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Solar Probe Plus: Unlocking the Sun's mysteries

A conversation with Sir Martin Sweeting

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Separated from its launch vehicle and booster rocket, the spacecraft will head for the inner solar system and an unprecedented study of the Sun. Credit: JHU/APL.

UNLOCKING THE SUN'S MYSTERIES

Five decades in the making under various plans, NASA's Solar Probe Plus mission will launch a spacecraft toward the Sun on the closest approach ever attempted. Advances made in recent decades will enable the probe to dive into the low solar corona, allowing scientists to "touch, taste, and smell the Sun" for the first time. In so doing, it will seek to answer two major questions that continue to mystify solar physicists.

In the tradition of *Star Trek*, NASA's Solar Probe Plus (SPP) will go where no spacecraft has gone before, on a daring and technologically demanding adventure that will take it to our nearest star, the Sun.

At its closest approach, the probe will fly by Earth's fiery neighbor at a distance of just 7 million km. It will be the first robotic craft to dive into the low solar corona—the Sun's extended outer atmosphere. To do this, the probe itself hides behind a specially developed carbon-composite heat shield that must beat the heat as the spacecraft pumps out science data.

Because of its proximity to Earth, the Sun is among the most fully studied stars. Yet there are some secrets it still holds tightly. SPP is designed to help solve two fundamental mysteries: How the Sun's corona is heated, and how the solar wind is accelerated.

SPP's mission is part of NASA's Living With a Star program. The small, auto-sized spacecraft now under development at the Johns Hopkins University Applied Physics Laboratory (APL) in Laurel, Maryland, is slated for launch no later than 2018. APL is responsible for formulating and conducting the probe's mission. NASA Goddard manages the program, with oversight from the Heliophysics Division of the agency's Science Mission Directorate.

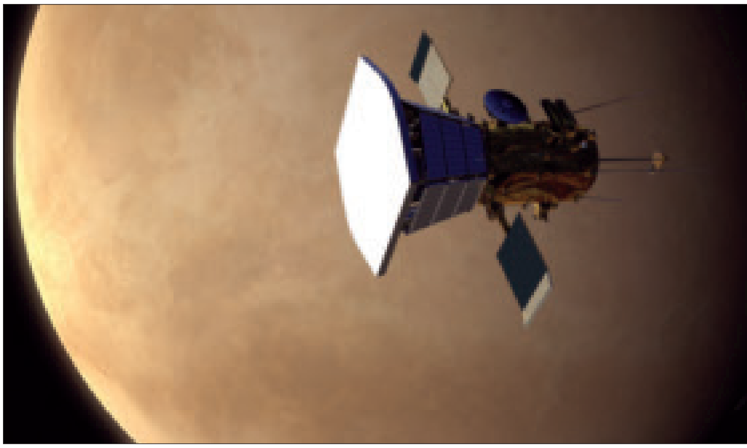
The booster for the spacecraft is based on an Atlas V 551, with an upper stage that is still being defined. The NASA budget for SPP is $1.2 billion for the entire mission, out to 2018, plus seven years—to 2025. That tally—in 'spend year' dollars—includes the launch vehicle and operations, along with money already spent on the project.

WALK RIGHT IN

Since the mid-1970s, NASA has stacked up reviews and reports to characterize a solar probe mission. Now, decades later, bolstered by a 2003 National Research Council decadal survey report that put priority on solar and space physics studies, the agency has given the green light to such a project, to be executed "as soon as possible."

Over the years, several changes have made SPP a doable mission, explains Richard Fisher, director of NASA's Heliophysics Division. Early plans had the spacecraft use a gravity assist from Jupiter in order to achieve a very highly inclined orbit.

"I think the second thing that has changed to enable this mission is the abandonment of a nuclear power system…needed because of the Jupiter gravity assist," Fisher tells *Aerospace America*. "You can use solar panels, but they have to be quite large. The key event that enabled us to think about this mission," he says, was finding "that we can achieve the scientific goals by being near the plane of the ecliptic...and use an assist from Venus."



SPP, fully deployed in cruise configuration, will fly past Venus during one of the seven gravity assists that sends it closer to the Sun. Credit: JHU/APL.

by Leonard David
Contributing writer

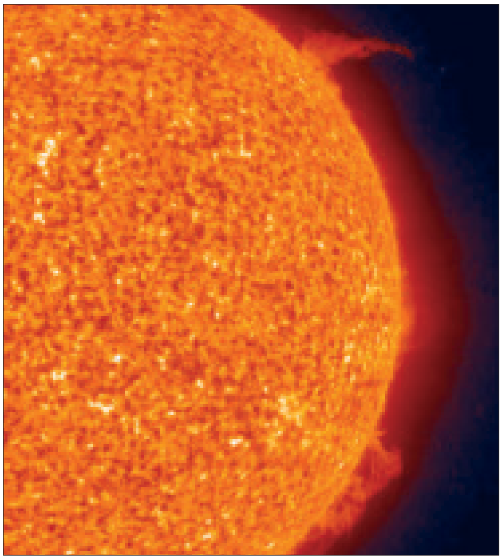
Fisher portrays SPP's mission as "much more exploratory" than what NASA typically attempts. "Usually, we're aiming at a well-enunciated scientific problem. There's a lot of exploration and discovery in this mission…it's going to be quite an advance in space physics, I think."

As now defined, SPP is a compact, solar-powered vehicle that will tip the scales at about 1,350 lb. Preliminary designs include an 8-ft-diam., 4.5-in.-thick carbon-foam-filled solar shield atop the spacecraft body. At its closest passes of the Sun, SPP must stay alive while beating the heat—thwarting a solar intensity more than 500 times what spacecraft encounter while orbiting Earth.

The mission plan calls for the craft to orbit the Sun 24 times over a seven-year period, steadily 'walking in' more closely with each orbit. Seven Venus gravity assists are needed to gradually reduce perihelion, the closest point to the Sun. On the final three orbits, SPP will fly to within 8.5 solar radii of the Sun's 'surface,' or about 3.7 million mi. In doing so SPP will eclipse the closest solar pass to date, made by the Helios 2 spacecraft, a joint venture of the Federal Republic of Germany and NASA.

"Solar Probe Plus is going where no spacecraft has gone before," says Lika Guhathakurta, SPP program scientist at NASA Headquarters. "For the first time, we'll be able to 'touch, taste, and smell' the Sun."

The point is that what SPP will find by perusing unexplored territory is unknown. "The possibilities for discovery," Guhathakurta adds, "are off the charts."



NASA's STEREO mission returns images of solar prominences. Credit: JHU/APL.

SHADOW DANCING

The reasons that SPP fits within the guidelines of NASA's Living With a Star effort are clear: We live in the extended atmosphere of an active star. While sunlight enables and sustains life, the Sun's variability produces streams of high-energy particles and radiation that can affect life.

Moreover, under the protective shield of its magnetic field and atmosphere, the Earth is an island in the solar system where life has developed and flourished. The origins and fate of life on Earth are intimately connected to the way Earth responds to the Sun's variations. Understanding the changing Sun and its effects on the solar system, life, and society is NASA's mantra in examining the connection between the two bodies.

Under the Living With a Star projects, SPP is part of a developmental approach to sorting out what is changing with time and what is changing with space, as Fisher sees it. Nevertheless, he points out, the SPP mission is rife with technical 'gotchas.'

What is Fisher keeping an eye on as the project moves forward from PowerPoint to probe development?

"I think it's the integrated system of the spacecraft. It's going to a strange place that is really exotic. We're attempting to hide everything behind a shield. So there are all kinds of things that crop up as a result of that," Fisher says.

Fisher confirms the view that the SPP's thermal protection system is vital, as are the craft's power system, navigation, and stability. "They are very important, because you can't have this thing wobble very much…or have something that is going to pop out from behind the shadow and melt. I think it's the environmental challenges that are the real stressor for this mission," he says.

There are countless cross-your-fingers features, Fisher observes, both in building the spacecraft and in the activity it is destined to carry out. "It is the first time that we'll be that close to a star. There are a lot of firsts…and a lot of unknowns. We know that it's going to be significant from the outset, just in the discovery mode. It might be, in some sense, one of the riskiest missions we've ever undertaken," he believes.

TOP-PRIORITY SCIENCE OBJECTIVES

Clearly SPP is an ambitious mission, one that will require significant technology development in several major areas. After the decades it has taken to pull such an endeavor together, the project today has come about because of two factors, notes Brian Morse, SPP project manager at APL. The first is "getting the technology in place to be able to do the mission in an affordable and technically viable manner," Morse tells *Aerospace America*. "The other is the overall mission design, which has evolved over the years. Solar Probe Plus is notably less expensive than previous concepts and yet is able to achieve the desired science. It took a while, I think, to come around to something that would fit within budgetary constraints and was technically viable."

Morse adds that one major SPP milestone that APL is pushing toward is a mission design review, now targeted for this summer.

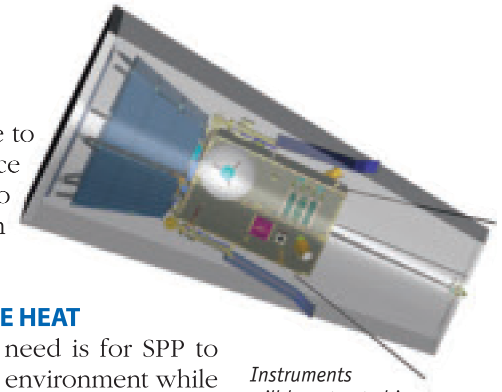
SPP will be able to take advantage of advances in instrumentation that have occurred over the years. But its top-priority science objectives date all the way back to the late 1950s, and these have not changed, says Andy Dantzler, APL's civilian space program area manager. They are:

- Determine the structure and dynamics of the magnetic fields at the sources of the fast and slow solar wind.
- Trace the flow of energy that heats the Sun's corona and accelerates the solar wind.
- Probe the mechanisms that accelerate and transport energetic particles at the Sun and in the inner heliosphere.
- Explore the dusty plasma phenomena in the near-Sun environment and their influence on the solar wind and on energetic particle formation.

Jim Kinnison, APL's SPP mission system engineer, says much of the spacecraft, especially in the electronics, avionics, and power systems, is derived from a heritage of work done earlier at APL. SPP will draw from the New Horizons spacecraft now en route to Pluto; the MESSENGER (Mercury surface, space environment, geochemistry, and ranging) mission to Mercury; STEREO (solar terrestrial relations observatory); and another APL undertaking now in the works, the Radiation Belt Storm Probes mission.

"So there is a continuum of technologies there from mission to mission, in the areas of structures and avionics, power system control, and guidance and control," Kinnison says. "It is true that we've got some new technologies to develop. Those are limited to a few areas."

That being said, Morse notes that SPP is a 'purpose-built' craft, one that necessitates new technologies but also endeavors to use heritage hardware to save money and reduce risk, "even when you do have a unique mission like this."



Instruments will be retracted inside the umbra of the thermal protection system to limit solar exposure. Credit: JHU/APL.

BEATING THE HEAT

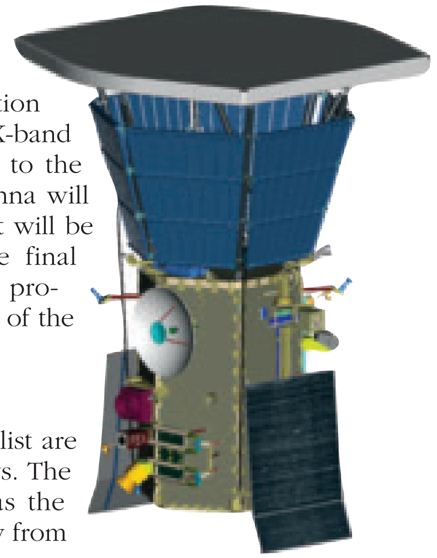
An obvious technology need is for SPP to survive an extreme solar environment while operating at standard space temperatures. The 3-m-high spacecraft will be packaged behind a carbon-carbon thermal protection system, which will experience temperatures of 1,400 C on its Sun-facing surface. This solar shield concept was partially influenced by designs of MESSENGER's sunshade. In addition, SPP is to use actively cooled solar arrays for power generation.

"The shield itself is basically a carbon-carbon shell that's filled with carbon-carbon foam," says APL's Kinnison. "Where we are pushing the boundary is in mass efficiency for that material," and also in using a very low-density foam that has little pedigree in terms of space application. Getting close scrutiny is how best to shape the foam and bond all of the material to the carbon-carbon composite shield.

That thermal protection system shield is 2.3 m in diameter. Struts are used to attach the shield to the tightly packaged spacecraft, protecting the bus and payload within its own self-cast umbra during solar encounter. The science instruments are fastened either directly to the bus, on a standoff bracket near the fairing attachment, or on a science boom extended from the rear of the spacecraft.

As diagrammed through trade studies, the three-axis-stabilized SPP would be outfitted with three deployable carbon-carbon plasma wave antennas mounted 120 deg apart on the side of the hexagonal bus that houses the probe's subsystems. A combination Ka-band high-gain antenna and X-band medium-gain antenna is affixed to the craft's body. The high-gain antenna will pump out 128 Gb of science that will be downlinked during each of the final three solar encounters. SPP also provides that high data rate for most of the earlier 21 orbits.

Solar Probe Plus starts out with solar array panels in a stowed position. Credit: JHU/APL.



INSTANT GRATIFICATION

Also on the key SPP technology list are the specially designed solar arrays. The arrays will retract and extend as the spacecraft swings toward or away from the Sun during several loops around the inner solar system, making sure the panels stay at proper temperatures and power levels. When the spacecraft is close to the Sun, the solar-cell-laden hardware is extended out.

"We refer to it as our secondary array," says Morse. "It's really the tip of the solar array that is extended…out into the penumbra of the Sun," exposed to extremely high heat loads. "Obviously, we have to get that heat away from the cells. So the cell development is another key technology, as is the cooling system for the solar arrays."

The bulk of the solar array panel is filled with 'primary cells' similar to the cells used on the MESSENGER mission to Mercury; the angled panel on the end of the solar arrays uses cells designed to withstand the high illumination during perihelion.

"It's impossible to reject the level of heat through simple passive radiation. So we have an active cooling system that circulates water behind the solar arrays, up through radiators that radiate the heat out," Morse says. "So that's a new development that we're working on…taking a step-wise advancing technology approach." A number of configurations have been reviewed—systems that need to work well not just near the Sun, but also in cold regimes that the SPP encounters on its swing-outs to grab gravity assists from Venus.

APL spacecraft engineers are also focusing on the solar environment itself. "We are flying through an area around the Sun that's never been visited before. So the exact environment is not known. We have to extrapolate that from data that we have…and determine the environment that we're going to see," says Morse. With SPP speeding along at nearly 200 km/sec, he says, running into dust at that velocity has to be taken into account in the design of the spacecraft.

"Staying pointed at the Sun is so important," Morse notes, with SPP having a backup safe-mode system that is independent of the main control systems. "So if something does go awry with the main control system, the safing system will prevent SPP from coming off the Sun by enough to hurt the spacecraft."

In terms of additional engineering marvels for SPP, APL's Dantzler tells *Aerospace America*, "This is a very instant gratification kind of mission, unlike your typical planetary mission. The good news is that 90 days after launch we'll already be making our first pass around the Sun. The bad news is that we won't have time for a long checkout campaign…if we want that first pass to do real science."

Key investigations

Last September, NASA announced the suite of science investigations selected for the Solar Probe Plus mission. The total dollar amount for the five investigations is approximately $180 million, for preliminary analysis, design, development, and tests.

The experiments seek to solve two key questions in solar physics: Why is the Sun's outer atmosphere so much hotter than the visible solar surface? What propels the solar wind that affects Earth and our solar system?

"We've been struggling with these questions for decades, and this mission should finally provide the answers," says Dick Fisher, director of NASA's Heliophysics Division in Washington, D.C.

The selected investigations are:

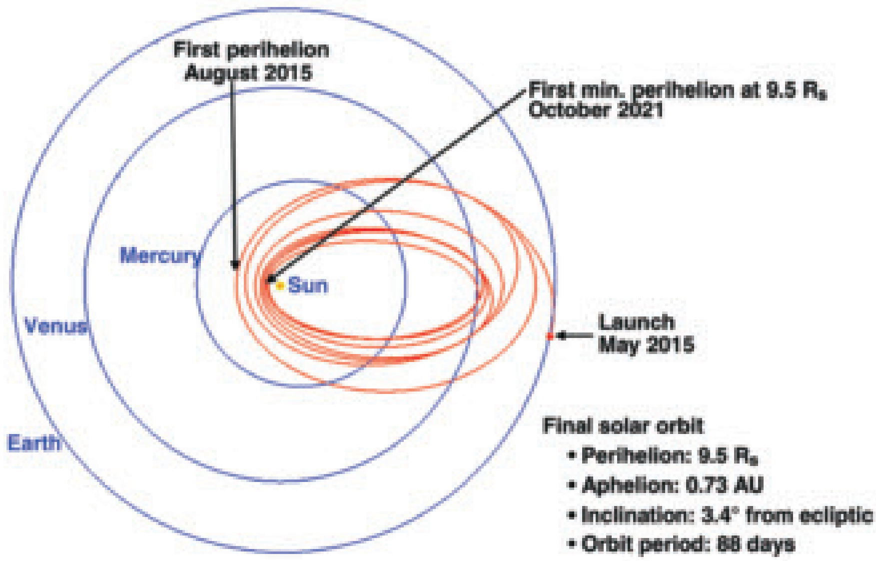
- *Solar Wind Electrons Alphas and Protons Investigation: This will specifically count the most abundant particles in the solar wind—electrons, protons, and helium ions—and measure their properties. The investigation also is designed to catch some of the particles for direct analysis. The principal investigator (PI) is Justin Kasper of the Smithsonian Astrophysical Observatory in Cambridge, Massachusetts.*
- *Wide-field Imager for Solar Probe Plus: This telescope produces 3D images of the Sun's corona. The experiment will also provide 3D images of the solar wind and shocks as they approach and pass the spacecraft. The PI is Russell Howard of the Naval Research Laboratory in Washington, D.C.*
- *Fields Experiment: This will make direct measurements of electric and magnetic fields, radio emissions, and shock waves that course through the Sun's atmospheric plasma. The PI is Stuart Bale of the University of California, Berkeley.*
- *Integrated Science Investigation of the Sun: This investigation consists of two instruments that will monitor electrons, protons, and ions that are accelerated to high energies in the Sun's atmosphere. The PI is David McComas of the Southwest Research Institute in San Antonio, Texas.*
- *Heliospheric Origins with Solar Probe Plus: This noninstrument investigation will be led by a PI who guides 'big picture' science tasks as the spacecraft penetrates the Sun's atmosphere. Another duty of the PI is to ensure that adjacent in-situ instruments do not interfere with each other as they sample the solar environment. Marco Velli of JPL in Pasadena, California, is the PI and the mission's observatory scientist.*

ACCOMMODATING UNKNOWNS

"A major concern that we have for the mission, one we've been working on for quite a while, is how end-to-end testing is done for something like this," says Kinnison. "And the bottom line…there isn't a facility that's big enough to do a full-up, 512 Sun exposure on the entire shield, plus spacecraft, and everything that goes along with it."

A multistep process will involve building test coupons from which prototypes are to be fabricated, likely not full-scale. "We again test the heck out of those and understand their properties," he adds. "By the time you get done with this process, you build up a confidence in your modeling, so that you believe you understand how the system works. On top of that, we have the ability to simulate the heat input from the heat shield into the spacecraft itself."

Normal thermal vacuum testing also is on tap, along with simulator runs on the SPP's shield and solar arrays that will test the overall system. "In doing all this testing,



The baseline SPP trajectory uses seven Venus flybys to reach a minimum orbit perihelion of 9.5 solar radii in 6.4 years. Credit: JHU/APL.

all this modeling, all this validation, you build up the confidence you need that your systems are going to work," Kinnison continues. "Plus you appropriately build margins into the system that will accommodate unknowns."

Morse adds that from the thermal capability and properties standpoint, SPP testing can be done at the subscale level. The shield also can be assessed at that level. "Then we still build a full-scale prototype, but that is more to address the issues of manufacturability, mechanical properties of the overall shield, and so forth. We'll do simulations, but it's not unusual to have a number of things that fly in space that can't be tested completely as an assembly."

PUTTING THE PLUS INTO SOLAR PROBING

In various conceptual forms, SPP has been five decades in the making. It is viewed as the keystone of NASA's Living With a Star program and as one of history's most significant solar research initiatives.

The original mission, says NASA's Fisher, was a kind of one-shot effort—the probe would pass the Sun and yield on the order of 10 days of prime data operation, then head back out toward Jupiter. Hence the current name reflects its expanded mission. "Solar Probe Plus gives an observer several hundred days, rather than just a few," says Fisher. "So the 'plus' is better and richer data.

"This is a fairly long mission to start with; it isn't over the first time it goes past the Sun. We intend to use the spacecraft in a number of encounters, to raise the amount of time that we're really near the Sun…to a scientifically significant amount."

SPP will be the defining mission in solar physics for the next several decades, "and one of the definitive science missions of the 21st century," says Gary Zank, Pei Ling Chan eminent scholar in physics and director of the University of Alabama at Huntsville's Center for Space and Aeronomic Research.

UA at Huntsville is one of six institutions selected by NASA to provide scientific leadership on SPP. "This is an opportunity to better understand the Sun's atmosphere, one of the great scientific mysteries in our universe," Zank says.

For solar astrophysics, SPP is the equivalent of a Hubble-class mission, so the data gathered are expected to be "really dramatic and revolutionary" in terms of their effects on the field," says solar physicist Jonathan Cirtain of NASA Marshall.

Similar praise comes from Russell Howard of the Naval Research Laboratory. The principal investigator for SPP's wide-field imager, he will be heading one of the mission's five science efforts. His experiment will see the solar wind and provide 3D images of clouds and shocks as they approach and pass the spacecraft.

Says Howard, "We'll be flying through the structures that we've only seen from 100 million miles away," with the imager providing close-up looks at mass ejections, streamers, shocks, comets, and dust. He and his team, he says, feel "like the early voyagers of the Earth: We don't really know what to expect, but we know whatever it is, it is going to be spectacular."