

Research on the Parker Solar Probe Thermal Protection System and Its Implications (Post-print)

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Date: 2020-05-06T00:00:00+00:00

Abstract

Parker Solar Probe (PSP), named after Eugene Newman Parker—the pioneer of modern solar wind and magnetic reconnection theory—is a spacecraft that will traverse the Sun’s corona, exploring previously unvisited regions and conducting direct investigations into the origin and dynamics of the corona and solar wind. It holds the potential to resolve the two major enigmas of coronal heating and the anomalously high solar wind velocities, with its thermal protection system facing challenges that far surpass those of any existing spacecraft. This paper first introduces the significance of solar exploration and the scientific objectives of PSP, then briefly outlines PSP’s orbital trajectory and thermal environment while identifying the key challenges in thermal protection. The structure of PSP’s thermal protection system is analyzed, followed by a detailed exposition of the heat shield and sun-facing coating, solar panel, and cooling system designs. Finally, the implications of PSP’s thermal protection system for the design of thermal protection systems in China’s near-Sun probe missions are presented.

Full Text

Preamble

Research and Enlightenment of the Parker Solar Probe Thermal Protection System

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Abstract

The Parker Solar Probe (PSP), named after Eugene Newman Parker—the founder of modern solar wind and magnetic reconnection theory—will traverse

the Sun's corona to explore regions never before visited by spacecraft. By conducting direct measurements of the origin and dynamics of the corona and solar wind, it aims to solve two major mysteries: the extremely high temperature of the corona and the remarkably high acceleration of the solar wind. The thermal protection system of PSP faces difficulties and challenges far exceeding those of any previous spacecraft. This paper first introduces the significance of solar exploration and the scientific objectives of PSP, then briefly describes PSP's orbit and thermal environment while highlighting the challenges of thermal protection. We analyze the structure of PSP's thermal protection system and elaborate in detail on the design of its heat shield and sun-facing coating, solar panels, and cooling system. Finally, we provide insights from PSP's thermal protection system for the design of thermal protection systems for China's future near-Sun exploration missions.

Keywords: Parker Solar Probe; Thermal protection system; Heat shield

The Sun is the nearest star to Earth and dominates the environment of the entire solar system, including our planet. Nearly all human activities depend on energy from the Sun, and any solar activity or variation affects human life and the safety of our surroundings in various ways. Particularly during violent solar events such as solar flares and coronal mass ejections (CMEs), Earth's surrounding space magnetic field and plasma environment (known as space weather) experiences severe impacts, leading to hazardous space weather conditions. As technology advances, humanity has established increasingly large-scale high-tech systems—including power grids, communications, the internet, and satellite navigation systems—upon which daily life depends more heavily. High-energy charged particles from solar activities like flares and CMEs significantly affect these modern technological systems. Strong solar events such as the “Carrington Event” and the “1989 Quebec Event” can severely impact modern human life and even survival quality. To address the potential impacts of solar activity, we must monitor and study solar activity patterns to provide early warnings. Furthermore, as the only star that humans can explore at close range, the Sun provides unique opportunities for in-situ measurements of magnetized plasma environments that are impossible to obtain for other stars or similar environments in the universe [1].

At 3:31 am Eastern Time on August 12, 2018, the Parker Solar Probe launched from the Kennedy Space Center in Florida, USA. It will pass through the Sun's corona to explore regions never before probed by spacecraft, conducting direct measurements of the origin and dynamics of the corona and solar wind. The mission aims to solve the two major mysteries of coronal heating and the extremely high acceleration of solar wind. Its specially developed thermal protection system safeguards PSP's scientific instruments from solar radiation damage.

With the implementation of near-Sun exploration projects such as Europe's Solar Orbiter and Russia's “Interheliozond” mission, humanity's exploration of the Sun will reach a new climax. The Yunnan Observatories of the Chinese Academy of Sciences has also proposed and begun advancing a Chinese

near-Sun exploration project, which will develop a near-Sun probe to conduct close-up observations of solar eruption processes and corresponding magnetic field structures. The thermal protection system of a near-Sun probe is critical for protecting its instruments from the effects of intense solar radiation heating, high-energy charged particle bombardment, and cooling by the cold cosmic background radiation, making it essential for mission success. Studying the thermal protection system of the Parker Solar Probe provides a valuable reference for thermal protection design of China's near-Sun exploration missions.

1 PSP Orbit and Thermal Environment

PSP operates in a low-inclination elliptical orbit with its aphelion near Venus and perihelion at approximately 9.5 solar radii. The spacecraft uses seven Venus gravity assists to gradually approach the Sun. During its first orbit, the perihelion was at 35 solar radii, where solar radiation intensity was relatively low. In its final orbit, the perihelion reaches 9.5 solar radii with an aphelion of 0.73 AU, an orbital inclination of 3.4 degrees relative to the ecliptic plane, and a period of 88 days [2]. PSP has 24 opportunities to approach the Sun, spending a total of about 20 hours in the near-Sun region within 10 solar radii [1]. At closest approach, the solar flux on PSP's sun-facing surface is approximately 500 times that near Earth. PSP's orbital thermal environment includes intense and continuously varying solar radiation, sustained erosion from solar wind, and intermittent bombardment by high-energy charged particles from violent solar activities such as CMEs and flares. Additionally, the spacecraft's anti-sunward side faces the cosmic background with an effective temperature of about 3 K, experiencing cooling from the cold black background of space.

2 PSP Thermal Protection System

PSP features a heat shield that directly faces solar radiation. The shield has an effective diameter of 230 cm and thickness of 11.4 cm, designed to withstand intense solar radiation, CMEs, flares, solar wind, and other hazards while creating a protected workspace for scientific instruments. The shield exhibits characteristics of high-temperature resistance, ultra-high solar radiation tolerance, high solar reflectance, resistance to space charged particle radiation, low mass density, and high structural strength. PSP's heat shield is sized with margin to tolerate a 2° pointing error, ensuring scientific instruments remain in the shield's shadow even when PSP's orientation deviates by 2° from the Sun's center [2]. In addition to the heat shield, PSP's thermal protection system components include a radiator, truss structure, multi-layer insulation (MLI), solar panels, and their water cooling system. The truss serves as PSP's "backbone," connecting, securing, and supporting the heat shield, radiator, solar panels, and equipment compartment. The radiator is mounted on the truss structure beneath the heat shield, exchanging thermal radiation with the cold cosmic background. Both the radiator's inner surface and PSP's scientific instruments are covered with silver-white MLI material, which has low thermal emissivity and high solar re-

flectance. The solar panels supply power to the spacecraft and are equipped with a water cooling system to remove heat generated during power generation. The heat shield blocks intense solar radiation and space charged particle bombardment, creating a long-term working environment for PSP' s scientific instruments. The sun-facing coating on the heat shield surface is the first line of defense against ultra-intense solar radiation.

2.1 Sun-Facing Coating

PSP' s sun-facing coating consists of a white alumina ceramic coating combined with a tungsten metal barrier coating. Beneath the coating lies the heat shield substrate made of carbon/carbon composite and carbon foam. The tungsten metal barrier coating is applied to the substrate surface, with the white alumina ceramic coating covering the tungsten layer. The white alumina ceramic coating maintains its whiteness throughout the 7-year mission, exhibiting high reflectance in both visible and near-infrared bands, excellent radiation damage resistance, and strong ability to withstand bombardment by radiation, electrons, and protons. The coating' s melting point exceeds 2000°C. The ratio of solar absorptance (S) to thermal emittance (IR) for PSP' s sun-facing coating is approximately 0.6, with the coating reaching a maximum temperature of about 1400°C at closest approach [3]. The mission requires PSP to withstand 24 orbital thermal cycles. In the first orbit, the sun-facing coating temperature ranges from 70°C to 600°C, while in the final orbit it ranges from 130°C to 1400°C. Without the sun-facing coating, the carbon/carbon composite material of the heat shield would behave nearly as a blackbody, reaching surface temperatures of up to 1600°C at closest approach.

Conventional alumina coatings suffer from brittleness and poor toughness. Typically, additives such as titanium dioxide/magnesium oxide, rare earth elements/oxides, carbon nanotubes, and carbon fibers are incorporated to form composite powder materials that overcome these deficiencies [4]. Titanium dioxide has a lower melting point than alumina, and when doped into alumina, it homogenizes the microstructure and improves coating properties. Jia SK and Zou Y et al. found that adding titanium dioxide to alumina coatings increases coating density, toughness, corrosion resistance, and thermal conductivity while releasing stress and reducing cracks [5]. Density is defined as the ratio of actual density to theoretical density, and coating density is closely related to surface optical reflectance [3]. Magnesium oxide can increase oxygen vacancies in alumina ceramics, promoting diffusion and facilitating sintering. The mechanism of MgO for grain refinement and densification involves its dissolution in the alumina lattice. When MgO content is below the solid solubility limit, it simultaneously promotes sintering and inhibits grain growth. When exceeding the solubility limit, MgO may react with alumina to form a second-phase magnesium aluminate spinel, which primarily inhibits grain growth but hinders densification. Cheng Cheng, Ji Zhen et al. found [6] that adding appropriate amounts of MgO can lower the sintering temperature of

alumina ceramics, inhibit grain growth, and increase density. As MgO addition increases from 0 to 0.25% (mass fraction), alumina ceramic density rapidly improves from 97.16% to 98.87%, with 0.25% being the optimal MgO content. Excessive MgO causes abnormal grain growth and decreases density; at 0.5% MgO addition, material density declines. Carbon nanotubes and carbon fibers have high strength and stiffness; adding them to alumina powder improves the bonding within the coating microstructure and enhances mechanical properties. With carbon fibers or nanotubes restraining the microstructure, coating toughness increases along with wear resistance and bonding strength. Rare earth oxides/elements distributed as hard phases in the coating improve microstructure and properties. Li Shuhua et al. found that rare earth elements refine alumina coating grains, forming a mixed structure of amorphous and microcrystalline phases that improves coating bonding strength and corrosion resistance [7]. Additionally, CeO₂ can effectively reduce the porosity of alumina coatings [8].

PSP's alumina ceramic coating contains magnesium oxide dopant as a grain growth inhibitor (GGI). In 2006, PSP technicians discovered in preliminary research that alumina undergoes phase transformation near 1180°C, with grain growth occurring as heat treatment temperature increases, leading to higher solar absorptance and consequently higher heat shield temperatures [9]. Adding MgO dopant to alumina can prevent this growth, stabilize optical properties after phase transformation, and increase coating density. Table 1 compares the optical properties of samples with and without MgO GGI [3]. Both samples used the same alumina powder and barrier coating, with Metco105SFP alumina ceramic powder and a TAN barrier coating approximately 76.2 μm thick.

The two alumina ceramic samples contained either 5% MgO by mass or none. As shown in Table 1, the S/IR ratio of the MgO-doped sample was higher than the undoped sample at room temperature (RT). After 6 hours of heat treatment at 1180°C (T1) in 10⁻³ Torr vacuum, both samples showed similar S, S/IR, and IR values. However, after 6 hours at 1400°C (T2) in the same vacuum conditions, the S of the sample without MgO GGI increased by nearly 8%, while the MgO-doped sample maintained S within 1% of its original value. MgO GGI did reduce IR values. Since PSP's heat shield reaches approximately 1400°C, the S/IR ratio of the MgO-doped alumina ceramic after 1400°C heat treatment was 17.4% lower than the undoped sample, thereby reducing the shield's thermal equilibrium temperature. MgO doping not only improves the solar absorptance/thermal emittance ratio but also reduces the coating's thermal expansion coefficient at high temperatures, making it closer to that of the underlying tungsten coating. This improves interfacial bonding and enables the coating to withstand large thermal gradients without cracking or spalling [3].

In high-temperature vacuum environments, alumina ceramic reacts with the carbon substrate of the heat shield, turning gray. PSP incorporates a barrier coating thinner than a human hair between the alumina coating and carbon substrate. Candidate barrier coatings considered for PSP included refractory

metals, nitrides, carbides, or oxides. Elizabeth A. Congdon et al. measured [3] that adding a 76.2 μm plasma-sprayed TAN layer between the alumina ceramic coating and carbon substrate reduced the sun-facing coating's solar absorptance from about 60% to approximately 30% while maintaining thermal emittance near 55%. Parker Solar Probe ultimately selected a tungsten metal coating to block high-temperature interaction between the alumina ceramic and carbon substrate. Tungsten has a melting point exceeding 3000°C, the highest of any metal, enabling long-term use at extreme temperatures.

PSP researchers also investigated the relationship between alumina ceramic coating purity, initial powder particle size, and solar absorptance. Without heat treatment, the spectral reflectance of alumina with different purities under identical spraying conditions is shown in Figure 1 [Figure 1: see original paper] [3].

[Figure 1: see original paper]

As shown in Figure 1, 99.8% purity alumina ceramic exhibits higher spectral reflectance than 99.95% purity alumina but lower solar absorptance. After heat treatment at 1180°C, the spectral reflectance of both purities at room temperature becomes similar, as shown in Figure 2 [Figure 2: see original paper] [3].

[Figure 2: see original paper]

PSP technicians also studied optical property differences in alumina ceramics prepared from various initial powder particle sizes. With identical barrier coatings and heat treatment, the spectral reflectance of alumina ceramics prepared from Metco 105NS powder (15-45 μm initial particle size) and Metco 105SFP powder (4-30 μm initial particle size) is shown in Figure 3 [Figure 3: see original paper] [4].

[Figure 3: see original paper]

The red curve corresponds to the coating prepared with Metco 105SFP, while the blue curve represents Metco 105NS. Alumina ceramics prepared from smaller powder particles show lower spectral reflectance than those from larger particles, with greater differences at shorter wavelengths. In the long-wave infrared band above 7 μm , both show similar reflectance. Consequently, alumina ceramics from smaller particles have higher solar absorptance with comparable thermal emittance.

PSP controls coating microstructure to tune optical and adhesion properties. Modeling of porosity-related effects indicates that density is crucial for short-wave optical properties. To some extent, coating spectral absorptance is a function of coating density. PSP uses MgO dopant to control alumina microstructure and thereby adjust the solar absorptance-to-thermal emittance ratio. The emittance of PSP's sun-facing coating is a function of both alumina ceramic properties and temperature. As temperature increases, the coating's spectral thermal emittance shifts toward the solar spectral irradiance, causing its solar

absorptance-to-emittance ratio to approach 1. Lower absorptance can reduce the coating's surface temperature.

2.2 Heat Shield

Both the sun-facing and anti-sun-facing surfaces of PSP's heat shield are C/C composites. The sun-facing coating is applied to the sunward C/C composite surface, while the bottom C/C composite layer lacks this coating. Low-thermal-conductivity carbon foam sits between the two C/C layers. The cross-sectional structure of PSP's heat shield is shown in Figure 4 [Figure 4: see original paper] [10].

[Figure 4: see original paper]

C/C composites exhibit ablation resistance, excellent thermal stability, low density, high strength, high fracture toughness, and good thermal conductivity, making them suitable for high-temperature structural components such as warheads, rocket engine nozzles, and brake discs. C/C composites are among the few materials that can be used at temperatures up to 3000°C [11] and are currently the only known materials whose strength does not decrease up to 2500°C. Their most distinctive characteristic is that strength increases rather than decreases with temperature [12]. This lightweight material provides excellent mechanical properties and serves as the heat shield's "backbone." Both C/C composite layers of the Parker probe are very thin—less than one-tenth of an inch [13]—and are sufficiently flexible to bend even when layered together. Solar irradiation causes resin volatilization, so to ensure shield strength, the C/C composite layers contain no resin or other impurities, consisting purely of carbon fibers wound together in a carbon-carbon composite structure.

PSP's C/C composites undergo repeated high-temperature baking in a 3000°C electric oven 4-5 times. At high temperatures, the turbostratic carbon/carbon material structure undergoes three-dimensional rearrangement of graphene planes, reducing interlayer spacing and increasing crystallite size. This transforms the C/C composite from a turbostratic carbon structure toward a graphite crystal structure. After high-temperature treatment, the strength and high-temperature capability of C/C composites are further enhanced. The carbon foam between C/C layers serves as a thermal insulator, blocking heat conduction to the truss and backend equipment. While carbon itself conducts heat, carbon foam is mostly empty space. Besides reducing spacecraft weight to facilitate orbital insertion, the foam structure significantly decreases heat conduction. Carbon foam features high-temperature resistance, corrosion resistance, high thermal shock resistance, thermal stability, low density, high strength, easy machinability, and low thermal expansion. Its thermal conductivity, electrical conductivity, and density are adjustable during manufacturing [14]. This design reduces overall heat shield mass while ensuring strength—the 2.3-meter diameter, 10+ cm thick PSP heat shield weighs only about 160 pounds. The heat shield cross-section is shown in Figure 5 [Figure 5: see

original paper], demonstrating how this structural design ensures strength while substantially reducing mass.

[Figure 5: see original paper]

The manufacturing process for C/C composite layers is similar to epoxy resin application in tennis rackets: first applied, then gradually cured into a high-strength solid layer, as shown in Figure 6 [Figure 6: see original paper].

[Figure 6: see original paper]

2.3 Radiator

Since it does not directly face the Sun, PSP's radiator operates in an environment similar to conventional spacecraft. PSP's radiator consists of multiple panels joined together, with high-emissivity coating on the outer surface and silver-white MLI material on the inner surface, as shown in Figure 7 [Figure 7: see original paper].

[Figure 7: see original paper]

2.4 Solar Panels and Cooling System

PSP employs solar panels designed to mitigate UV degradation. The two panels have a total area of approximately 1.55 m², with each panel consisting of primary and secondary sections. The secondary section is located at the end, and both sections comprise cells of different sizes. At perihelion in the final orbit, solar irradiance near PSP reaches 70 W/cm², more than 50 times that experienced by any previous spacecraft [2], as shown in Figure 8 [Figure 8: see original paper].

[Figure 8: see original paper]

At 9.5 solar radii, the Sun cannot be treated as a point source, and the shadow region divides into umbra and penumbra zones. The umbra is completely dark, with solar rays fully blocked by the heat shield. The penumbra receives partial sunlight, as shown in Figure 9 [Figure 9: see original paper] [2].

[Figure 9: see original paper]

On a plane perpendicular to the Sun line, solar irradiance in the penumbra varies from 0 suns at the umbra boundary to 100% sun at the penumbra outer edge, where the solar flux is about 512 times that near Earth. Although solar irradiance on penumbra-area solar panels is non-uniform, cell strings parallel to the sun-facing surface receive relatively uniform irradiance. To minimize solar array temperature and temperature gradients driven by local heat flux, the panels are designed to see only 25% of the Sun at closest approach.

PSP also controls the angle between the panels and incident sunlight to further reduce heating. When sunlight strikes the panel surface perpendicularly at closest approach, the solar flux is 512 solar constants. As the angle between the panel normal and incident light increases, solar irradiance decreases. PSP uses

closed-loop control of the tilt angle between the panel normal and heat shield normal to vary the panel area exposed to solar radiation. Near perihelion, the solar array tilts inward to reduce exposed area, leaving just enough surface to generate required power. At greater distances, the panels fully deploy to maximize solar exposure [2].

At closest approach, PSP's panels generate about 13 W of waste heat for every 1 W of electricity produced. With maximum power consumption of approximately 462 W, the system must dissipate up to about 6000 W of heat. Solar panel operating temperature must not exceed 150°C, so PSP employs a cooling system in addition to tilt angle control. PSP engineers compared heat pipe cooling and single-phase pumped liquid cooling systems. The pumped liquid cooling system had a total mass of about 55 kg versus 115 kg for the heat pipe system, leading to selection of the former.

PSP's single-phase pumped liquid cooling system is shown in Figure 10 [Figure 10: see original paper] [2]. The pump unit circulates cooling water through channels in the solar panels, then through the radiator panels and back to the pump, forming a closed-loop water cooling system that transfers heat from the two solar panels to the radiator. Each panel receives 3 L/min flow, for a total flow of 6 L/min. Both panel cooling circuits are identical in size and function, using 3/8-inch diameter tubing with 0.028-inch wall thickness. Radiator tubing is 0.25-inch diameter with 0.028-inch wall thickness.

[Figure 10: see original paper]

Zero-gravity, closed-loop liquid cooling systems require a volume compensation device—the accumulator shown in the diagram. Welded from metal plates with approximately 320 cubic feet total capacity, the accumulator accommodates density changes from temperature variations and system leakage. To prevent pump cavitation, the accumulator must maintain system pressure 15 psi above water vapor pressure at the maximum fluid temperature of 160°C. The accumulator's Maximum Expected Operating Pressure (MEOP) is 325 psi, with a mass of 4 pounds and dimensions of 5 feet diameter by 11 feet height. The overall layout of PSP's solar panel pumped liquid cooling system is shown in Figure 11 [Figure 11: see original paper].

[Figure 11: see original paper]

As shown in Figure 11 [2], the cooling system uses flexible hoses, with total system mass of 54.7 kg and maximum pump input power not exceeding 43 W. The centrifugal pump, a classic product from Hamilton Sundstrand Corporation widely used in long-life flight applications, achieves about 40% efficiency at a specific speed of 500 and fluid temperature of 70°C. The pump features flow rate and volume control capabilities to reduce power consumption during non-peak temperature operation. Input power decreases as water temperature increases. At 10°C water temperature and 6 L/min flow, maximum pump input power is 43 W; at higher temperatures, input power can be less than 40 W.

Ceramic heat spreaders that are electrically insulating yet thermally conductive are welded to the back of solar cells, which are bonded to the panel substrate with thermally conductive adhesive. Heat transfers from cells through the ceramic spreader to the substrate, then to cooling water in microchannels within the substrate. Each panel contains two microchannels—one for the primary section and one for the secondary. A centrifugal pump drives cooling water circulation; after absorbing panel heat, the water flows through the radiator to dissipate heat to space. The single-phase pumped liquid cooling system serves as PSP's "heart and circulatory system," using a sealed design with pressurized deionized water as coolant. The deionized water contains no minerals that could contaminate or damage the system, with total volume of about 2.53 liters and boiling point above 125°C. After launch, Parker Solar Probe will experience an eclipse during which the cooling system becomes extremely cold, with radiator temperatures dropping to -150°C. To ensure survival, the cooling system plumbing must be dry and uncharged at launch, with deionized water stored in onboard tanks to prevent freezing. After the eclipse, the solar panels must heat the cooling system. Once plumbing and components are warmed to 20°C, fill valves open, and the spacecraft can operate safely when the tank is half full. The cooling system must maintain a minimum temperature of 10°C to prevent freezing. To meet the 7-year mission and 3-year ground storage requirements, wetted materials including tanks, tubing, and fittings primarily use CP-grade titanium alloy, 316L stainless steel, and Inconel alloy to minimize corrosion and ensure long-term reliable operation.

PSP is the first spacecraft humanity has developed to fly into the solar corona, with its thermal protection system achieving an excellent optimization balance among protection capability, volume, and mass. Studying PSP's thermal protection system helps explore suitable thermal protection methods for China's near-Sun exploration missions. This paper identifies several enlightening aspects for China's near-Sun exploration program:

- 1) PSP's heat shield dissipates heat through radiative exchange with the cold black cosmos. The ratio of solar absorptance (S) to thermal emittance (IR) of the sun-facing coating is the dominant factor determining heat shield equilibrium temperature—lower ratios yield lower equilibrium temperatures, reducing design pressure on the shield substrate. Higher spectral emittance near the wavelength of maximum thermal radiation capability yields better radiative cooling. Although PSP adjusted coating microstructure to improve solar reflectance and thermal emittance, no special design was implemented for spectral emittance near the wavelength of maximum thermal radiation, resulting in a relatively high S/IR ratio and weak radiative cooling capability, with sun-facing coating temperatures reaching 1400°C at closest approach. For a probe operating at 5 solar radii, equilibrium temperatures would far exceed alumina ceramic's melting point. Additionally, alumina ceramic coatings have high hardness and modulus, leading to low fracture toughness and damage tolerance at high temperatures, making them prone to cracking and spalling.

Current PSP sun-facing coatings cannot meet China's near-Sun probe requirements. Research should focus on reducing the S/IR ratio, improving high-temperature capability, and enhancing alumina ceramic coating toughness through doping to develop suitable sun-facing coatings.

- 2) The orbital distance from the Sun is fundamental to the entire thermal protection system design. The enormous difference in radiation flux density between 10 solar radii and 5 solar radii significantly impacts heat shield design, cooling methods, and solar panel cooling approaches. For China's near-Sun probe, beyond optimizing sun-facing coatings with lower S/IR ratios and better high-temperature resistance, specific orbital designs should be combined with new methods to further reduce temperatures of sun-facing components like the heat shield and solar panels. This includes improving heat transfer from the heat shield to the radiator and increasing solar reflectance on solar panel surfaces to reduce thermal control demands, exploring novel thermal control designs suitable for China's near-Sun exploration program.
- 3) Total spacecraft mass determines whether existing launch vehicles can deliver the probe to its designed orbit and is key to project feasibility. PSP engineers made tremendous efforts to reduce thermal protection system mass while meeting requirements. Design choices such as the ultralightweight 160-pound heat shield and the selection of the 55 kg pumped liquid cooling system over the 115 kg heat pipe cooling system significantly reduced overall mass and greatly improved project feasibility. Since China's heavy-lift rocket capabilities currently lag behind those of the United States, we must build upon PSP's thermal protection system and effectively leverage new materials and thermal control technologies developed in recent years to further explore mass reduction methods.

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