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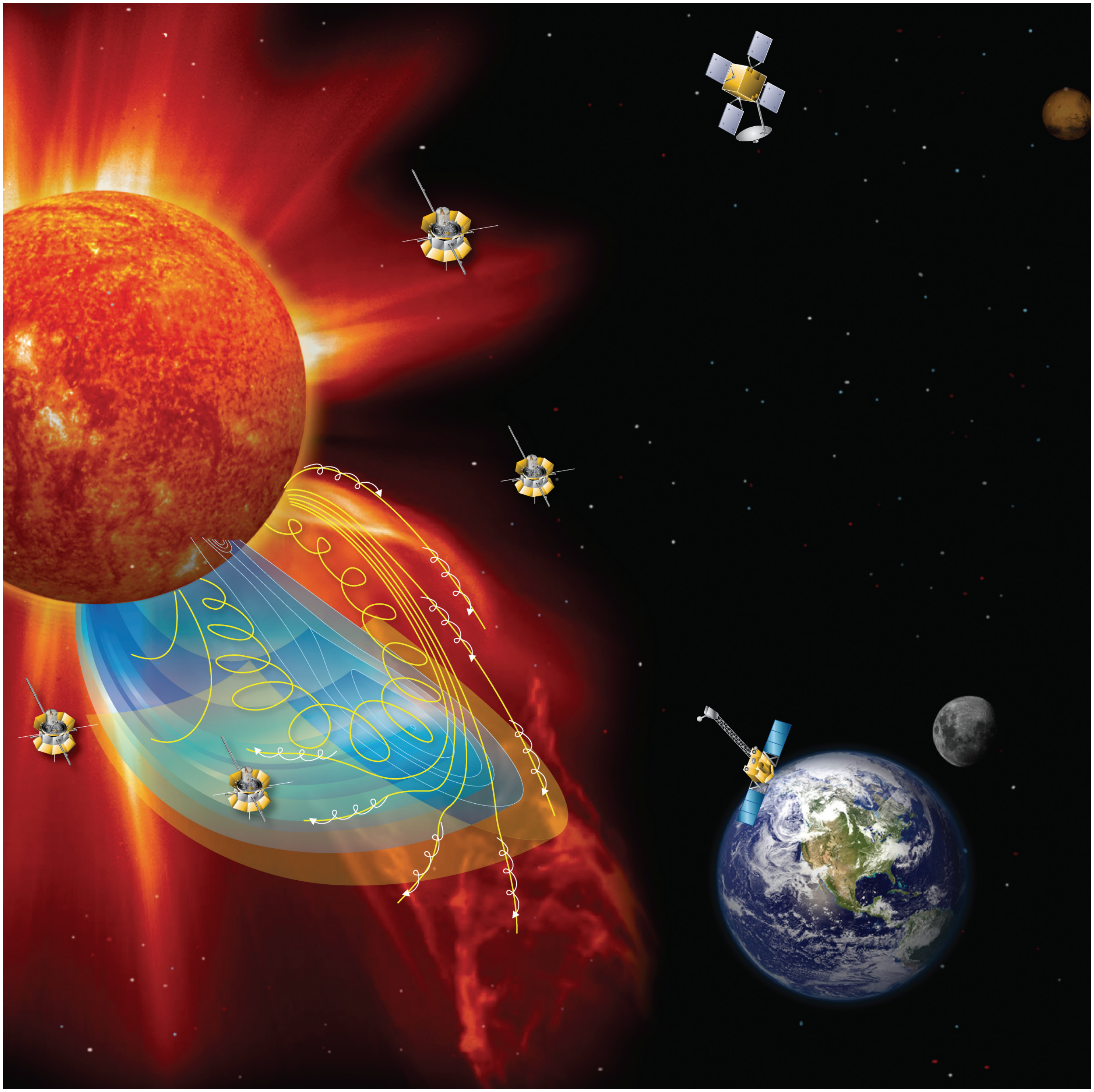
Solar Sentinels: Report of the Science and Technology Definition Team



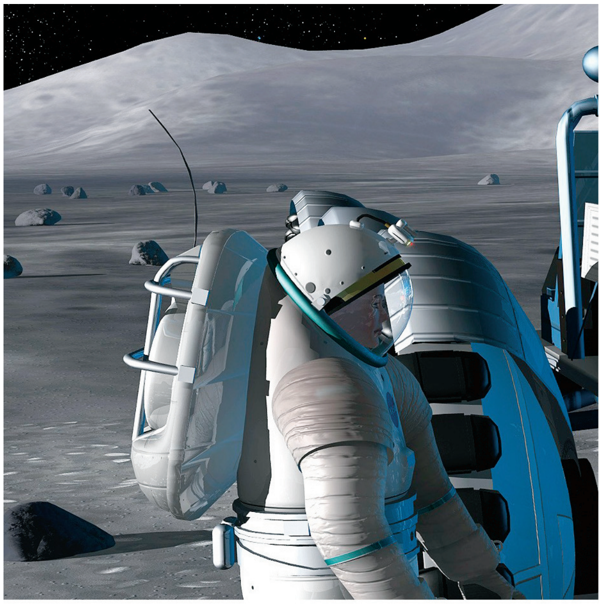
August 2006

Executive Summary: The Living With a Star Sentinels Mission

NASA's Sentinels mission is a multispacecraft mission that will study (1) the acceleration and transport of solar energetic particles (SEPs) and (2) the initiation and evolution of coronal mass ejections (CMEs) and interplanetary shocks in the inner heliosphere. As presently envisioned, the Sentinels mission comprises (1) a constellation of four identically instrumented Inner Heliospheric Sentinels to make in-situ measurements of the plasma, energetic particle, and fields environment as close to the Sun as 0.25 AU as well as multipoint remote-sensing observations of solar X-ray, radio, gamma-ray, and neutron emissions; (2) a Near-Earth Sentinel in Sun-synchronous orbit for ultraviolet and white-light observations of the corona; and (3) a Farside Sentinel in heliocentric orbit at 1 AU to measure the photospheric magnetic field from positions 60° to 120° ahead of the Earth. During the 3-year nominal mission, Sentinels observations will be supplemented by observations both from other spacecraft such as the Solar Terrestrial Relations Observatories (STEREO), the Solar Dynamics Observatory (SDO), and Solar Orbiter and from ground-based observatories such as the proposed Advanced Technology Solar Telescope as well as existing radio and optical telescopes. Theory and modeling will play an integral role in the Sentinels mission during both the development and operations phases of the mission.

Sentinels is a key component of NASA's Living With a Star (LWS) program and as such is designed to advance our knowledge and understanding of those processes and phenomena in the space environment that can adversely affect life and society. ***The Sentinels mission is of particular importance to efforts to characterize, understand, and eventually forecast the radiation environment that will be encountered during human expeditions to the Moon and Mars.***

This summary and the following report describe the results of an intensive 2-year study by the Sentinels Science and Technology Definition Team (STDT) to define the science objectives, measurement requirements and observational strategies, and mission design for the Sentinels mission. The STDT worked closely with engineering teams at The Johns Hopkins University Applied Physics Laboratory and NASA's Jet Propulsion Laboratory to ensure that ***the Sentinels mission described in this report can achieve the scientific objectives established by the STDT and can be implemented with no new technology development.***



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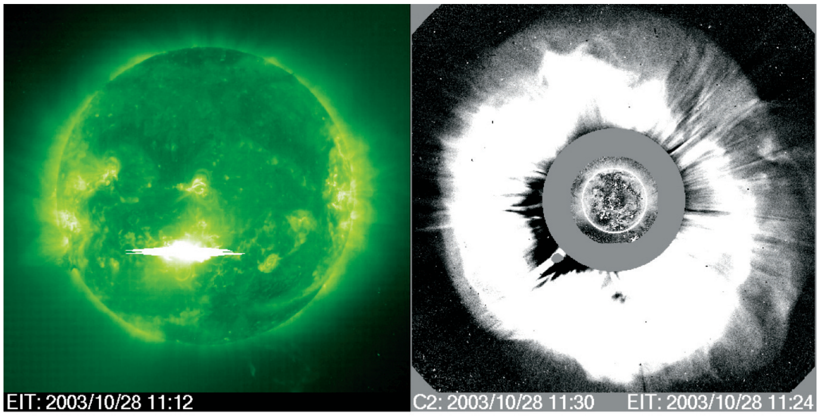
Intense solar energetic particle (SEP) events will present a serious health hazard for astronauts on future expeditions to the Moon and Mars. Sentinels science will enable the development of a forecasting capability for SEP events.

Energetic Events in the Inner Heliosphere: Sentinels Science Objectives

With ion energies up to tens of gigaelectron volts and electron energies up to hundreds of megaelectron volts, solar energetic particles (SEPs) are one of the principal sources of space radiation and represent a serious threat to both spacecraft systems and astronauts. For example, the Japanese Mars probe Nozomi was crippled by penetrating radiation during an intense SEP event in April 2002, and the mission was eventually lost as a result. Fortunately, no astronauts are known to have suffered from acute radiation sickness as a result of exposure to SEPs. However, studies have shown that the health risk is real and serious. An astronaut caught on the surface of the Moon during the large SEP event of August 1972 and protected only by a space suit could have experienced acute radiation syndrome effects, including severe skin damage, nausea or vomiting, and blood count changes, as well as the early development of cataracts. The radiobiological effects of SEP exposure can be mission-threatening and, in the case of an extreme event such as the 1859 Carrington event, could even be fatal.[1]

SEPs are produced in association with both solar flares and coronal mass ejections (CMEs). Flare-related or "impulsive" SEP events differ in certain key characteristics from CME-related or "gradual" events. Impulsive events have durations of hours, high electron/proton ratios, and are characterized by ^{3}He/^{4}He, Fe/O, and Fe/C ratios appreciably greater than average coronal and solar wind values, as well as by high average Fe charge states. Gradual events are associated with fast CMEs, occur over a wide longitude range (~100° to 180°), last for days, have low electron/proton ratios, and show low average Fe charge states.



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A powerful (X17) flare (left) and halo CME (right) were observed by SOHO during the extreme space weather events of October–November 2003. The SEP event produced by the 28 October solar events was one of the largest observed during the last two solar cycles.

Although the two-class paradigm is a useful classification scheme, recent observations have shown that the distinction between impulsive and gradual events is not as clear-cut as it may seem. While the energetic particles in the most intense events appear to be accelerated predominantly by a CME-driven shock, in many large gradual events enhanced ^{3}He and Fe abundances as well as higher-than-expected Fe charge states are observed. Do these impulsive-event particles come directly from a flare associated with the CME, or are they relics from previous impulsive events that populate the inner heliosphere and then serve as a seed population to be re-accelerated to higher energy in subsequent gradual events? What are the relative roles of flare acceleration and shock acceleration in such events? Where and when are the particles accelerated at the Sun? A major science objective of the Sentinels mission is ***to determine the roles of CMEs, flares, and other processes in accelerating energetic particles***.

The properties of SEPs accelerated at CME-driven shocks are highly variable. This variability is likely the result of the interplay of many factors, including the composition and distribution of the seed population, the properties of the CME and shock, and the preconditioning of the inner heliosphere by earlier events. Understanding the causes of SEP variability in large gradual events is an essential condition for the development of predictive models. Thus a second major Sentinels objective is ***to identify the conditions that determine when CME-driven shocks accelerate energetic particles.***

The transport of SEPs from their acceleration site through the inner heliosphere to 1 AU and beyond is a problem of critical importance for understanding and eventually predicting SEP events. SEP transport is a complex phenomenon involving a variety of processes: field-line wandering, pitch-angle scattering by turbulent magnetic fluctuations, magnetic focusing by the radially diverging heliospheric magnetic field, adiabatic cooling, and solar wind convection. In the case of shock-accelerated events, the propagation and evolution of the shock must also be taken into account. A particular source of uncertainty in our understanding of SEP propagation is a lack of knowledge of the particle scattering mean free path inside 1 AU. As its third objective, Sentinels will ***determine how energetic particles are transported from their acceleration site and distributed in radius, longitude, and time.***

In order to provide useful warning of SEP events, it is necessary to be able to predict the onset of a CME/eruptive flare from observations of solar conditions. Developing this capability requires achieving a deep physical understanding of the CME/eruptive flare onset. What solar conditions lead to CME onset? By what mechanism is stored

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[1] L.W. Townsend, Implications of the space radiation environment for human exploration in deep space, *Radiat. Prot. Dosimetry*, **115**, 44, 2005.

Sentinels Science Goals and Objectives

I. Understand and Characterize the Sources, Acceleration, and Transport of Solar Energetic Particles

Determine the roles of CME-driven shocks, flares, and other processes in accelerating energetic particles

- When and where are energetic particles accelerated by the Sun?
- How are energetic particles observed at the Sun related to those observed in the interplanetary medium?
- What conditions lead to the jets/narrow CMEs associated with impulsive SEP events?
- What physical processes accelerate SEPs?

Identify the conditions that determine when CME-driven shocks accelerate energetic particles

- What are the seed populations for shock-accelerated SEPs and how do they affect SEP properties?
- How do CME/shock structure and topology as well as ambient conditions affect SEP acceleration?

Determine how energetic particles are transported from their acceleration site and distributed in radius, longitude, and time

- What processes scatter and diffuse SEPs both parallel and perpendicular to the mean heliospheric magnetic field?
- What are the relative roles of scattering, solar wind convection, and adiabatic cooling in SEP event decay

II. Understand and Characterize the Origin, Evolution, and Interaction of CMEs, Shocks, and Other Geoeffective Structures

Determine the physical mechanisms of eruptive events that produce SEPs

- What solar conditions lead to CME onset?
- How does the pre-eruption corona determine the SEP-effectiveness of a CME?
- How close to the Sun and under what conditions do shocks form?

Determine the multiscale plasma and magnetic properties of ICMEs and shocks

- How does the global 3D shape of ICMEs/shocks evolve in the inner heliosphere?
- How does CME structure observed at the Sun map into the properties of interplanetary CMEs?

Determine how the dynamic inner heliosphere shapes the evolution of ICMEs

- How is the solar wind in the inner heliosphere determined by coronal and photospheric structure?
- How do ICMEs interact with the pre-existing heliosphere?
- How do ICMEs interact with each other?

magnetic energy explosively released in the CME/eruptive flare? The fourth major Sentinels objective is ***to determine the physical mechanisms of eruptive events that produce SEPs.*** Because CMEs are the major drivers of space weather at Earth, as well as the primary sources of intense SEP events, this knowledge is also essential for our ability to forecast major geomagnetic disturbances like the storms of October–November 2003.[2] Such severe space weather events can interfere with communications and navigations systems, disrupt satellite operations, and cause electric utility blackouts.

Development of a forecasting capability also requires a knowledge and understanding of what the properties of an interplanetary CME (ICME) are, how they are related to the structures observed at the Sun, how they evolve during the ICME's transit to 1 AU (and beyond), and how they are affected in their evolution by the density and velocity structures of the background solar wind, as well as by interactions with other transients. Thus the fifth and sixth objectives of the Sentinels mission are ***to determine the multiscale plasma and magnetic properties of ICMEs and shocks*** and ***to determine how the dynamic inner heliosphere shapes the evolution of ICMEs.***

Measurement and Observational Requirements

To achieve the Sentinels science objectives, a combination of in-situ measurements and remote-sensing observations is required, although not necessarily from the same platforms. Required in-situ measurements include high- and low-energy ion energy spectra and composition; energetic electrons and protons; suprathermal and energetic (up

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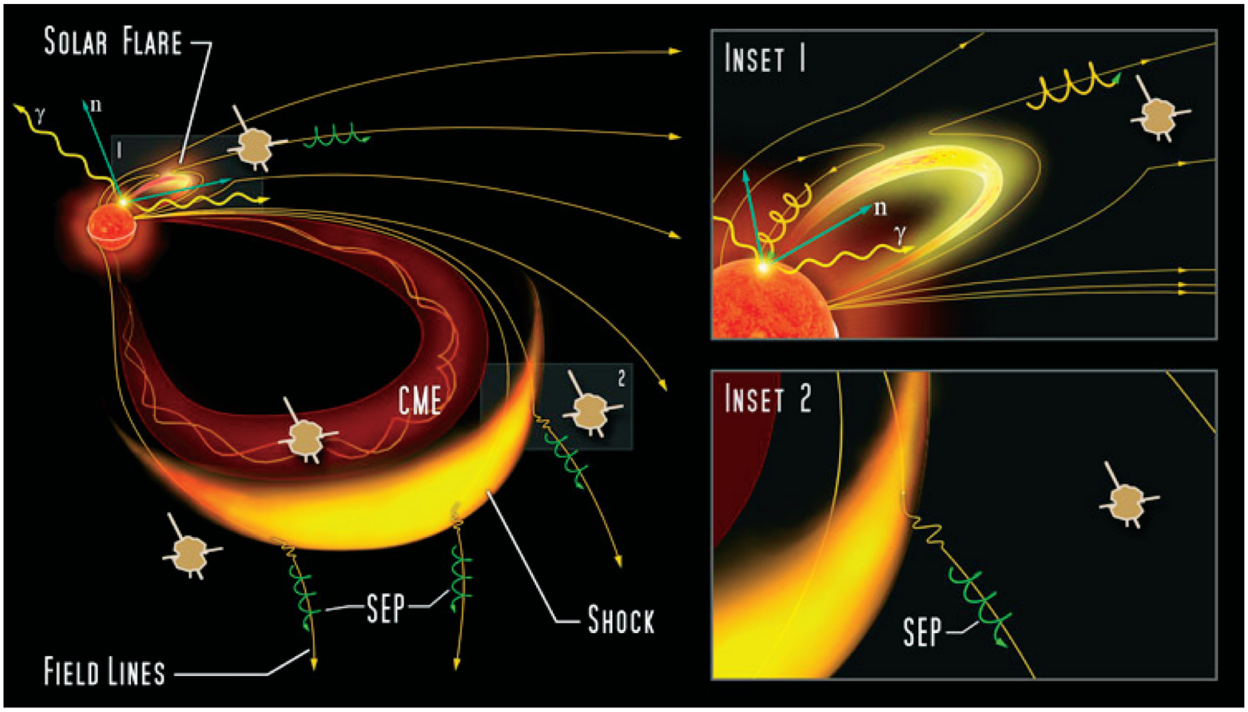
[2] NOAA, *Intense Space Weather Storms October 10–November 07, 2003*, April 2004.



A cartoon demonstrating the need for multiple in-situ observations of SEPs in the inner heliosphere. Simultane-ous observations of magnetic field lines connecting back to flare sites (inset 1) and to shock fronts driven by ICMEs (inset 2) are required to determine the relative importance of the associated acceleration processes.

to ~100s of keV/nucleon) ion charge states; suprathermal electrons; solar wind ion distributions, composition, and charge state; solar wind electrons; and DC and AC magnetic fields. These measurements are needed to characterize SEPs, their seed populations, the plasmas and fields of the associated transients, and the environment in which they propagate. To characterize the spatial and temporal variations in the SEP spectra and elemental abundances and to study the evolving global structure of ICMEs and shocks as they propagate through the inner heliosphere, simultaneous in-situ measurements should be made from at least four locations, separated in longitude and/or radial distance. Moreover, the in-situ measurements should be made as deep within the inner heliosphere as possible, within 1 to 2 scattering mean free paths (i.e., at radial distances inside 0.35 AU), thus minimizing transport effects and allowing the characteristics of freshly accelerated SEPs and the associated fast shocks, waves, and ICMEs to be determined before significant evolution has occurred. It is desirable that as many SEP events as possible, especially gradual events, be observed within 0.35 AU in order to be able to determine the source of the SEPs and the physics of the acceleration mechanisms. Optimally, the inner heliospheric portion of the Sentinels mission should be flown around solar maximum, when the greatest number of SEP events occur. However, even if this phase of the mission occurs near solar minimum, a statistically meaningful sample of SEP events would be observed.

Critical remote-sensing observations include hard/soft X-rays; neutrons and gamma-rays; radio bursts (type II and III); coronal ultraviolet (UV) and white-light emissions; and photospheric magnetic fields. Observations of radio, X-ray, and gamma-ray emissions and of neutrons in the inner heliosphere will provide crucial information about the location and height of accelerated electrons and ions near the Sun, and combined X-ray, radio, and in-situ electron measurements will allow direct tracing of magnetic field structure and connectivity. UV spectroscopy is necessary to determine plasma conditions in the SEP acceleration region in the corona, while white-light coronagraph observations are needed to observe the onset and initial acceleration of CMEs and to track the evolution of ICMEs out to heliocentric distances of 0.3 AU, where they can be detected directly. This wide field of view will allow the in-situ ("ground truth") measurements of ICMEs and shocks made inside 0.3 AU to be related to the structure and internal topology of ICMEs (and other coronal structures) imaged by coronagraphs. Measurements of photospheric magnetic fields at heliolongitudes not observable from Earth are needed to provide more realistic boundary conditions for accurate modeling of the heliosphere.

Remote-sensing observations of coronal UV and white-light emissions as well as those of the photospheric magnetic field can be made from spacecraft located at 1 AU. Radio, X-ray, neutron/gamma ray observations will be made from the inner heliospheric platforms, which will allow stereoscopic and limb occultation measurements to be made as well as the first-ever measurements of solar neutrons with energies below 10 MeV.

Mission Implementation

The baseline Sentinels mission recommended by the STDT consists of three flight elements: the ***Inner Heliospheric Sentinels (IHS)***, four spin-stabilized spacecraft in elliptical heliocentric orbit with perihelia at ~0.25 AU and aphelia at ~0.75 AU; a 3-axis stabilized ***Near-Earth Sentinel (NES)*** in Sun-synchronous orbit at 1 AU; and a small ***Farside Sentinel (FSS***) that drifts slowly away from Earth in a heliocentric orbit at 1 AU. The four IHS spacecraft will be identically instrumented to make both the in-situ particles and fields measurements listed above and the remote-sensing observations of radio bursts and X-ray, gamma ray and neutron emissions. NES will carry a UV spectroscopic coronagraph to determine the physical conditions and mechanisms that govern SEP acceleration near the Sun (1.2 to ~10 R_S), and a white-light coronagraph suite to provide inner-field (1.3 to 4 R_S) and wide-field (4 to 30 R_S) coverage. FSS will be equipped with a simple filter-based magnetograph to provide measurements of the photospheric magnetic field from longitudinal locations between 60° and 180° ahead of the Earth.

Sentinels Strawman Payloads	
Inner Heliospheric Sentinels	
High Energy Ion Composition Analyzer	Solar Wind Electron Instrument
Low Energy Ion Composition Analyzer	Search Coil Magnetometer
Solar Energetic Particle Charge State Analyzer	Dual Magnetometer
Energetic Electron and Proton Instrument	Radio/Plasma Wave Instrument
Suprathermal Electron Instrument	X-Ray Imager
Solar Wind Proton/Alpha Instrument	Neutron Spectrometer
Solar Wind Composition Analyzer	Gamma Spectrometer
Near-Earth Sentinel	**Farside Sentinel**
Ultraviolet Spectroscopic Coronagraph	Magnetograph
Wide- and Inner-Field Coronagraph	

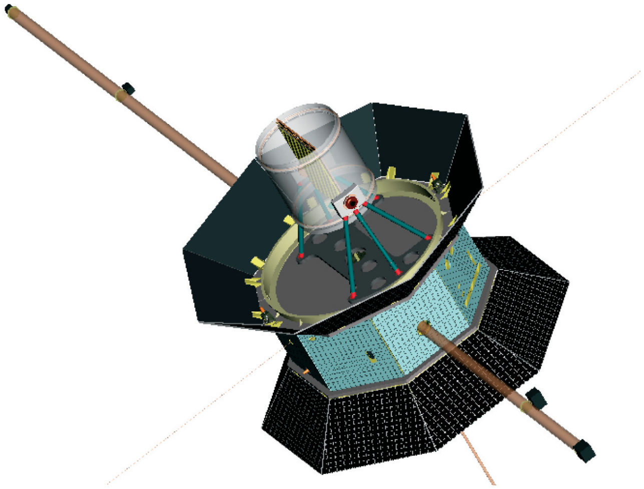
The STDT recommends that the Sentinels mission be implemented in stages. The IHS will be developed and launched first, preferably near solar maximum (~2012) to maximize the number of SEP events detected in the inner heliosphere and to provide critical overlap with SDO to determine the conditions for initiation of the flares/fast CMEs that lead to SEP events. NES would be developed in time to have overlapping coverage with IHS to study the coronal acceleration process and the Sun-heliosphere connection. This schedule would also likely result in an overlap with ESA's highly complementary Solar Orbiter mission (planned launch in 2015), which will provide both imaging of the Sun and in-situ measurements, initially from the ecliptic while nearly co-rotating with the Sun and later from higher latitudes. The FSS launch should be timed to provide overlap with Solar Orbiter, since near-Earth ground or space-based magnetograph measurements are expected to be continuously available.

The baseline mission concept for the IHS component of the Sentinels mission calls for four spacecraft to be launched on a single launch vehicle and, through the use of multiple Venus gravity assists, to be placed into slightly different, near-ecliptic heliocentric orbits of approximately 0.25 × 0.74 AU. The motion of the four IHS spacecraft relative to one another caused by differences in the perihelia and periods of the final heliocentric orbits will result in a number of scientifically desirable orbital configurations, with the spacecraft distributed at different radial and azimuthal positions to make the multi-point measurements discussed above. The IHS orbit has been designed to ensure adequate dwell time close to the Sun.

NES observations can be performed from a medium-altitude Sun-synchronous orbit like that used by TRACE. Such an orbit will allow nearly continuous observations without the additional costs associated with a geostationary or L1 mission. The baseline FSS orbit design will place the spacecraft 60° ahead of Earth 1.8 years following launch, after which the spacecraft will drift slowly to 120° during the 2-year FSS prime mission phase and to 180° during the subsequent 2-year extended phase. This design provides for a 1.2-year overlap with IHS. Launch on a Taurus is assumed.

Sentinels Spacecraft

The four IHS spacecraft baselined for the Sentinels mission are designed to meet the unique thermal control and power challenges presented by the variations in solar flux over the 0.25 × 0.74 AU IHS orbit. The spacecraft are spin-stabilized, with the spin axis perpendicular to the ecliptic and a rotation rate of 20 rpm. This spin rate reduces the effective solar constant at the spacecraft from 16 to 5 Suns at perihelion. Optical solar reflector material and thermal louvers maintain a core spacecraft temperature of 0° to 25° C, while various passive techniques provide thermal control of exposed subsystems and instruments. Power is supplied by 16 solar panels mounted around the top and bottom of the octagonal spacecraft body and tilted at 45° to maintain the array operating temperature below the 180° C design limit. A peak power tracker architecture is used to regulate and control the power output from the arrays. The X-band telecommunications subsystem uses a gimbaled phased-array high-gain antenna for high-rate downlink and a medium-gain antenna for uplink and low-rate downlink. The two antennas are housed, together with a low-gain antenna, in a thermal-protective radome and mounted on a despun platform located on the top deck of the spacecraft. Data will be stored in the solid state recorders of the redundant command and data handling units and downlinked at a rate that ranges from 750 kbps to 23 kbps depending on the spacecraft–Earth range. In addition to science and housekeeping data, space weather data will be continuously downlinked from each spacecraft. The guidance and control subsystem consists of a spinning Sun sensor and a star scanner for attitude determination and twelve 4-N thrusters for attitude control. The propulsion subsystem is a simple blowdown hydrazine system.



The Inner Heliospheric Sentinels spacecraft design will accommodate the strawman IHS payload and meet the unique thermal and power challenges presented by the mission environment.

The IHS spacecraft are identically instrumented to make the in-situ and remote-sensing measurements described above. All instruments are mounted within the body of the spacecraft except the radial and axial antennas of the radio and plasma waves instrument, the boom-mounted search coil and dual magnetometers, and the solar wind electron instrument.

The baseline FSS spacecraft is a 3-axis stabilized spacecraft with four deployable solar arrays and an articulating 1.25-m Ka band high-gain antenna. It is designed to be accommodated on a Taurus launch vehicle. The NES presents no unusual mission, spacecraft design, or resource requirements and can be implemented with any of a number of standard spacecraft buses.

Sentinels and the Vision for Space Exploration

NASA's new Vision for Space Exploration (VSE) calls for "a human return to the Moon by 2020, in preparation for human exploration of Mars and other destinations."[3] One of the challenges to be confronted in implementing the VSE is to develop

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[3] NASA, *The Vision for Space Exploration*, p. 5, NP-2004-01-334-HQ, February 2004.

the understanding, technologies, and procedures needed to protect astronauts from the hazardous radiation environments that they will encounter on the surface of the Moon and Mars and in transit. The Sentinels mission will contribute to this effort by discovering the physical conditions and mechanisms that govern the production of SEPs and their transport in the heliosphere. The physical understanding gained from Sentinels observations will dramatically improve our ability to model SEP acceleration and transport, which will be a major advance toward our ability to forecast SEP events. ***The STDT strongly recommends that the IHS be launched during the upcoming solar maximum (~2012), which will be the last opportunity before the first manned lunar missions to develop critical knowledge necessary for the development of a space radiation environment forecasting capability.***

Sentinels and Other Living With a Star Missions

The goal of NASA's LWS program is to provide the physical understanding needed to mitigate the adverse effects of space weather. Three missions are planned for launch during the next solar cycle. The Solar Dynamics Observatory (SDO) will study solar magnetic activity and the storage and release of magnetic energy in flares and CMEs. The two flight elements of the Geospace mission—the Radiation Belt Storm Probes and the Ionosphere–Thermosphere Storm Probes—will investigate the response of Earth's coupled magnetosphere-ionosphere-thermosphere system to CMEs and high-speed streams, with particular emphasis on radiation belt enhancements and poorly characterized midlatitude ionospheric disturbances. Sentinels is the third of the planned LWS missions. As an integral element in the LWS program, it will (1) provide contextual information about heliospheric activity for the SDO investigation of active regions emerging from the solar interior, (2) contribute to the Geospace investigation of magnetospheric and ionospheric disturbances by specifying the origin, evolution, and dynamics of geoeffective structures in the solar wind, and (3) enable the development of improved models of energetic events. ***Sentinels will also develop the scientific and technical understanding necessary to implement a future heliospheric space weather warning system by employing real-time capabilities on IHS that allow prototyping and testing of space weather monitoring and forecasting functions.***

Summary

The Sentinels mission will combine multipoint in-situ particles and fields measurements as well as multipoint remote-sensing observations of solar energetic emissions from as close to the Sun as 0.25 AU and remote-sensing observations of the corona from 1 AU. ***Sentinels will yield breakthrough advances in our knowledge and understanding of the origin and evolution of solar energetic particles, a major source of hazardous space radiation, and of coronal mass ejections, the main drivers of space weather at Earth. The Sentinels mission is thus of central importance to the goals of the Living With a Star program and the Vision for Space Exploration.*** Mission implementation studies conducted in support of the STDT study demonstrate that the Sentinels mission, as described in this report, is fully feasible from an engineering standpoint and can be implemented with no new technology. The STDT recommends that the first flight element of the Sentinels mission, the Inner Heliospheric Sentinels, be launched as close as possible to the next solar maximum.