 April 2011 the ground system is forwarding 99.97% of the transmitted Instrument Multiplexing Protocol Data Units (IM_PDUs) to the Science Operation Centers (SOCs) and HMI has recovered 97% of the Dopplergrams and magnetograms. As anticipated, the eclipse seasons suffer from the greatest loss of data.

7.1. Ground System and Mission Operations

SDO uses a dedicated ground station with dual antennas to meet science-data downlink completeness requirements. The ground system can receive a science-data downlink rate of 130 Mbps for 24 hours per day and seven days per week to achieve full mission success. Once on the ground, the science data are assembled into files and transmitted to the instrument SOCs. A local, 30-day science data cache is available at the ground station. The ground station also provides S-band frequency command, telemetry and tracking functions in support of SDO mission operations. The SDO Ground System is described by Tann, Pages, and Silva (2005).

Because the instruments view the full disk of the Sun, there is no need to have an elaborate commanding process. SDO is pointed at the center of the Sun except for calibration and spacecraft maneuvers. Thus the data are quite uniform, simplifying the data access, *i.e.* no campaigns. The high-duty cycle allows external users to obtain concurrent observations by "observing the database" of SDO rather than coordinating special observing sequences.

8. SDO Orbit and Mission Phases

The rapid cadence and continuous coverage required for SDO science observations led to placing the satellite into an inclined geosynchronous orbit. This allows for a continuous, high data rate, contact with a single, dedicated ground station. When viewed from the ground station, the orbit resembles an elongated figure-eight (or annalemma) with a width of $(i/4)\sin i = 3.3°$ as it orbits the Earth once per day. Relying on a single site reduces the complexity of the ground system by removing the need to combine data from multiple, widely spaced antennas scattered around the globe.

Nearly continuous observations of the Sun can be obtained from other orbits, such as a Sun-synchronous, low-Earth orbit (LEO). If SDO had been placed into a LEO, it would have been necessary to store large volumes of scientific data onboard until a downlink opportunity was available, and multiple sites around the globe would be needed to downlink the data. However, no space-qualified data recorder with the capability to handle this large data volume exists. The large data rate of SDO, the unavailability of a data recorder, and the ability to continuously stream data from the spacecraft if a geosynchronous orbit were selected led to the selection of the inclined geosynchronous orbit.

Disadvantages of the inclined geosynchronous orbit include higher launch costs (relative to LEO) and two Earth-shadow (eclipse) seasons each year. During these two – three week long eclipse periods, SDO will experience a daily interruption of solar observations, and these interruptions have been included in SDO's data-capture budget (see Section 7). There will also be three lunar transits per year from this orbit.

This inclined geosynchronous orbit is located on the outer edges of Earth's radiation belt, where the radiation dose can be quite high. Additional shielding was added to reduce the effects of exposure to this ionizing radiation.

The combined Atlas V/Centaur launch vehicle placed SDO into a geosynchronous transfer orbit with an apogee altitude of 35 350 km and a perigee altitude of 2500 km. A series of nine apogee-motor burns were used to raise perigee altitude to 35 350 km, and then three thruster motor burns were used to raise both apogee and perigee altitudes to their final values of 35 800 km (Figure 2). Excessive fuel-slosh during the early main engine burns delayed the reaching of the final orbit until 16 March 2010. Once SDO was on-orbit the main engine was disabled, leaving only the thrusters to perform maneuvers.

Two types of on-orbit maneuver are used. One maneuver changes the spacecraft velocity, known as a delta-V maneuver, and is used to keep the spacecraft within its assigned orbit. The other maneuver, called a delta-H (where "H" is the symbol for angular momentum), is used to dissipate the momentum stored during regular operations. At the end of its mission, SDO will be moved to a disposal orbit outside of the geosynchronous belt and all energy sources depleted.

9. SDO Data

Science data from SDO are transmitted via Ka-band to the dedicated ground station in New Mexico. From there the data stream is converted into telemetry files and forwarded to the SOCs. Each instrument is assigned a fraction of the telemetry stream. Because continuous contact is maintained with the spacecraft, the science-data return is maximized.

Data from the SDO mission consist of images, full-disk maps, and spectra. Each SDO science investigation team maintains a data archive of its science data products for the life of the SDO mission, and have made these data publicly available. Given the volume of data produced by SDO, a variety of methods have been developed to obtain data at both reduced and full resolutions. The data latency for near-realtime data has been 15 minutes during the mission operations phase.

Full-resolution science data from HMI and AIA are served by the Joint-SOC (JSOC) at Stanford University (http://jsoc.stanford.edu/ajax/lookdata.html). The data are provided as FITS formatted files (a description of the FITS format can be found at Pence *et al.*,

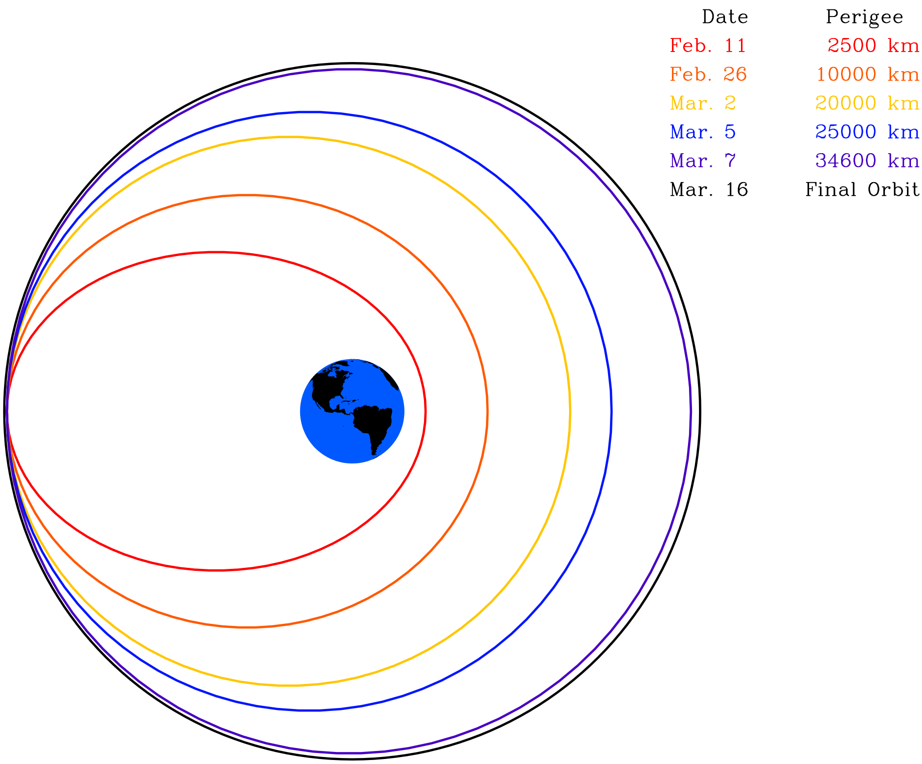


Figure 2 The raising of the SDO orbit from GTO to inclined geosynchronous. The initial GTO, two intermediate orbits, and the estimated final orbit are shown to scale. Apogee Motor Firings (AMFs) all took place at the apogee of the orbit (the left side of the diagram) and were designed to lift the perigee up to a geosynchronous altitude. A few trim maneuvers then moved SDO into its final orbit. Perigee values are altitudes (height above the Earth).

2010). Readers for files in the FITS formats for most languages can be found at http://heasarc.gsfc.nasa.gov/docs/software/fitsio/fitsio.html. The HMI full-disk maps, such as Dopplergrams and magnetograms, along with supporting images are served at Level 1.5. AIA data can be obtained as Level 1.5 images or as Level 1.0 data that must be promoted to Level 1.5 by user software. Descriptions of the AIA data-product levels can be found in Lemen *et al.* (2011). Routines for this purpose are available in the IDL language through the SolarSoft package (Freeland and Handy, 1998) available at http://www.lmsal.com/solarsoft/. A synoptic sequence of all AIA bandpasses in 1K $\times$ 1K FITS files with three-minute cadence is also provided for long-term analysis.

Full-resolution science data from EVE are served by the EVE SOC at the University of Colorado (http://lasp.colorado.edu/eve/data/data_access.htm). These data are available in compressed FITS files. The EVE team also produces daily averaged data at three resolutions. The EVE team provides a FITS reader routine in the IDL language that can be used to read their data files.

9.1. Rules of the Road for Data Use

The SDO science investigators agree to abide by the "Rules of the Road" developed for the Sun–Earth Connection and its successor, the Heliophysics Science Division. These rules are available at http://lwsde.gsfc.nasa.gov/Rules_Revised20030327.html and repeated here:

i) The Principal Investigators (PI) shall, in a timely manner, make available to the science-data user community (Users) data and access methods to reach the scientifically useful data and provide analysis tools equivalent to the level that the PI uses.
ii) The Principal Investigators (PI) shall make available appropriate data products to the public that assist the PI's Education and Public Outreach responsibilities.
iii) The PI shall ensure that all scientifically important data are archived to ensure long-term accessibility of the data and their correct and independent usability.
iv) The PI shall notify Users of updates to processing software and calibrations via metadata and other appropriate documentation.
v) Users should consult with the PI to ensure that the Users are accessing the most recent available versions of the data and analysis routines.
vi) Browse products are not intended for science analysis or publication and should not be used for those purposes without consent of the PI.
vii) Users should acknowledge the sources of data used in all publications, presentations, and reports.
viii) Users should transmit to the PI a copy of each manuscript that uses the PI's data upon submission of that manuscript for consideration of publication. On publication the citation should be transmitted to the PI and any other providers of data.
ix) Users are encouraged to make tools of general utility and/or value-added data products widely available to the community. Users are encouraged to notify the PI of such utilities or products. The User should also clearly label the product as being different from the original PI-produced data product.
x) The editors and referees of scientific journals should avail themselves of the expertise of the PI while a data set is still unfamiliar to the community, and when it is uncertain whether authors have employed the most up-to-date data and calibrations.

9.2. Browse and Public Access Data

SDO data are made available to the public in common graphics formats at several websites. For example, the mission website at http://sdo.gsfc.nasa.gov/ serves images in the JPEG format at a roughly 15-minute cadence and several spatial resolutions. Movies covering the previous 48 hours are available in both mpeg format and as self-updating kiosk movies. The instrument teams provide access to similar graphics formats at more rapid cadences. Helioviewer (http://helioviewer.org/) and jHelioviewer (http://jhelioviewer.org/) allow one to browse the AIA images, making and sharing movies from an archive of images in the JPEG2000 format.

Press releases, graphics of wide interest, and other announcements are available from NASA Headquarters at http://www.nasa.gov/sdo.

9.3. Final Data Archive

At the end of the SDO mission, each SIT will deliver the data obtained during the prime mission to a data archive for permanent storage.

10. Summary

The *Solar Dynamics Observatory* is setting the standard for new rapid-cadence science data that enables the study of the energetics of solar events in the corona and the internal structure and surface magnetic of the Sun. SDO data are being combined with that from other satellites in NASA Heliophysics Great Observatory, such as STEREO, SOHO, *Wind*, TIMED, and ACE, to develop an understanding of how solar activity is generated and how it can affect the Earth.

Many new, significant discoveries have already occurred, with more to follow as this mission progresses. In particular, researchers hope to learn how storms get started near the solar surface and how they propagate upward through the solar atmosphere toward Earth and elsewhere in the solar system. Scientists will use SDO data to help them understand how the Sun's changing magnetic fields are created and how they evolve to release the energy that heats the corona and creates the eruptions that are the storms of solar activity and the seeds of space weather.

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The *Atmospheric Imaging Assembly* (AIA) on the *Solar Dynamics Observatory* (SDO)

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Abstract The *Atmospheric Imaging Assembly* (AIA) provides multiple simultaneous high-resolution full-disk images of the corona and transition region up to 0.5 $R_{\odot}$ above the solar limb with 1.5-arcsec spatial resolution and 12-second temporal resolution. The AIA consists of four telescopes that employ normal-incidence, multilayer-coated optics to provide

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narrow-band imaging of seven extreme ultraviolet (EUV) band passes centered on specific lines: Fe XVIII (94 Å), Fe VIII, XXI (131 Å), Fe IX (171 Å), Fe XII, XXIV (193 Å), Fe XIV (211 Å), He II (304 Å), and Fe XVI (335 Å). One telescope observes C IV (near 1600 Å) and the nearby continuum (1700 Å) and has a filter that observes in the visible to enable coalignment with images from other telescopes. The temperature diagnostics of the EUV emissions cover the range from 6×10^4 K to 2×10^7 K. The AIA was launched as a part of NASA's *Solar Dynamics Observatory* (SDO) mission on 11 February 2010. AIA will advance our understanding of the mechanisms of solar variability and of how the Sun's energy is stored and released into the heliosphere and geospace.

Keywords Solar corona · Solar instrumentation · Solar imaging · Extreme ultraviolet

1. Introduction

The primary goal of the *Solar Dynamics Observatory* is to understand the physics of solar variations that influence life and society. It achieves that goal by targeted basic research focused on determining how and why the Sun varies, and on improving our understanding of how the Sun drives global change and space weather. As one of the SDO instruments designed to meet this goal, the *Atmospheric Imaging Assembly* (AIA) focuses on the evolution of the magnetic environment in the Sun's atmosphere, and its interaction with embedded and surrounding plasma. Figure 1 shows the four AIA telescopes mounted to the SDO spacecraft, and Figure 2 shows schematically the layout of the telescopes with respect to their wavelength band passes.

The images of the corona taken by *Yohkoh*, the *Extreme ultraviolet Imaging Telescope* (EIT) on the *Solar and Heliospheric Observatory* (SOHO), the *Sun Earth Connection Coronal and Heliospheric Investigation* (SECCHI) on the *Solar Terrestrial Relations Observatory* (STEREO), and the *Transition Region and Coronal Explorer* (TRACE) have shown that all coronal structures evolve in density, temperature, and position on time scales as short as seconds. Conditions within coronal-loop volumes and open magnetic structures appear to depend primarily on "local" conditions, *i.e.* on conditions determined by the path of the field line, or loop, from end to end in the photosphere. Combined with the marked temporal evolution of the atmospheres contained within coronal loops or open-field regions on relatively short time scales, EUV images are dissimilar for different band passes. Apart from

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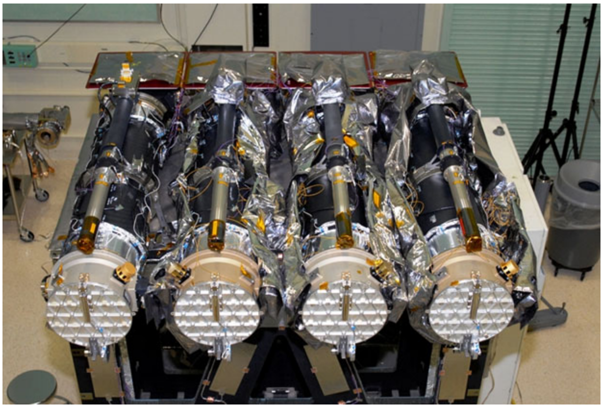

Figure 1 The AIA telescopes with their guide telescopes as seen mounted on the SDO spacecraft's instrument module during integration in the clean room at NASA's Goddard Space Flight Center.

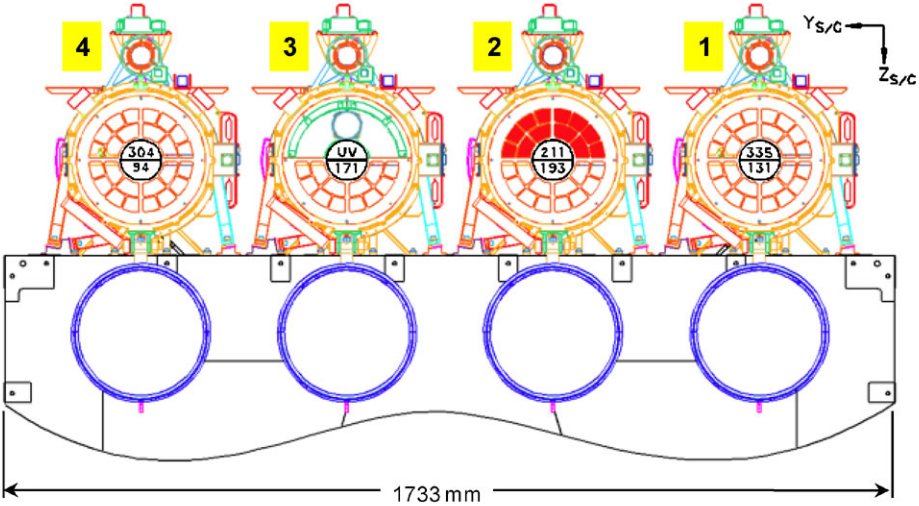

Figure 2 The layout of the wavelength channels or band passes in each of the four AIA telescopes. Telescope 2 has an aperture blade to select between wavelength channels. The other telescopes rely on filters in filter wheels to select between channels. The top half of telescope number 3 has a MgF_2 window with a coating centered at 1600 Å.

thermal evolution, there is an abundance of waves, flows, and impulsive phenomena that occur on short time scales of minutes or less.

The coronal magnetic field itself evolves on time scales that range from seconds to years. Slowest is the evolution of the largest-scale field. On shorter time scales, electrical currents that are induced in, and carried with, the magnetic field may build up over weeks or months, while release of those stresses may take only a fraction of a minute. *Yohkoh* and SOHO have shown, moreover, that there are no purely local field topologies: the short- and long-term evolution of the corona is affected by both nearby and distant magnetic sources.

AIA was designed to study these characteristics of the Sun's dynamic magnetic field and the coronal response to it. AIA provides the following essential capabilities:

i) a view of the entire corona at the best feasible resolutions compatible with SDO's constraints, providing coverage of the full thermal range of the corona;

ii) a high signal-to-noise ratio for two- to three-second exposures that reaches 100 in quiescent conditions for the low-temperature coronal-imaging channels and during flaring in the higher-temperature channels, with a dynamic range of up to 10 000; and
iii) essentially uninterrupted viewing for months at a time at a temporal resolution of approximately 10 to 12 seconds, and sometimes faster to study energetic transient phenomena.

These capabilities are met by a design that includes the following.

i) Four 20-cm, dual-channel, normal-incidence telescopes, which observe a 41 arcmin field of view in ten EUV and UV channels, with 0.6-arcsec pixels and 4096 × 4096 CCDs. Four of the EUV wavelength bands open new perspectives on the solar corona, having never been imaged or imaged only during brief rocket flights. The set of six EUV channels that observe ionized iron allow the construction of relatively narrow-band temperature maps of the solar corona from below 1 MK to above 20 MK.
ii) Detectors with a full well of at least 150 000 electrons, with typically 18 e^- photon^{-1} (for 193 Å), and a readout noise of <25 e^-, and data compression that is nearly lossless.
iii) A standard baseline observing program running most of the time, while observing continuously from SDO's geo-synchronous orbit. AIA has the capability to adjust its observing program to changing solar conditions in order to implement observing programs that are optimized to meet the requirements of specific scientific objectives. This allows, for example, a two-second cadence in a reduced field of view using four wavelengths for flare studies.

With these capabilities, AIA enables us to observe the changing topology of the magnetic field even as the coronal plasma is changing in temperature. In its standard operating mode, the AIA images the entire Sun ten times faster per wavelength than TRACE at twice the number of coronal channels, with a 16-fold increase in the number of pixels per image. Compared with the full-disk SOHO/EIT (Delaboudinière *et al.*, 1995), AIA runs at 700× the usual EIT image frequency, with 16 times more pixels per image, in typically eight instead of four channels. Compared to EIT and TRACE, the AIA thus represents an increase in the information rate for coronal observations by a factor of 400 to 22 000. AIA also advances on the *Hinode*/*X-Ray Telescope* (XRT) (Golub *et al.*, 2007) and SECCHI/*Extreme Ultra-Violet Imager* (EUVI) (Howard *et al.*, 2008) telescope designs, each which contained 2k × 2k pixel CCDs with one and 1.6-arcsec pixel sizes, respectively. And SDO's *Helioseismic and Magnetic Imager* (HMI) provides, among other things, high spatial resolution line-of-sight magnetograms at a cadence suitable for the evolution of the photosphere that is an order of magnitude faster than SOHO/MDI (Schou *et al.*, 2011).

The basic AIA observables are full-Sun intensities at a range of wavelengths. In combination with the higher-level and metadata products these comprise the data archive which is freely accessible to the research community; the archive and its interfaces (including those for data requests and archive queries) are described by Hurlburt *et al.* (2011).

2. Science Overview

The AIA investigation covers a broad range of science objectives that focus on five core research themes that both advance solar and heliospheric physics in general and provide advanced warning of coronal and inner-heliospheric disturbances of interest to the Living With a Star program, *i.e.*, global change, space weather, human exploration of space, and technological infrastructure in space and on Earth.

i) Energy input, storage, and release: the 3D dynamic coronal structure, including reconnection and the effects of coronal currents.
ii) Coronal heating and irradiance: origins of the thermal structure and coronal emission, to understand the basic properties of the solar coronal plasma and field, and the spatially-resolved input to solar spectral irradiance, as observed by, *e.g.*, SDO's *Extreme ultraviolet Variability Explorer* (EVE).
iii) Transients: sources of radiation and energetic particles.
iv) Connections to geospace: material and magnetic field output of the Sun.
v) Coronal seismology: a diagnostic to access sub-resolution coronal physics.

These five themes guide the AIA science investigation, and their fundamental observational needs have shaped the design of the instrument.

2.1. Energy Input, Storage, and Release: The Dynamic Coronal Structure

All coronal activity relies on energy dissipation within the plasma contained in the Sun's magnetic field. One of the primary objectives of the NASA's Living with a Star program, and of the AIA science investigation in particular, is to understand how energy is brought into the coronal field, how it is stored there, and how it is released. One key part of that objective is to understand the geometry of the magnetic field, and its evolution subject to external forcing and internal energy dissipation.

Plasma motions in and below the solar photosphere force the embedded magnetic field to move with the flows. These motions apply stress to the outer-atmospheric field on a broad range of spatial and temporal scales. This stress propagates throughout the outer atmosphere in the form of a variety of wave types and frequencies, as well as a broad spectrum of slower changes associated with evolving induced currents. Key questions to be answered are: How are these perturbations imposed upon the corona? How do they propagate? How do the electric currents close either within the atmosphere or through the photosphere?

TRACE observations reveal that the stresses that are applied to the coronal field by the photospheric motions lead to a magnetic field that is only moderately tangled on scales of the granular motions up to the largest scales, despite theoretical expectations that field-line braids should persist for long times in a coronal environment where reconnection was expected to proceed only slowly. Instead of a highly tangled field, however, TRACE images show that small-scale braids, driven by convective motions from the arcsecond scale of the granulation upward, are only seen around filaments and prominences. Even then, the images suggest that loop twists rarely exceed about half a turn. This implies rapid dissipation of the induced currents, which is mimicked by some recent numerical simulations. The fidelity of these simulations does not approach the real corona, however, with anticipated (but maybe not realized) magnetic Reynolds numbers for the bulk of the coronal volume many orders of magnitude larger than in the simulated volume. In contrast to the apparently efficient smoothing out of the small-scale complexity, many filament configurations erupt, requiring substantial amounts of stored energy. Why do small-scale twists dissipate readily, whereas large-scale stresses persist for long times in filament and sigmoid-field configurations which can eventually lead to instabilities?

2.2. Coronal Heating and Irradiance: Thermal Structure and Emission

Solar radiation at UV, EUV, and SXR wavelengths plays a significant role in the determining the physical properties of the Earth's upper atmosphere. Variations in solar radiation at these wavelengths drive changes in the density and ionization of the Earth's thermosphere and ionosphere, impacting the performance of ground-based communications systems and spacecraft in low-Earth orbit. Long-term observations of the solar irradiance with the required accuracy have proven difficult, however, and much of our knowledge of the solar irradiance and its variability remains uncertain.

Observations over the past several decades have clearly established that solar variability at UV, EUV, and SXR wavelengths is tied to the variability of the Sun's surface magnetic fields. Past studies of the Sun and Sun-like stars has revealed that the primary determinant of the radiation leaving the corona is the total magnetic flux threading the photosphere. At present, however, we do not possess a detailed understanding of how magnetic energy is released within the solar corona. Thus we cannot use our knowledge of the Sun's magnetic fields to model and predict changes in the solar irradiance. Such calculations are an invaluable aid to interpreting and extending direct measurements of the solar irradiance. One of the primary objectives of the SDO mission is to develop a physical understanding of solar irradiance and its variability, specifically at (E)UV wavelengths, with close collaboration between the science teams of AIA and of SDO's *Extreme ultraviolet Variability Experiment* (EVE: Woods *et al.*, 2011). AIA images will show the locations and structural/thermal changes associated with EUV irradiance changes measured with high precision by EVE.

2.3. Transients: Sources of Radiation and Energetic Particles

Most of the time, the coronal field appears to evolve smoothly. At times, however, massive explosions or eruptions disturb the coronal field. Many are not strong enough to rupture the encapsulating coronal magnetic field, and only the energetic radiation escapes toward Earth. Some, in contrast, are associated with opening magnetic fields into the heliosphere; these coronal eruptions appear to be the counterparts of coronal mass ejections. What triggers the eruptions or explosions? What determines whether the field confines the eruption to the corona or allows coupling into the heliosphere?

Flares, CMEs, filament destabilizations, sprays, and other transients are sources of radiation and energetic particles, and therefore prime drivers of violent solar weather. Transients result from the sudden conversion of magnetic energy into bulk, thermal, and non-thermal energy as the magnetic field reconnects. Theories of 3D reconnection are still in early stages of development, and advances in its understanding are hampered by observational limitations.

AIA is designed to make the next leap forward in understanding transient initiation and evolution. Its high-cadence, full-disk, multi-temperature observations are revealing the reorganizing field in the initial phases of flares and of filament eruptions, as well as the later evolution as the field relaxes into its new state. Particularly promising is the inclusion of four EUV pass bands that observe the evolution of the coronal plasma for the first time at near-arcsecond resolution for temperatures between 3 to 20 MK (94, 131, 211, and 335 Å).

2.4. Connections to Geospace: Material and Magnetic-Field Output of the Sun

The solar wind, the embedded magnetic field, and eruptive perturbations in the form of CMEs drive the variations in the space surrounding the Earth and other planets. The dynamic connections between Sun and geospace are a cornerstone of the ILWS program. To understand how the Sun's variability affects life and society, we must understand how the products of this variability are transported into and through the heliosphere, and how they interact with the Earth's magnetic field and atmosphere. The AIA investigation is expected to make substantial quantitative advances in many areas relevant to this problem. At the foundation of this expectation lies the improved understanding of the global coronal field and its extension into the heliosphere. In Sections 2.2 and 2.3 we discussed this for the pathways for escape of energetic particles into the heliosphere, the irradiance that affects the ionosphere and below, and the triggering of flares and CMEs. Here we focus on the magnetized solar wind and its perturbations.

The solar wind flows out radially into the heliosphere dragging along the magnetic-field lines that are forced "open" within the first few radii from the Sun. The successes of simple concepts such as the potential-field source-surface (PFSS) model suggest that more realistic and detailed models should explain why this is. What determines which field lines will open? Why does the PFSS work so well? The latter is particularly interesting because the PFSS model does not incorporate field dynamics. How is field opened, and how is it closed again as the connections evolve? This is somehow connected to the properties of the solar wind, which we know depend on the field geometry and strength. But although that dependence is empirically constrained, we still need to learn what determines the physical properties of the solar wind.

The eruptive coronal mass ejections perturb the background solar wind. How do they evolve through the coronal field? How do they couple into, and propagate through, the heliosphere on their way to the Earth and the other planets? HMI and AIA data will enable modelers to addresses these questions by advancing beyond PFSS models to full MHD models of the coronal and inner heliosphere.

2.5. Coronal Seismology: A Diagnostic to Study Coronal Waves and Oscillations

Recent observations from SOHO and TRACE show a variety of oscillation modes in the transition region and corona. These observations opened up the promising new field of coronal seismology. By studying the properties, excitation, propagation and decay of these oscillations and waves, we can reveal fundamental physical properties of the solar transition region and corona, such as the magnetic field, density, temperature, and viscosity.

Examples of seismic responses of the corona have been found in large-scale coronal Moreton and EIT waves, in polar plumes, sunspot fields, upper transition-region moss, and what appear to be ordinary loops. Perhaps most striking are the transverse oscillations seen by TRACE. Longitudinal oscillations and waves have also been observed in the upper transition-region moss and in coronal loops, both in cooler loops with TRACE and in hot (10^7 K) loops with the *Solar Ultraviolet Measurements of Emitted Radiation* (SUMER) spectrometer.

There are still many unresolved issues about these waves and oscillations. How do they get excited? Why does only a fraction of the observed flares lead to clear oscillations? Are longitudinal waves in coronal loops with five-minute periods related to *p* modes? How do any of these waves propagate? Which of the many possible theoretical mechanisms can explain the unexpectedly rapid decay of some of these waves? These are some of the questions that we need to answer before we can seismically probe coronal physics.

The AIA design enables us to develop the necessary improved understanding of the properties and other unresolved issues of the observed waves. The high cadence of AIA will extend the parameter space to higher frequencies (by a factor of two – four compared with TRACE). The broad, simultaneous temperature coverage positions us to study waves in parts of active regions that have not yet been seen. Guided by significant advances in the theory of these waves (from 3D MHD simulations), and complemented with spectroscopic measurements of densities and line-of-sight velocities (*e.g.* by the *EUV Imaging Spectrometer* on *Hinode*), and reliable magnetic-field extrapolations (*e.g.* from HMI and AIA), AIA will fully exploit the potential of coronal seismology.

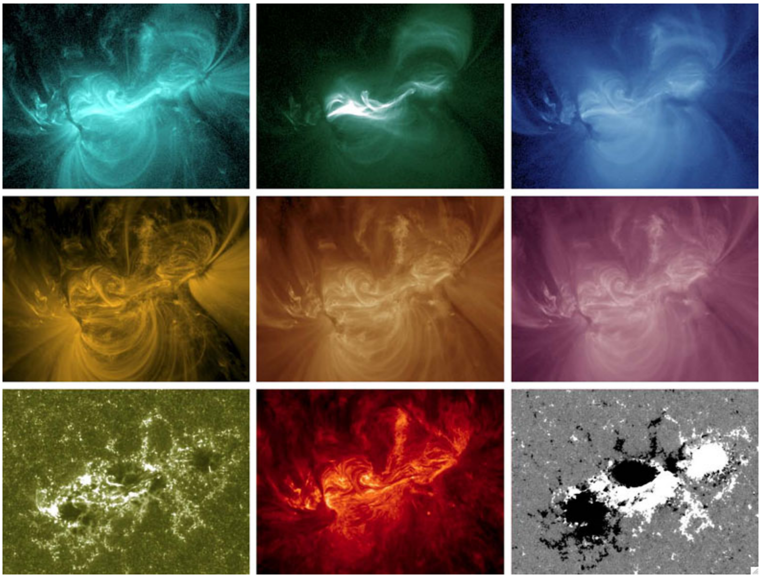

Figure 3 Images of an active region observed on 15 February 2011 at 01:45 UT with AIA. The top row panels are observations from the 131-, 94-, and 335-Å channels (from left to right). The middle row panels are from the 171-, 193-, and 211-Å channels, and the bottom row panels are from 1600 and 304 Å (left and middle, respectively). The bottom right corner panel is an HMI line-of-sight magnetogram showing the same field of view. The AIA images have been processed to Level 1.5 and each contains 480 × 360 pixels, which corresponds to 288 × 216 arcsecs.

3. Instrument Overview

The AIA instrument consists of four generalized Cassegrain telescopes that are optimized to observed narrow band passes in the EUV in order to observe solar emissions from the transition region and corona. An active region observed on 15 February 2011 is shown in Figure 3 for the seven EUV channels, the 1600-Å channel, and an HMI line-of-sight magnetogram. This mosaic of images illustrates how the various instrument-response functions sample the temperature-dependent structure of the solar corona. Table 1 lists the primary ions for each band pass and their characteristic emission temperatures, along with the types of solar features that may be observed.

Each AIA f/20 telescope has a 20-cm primary mirror and an active secondary mirror. Key parameters of the telescopes are given in Table 2. The telescope design is fully baffled to prevent charged particles from reaching the CCD, and the aperture pupil is located by a mask that is mounted in front of the primary mirror. Each telescope field of view is approximately 41 arcmin circular diameter. By design, the CCD corners do not receive solar emission from the optics (being shaded by the filter-wheel mechanism). These dark regions provide useful means to monitor detector noise levels and to check for the presence of energetic particles. The telescope mirrors have multilayer coatings that are optimized for the selected EUV wavelength of interest. Three of the telescopes, numbers 1, 2, and 4, have two different EUV band passes. Telescope number 3's mirror has a 171-Å band pass on one half and the other half has a broad-band UV coating. At the focal plane are back-thinned CCD sensors with 4096 × 4096 pixels; each 12-μm pixel corresponds to 0.6 arcsec. Entrance filters at the telescope aperture block visible and IR radiation. Filters in a filter-wheel mechanism located