Fictitious discussion between Helios and Solar Probe Plus (SPP) Mission- and Spacecraft Designers.

In order to find out whether there was some experience transfer from the Helios (He-A was launched 1974-10-12) mission/spacecraft design to the Solar Probe Plus (SPP, to be launched in 2015) design the following fictitious discussion was assembled by using still available Helios documents (see references below) and the NASA/APL Solar Probe Plus Mission Engineering Study Report (March 10, 2008) and the science report "Understanding Coronal Heating and Solar Wind Acceleration" (ref. 2). The questions posed by the Helios mission/spacecraft designers were answered by quoting from the SPP references below. This discussion does not strive for completeness – it just wants to point out similarities and "heritage" items.
Despite the basic differences in the design of the two spacecraft (spinning vs. three axis stabilized, Helios orbits within the ecliptic plane while the SPP is flying over the poles of the sun, SPP's seven times closer approach to the sun, thermal control and solar generator power designs) it was satisfying to find out that some spacecraft design and scientific advances were triggered by Helios data and measurements.

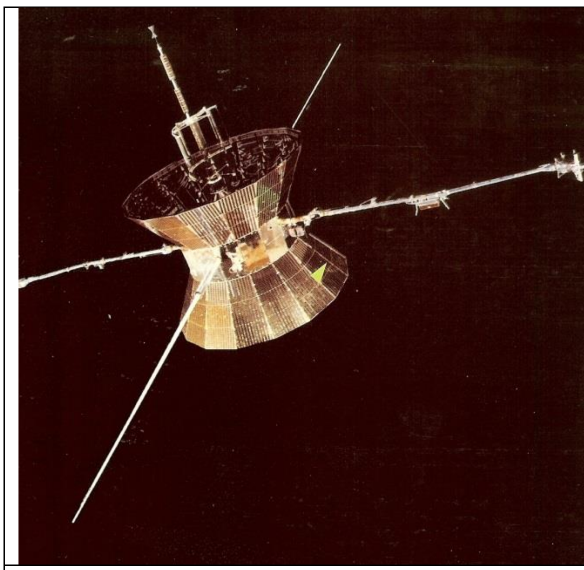

Figure 1. Helios-A in-flight configuration (size: approx. 2.77m cone diameter x 4.21 overall hight, total weight 369 kg)

Figure 2. Solar Probe+ shown with primary solar array panel deployed (size: approx. 2.7m diameter heat shield x 3.0m w/o HGA, total weight 481 kg) .

As stated in the SPP study report:

We now know more about the corona and the solar wind than ever before. Yet the two fundamental questions, raised by the spectroscopic studies Bernard Lyot and others in the 1930s and 1940s and by the confirmation of Parker's theory early in the space age, remain unanswered: Why is the Sun's corona several hundred times hotter than the photosphere? How is the solar wind accelerated?
The answers to these questions can be obtained only through in situ measurements of the solar wind as close to the Sun as possible. To date, however, the closest any spacecraft (Helios 1 and 2) has come to the Sun is 0.3 AU (65 R_S), which lies far outside the region where the acceleration of the solar wind occurs. Thus the need remains for a probe that will venture inside 0.3 AU, into the unexplored inner reaches of the heliosphere where the solar wind is born, and make in situ measurements of the solar wind plasma, energetic particles, and electromagnetic fields

as close to the Sun as possible. Such a mission, which must survive in the extreme environment near the Sun, presents significant technical challenges (ref. 2).

The science objectives 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 corona and accelerates the solar wind
• Determine what mechanisms accelerate and transport energetic particles
• Explore dusty plasma phenomena in the near-Sun environment and their influence on the solar wind and energetic particle formation (ref. 1).

The “heritage” question of the Helios mission designers would be: Which of the well documented Helios science results have been taken into account?

Although the twin mysteries of coronal heating and solar wind acceleration remain unsolved, remote-sensing observations from space-based platforms such as Yohkoh [Ogawara et al., 1991], Solar and Heliospheric Observatory (SOHO) [Domingo et al., 1995] and Transition Region and Coronal Explorer (TRACE) [Schrijver et al., 1999] as well as from ground-based observatories, together with in situ measurements by Helios [Schwenn and Marsch, 1990], IMP [Paularena and King, 1999], Ulysses [Balogh et al., 2001], Wind [Ogilvie and Desch, 1997], and ACE [Stone et al., 1998], have significantly increased our knowledge and understanding of both phenomena. As the temporal and spatial resolution of instrumentation has increased and sophisticated computational models have been developed, the fundamental role played by the Sun’s magnetic field in shaping dynamical processes on all scales in the three dimensional heliosphere throughout the solar activity cycle has become more apparent. Significant progress has been made in our knowledge of coronal structures, particularly of fine-scale structures such as polar plumes, coronal bright points [Golub et al., 1974], and the Sun’s ‘‘magnetic carpet’’ [Schrijver et al., 1998]; and we have witnessed fundamental advances in our understanding of the nature of the solar wind, the association of its fast and slow components with specific coronal structures, and its variability with changing solar activity.
Important early clues about the bimodal structure of the solar wind came from the Helios mission, the only mission to explore the inner heliosphere as close to the Sun as 0.3–0.7 AU. Helios demonstrated that properties such as solar wind speed, ion temperatures, and turbulence amplitude increase with distance from the heliospheric current sheet [Schwenn and Marsch, 1990; Grappin et al., 1990]. In its two orbits about the Sun’s poles, Ulysses has explored the three-dimensional structure of the solar wind as it changes over the course of a solar activity cycle [McComas et al., 2003]. Ulysses has shown that the fast solar wind, with a speed around 750 km s_{-1}, is the basic, quasi-steady outflow from the high-latitude solar corona during the minimum phase of the solar cycle and demonstrated that the fast wind originates from regions where the coronal electron temperature is relatively low [Geiss et al., 1995]. This inverse correlation between flow speed and coronal electron temperature poses a fundamental challenge to one of the basic tenets of the original theory of the solar wind, which assumed high coronal electron temperatures and consequent heat conduction as a basic driving mechanism. A further challenge to the original theory comes from SOHO measurements, which suggest that the open corona expands principally because of the very high, anisotropic temperatures of the coronal ions, with the minor species reaching temperatures of 10 MK at a few solar radii [Li et al., 1998; Kohl et al., 1998] (ref.2).

Energy particle acceleration and transport:
[57] About 1000 impulsive solar energetic particle (SEP) events per year are estimated to occur on the Sun during solar maximum, but the number may be much larger because many small events undoubtedly go undetected at 1 AU. A series of approx. 10 events could be observed at 1 AU during a several day period. Observations of the same ^{3}He-rich SEP event by IMP 8 at 1 AU and by Helios at 0.32 AU show that the event is approx. 100 times more intense at 0.32 AU and much more localized in time. Observed even closer to the Sun, these events will appear as intense bursts of only minutes in duration. In situ energetic ion measurements, together with simultaneous solar observations from 1 AU, should make it possible to trace such events to the flare site, to measure the flare properties, and to obtain the underlying magnetic field configuration. In addition to composition measurements, measurements of near-relativistic (V > 0.1 c) electrons from these events within a fraction of a minute of their release would be particularly important for untangling acceleration processes because the electron acceleration sites can be sensed remotely by microwave radio emission or hard X rays. As is the case with the energetic ion measurements, in situ observations of gamma rays and neutrons from these solar flare events would provide information on the accelerated particle components on closed field lines in the solar atmosphere (ref. 2).

The distance at closest SSP+ approach is 7 Mio km (Helios was as close as 43 Mio km). Assuming the field & particle measurements are similar to that of Helios - what drove the mission designers to increase the risk by a 7-times closer approach with respect to an additional gain for the scientific measurements?

As mentioned above, the key driver was to get as close as possible *and technically feasible* to the sun for in-situ measurements of the solar wind's acceleration process. *An* engineering team conducted studies of trajectories to develop a feasible mission concept for Solar Probe under NASA's new direction and guidelines. The baseline mission design meets the established mission requirements and program constraints.
The baseline trajectory uses seven Venus flybys and no deep-space maneuvers to reach a minimum perihelion of 9.5 RS in 6.4 years in October 2021, as shown in Figure 3.1- 1. The baseline mission will end after three orbits with at the minimum perihelion of 9.5 RS. From launch to the end of mission, the baseline trajectory consists of 24 solar orbits whose perihelia gradually decrease, from 35 RS down to 9.5 RS. Figure 3.1- 2 plots the solar distance over the entire mission and the perihelion distances of the 24 solar orbits. The first perihelion occurs only 3 months after launch. The Sun–Earth–probe (SEP) angle and Sun–probe–Earth (SPE) angle as functions of time are plotted in Figure 3.1-3 (see below: HGA pointing)

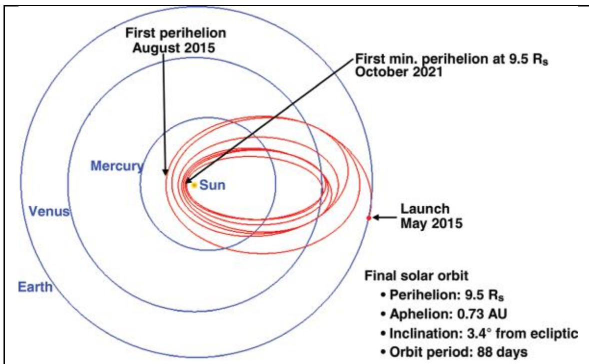

Figure 3.1-1 Baseline Solar Probe Plus trajectory

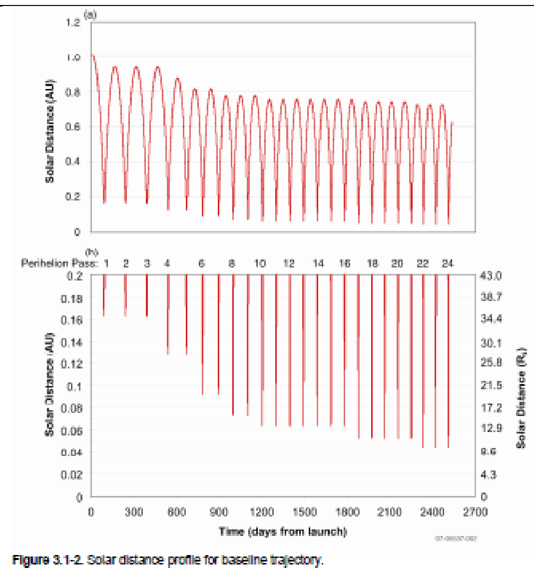

Figure 3.1-2 Solar distance profile for baseline trajectory

A completely integrated trajectory of the baseline mission from launch through the end of the nominal mission (after three 9.5-RS perihelion orbits) was computed with a full gravity field model including the Sun and all planets. The results of the trajectory were verified by different mission design software used for trajectory design, flyby targeting, and trajectory correction maneuver (TCM) planning for the ongoing interplanetary missions [New Horizons, MESSENGER (Mercury Surface, Space Environment, Geochemistry, and Ranging) and STEREO (Solar Terrestrial Relations Observatory)] managed by APL for NASA (ref. 1).

4. How is the S/C qualified with respect to solar constants and temperature resistance (solar simulation).

The approach is to use a heat shield design (Figure 2- above) rather than active and passive temperature controls as used for Helios. The Helios thermal design was qualified at the Solar Simulation test chamber at JPL (the largest available at that time using the S/C prototype.

SSP+ Shield Prototype Development.
The second of the developmental prototypes is used to verify the thermal performance of the shield. This unit is aimed at verifying the protection the shield will provide during the closest approach to the Sun and the resulting heat

leak to the spacecraft. The configuration is required to include only a representative section of the shield because there are no test facilities presently capable of taking the entire shield front surface to the required temperature via an applied radiative heat flux. As noted above, in flight, there will be ~4 MW incident on the shield's front surface. There is a test facility at Johnson Space Center (JSC) that is used for thermally testing the Space Shuttle surfaces protected by insulating tiles. The facility includes a "hot wall," ~30 in. square, inside a vacuum chamber. The limited size of the hot area requires a section of the shield be built as a test specimen. The test section would contain the C-C pan and cover, including an edge section. Several foam packing approaches would be included. The test unit would include truss and spacecraft bus simulators that would allow the heat flow through the test item to be measured . As with the mechanical prototype unit, the thermal testing would be completed and the test data correlated with the analytical models by program PDR.

This timing of the prototype unit would allow any design updates to be included into the flight designs. As part of the planning for the developmental testing, a discussion was held with the Mars Science Laboratory TPS team to review their testing efforts. The bulk of their high temperature testing has been aimed at defining the ablation parameters and quantifying material erosion. Testing was performed by using arc jets in a high-enthalpy flow field. They also used the Sandia Solar Tower for testing the radiation transmission of TPS coupon materials, but they have not tested the TPS there.

The consensus was that it will be extremely difficult, if not impossible, to subject the full size probe to heating on the order of 100 W/cm2. The best option would be to use a radiant lamp facility, such as the ones at NASA JSC or NASA Dryden, as described in the preceding paragraph (ref.1).

5. Are you "counting" on a solar cell annealing effect (was expected to take place above +120 deg C)? What is the expected E.O.L power degradation of the cells? If you can tell - what radiation models were used for calculating the degradation effects?

It should be mentioned that the post mission analysis of the two Helios power generators yielded the following results: HE-1 aphelion power degradation after 125 months in orbit from 216 W to 43 W (80.1%), HE-2 aphelion power degradation after 49 months in orbit from 216 W to 104 W (51.9%). It would be interesting to see the SPP resulta after the mission (refs. 3, 5)

SSP+Power System Performance

Power analysis was performed taking into account solar array optical, assembly, and wiring losses; temperature effects; degradation due to ultraviolet radiation; and charged particle radiation. The analysis also includes the effects of intensity variations with Sun distance and other power system losses, including solar array string isolation diodes, PPT conversion efficiency, power subsystem wiring, and spacecraft wiring harness. The power subsystem was designed to provide 482 W of load power between 0.044 AU and 0.9 AU distance from the Sun. The Sun– probe distance is greater than 0.9 AU only immediately after launch and around aphelion of the first few orbits. During these times using X-band rather than Ka-band will reduce power used by the telecommunications subsystem. The amount of data transferred to the ground also will be reduced.

However, because the spacecraft spends relatively little time at these greater distances, there will be no impact on science return.

Between 0.9 AU and 0.25 AU the angle of the primary array is adjusted to deliver adequate power to the spacecraft. Inside of 0.25 AU, the primary array is folded into the umbra behind the spacecraft heat shield. As the spacecraft approaches the Sun and illumination intensity increases, the secondary array is retracted behind the shield as needed to expose enough photovoltaic cell area to maintain the desired electrical power output level.

As mentioned above the nominal power is 482 W (high power mode) with a 34% margin.

The solar cells used for the secondary solar array are triple-junction GaAs-based cells optimized for high-intensity illumination and high current density. These cells use the same epitaxial growth as high-efficiency cells with spaceflight heritage. The gridlines and contact metallization is the same as used for concentrator photovoltaic cells, which have been used for terrestrial applications with optics having a very high concentration ratio. Although optical concentration is not being used on this solar array, the close proximity to the Sun results in high flux, which the cell must accommodate.

For this application, the illumination intensity varies between 16 and ~250 equivalent Suns. This intensity is well within the range for which concentrator photovoltaic cells have been designed. Characterization tests for concentrator photovoltaic cells have been performed at up to 1000 equivalent Suns. Each cell has an active

“aperture” area of 0.989 cm2. The cell front-side metallization, dual bus bars, and gridlines are designed to minimize resistive losses to accommodate the relatively high current. Wide electrical interconnects with stress-relief and multiple-welded contact points are used to conduct the relatively high current between cells. OSRs and electrical insulation cover the cell-to-cell electrical interconnects to minimize thermal load.
The coverglass, which is cerium-doped microsheet with dual antireflective coating, is used for radiation protection and optical filtering. Tradeoffs will be performed to optimize the coverglass thickness and type of coating.
The thermal effects of the coverglass thickness and filter coating are much more dominant than typical for this application because of the high solar flux and will be studied as part of tradeoffs to determine specifics of the coverglass design.
Under the predicted range of operating conditions, the effective conversion efficiency varies between 13% and 20% with a junction temperature of 120° C, resulting in additional 2259 to 1897 W of thermal energy absorbed by the cells. Effective conversion efficiency was estimated by using a conservative combination of specifications for spaceflight qualified solar cells and concentrator photovoltaic cells at a 120° C operating temperature.
Most of the Solar Probe+ mission will occur during solar minimum conditions. During this period of the solar cycle, the total dose is negligible, nd significant radiation damage will occur only in the later years when the Sun becomes active during the solar maximum period. The total dose requirement for Solar Probe+ is 30 krad behind 100 mils of aluminum shielding, based on the 95% worst-case Jet Propulsion Laboratory solar proton model for the 2 years of maximum conditions and correcting for Sun–spacecraft distance through the orbit as defined (ref. 1).

6. The pointing of the antenna might be tricky: you have to avoid overheating of the compartment on the other hand I assume there are "black-outs" and "gray-outs" (i.e. the sun in the line of sight between the earth and the probe).

High-Gain Antenna Control
The HGA will be pointed by rotating the spacecraft about the spacecraft sunline and rotating the antenna using the rotary actuator to keep it oriented toward Earth. The second axis of motion for the HGA is used to deploy the HGA mast to a fixed position to give the HGA a clear field of view to Earth. The G&C subsystem will compute the necessary positioning of the gimbal for the HGA based on onboard ephemeris models for the Earth, Sun, and spacecraft. In the event of loss of onboard ephemeris knowledge or other fault conditions, the HGA will be commanded to its safe stowed position (ref. 1).

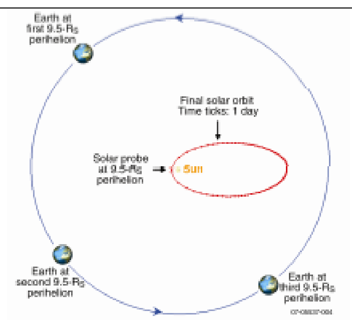

Figure 3.1-5. Location of Earth during solar encounters with perihelion below 10 R_S.

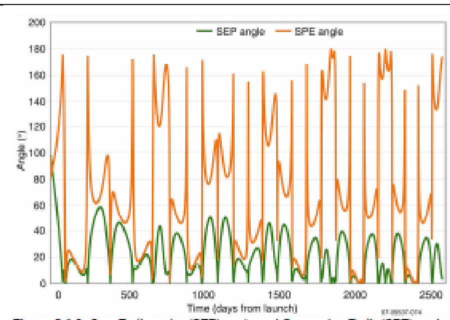

Figure 3.1-3. Sun–Earth–probe (SEP) angle and Sun–probe–Earth (SPE) angles for the baseline Solar Probe+ trajectory.

8. Are there any "Celestical Mechanics" or "Wave Propagation" (see attached Helios list of experiments) experiments being carried out?

Not planned, see mission goals above.

References:
1) Solar Probe+ Mission Engineering Study Report (NASA/APL, March 10, 2008)
2) Understanding Coronal Heating and Solar Wind Acceleration: Case for in situ Near-Sun Measurements (D.J. McComas et al, published 17. March 2007).

3) "Helios – Interplanetary Experience (DLR/GSOC)". The GSOC operational experience with the two solar probes is available for download (.pdf) at ResearchGate:

4) "10 Years Helios", a publication celebrating the 10th launch anniversary of Helios-1 by H. Porsche (ISBN 3-88135-156-6), bilingual issue.

5) "Das Langzeitverhalten von Energieversorgungssystemen am Beispiel Helios und Symphonie" (Dissertation, Joachim Kehr, Technische Universität München 17. März 1987, summary "PhD eng")

Joachim J. Kehr, Editor SpaceOps News, April 2014_U1