

## Solar Probe: Executive Summary

Solar Probe will be a historic mission, flying into one of the last unexplored regions of the solar system, the Sun's atmosphere or corona, for the first time. Approaching as close as  $3 R_S$  above the Sun's surface, Solar Probe will employ a combination of in-situ measurements and imaging to achieve the mission's primary scientific goal: to understand how the Sun's corona is heated and how the solar wind is accelerated. Solar Probe will revolutionize our knowledge of the physics of the origin and evolution of the solar wind. Moreover, by making the only direct, in-situ measurements of the region where some of the deadliest solar energetic particles are energized, Solar Probe will make unique and fundamental contributions to our ability to characterize and forecast the radiation environment in which future space explorers will work and live.

### Our First Visit to a Star

Two of the transformative advances in our understanding of the Sun and its influence on the solar system were the discovery that the corona is several hundreds of times hotter than the visible solar surface (the photosphere) and the development—and observational confirmation—of the theory of the corona's supersonic expansion into interplanetary space as a “solar wind.”

In the decades that have followed these important milestones in solar and space physics, the composition, properties, and structure of the solar wind have been extensively measured, at high heliolatitudes as well as in the ecliptic and at distances far beyond the orbit of Pluto. The corona and the transition region above the photosphere have been imaged with unprecedentedly high resolution, revealing a complex architecture of loops and arcades, while photospheric magnetography has uncovered the “magnetic carpet” of fine-scale flux bundles that underlies the corona. Observational advances have been accompanied by advances in theory and modeling, with a broad range of models offering plausible scenarios to explain coronal heating and solar wind acceleration.

We now know more about the corona and the solar wind than ever before. And yet the two fundamental questions, raised in the 1940s by the discovery of the corona's million-degree temperature and in the early 1960s by the proof of the supersonic

solar wind's existence, remain unanswered: *why is the solar corona so much hotter than the photosphere? And how is the solar wind accelerated?*

The answers to these questions can be obtained only through in-situ measurements of the solar wind down in the corona. A mission to provide these measurements, to probe the near-Sun particles-and-fields environment, was first recommended in 1958, at the dawn of the space age, by the National Academy of Science's “Simpson Committee.” Since then, NASA has conducted several studies of possible implementations of a Solar Probe mission, and Solar Probe has remained at the top of various National Academy and NASA science priority lists. Most recently, the National Research Council's “decadal survey” in solar and space physics recommended implementation of a Solar Probe mission “as soon as possible” (NRC, 2003), while NASA's Sun-Solar System Connection Roadmap identifies Solar Probe as a “Flagship” mission that “is ready to fly and is our highest priority for new resources” (NASA, 2005).

To date, however, nearly 50 years after the Simpson Committee report and despite strong and repeated endorsements of a Solar Probe by the National Academy, NASA, and the solar and space physics community, the closest any spacecraft has come to the Sun is  $65 R_S$ , far outside the region



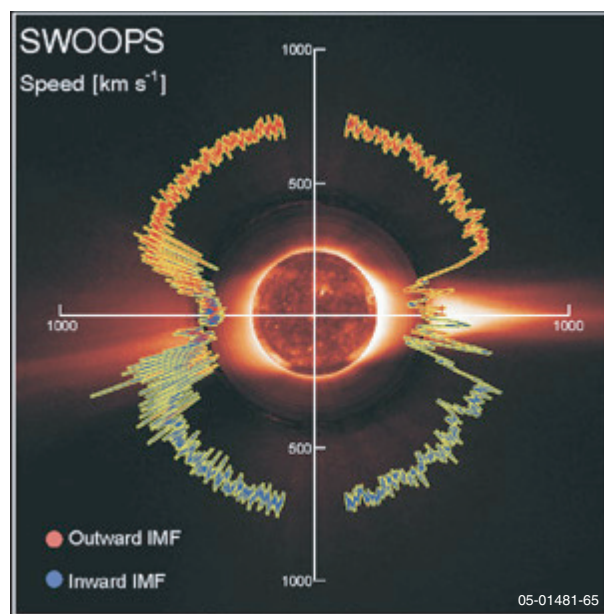
Artist's concept of the Solar Probe, with the glowing cone of the Thermal Protection System pointed toward the Sun inside 0.8 AU.

where the acceleration of the solar wind occurs. ***Thus the need for a Solar Probe remains.***

This report describes the results of an intensive year-and-a-half study by the Solar Probe Science and Technology Definition Team which demonstrates that Solar Probe is fully ready to move forward as a cost-effective and acceptably low risk mission. ***Solar Probe will be the first spacecraft to venture into the unexplored inner reaches of the heliosphere where the solar wind is born. Through high-cadence in-situ measurements of the solar wind plasma, energetic particles, and fields as close to the Sun as  $3 R_S$ , supplemented by coronal and photospheric imaging, Solar Probe will provide the data needed to solve, finally, the twin mysteries of coronal heating and solar wind acceleration.*** This historic mission will transform our understanding both of our Sun and of other stars with hot, x-ray-emitting coronas and supersonic winds as well.

### Solar Probe Science Objectives

Present observation, theory, and modeling provide the following general picture of the corona and solar wind. At times of lower solar activity, the solar wind is bimodal, consisting of a dominant quasi-steady high-speed wind that originates in open-field polar coronal holes and a variable, low-speed wind that

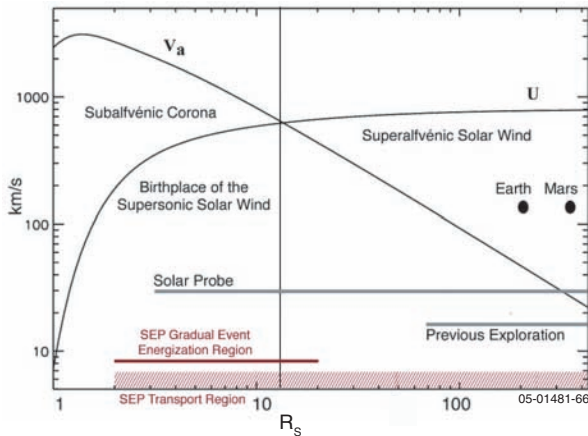


At solar minimum the solar wind is dominated by a high-speed flow from polar coronal holes, with a slower, variable flow emanating from the equatorial streamer belt.

originates around the equatorial streamer belt. With increasing activity, this orderly bimodal configuration of the corona and the solar wind breaks down, as the polar holes shrink and streamers appear at higher and higher heliographic latitudes. At these times, the bimodal wind structure is replaced by a complex mixture of fast flows from smaller coronal holes and transients, embedded in a slow-to-moderate speed wind from all latitudes. The energy that heats the corona and drives the wind derives from photospheric motions and is channeled, stored, and dissipated by the magnetic fields that emerge from the photosphere and structure the coronal plasma. Several fundamental plasma physical processes—waves and instabilities, magnetic reconnection, turbulence—operating on a vast range of spatial and temporal scales are believed to play a role in coronal heating and solar wind acceleration.

Thus we have the general picture. But the devil—and the physics—is, as always, in the details. For example, the association of the fast and slow components of the solar wind with large-scale magnetic structures (coronal holes, streamers) in the corona is well established. However, to understand coronal heating and solar wind acceleration in coronal holes, it is necessary to know the geometry and dynamics of the expanding magnetic field and to determine the role of fine-scale structures (such as polar plumes and macrospicules) in coronal heating. In the case of the slow wind, a critical unknown is the morphology of the magnetic field in the regions where the wind forms. Similarly, the morphology of the magnetic field in active regions, which contribute to the solar wind at least during solar maximum, is also unknown. Thus a major science objective of the Solar Probe mission is ***to determine the structure and dynamics of the magnetic fields at the sources of the fast and slow solar wind.***

The precise mechanisms by which energy is transferred from the photosphere and subsequently dissipated to heat the corona and accelerate the solar wind are not known. For example, low-frequency Alfvén waves are thought to be launched into the corona by photospheric motions. What is the energy flux in these waves close to the Sun? How is the energy of the waves dissipated? Through phase mixing? Through resonant absorption by coronal loops? Through nonlinear cascade processes? Observations suggest that ion cyclotron waves play an important role in heating the corona



Model profiles of the solar wind speed ( $U$ ) and the Alfvén wave speed ( $V_a$ ) with distance from the Sun. The vertical bar separates the source, or sub-Alfvénic, region of the wind from the supersonic solar wind flow. Solar Probe is the first mission to fly inside the solar wind source region.

and fast wind. But how and where are these waves generated? Are they produced locally by plasma instabilities, through turbulent cascade from lower-frequency waves, or in the lower corona by reconnection? And generally, what is the role of reconnection (e.g., in nanoflares) relative to that of wave dissipation in coronal heating? To answer these and similar questions, Solar Probe will, as a second main objective, *trace the flow of energy that heats the corona and accelerates the solar wind.*

Solar Probe's third major science objective is *to determine what mechanisms accelerate and*

*transport energetic particles* at the Sun and in the inner heliosphere. Two kinds of solar energetic particle (SEP) events occur during active periods, often both together: gradual events, in which particles are accelerated in the corona by shocks driven by fast coronal mass ejections (CMEs), and impulsive events, in which particles are accelerated by solar flares. In addition, even at the quietest times there is a continuous outflow from the Sun of particles of intermediate energies (suprathermal to  $>10$  MeV). The mechanism responsible for this outflow is not known. Further questions concern the relative contributions of reconnection, shocks, and turbulence to particle acceleration in impulsive events, the identity and source of seed populations for gradual events, and the means by which energetic particles are transported to high latitudes. Accomplishment of this objective will not only advance our understanding of a fundamental plasma process, energetic particle acceleration, but will also significantly contribute to efforts to predict SEPs, which present one of the most serious threats to astronaut health and safety.

The inner heliosphere is populated with dust grains originating from comets and asteroids. This inner heliospheric dust cloud, the source of the zodiacal light and the Sun's F-corona, has not been well characterized. Solar Probe's unique path near the Sun will make it possible to answer questions about the size and mass distribution of the dust, about its

### Solar Probe Science Objectives

#### Determine the structure and dynamics of the magnetic fields at the sources of the solar wind

- How does the magnetic field in the solar wind source regions connect to the photosphere and the heliosphere?
- How do the observed structures in the corona evolve into the solar wind?
- Is the source of the solar wind steady or intermittent?

#### Trace the flow of the energy that heats the solar corona and accelerates the solar wind

- How is energy from the lower solar atmosphere transferred to and dissipated in the corona?
- What coronal processes shape the non-equilibrium velocity distributions observed throughout the heliosphere?
- How do the processes in the corona affect the properties of the solar wind in the heliosphere?

#### Determine what mechanisms accelerate and transport energetic particles

- What are the roles of shocks, reconnection, waves, and turbulence in the acceleration of energetic particles?
- What are the seed populations and physical conditions necessary for energetic particle acceleration?
- How are energetic particles transported radially and across latitudes from the corona to the heliosphere?

#### Explore dusty plasma phenomena and their influence on the solar wind and energetic particle formation

- What is the dust environment of the inner heliosphere?
- What is the origin and composition of dust in the inner heliosphere?
- What is the nature of dust-plasma interactions and how does dust modify the spacecraft environment close to the Sun?
- What are the physical and chemical properties of dust-generated species?



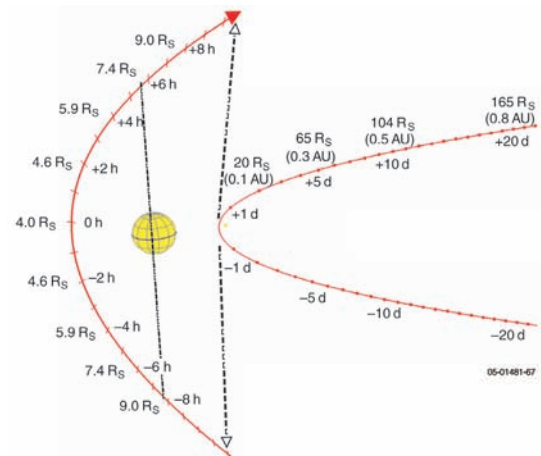
composition and origin, and about its interaction with the near-Sun plasma and gas environment. Of particular interest is the contribution of the dust to the “inner source” of energetic particles. As its fourth objective, Solar Probe will *explore dusty plasma phenomena in the near-Sun environment and their influence on the solar wind and energetic particle formation.*

To address these objectives, Solar Probe will **explore** a region of the solar system never before visited by a spacecraft. With the data it transmits back to Earth, solar and space physicists will answer questions that cannot be answered by any other means and will attain a **deep understanding** of phenomena and processes in this fascinating and critical region. And as with any great voyage into uncharted realms, Solar Probe’s journey to the Sun holds the promise of many more unanticipated **discoveries**—new mysteries to challenge humankind’s ever-expanding knowledge of our home in the universe.

### Science Implementation

Solar Probe will address the four science objectives through a combination of in-situ and remote-sensing observations performed from a polar orbit about the Sun. Inside a distance of 0.3 AU on both sides of perihelion, Solar Probe will make in-situ measurements of plasma, suprathermals, energetic particles, magnetic fields, waves, and dust in the near-Sun environment. Extreme ultraviolet and magnetic imaging of solar wind source regions and white-light imaging of coronal structures will be performed on both inbound and outbound legs of the solar pass. The remote-sensing observations will allow in-situ measurements to be related to magnetic and plasma structures at the Sun. Closest approach will occur at a perihelion altitude of  $3 R_S$  above the surface. Supporting remote-sensing observations from ground-based, sub-orbital, and space-based assets will be coordinated with the perihelion pass to provide context for Solar Probe’s in-situ measurements. A large and dedicated theory and modeling program will be an integral part of the Solar Probe mission, starting 3 years before the first perihelion pass.

*Solar Probe’s baseline payload is a single, integrated package consisting of both in-situ and remote-sensing instruments serviced by a common Data Processing Unit (DPU) and Low-Voltage Power Supply (LVPS).* The in-situ



The Solar Probe trajectory. Encounter science begins at 0.3 AU, 5 days before closest approach, and lasts until 5 days after closest approach.

instrumentation includes a Fast Ion Analyzer (FIA), two Fast Electron Analyzers (FEAs), an Ion Composition Analyzer (ICA), an Energetic Particle Instrument (EPI), a Magnetometer (MAG), a Plasma Wave Instrument (PWI), a Neutron/Gamma-ray Spectrometer (NGS), and a Coronal Dust Detector (CD). The remote-sensing instrumentation comprises a Polar Source Region Imager (PSRI), for EUV and magnetographic imaging of the solar wind source regions, and a white-light Hemispheric Imager (HI), for imaging coronal structures. An integrated payload developed by a single combined investigator team was baselined in the study as a means of achieving the maximum science return for the minimum mission costs and of reducing payload mass and power while providing added functional redundancy.

### Baseline Mission

The baseline mission provides for two flybys of the Sun, separated by  $\sim 4.6$  years, thus allowing Solar Probe to measure the solar wind and corona at different phases of the 11-year solar cycle, independent of launch date. For a launch in 2014, the first flyby will take place in 2018, around the projected activity minimum of solar cycle 24. The second solar flyby will occur in 2023, at a time of increasing solar activity.

Solar Probe will use a Jupiter gravity assist flyby (closest approach  $\sim 12 R_J$ , minimizing exposure to the jovian radiation belts) to achieve a polar orbit about the Sun with a perihelion of  $4 R_S$  ( $3 R_S$  above the surface). The spacecraft will arrive at the Sun

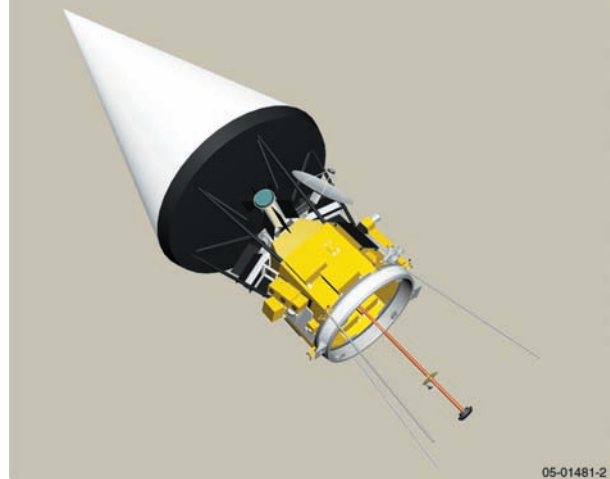
~4.1 years after launch, approaching from the south with a maximum velocity of 308 km/s at perihelion. For the first encounter, the perihelion pass is designed to take place with Earth 15° off quadrature, allowing for a high data rate (at least 25 kbps) for real-time science telemetry and for simultaneous supporting remote-sensing observations from Earth. Because of coronal scintillation effects, the Ka band will be used for the real-time data transmission. Pole-to-pole passage occurs entirely within 9  $R_S$  and lasts ~14 hours.

The Earth–Sun geometry for the second encounter (34° off quadrature) will again allow for simultaneous remote-sensing observations from Earth. However, the high-gain antenna will point away from Earth so that only low-data-rate real-time telemetry using the low-gain antennas will be possible. Extensive recorded data will be downlinked after both encounters to provide the complete detailed observations.

The Atlas 551 is baselined as the Solar Probe launch vehicle, although the mission design allows for dual-launch compatibility with a Delta IV Heavy.

### Solar Probe Spacecraft

*The baseline Solar Probe is a 3-axis stabilized spacecraft designed to survive and operate successfully in the intense thermal environment that it will encounter during its voyage around the Sun.* The spacecraft's most prominent feature is the Thermal Protection System (TPS), comprising a large 2.7-m diameter carbon–carbon conical primary shield with a low-conductivity, low-density secondary shield attached to its base. The TPS protects the spacecraft bus and instruments within its umbra during the solar encounter. The bus consists of a hexagonal equipment module and a cylindrical adapter. It provides an efficient mechanical structure that accommodates the instruments and spacecraft subsystems and handles the loads from the TPS and the launch loads. Solar Probe will be powered by three multi-mission radioisotope thermoelectric generators (MMRTGs). Simple monopropellant will be used for  $\Delta V$  maneuvers and attitude control. The Guidance and Control System consists of two redundant star trackers, an inertial measurement unit, digital Sun sensors, 4 reaction wheels, and 12 thrusters. The spacecraft is equipped with one high-gain antenna for data downlink during the first solar



The design of the Solar Probe spacecraft is based on rigorous engineering studies that demonstrate the technical feasibility and affordability of the mission.

encounter; a medium-gain antenna, the primary antenna during the cruise phase of the mission; and two low-gain antennas for emergencies or periods when the pointing of the medium and high-gain antennas is precluded. The X band will be used for both data downlink and command uplink; the Ka band will be used only for data downlink.

The imagers, CD, EPI, NGS, and one FEA are mounted on the Solar Probe bus. The FIA, the second FEA, and the ICA are mounted on a movable ram-looking arm, which will be gradually retracted as the spacecraft approaches the Sun. This arrangement provides viewing to near (2° inside of) the edge of the TPS umbra. To enable imaging of the solar wind source regions, a retractable, thermally robust periscope will be used to extend the PSRI optics beyond the TPS umbra. Both the side-looking arm and the periscope are designed to be fail-safe. The MAG is mounted to the 2-m axial boom that extends from the bottom deck of the spacecraft and that also accommodates a solar horizon sensor used for attitude safing during the solar encounter. The PWI consists of three actuator-controlled 1.75-m antennas mounted to the bottom deck.

### Solar Probe and Human Exploration

Solar energetic particle (SEP) events present a serious radiation threat to human explorers living and working outside low-Earth orbit. Development of an SEP forecasting capability is critical to space radiation risk mitigation and management. By making the first direct measurements of the

near-Sun regions through which all SEPs must travel, by directly sampling the regions where gradual SEPs are energized, and by identifying the seed populations for these dangerous particles, *Solar Probe will provide critical ground-truth data needed for the development of the predictive models that, combined with solar and heliospheric monitoring, will enable forecasting of the space radiation environment in support of human exploration.*

### Summary

*Solar Probe is an exciting mission of exploration, discovery, and deep understanding.* It will journey to one of the last unexplored regions of the solar system and reveal how the corona is heated and the solar wind accelerated, solving two

fundamental mysteries that have been top-priority science goals for many decades. The mission described in this report is based on an exhaustive and rigorous engineering study directed by the present Science and Technology Definition Team. Of paramount importance in the engineering study were trades concerning mission safety and cost, with the recommendation of a single integrated payload and the baselining of the Atlas 551 as the launch vehicle being key factors in achieving an affordable mission. *The rigor and thoroughness of this study ensures that the described mission is technically feasible, can be accomplished within realistic resources, and can fully achieve its four science objectives, thus transforming our understanding of the Sun and its sister Sun-like stars and enabling exploration.*

To understand the genesis of the heliospheric system, it is necessary to determine the mechanisms by which the solar corona is heated and the solar wind is accelerated and to understand how the solar wind evolves in the innermost heliosphere. These objectives will be addressed by a Solar Probe mission. Because of the importance of these objectives for the overall understanding of the solar-heliosphere system, as well as of other stellar systems, a Solar Probe mission should be implemented as soon as possible within the coming decade.

NRC, *The Sun to the Earth—and Beyond, a Decadal Research Strategy in Solar and Space Physics* (2003)