The NASA Living With a Star (LWS) Sentinels Mission

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ABSTRACT

The NASA Living With a Star (LWS) Sentinels mission is presently being defined by its Science and Technology Definition Team (STDT). Sentinels is the third element of the LWS program. Its primary scientific objective is to discover, understand and model the connection between solar phenomena and the interplanetary/geospace disturbances, specifically, the heliospheric initiation, propagation and solar connection of those energetic phenomena that adversely affect space exploration and life and society here on Earth. Sentinels will play a particularly important role in support of NASA's new Vision for Space Exploration (VSE), in providing key new measurements required to understand the production of Solar Energetic Particles (SEPs) that are hazardous to human and robotic missions to the Moon and Mars. Here we describe the planning for Sentinels, and the preliminary design of the first phase, the Inner Heliosphere Sentinels, a four spacecraft mission to provide multi-point longitudinally and radially distributed in situ observations of SEPs, plasma, fields, and X-rays/gamma-rays/neutrons in the inner heliosphere (~0.25-0.76 AU), close to the site of SEP acceleration and rapid transient evolution.

INTRODUCTION

Early in 2000, NASA established the Living With a Star (LWS) program whose goal is to develop the scientific understanding necessary to effectively address those aspects of the connected Sun-Earth system that directly affect life and society. Specifically, the program has a threefold objective: (1) understand the changing flow of energy and matter throughout the Sun, heliosphere, and planetary environments; (2) explore the corresponding fundamental physical processes of space plasma systems; (3) and define the origins and societal impacts of variability in the Sun-Earth connection. It was recognized early that in order to make significant progress in this quest new observations will have to be made in all key areas of solar, heliospheric, magnetospheric and ionospheric physics to allow the development of a systems approach to this problem. The first LWS mission, presently under development, is the Solar Dynamic Observatory (SDO) mission that will address the question of transient formation from the solar core to the corona. The next element is the Geospace Network (Radiation Belt Storm Probes and Ionosphere-Thermosphere Storm Probes) that focuses on the impact of solar transients on the Earth's magnetosphere and ionosphere. The final element of the LWS program is the heliospheric Sentinels that will connect the solar and geospace observations into a single unified system (Fig. 1).

In 2004 NASA formed the Sentinels Science and Technology Definition Team (Table 1). This STDT is currently in the process of defining the Sentinels mission, so what is presented here is preliminary. The final report is planned for Fall 2005.

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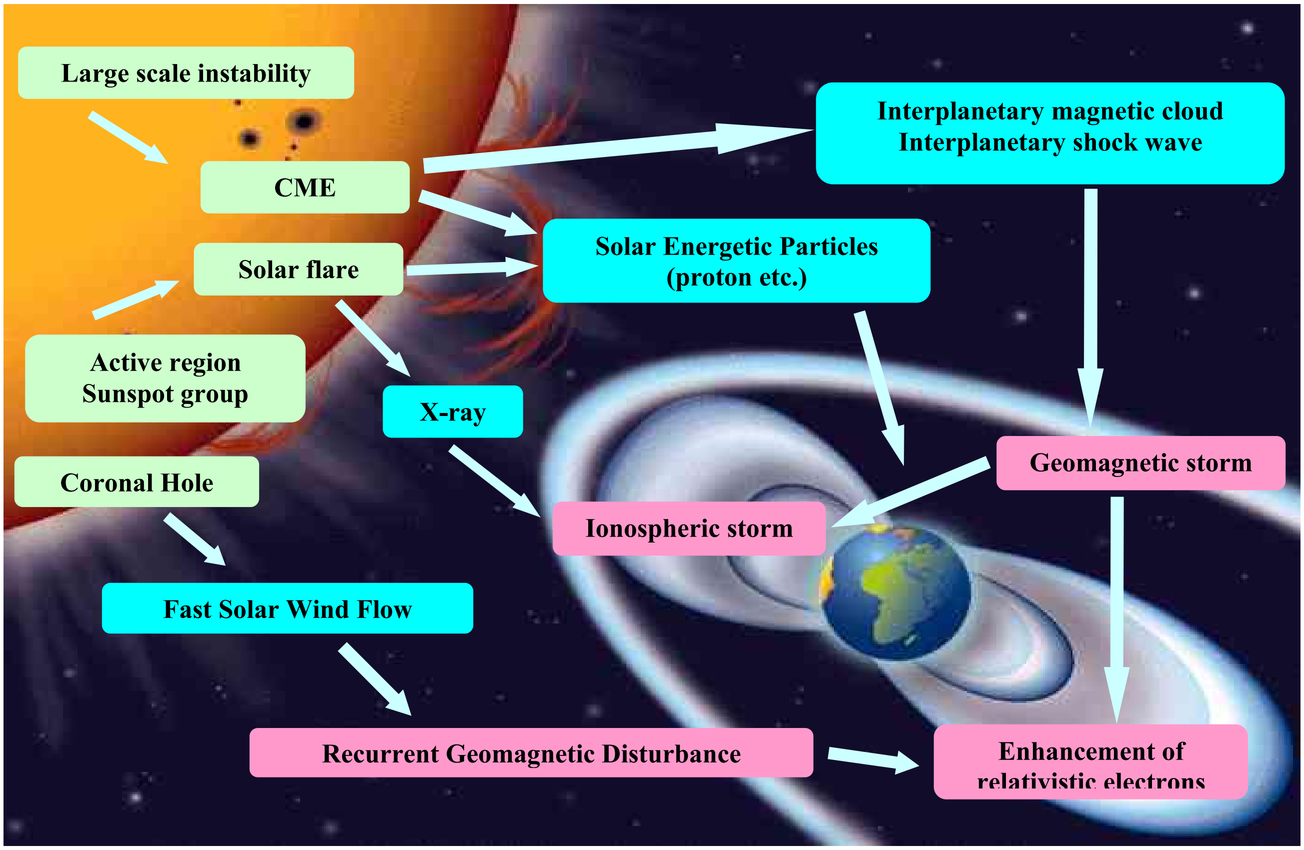

Figure 1. Sentinels Primary Objective: Discover, understand and model the connection between solar phenomena and interplanetary/geospace disturbances.

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Table 1. Sentinels STDT

The primary Sentinels scientific objective is to discover, understand and model the *connection* between solar phenomena and the interplanetary/geospace disturbances, specifically, the heliospheric initiation, propagation and solar connection of those energetic phenomena that adversely affect space exploration and life and society here on Earth. This science objective is focused on three main areas:

1. How, where, and under what circumstances are solar energetic particles (SEPs) accelerated to high energies and propagate through the inner heliosphere?

2. How do geo-effective solar wind structures, like CMEs, shocks, and high-speed streams propagate, evolve and interact in the inner heliosphere?

3. What is the structure of the ambient solar wind in the inner heliosphere and how does it respond to solar variations? This is an essential prerequisite of questions 1 and 2.

Table 2 breaks these areas into more detailed science questions.

SEPs	SEP Source Population	What is the origin/source of the see particles?
	SEP Acceleration	How, when and where are energetic particles accelerated?
		What is the role of CMEs and flares producing SEPs?
		How are the highest energy solar particles (>100 MeV/nuc) produced?
	SEP Propagation	How do SEPs propagate in the inner heliosphere?
		What determines the radial, longitudinal and latitudinal distribution of SEPs?
Transients	ICMEs	How are CMEs initiated? Constraints on models and mechanisms.
		What is the internal structure and solar connection of ICMEs? (Why do many CMEs become irregular ejecta?)
		How do ICMEs propagate and evolve?
	IP Shocks	What is the structure, propagation and evolution of interplanetary shocks?
Global Structure of the Inner Heliosphere		How do the heliospheric magnetic fields and plasma connect to and disconnect from the solar corona?
		How do the fast and slow streams interact to form the heliosphere?
		What is the origin of waves and turbulence and their significance for particle acceleration and dissipation?

Table 2. Sentinels Science Questions

Sentinels play a particularly important role in support of NASA's new Vision for Space Exploration (VSE). VSE plans to place both robotic and human missions in the interplanetary medium for extended periods. Solar energetic particles (SEPs) are particularly hazardous for astronauts during operations in space, i.e., EVAs or activities on the lunar and planetary surface, etc. The key questions to be answered are:

- How are SEPs accelerated in large solar flares and fast CMEs?
- What are the physical mechanisms that produce these large eruptive events?

- What are the solar conditions that lead to eruptive events?
- How do the quasi-steady-state solar wind and solar eruptive events interact and evolve to form the dynamic plasma and fields environment of the heliosphere?
- How do SEPs propagate throughout this heliospheric environment?
- How does this environment globally modulate the background of galactic cosmic radiation (GCR)?
- How does this environment interact with the Earth, Moon, Mars, other solar system bodies, and interstellar medium?

The goal of LWS Sentinels in VSE is to develop the *physical understanding* necessary to reliably model and predict the radiation environment for VSE Lunar and Martian missions. Sentinels will accomplish this by discovering the physical conditions and mechanisms that govern SEP production and their transport in the heliosphere. Sentinels will also develop the scientific and technical understanding necessary to implement a future heliospheric space weather warning system by employing real-time capabilities that allow prototyping and testing of space weather monitoring and forecasting functions.

SCIENTIFIC BACKGROUND

SEP events (Figure 2) were first discovered through increases in ground-level detectors more than six decades ago, and it was soon noticed that they occurred in association with large solar flares observed by ground optical telescopes. By ~1985, spacecraft measurements of SEP event onsets and longitudinal extent, composition (especially ^{3}He) and charge states, indicated that the largest SEP events were accelerated by the shock wave generated by giant solar eruptions-coronal mass ejections (CMEs) that eject more than a billion tons of material into the interplanetary medium at huge speeds, and by the large solar flares associated with these eruptions. These shock waves continue to accelerate more particles as they spread out over ~100-180° in longitude and move through the inner heliosphere. Upon reaching Earth these shock waves can cause giant magnetic storms that can damage spacecraft systems and disrupt communications. Because SEPs travel at near-relativistic speeds, the available warning after the solar eruptive event is first observed is typically less than an hour. Reliable forecasting of those eruptive events that produce intense fluences of SEPs is needed, but not currently available because the basic physics of the phenomena are not well understood.

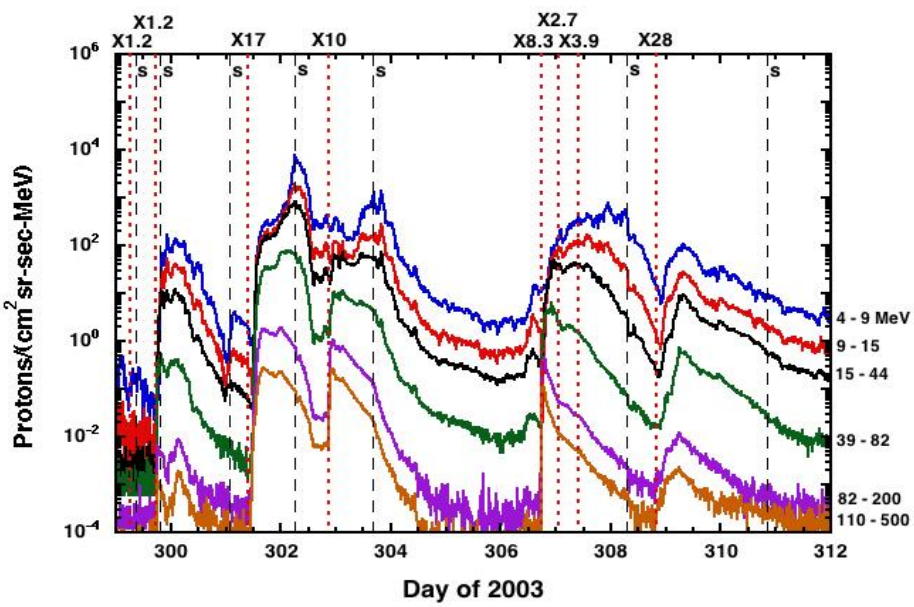

Figure 2. SEP Events in Oct-Nov 2003 (Mewaldt et al 2005).

Small SEP events generally are dominated by non-relativistic electrons and show strong enrichments of ^{3}He, and were believed to be due to flare acceleration. Recently, with much more sensitive ^{3}He measurements from ACE and other spacecraft, however, even large SEP events were found often to have ^{3}He enhancements. Furthermore, the detailed examination of the radio emission associated with large SEP events suggests that the SEP acceleration may be related to the reconfiguration of the corona after the CME passage. Finally, very recent measurements of flare accelerated energetic particles (inferred from RHESSI observations of flare gamma-ray lines) show that their energy spectrum and total numbers are remarkably similar to the SEPs that escape to the interplanetary medium for magnetically well-connected flares. At present, then, four or five possible sources have been proposed for the SEPs in a large event.

Presently there are significant efforts using currently available assets to study solar eruptive events. The unique imaging and spectroscopy capabilities of RHESSI, SOHO, and TRACE for energetic particles and eruptive events at the Sun, combined with near Earth measurements of SEPs by ACE and WIND, can significantly improve our understanding of the radiation environment produced by flares versus shocks driven by fast CMEs. Ulysses, Cassini, and Voyager are characterizing SEPs and plasma/fields effects in the outer heliosphere and are providing our first glimpse of the interaction with the interstellar medium. The SOHO, TRACE and RHESSI observations also provide initial measurements of potential SEP and solar wind source region characteristics and input for numerical models to investigate the emergence and transport of magnetic flux and release of solar eruptive events.

In 2006, the 2-spacecraft STEREO mission will be launched and in 2007-8 Ulysses will cross the ecliptic at ~1.5 AU in its high inclination orbit. This, together with the L1 spacecraft, will provide an unprecedented opportunity to establish the three-dimensional shape and structure of interplanetary shocks and coronal mass ejections (ICMEs) in the inner solar system, and to study the longitudinal and latitudinal spatial variability of SEPs. These are crucial pieces of the puzzle to improve the current limited capability to forecast the arrival times of these geo-effective structures. In addition, Solar B (also 2006 launch) will provide spectroscopy at the coronal base and detailed imaging observations of the vector magnetic fields of the solar active regions, flares, and CME sources. SDO (~2008 launch) will provide continuous full disk, high cadence imaging of the Sun to study eruptive events. It is essential to coordinate and focus these efforts.

Most SEPs in large events appear to be accelerated in the high (>~2Rs) corona by the fast CME and the associated large solar flares. The SEPs then scatter and diffuse in the interplanetary medium while propagating to ~1AU, so most of the crucial information about their acceleration is lost. Spacecraft that approach within ~1-2 scattering mean free paths (estimated to be typically ~0.1-0.3 AU) of the acceleration region, however, could measure freshly accelerated SEPs, and measure the CME/hock and upstream/ downstream wave before they are significantly modified or completely dissipated. Such near-Sun spacecraft could also provide information on SEPs in the high coronal acceleration region, through high sensitivity measurements of the gamma rays, neutrons, and hard X-rays emitted by the SEPs. Thus, a major goal of Sentinels is to provide multi-point longitudinally and radially distributed in situ SEPs, plasma, fields, and X-ray/gamma-ray/neutron observations in the inner heliosphere, close to the site of SEP acceleration and rapid transient evolution.

A second goal is to provide global or near global imaging coverage of the Sun, especially solar magnetic fields, so accurate models of the solar to heliospheric magnetic structure can be obtained. In addition, simultaneous powerful new EUV and white light coronagraphic and spectroscopic measurements (likely from a near-Earth spacecraft) can determine the plasma parameters, magnetic reconnection rates, magnetic field topology and evolution of magnetic structures, suprathermal seed particle energies and densities, and shock parameters in the high coronal acceleration region.

Ground-based (e.g., FASR) and spacecraft radio observations can image shocks and electron beams in the high corona and inner heliosphere, respectively. This comprehensive set of measurements will permit current theories of SEP acceleration, including impulsive production in current sheets and gradual production in CME shocks, to be tested and refined. Together with measurements from the above-mentioned missions (SDO,Solar B, etc.), this will provide the understanding of the physical processes for CME and flare initiation required for an advance predictive capability.

SENTINELS IMPLEMENTATION

The Sentinels STDT recommends that the LWS Sentinels be implemented in a phased approach with multiple components to support Moon and Mars missions and LWS system objectives. The preliminary recommendation is for the first phase is a four spacecraft Inner Heliosphere Sentinels (HIS) launched in the 2012-2015 time frame, depending on the level of funding. Ideally IHS is in orbit near solar maximum (2012) with simultaneous SDO (& STEREO, Solar B) and LWS Geospace to determine SEP acceleration and the propagation, and impact of CMEs on Earth's geospace environment and throughout the solar system. This would overlap the highly complementary European Space Agency's Solar Orbiter mission that would provide both imaging of the Sun and in situ measurements, nearly co-rotating with the Sun in the ecliptic, and later from higher latitudes to establish solar - heliospheric connection.

The following phases are not well defined at present. One or possibly two Far-side Sentinels is needed to provide global solar photospheric magnetic field and coronal plasma density and composition observations in addition to the inner heliospheric data to allow the extension of SEP forecasting to the whole heliosphere and for longer lead times. Int is highly desirable to have measurements of coronal density, temperature, magnetic field topology, suprathermal seed particles, and shock parameters in SEP source regions, as well.

Inner Heliosphere Sentinels' orbits with perihelions down to 0.25 AU can be achieved with multiple Venus gravity assists (Fig. 3). Using a launch C_3 of ~20 km^2/s^2 and a single Venus gravity assist, an in-ecliptic orbit of 0.35 x 0.78 AU is reachable without any significant course corrections during cruise. Two additional Venus gravity assists can yield a final orbit of 0.24 AU x 0.73 AU in the ecliptic plane in about 2 year total cruise time. A desirable configuration is to launch 4 identical satellites on the same EELV launch vehicle[such as the Atlas V 501 or Delta IV M+(4,2)], and place two of them in an inner most orbit of 0.24 x 0.73 AU in close proximity (~ 100,000 km) of each other. The other two satellites can be placed in a slightly larger orbit of 0.35 x 0.78 AU shifted in phase by ~30º. Launch can take place when Venus is properly aligned with Earth; that occurs roughly every 584 days. Two-week launch windows exist in 2012, 2014, 2015 and 2017.

Solar Wind Protons/Alphas	**Magnetometer**
Solar Wind Electrons	**Radio & Plasma Waves**
Suprathermal Electrons	**Neutron Spectrometer**
High Energy Ions & Electron	**Gamma-ray Spectrometer**
Radio & Plasma Waves	**X-ray Imager**
Suprathermal Ions Composition & Charge States	
Solar Wind Ion Composition & Charge States	
Payload mass ~50 kg, Power ~40 W, Bit rate ~7 kbps	

Table 3. Inner Heliosphere Sentinels: Strawman Instrument Complement

The Inner Heliospheric Sentinels will focus on in-situ observations of solar wind plasma and suprathermal and high-energy energetic particles (proton/alpha, electrons, composition and charge states), magnetic fields, radio and plasma waves, neutrons and gamma-ray spectra, and X-ray imaging (Table 3). This suite of instrumentation favors spin-stabilized spacecraft. Preliminary studies have shown that for the Inner Heliospheric Sentinels a spinning (~20 RPM) spacecraft with the spin axis perpendicular to the ecliptic and solar arrays tilted at 45º (Figure 4), will keep the solar arrays below the recommended design limit of 200ºC and the instruments at temperatures below ~40 C, even at 0.25 AU. An average of ~7 kbps telemetry rate can be provided with a < 1 m high gain X-band antenna on a despun platform, with an average of one 8-hour downlink per week per spacecraft. A very low (~1-10 bps) near-continuous real-time link would provide space weather monitoring. All of the spacecraft components can be built using currently available parts and technologies with no new development required.

The Far-side Sentinel and possible near-earth components of Sentinels are still being defined, but it is clear that the Sentinels mission will provide a tremendous advance in our understanding of the connections between the Sun, the heliosphere, geospace, and other planetary bodies such as the Moon and Mars.

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