[[1]](#endnote-1)**Section D: Solar-power for deep space science missions**

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**Abstract**

Solar power systems have enabled dazzling planetary science missions to much of the Solar System. This chapter outlines the types of solar array structures that have been used on U.S.-led robotic planetary science missions since the beginning of the space age, including several in development for future launch. The first solar-powered spacecraft employed body-mounted solar cells but designs quickly moved to extended panels to generate more electrical power. Early “paddle” designs were replaced by deployable twin rectangular “wings” which are still common in science missions and nearly ubiquitous in commercial telecommunications satellites. The increasing complexity of science missions investigating the nature of the space environment drove the development of the solar-powered satellites from the very beginning, and unique mission requirements to explore ever more distant and harsher regions of our solar system continue to drive innovations in spacecraft design, including solar arrays. This general progression to ever larger solar arrays to power ever more sophisticated spacecraft in ever harsher environments, punctuated by missions that emphasize lower cost and complexity, is a pattern that began in the 1960s and continues to this day. This chapter describes the solar array configurations used on deep space missions, with an emphasis on NASA’s planetary science missions, including specific design requirements that led to individual design selections. Future trends are also described.

**1.0 Introduction**

Photovoltaics have been used to generate electrical power since the beginning of the space age, when the benefits of harnessing the sun’s energy to power spacecraft were recognized almost immediately after the invention of silicon photovoltaic cells at Bell Laboratories in 1954. In 1958 the U.S. Naval Research Laboratory’s **Vanguard I** was the first spacecraft to make use of solar power. Six solar cells mounted to the body of the satellite as shown in Figure 1a produced only a single watt of power, but demonstrated that mission life could be extended to years instead of the then-standard few days provided by batteries.

By the very next year, the **Pioneer 5** (and subsequent **Pioneer P-Series**) spacecraft produced enough power to operate six scientific instruments by deploying four 60 cm x 60 cm solar “paddles” in flight as shown in Figure 1b. These paddles were mounted on struts distributed equidistantly around the spherical spacecraft, with the solar cells on each paddle facing a different plane so that at least two would capture sunlight for any orientation of the spin-stabilized spacecraft. Pioneer 5 mapped the magnetic field between Earth and Venus, and the P-Series were intended to enter Lunar orbit but none were successful.

The **Ranger** series, beginning in 1961, was a series of missions to image the Moon in advance of the Apollo landing. Each spacecraft carried six television cameras that required a stable platform to provide clear images. Spin stabilization was therefore no longer sufficient and a gas jet attitude control system was developed to provide 3-axis stabilization. This enabled a planar configuration for the solar arrays, since the spacecraft could be continuously oriented towards the Sun for full solar illumination upon the solar cells. The Block 1 and 2 Ranger spacecraft (Ranger 1 through 5) each had a total of 2,200 solar cells mounted on trapezoidal panels that deployed after launch as shown in Figure 1c, producing 135 W to power the cameras and spacecraft. Each Block 3 spacecraft (Ranger 9 and 10) had a total of 9,792 cells on two rectangular panels with a total of 2.3 m2 surface area, producing 200 W.

In 1966 **AIMP-D** (Explorer 33) became the first US mission to approach the Moon, flying in a highly elliptical Earth orbit, coming within 40,000 km at nearest approach (perilune). Its spacecraft design was similar to that of Pioneer 5, including spin stabilization and four paddles that produced a total of 38 W. Five weeks later, **Lunar Orbiter 1** became the first US mission to enter a truly lunar orbit, with a perilune of 189 km. Within the span of two years, five Lunar Orbiters successfully mapped out 99% of the Moon with a resolution of at least 60 m. Similar to Ranger, gas jets were used to provide the three-axis stabilization needed for high resolution imaging. This in turn enabled the use of deployable, fixed-orientation solar panels, in this case four square panels that folded down in-flight as shown in Figure 1d, producing 375 W total spacecraft power.[[2]](#endnote-2) The choice to use four, rather than two, panels may have been because at 1.65 m tall, Lunar Orbiter 1 was almost half the height of the 3.1 m Ranger spacecraft, but required almost double the power. Had Lunar Orbiter used only two panels, they would likely have needed to be hinged or else extend above the spacecraft bus when stowed for launch.

In 1973 the **Mariner 10** mission to flyby Venus and Mercury employed the two-wing, gimbaled solar array design shown in Figure 1e and found in common usage today. The driving design challenge was protecting the spacecraft from the heat loads generated at 0.3 AU during the Mercury flybys, where solar irradiation is 11 times that at Earth. A large sun shade, also shown in Figure 1e, protected the spacecraft bus and instruments, but the solar arrays necessarily needed to remain exposed to the Sun. The first design considered was to rigidly swing the dual wings back towards the aft end of the spacecraft (known as a “V-tilt”) to reduce the surface area normal to the Sun and therefore minimize radiative heat loads while still generating power. However, this created an unacceptable thermal path back to the bus, so instead the decision was made to rotate the arrays about their long axis, a configuration then referred to as the “sail” configuration and now used almost universally for gimbaled arrays. For Mariner 10, this configuration also allowed the gas jets used to control roll and yaw to be mounted on the solar array tips, providing a long moment arm that reduced the amount of gas needed to effect orientation changes.[[3]](#endnote-3) Even with this conservative arrangement, an oscillation problem occurred during flight that depleted much of the compressed gas needed for control. To conserve the remaining gas, flight controllers oriented the solar panels and high-gain antenna so that solar radiation pressure could spin the spacecraft to stabilize it during cruise.[[4]](#endnote-4) While **Mariners 1 through 4** experimented with solar sailing (including a Dacron “sail” to balance solar pressure on the unequal solar panels on Mariner 1[[5]](#endnote-5) [NASA Coordinated Archive] and solar vanes on tips of Mariner 4’s solar panels[[6]](#endnote-6)), Mariner 10 was the first spacecraft to use solar wind as a major means of spacecraft orientation, and the technique enabled a second and third flyby of Mercury. Of note is that the large solar arrays used on Mariner 10 (5.1 m2 total area)[[7]](#endnote-7) extended well above the spacecraft bus when stowed.[[8]](#endnote-8) The power was used to drive six instruments, with the largest power draw of these a TV camera that consumed 67 W,[[9]](#endnote-9) and the substantially taller Centaur upper stage (as compared to the Agena used to launch the Ranger and Lunar Orbiter series) allowed for this single panel per wing configuration.

Landed spacecraft are now often powered by solar arrays, and the first was **Surveyor 1** launched in 1966. Within two years, seven Surveyor missions were launched based on the same single-panel solar array design shown in Figure 1f that provided power not only on the surface but also during the cruise phase to the Moon. The solar panel was mounted on a mast that provided four-axis rotational control as shown in Figure 6a. For launch, the solar panel was stowed vertically, and then after launch was positioned horizontal to the spacecraft deck such that the solar cells were oriented towards the Sun and along the thrust vector for the cruise period to the Moon.[[10]](#endnote-10) Upon landing near the equator at the beginning of a lunar day, the solar panel was rotated up to near vertical to point to the Sun low in the horizon, using a secondary sun sensor embedded within the solar panel to help locate the Sun. The panel tracked the Sun’s motion, lowering to horizontal at lunar Noon, and back to near-vertical facing the other horizon for sunset. At sundown the solar panel was positioned near-horizontally to minimize the solar panel output at the next dawn, allowing time for the batteries and electronics to warm up gently. In addition to providing primary power, the mast-mounted solar panel was used to shadow the lander, significantly reducing thermal loads on the television camera and other subsystems. The Surveyor solar panel had a surface area of 0.855 m2 and generated between 55 and 90 watts of power depending on the temperature on the lunar surface over the course of the day.[[11]](#endnote-11)

Finally, while not a deep space mission, the 1970 **SERT 2** satellite used solar arrays to demonstrate electric propulsion for later deep space use. Twin wings with 6 panels each to allow for compact stowage generated a total of 1,500 W to power two ion thrusters (Figure 1g). While the thrusters were gimbaled the solar arrays were not, and the spacecraft flew in a Sun-synchronous Earth orbit using gravity gradient control augmented by gyroscopes to maintain Solar-pointing at all times.[[12]](#endnote-12)

The spacecraft described so far show a progression towards increasing power requirements and towards use in new environments that place new demands and constraints on solar arrays. However, spacecraft are designed to accomplish specific mission objectives, and simpler designs are used wherever possible to reduce cost and complexity. In 1965, after the Ranger series had launched, the **Pioneer 6 through 9** spacecraft were developed to create the world’s first space-based solar weather network. Each spacecraft carried field and particle instruments needed to map out the solar wind, solar magnetic field, and cosmic rays. These instruments, like those on Pioneer 5, did not need to point at a fixed target and so spin stabilization was all that was needed. To remove the need for a power-hungry omnidirectional antenna, the Pioneer 6-9 spacecraft used an orientable spin-stabilized control system whose spin axis was oriented with a simple gas jet.[[13]](#endnote-13) This permitted the use of a cylindrical spacecraft with body-mounted solar cells on the curved surface, with an antenna mounted at one end of the cylinder.

This general progression to ever larger solar arrays to power ever more sophisticated spacecraft in ever harsher environments, punctuated by missions that emphasize lower cost and complexity, is a trend that continues to this day. While Mariner 10 ventured close to the Sun, recent missions such as Juno and Europa Clipper are expanding the use of solar power deep into the Solar System.

Tables 1 through 3 list NASA’s deep space robotic science missions (conducting primarily planetary science) grouped by fundamental solar array type: body mounted following in the path of Vanguard I and Pioneer 6; multi wing, both fixed following in the path of the Pioneer, Ranger, AIMP, and Lunar Orbiters, and gimbaled following in the path of Mariner 10; and single wing following in the path of Surveyor I. Table 4 lists rideshare missions conducting planetary science. Within each table the missions are listed in chronological order by destination. Sections 2.0, 3.0, and 4.0 summarize solar array design considerations for these missions, and Section 5.0 rideshare missions which encompass these design types. Finally, future trends in solar array configurations are discussed in Section 6.0.

The focus of this chapter is the configuration of the solar arrays, not the photovoltaic cells themselves. In almost every case, the arrays were configured using commercially available cells with the highest efficiency at the AM0 standardized sun light spectrum outside the earth atmosphere, even though that cost was higher than lower efficiency cells. This is because, in general, solar array fabrication costs are dominated by the labor needed to install the arrays rather than the cost of the cells, and the use of high efficiency cells reduces the mass and stowed volume of the arrays which has a ripple effect on the entire spacecraft mass, which almost always directly scales with spacecraft cost.

Also, all missions discussed are NASA’s and all dates refer to launch dates unless otherwise noted. All mission destinations refer to the design mission since several missions did not successfully reach their destination.

**2.0 Modern Missions Using Multiple Wings or Paddles**

**2.1 Classic Gimbaled Wings**

As shown in Figure 2, the Magellan, Deep Space 1, Clementine, and Dawn missions all use dual solar arrays gimbaled about their long axis to control their orientation with respect to the Sun, tracing this design heritage straight to Mariner 10. While the configuration may be classic, the details of designs were set by the unique mission requirements.

In 1989 **Magellan** returned to Venus, using aluminized Kapton reflectors on the solar arrays, as well as solar off-pointing, to keep the temperature below 115 °C. In addition to covering the entire back surface of the arrays, these solar reflectors also covered about 35% of the front surface[[14]](#endnote-14). Magellan also carried a synthetic aperture radar which required 200 W to operate.[[15]](#endnote-15) These requirements resulted in two panels each with an area of 6.25 m2,[[16]](#endnote-16) almost two and a half times as large as those on Mariner 10.

From the 1970s to the early 1990’s, the size of planetary science missions grew to be consistently about 1,000 kg or more. The 1994 **Clementine** mission was designed to demonstrate that missions could be accomplished with small, low cost spacecraft. The 424 kg spacecraft relied on a launch vehicle upper stage for transport to the Moon. Its twin solar arrays were the second science mission to use GaAs solar cells (following NASA’s 1992 Solar Anomaly and Magenetospheric Explorer (SAMPEX) mission[[17]](#endnote-17)). The success of the mission led to the initiation of NASA’s Discovery program two years later to continue with competed, lower cost missions.

The 1998 **Deep Space 1** solar electric propulsion technology demonstration mission built upon the legacy of **SERT 2**, and was the first to use a solar concentrator array to provide primary power in space, and the first to use two types of solar cells on a single wing (dual and triple junction). The refractive, thin film concentrators passively deployed as the wings were unfurled to provide a 7X linear solar concentration, which reduced the area of the cells and coverglass material by nominally the same amount. The two concentrator arrays produced a total 2.5 kW of power[[18]](#endnote-18) needed to drive the maximum throttle level of the ion engines (2.3 kW).[[19]](#endnote-19) In 2007 the **Dawn** mission made operational use of the solar electric propulsion system demonstrated by Deep Space 1. Its five-panel twin wings with triple junction cells were sized to generate an end-of-life power of 10.3 kW at 1 AU, enough to power the thrusters in the main asteroid belt (3 AU) to explore the asteroids Vesta and Ceres. Although it did not employ the concentrator array earlier demonstrated, the InGaP/InGaAs/Ge cells were screened for best performance at low intensity conditions. [[20]](#endnote-20)

**2.2 Fixed Wings or Paddles**

In the early 1990s, NASA established the Discovery program to reduce the time and cost needed to develop planetary science missions, using competitively-selected missions led by a principal investigator. NEAR Shoemaker was the first Discovery mission selected, followed shortly thereafter by Stardust, and Genesis. To reduce costs, each of these three missions rigidly affixed their solar arrays to the spacecraft bus instead of providing gimbaled sun-tracking. GRAIL launched nearly a decade later, but adopted a similar solar array design to enable a dual-spacecraft mission within the constrained cost cap. These spacecraft are shown in Figure 3.

The 1996 Near-Earth Asteroid Rendezvous mission **(NEAR Shoemaker)** was able to use this lower cost, simpler fixed-panel design because the trajectory used to reach its mission target of asteroid 433 Eros permitted the Sun-spacecraft-Earth angle to never reach more than about 30 degrees except for brief periods that could be covered by battery power. The solar arrays were sized to accommodate the roughly 10% loss caused by off-pointing, resulting in a total needed area of roughly 9 m2 to generate 2,000 W with GaAs cells. To further simplify the spacecraft design, this area was distributed among four rectangular panels, each of which had only to swing up and latch for deployment after launch. This robust design performed well during the rendezvous with 433 Eros; the spacecraft survived the touchdown and provided data for two weeks after landing. Although 433 Eros is considered a near-Earth object, NEAR Shoemaker rendezvoused with it while it was about 2.3 AU from Earth, making it the first spacecraft to use solar cells for primary power beyond Mars orbit as well as the first to orbit and land on an asteroid.

Launched in 2001, the Gravity Recovery and Interior Laboratory (**GRAIL**)mission studied the interior of the Moon by measuring the relative changes in the position of its two identical spacecraft as they flew over regions of differing lunar gravity. The mission was inspired by the success of NASA’s **GRACE** mission which mapped Earth’s gravity using the same twin spacecraft technique. While the GRACE spacecraft employed body mounted solar arrays on a trapezoidal bus, each GRAIL spacecraft used twin single-panel wings deployed after launch and rigidly latched open. In this case the choice of solar array design lies not in the unique demands of the mission, but rather in the reuse of existing hardware by the spacecraft bus providers to keep costs low. For GRACE, Astrium GmbH reused their CHAMP spacecraft bus and for GRAIL, Lockheed Martin reused much of their XSS-11 spacecraft developed for the U.S. Air Force, including the pair of fixed-wing single panel arrays. GRAIL’s solar arrays were sized to allow for data acquisition at solar beta angles > 49°.[[21]](#endnote-21)

The 1999 **Stardust** mission was the first to return samples from a known comet. Its capture of material from comet Wild 2’s tail took place 2.72 AU from the Sun, setting a distance record at the time for a solar powered spacecraft. Over the course of the mission the solar irradiance varied from 13% of Earth’s at its furthest distance, to 29% at the comet, and back to 100% for the return to Earth, with temperatures ranging from -61 °C to +79 °C. Rather than building a custom peak power tracking system, to save costs a hybrid direct energy transfer system coupled with a solar array switching unit was used instead, with solar cell strings sized optimally for the comet encounter, and then reconfigured in-flight to increase the voltage generated near Earth.[[22]](#endnote-22) Another unique feature of the Stardust solar arrays was the Whipple shields mounted on the ends of each array as shown in Figure X, with a central shield to protect the spacecraft bus. The spacecraft was oriented so that the cometary material impacted the shields to protect the spacecraft from high speed particle impacts, with the solar arrays oriented perpendicular to the particle flow to minimize their frontal surface area.

Although launched two years after Stardust, the 2003 **Genesis** mission to capture solar wind material lasted just under three years and so holds the distinction of the first mission to return to Earth a robotically-captured sample collected beyond the Moon. Genesis flew in a halo orbit around the Sun-Earth Lagrange point 1. The trajectory during cruise and science operations oriented the spacecraft to be sun-pointing except when executing trajectory maneuvers, allowing for a spin-stabilized fixed-wing design. The single-panel solar arrays stowed for launch in a triangular configuration similarly to **Mariner 10**.

**2.2.1 Landers**

The 1996 **Mars Pathfinder** mission delivered **Sojourner** to Mars, the first robotic rover to another planet. The Pathfinder cruise stage is described in Section 4.1 and the rover in Section 4.2; they and the lander all used solar arrays for primary power. Mars Pathfinder used an airbag landing system pioneered in 1966 by the Soviet **Luna 9** lunar lander, complete with triangular “petals” that unfurled close to the surface once the craft was settled on the surface. However unlike the Luna 9 lander, Mars Pathfinder lined the petals with solar cells to power a communications relay between Sojourner and Earth (Figure 4a).

The 1999 **Mars Polar Lander**, as its name describes, landed very close to the southern Mars pole. At that latitude the Sun stays about 30° above the horizon for continuous illumination during the summer, and the Mars Polar Lander expected to operate there for 337 days, or roughly half of a Mars year (although it actually failed during the descent stage). Two primary solar arrays and two auxiliary solar panels were configured to capture this polar light as shown in Figure 4b. The two primary arrays consisted of two panels each. The top panels were rigidly mounted to the lander structure at 30° to directly face the summer Sun. The bottom panels, folded down after landing, were positioned horizontally to prevent potential terrain clearance problems like interference with large rocks. The horizontal orientation still allowed the capture of nearly 90% of the incident radiation. The auxiliary panels, added to provide needed power while keeping the primary arrays small enough to stow within the conical backshell portion of the entry aeroshell, were also canted at 30°. The two auxiliary panels were located on the north side of the lander to capture the Sun, leaving room on the spacecraft’s southern (shadowed side) for a robotic arm. In total, the primary and auxiliary panels provided nominally 200 W. In addition to orienting the panels directly at the low-horizon Sun, the 30° tilt also reduced dust accumulation.

After the failure of the **Mars Polar Lander**, NASA initiated the Scout program to develop lower cost, PI-led missions to Mars, similar to the Discovery program. The first Scout mission was **Phoenix**, launched in 2007. Like the Mars Polar Lander, Phoenix was designed to conduct environmental science in the polar regions during the summer months. However, the Phoenix lander used a new Ultraflex solar array design that affixed solar cells onto a flexible, rather than rigid, substrate, and with a unique circular design that provided stiffness through radial spokes. This design allowed for large arrays (each 2.1 m diameter, 7 m2 total area) with reduced mass, that provided about 338 W at Mars noon[[23]](#endnote-23) using advanced triple junction photovoltaic cells[[24]](#endnote-24), substantially more than provided by the geometrically constrained Mars Polar Lander. These fixed arrays were oversized to compensate for cosine losses stemming from the mismatch between the horizontal arrays and varying Sun angle, allowing for a straightforward horizontal deployment without risk of ground clearance interference with large rocks and boulders (Figure 4c).

Launched in 2018, the **InSight** mission adopted the core UltraFlex design demonstrated on Phoenix, which by then was also in use as the primary power system for the Cygnus commercial resupply spacecraft for the International Space Station (Figure 4d). However, the UltraFlex arrays on InSight are larger, and furthermore the equatorial landing site allows for the capture of more solar radiation. This makes the InSight lander the largest solar-generated electrical power source ever landed beyond Earth. Furthermore, it has surpassed even radioisotope-powered systems in the total amount of generated electricity, reaching 4,588 W-hr in 2018 and still going strong. The design driver for the large arrays is the requirement to provide power for science operations, not just keep-alive power, during the Mars nights to provide a continuous record of seismic activity and interior structure during the course of one year. Therefore, in addition to providing primary power for the spacecraft, this solar-generated electricity must also charge a bank of batteries needed to operate the full instrument suite during the Mars night. Furthermore, the solar arrays are oversized to compensate for expected dust accumulation, with the expectation that periodic cleaning occurs via “dust devil” events that sweep the dust off.

**2.2.2 Cruisers**

Almost without exception, the cruise stages needed to deliver landed payloads to their destination have been solar powered using body mounted panels or strut-supported fixed panels. The exceptions are Surveyor 1, which used the lander itself to power the transit to the Moon, and **Dragonfly**, a nuclear powered mission to Titan. The former didn’t need a cruise stage because of the simplicity of the mission, and the latter will be traveling out beyond 9 AU from the Sun where the solar irradiance is too low yet to be practical for use with solar arrays.

For the U.S., each solar-powered cruise stage carried landed assets to Mars. In each case the cruise stage was not required to operate sophisticated, power hungry instruments or communicate high data rates during flight, and either burned up in the Mars atmosphere or suffered an uncontrolled landing, ending the need for the cruise vehicle once the payload was delivered to the surface. The design of these spacecraft is correspondingly simple. The cruise stages for **Mars Polar Lander**, **Phoenix**, and **InSight** employed twin paddles, extending just slightly beyond the diameter of the spacecraft as shown in Figures 4e, 4f, and 4g, somewhat reminiscent of **Lunar Orbiter 1**.

**2.3 Missions with Unique Solar Arrays (fixed and gimbaled)**

**Figures 5a, 5b, and 5b show spacecraft using configurations for aerobraking, tilt-back, and other unique features.**

2.3.1 Aerobraking Configurations

The solar arrays on the 1996 **Mars Global Surveyor** (MGS) were configured similarly to the two-wing spacecraft described in Section 2.1, however the mission placed three major requirements on the solar arrays that had not been encountered before which led to the unique tilt-wing design shown in Figure 5a, named the “V-tilt” when considered by **Mariner 10**. First, there were severe cost constraints under NASA’s “better, cheaper, faster” program; this manifested in the first use of two types of solar cells on a single array to provide the required power within the cost constraint: then state-of-the-art GaAs/Ge cells populated the inboard solar panels providing roughly 55% of the spacecraft power, while lower cost and lower mass Si cells were used on the outer panels providing the balance of the roughly 2,100 W at 1 AU.[[25]](#endnote-25) Second, to reduce electromagnetic noise from the spacecraft bus, MGS was the first U.S. planetary mission to mount its magnetometers at the tips of the solar arrays. This required a circuit layout designed to minimize induced magnetic moments.[[26]](#endnote-26) Finally, and most significantly, the MGS mission required a low altitude near-circular Mars orbit to produce high-resolution maps of the planet’s entire surface. Such an orbit requires a very large amount of delta-V, which would require a significant amount of propellant to achieve propulsively, which would drive up the spacecraft’s mass and cost. Instead, MGS used its solar arrays for aerobraking to achieve the desired orbit. MGS methodically lowered its orbit by making multiple passes around the planet, each time lowering its periapsis and generating aerodynamic drag forces on the extended wings. To maintain aerodynamic stability while simultaneously reducing the thermal load on the solar arrays during each pass, the solar arrays were canted back by 30°. In addition, Kapton panels added to the tips of each solar array increased the surface area of each wing, serving as drag flaps to increase frictional forces to further decelerate the spacecraft.[[27]](#endnote-27) MGS was the first mission to employ aerobraking as a critical maneuver. (While **Magellan** had demonstrated the feasibility of the technique at mission end, its solar arrays had not been designed for that technology demonstration. After **Mars Global Surveyor** and **Mars Odyssey** (to be covered in Section 3.0), aerobraking was similarly used by the **Mars Reconnaissance Orbiter** in 2007 to reduce its orbit from over 45,000 km to around 450 km for close observations of the red planet, returning to a two-wing design but without any tilt and instead using a 120° in-plane separation with the high gain antenna occupying the symmetric third position as shown in Figure 5b.[[28]](#endnote-28)

In 2013 the Mars Atmosphere and Volatile Evolution (**MAVEN)** mission employed a unique “gull wing” solar array design as shown in Figure 5c to provide atmospheric control as it traversed the upper atmosphere of Mars to study the history of Mars’ atmosphere. The outer panel of each wing is bent up at 20° to use aerodynamic forces to stabilize the spacecraft.[[29]](#endnote-29) In addition, similar to the **Mars Global Surveyor**, Maven’s magnetometers were mounted at the solar array tips to reduce electromagnetic noise from the spacecraft bus.

2.3.2 Tilt-Back Configurations

The **MESSENGER** spacecraft used a solar array design similar to **Magellan** for its 2004 mission to orbit Mercury, using reflectors and solar off-pointing, although GaAs cells and thermally conductive composite face sheets were used together with off-pointing by folding the arrays back along the spacecraft body[[30]](#endnote-30) allowed for operations at temperatures up to 150 °C and survivability up to 275 °C.[[31]](#endnote-31) In addition, a large ceramic heat shield protected the spacecraft bus.

The Parker Solar Probe, launched in 2018, was designed to operate even closer to the sun, with a closest solar approach of about 6 million kilometers of the surface of the sun, where the incident solar flux is 650 kW/m2, 475 times the solar intensity at Earth orbit. Although the main body of the spacecraft was kept behind a shadow shield to avoid heating, the solar arrays were designed to operate even at closest approach. To operate in this high-flux environment, the Parker Solar Probe uses several techniques[[32]](#endnote-32). First, like MESSENGER and earlier spacecraft, it implemented off-pointing of the main solar arrays by folding the arrays back along the spacecraft body as it approached the sun. During the period of close approach to the sun, a secondary solar array using concentrator solar cells was used. Both the main and the high-concentration solar arrays used a water cooling to transfer heat to thermal radiators, which were shielded from direct solar illumination and hence could radiate absorbed heat to space.

The **OSIRIS-ReX** mission launched in 2016 to collect a sample from asteroid Bennu and return it to Earth. To increase the ground clearance and potential dust accumulation during the touch-and-go sample collection maneuver, the arrays were swung backwards to create a “Y-wing” configuration as shown in Figure 5d (what was called a “V-tilt” on **Magellan 10, and as used on MESSENGER and Parker Solar Probe**).

2.3.3 Other Configurations

In 2001 **Juno** launched to become the first solar-powered spacecraft to explore Jupiter, reaching a full 5.5 AU from the Sun. Reminiscent of the **Pioneer** spacecraft, Juno used spin-stabilization to reduce propellant during the long mission. This led to Juno’s unique solar array configuration: the total area needed to be 60 m2 to provide the 420 W needed at Jupiter where the solar irradiance is 25 to 30 times less than at Earth and temperatures reach -130 °C, but the arrays needed to be very stiff to maintain a highly accurate spin. The symmetric three-wing design aligned with the hexagonal-shaped bus as shown in Figure 5e represented the choice that met both requirements and allowed for an unconstrained view for the science instruments.[[33]](#endnote-33) The arrays are not gimbaled to track the sun, but each individual array can be articulated by a small amount for vehicle control and stability.[[34]](#endnote-34) Two magnetometers were mounted at the tip of one of the solar arrays, placing them 10 m and 12 m, respectively from the body of the spacecraft for magnetic cleanliness, and also taking advantage of the spacecraft’s spin to separate environmental fields from those that rotate along with the spacecraft.[[35]](#endnote-35) To maintain spin balance, that solar array was shortened so that the overall length of all three wings remained the same. Triple junction cells screened for low intensity performance were used and the spacecraft stayed predominantly in a high altitude orbit to minimize radiation exposure.

**Europa Clipper**, scheduled to launch in 2024, is notable because it has the largest solar arrays that will fly beyond Earth orbit, with a total area of 102 m2 to provide 728 W of power at the end of its mission to survey Jupiter’s moon Europa. The arrays have to survive the high temperature environment of a Venus gravity assist, but the triple junction cells (all 28,120 of them) are optimized for low intensity, low temperature operation at 5.46 AU (3.4% of AM0 irradiance) and -150 °C and the extreme radiation environment at Jupiter requires oversizing the array to compensate for significant degradation over the life of the mission. Clipper will carry an ice penetrating radar, whose antenna are mounted to the solar arrays as shown in Figure 5f. The solar panels are strengthened to carry the load, the wiring is designed to provide ground and conductivity, and an eddy current damper is included within the solar array to keep induced magnetic fields low.[[36]](#endnote-36)

The **Psyche** mission to be launched in 2022 uses the cruciform solar array configuration shown in Figure 5g which is uncommon for planetary science but very common for commercial telecommunications satellites orbiting the Earth. As the commercial space industry has exploded, a new trend is for the incorporation of more commercial, instead of custom, subsystems to reduce costs. Although maybe not so new; the 1992 **Mars Observer** mission used a similar strategy as described in Section 3.1. There is also an interdependence of technologies developed for NASA missions, becoming commercialized, and returning as commercial subsytems.

The circular, flexible-substrate solar arrays used on the 2007 **Phoenix** Mars lander described in Section 2.2.1 were developed under an SBIR contract for NASA and in turn have been flying since 2013 on the commercial **Cygnus** cargo spacecraft to resupply the International Space Station under NASA’s commercial crew and cargo program. They were used with small modifications on the **InSight** Mars lander in 2018 (Section 2.2.1) and now the **Lucy** mission to be launched in 2021 will also use these UltraFlex solar arrays, albeit much larger, as shown in Figure 5h. Lucy will tour several Trojan asteroids in Jupiter’s orbit, and like the two missions to the gas giant just mentioned it also requires a large solar array area to produce 500 W at over 5 AU. Lucy’s solar arrays have a dimeter of 7.3 m, substantially larger than those used on Insight or Cygnus, and the scale-up required a substantial amount of engineering, particularly to route the large number of electrical wires through the central hub.[[37]](#endnote-37)

The Double Asteroid Redirect Mission (**DART**) to be launched in 2021 will impact one body of a binary asteroid to study a deflection technique that may be used should a future asteroid arrive on a trajectory and with a mass that could seriously harm life on Earth. This technology demonstration was designed to minimize mass, and stowed volume for potential flight as a rideshare. DART uses a roll-out solar array (Figure 5i) that employs a flexible substrate for the solar cells, substantially reducing the solar array mass and stowed volume. In addition to being the first mission to fly these novel arrays as a primary power source, several reflector-based solar concentrators will be incorporated into the array to demonstrate 2X concentration on inverted metamorphic multijunction (IMM) solar cells for significantly improved performance on future LILT missions to the outer planets.[[38]](#endnote-38)

**3.0 Missions Using Single Solar Panels**

**3.1 Deployable Single Panels**

While most spacecraft use symmetrically located solar arrays to reduce the need for navigation corrections caused by asymmetric solar pressure, several planetary science missions found that even if power loads require the use of deployable solar arrays, using a single array can substantially reduce mission costs. The cost savings can be realized simply because of the reduced number of deployment mechanisms, yokes, and gimbals, but also because the reuse of prior Earth-orbiting designs can reduce development costs (such as for **Mars Observer** and **the Lunar Reconnaissance Orbiter**), and because a single wing can serve as an effective drag shield for aerobraking, which significantly reduces mission costs by eliminating requirement propellant mass which would otherwise be used to achieve final orbit (such as for **Mars Climate Orbiter** and **Mars Odyssey**). Missions with deployable single wings are listed in Table 2 and shown in Figure 6.

The **Mars Observer** mission, launched in 1992, was the first of NASA’s missions to Mars after the Viking program concluded in the 1970’s. Cost containment was a priority, and a fixed-price contract was awarded to a telecommunications satellite provider with the expectation of maximum reuse of existing subsystems. Although most of the subsystems were off-the-shelf, the mission itself was unique. The solar array, while derived from a commercial telecom satellite, was atypically located on one side of the spacecraft to provide sufficient fields of view for radiative coolers required for the scientific instruments. The six-panel solar array shown in Figure 6a was intended to be fully deployed once in Mars orbit to map geological features, with just four panels deployed during the cruise phase to Mars.[[39]](#endnote-39) The spacecraft never entered Mars orbit, most likely because of a propulsion system failure.[[40]](#endnote-40)

The **Lunar Reconnaissance Orbiter** mission (LRO) was designed as a low-cost mission to the Moon. A single solar array as shown in Figure 6b was used to minimize the number of mechanisms and deployables. Launched in 2009, solar cell technology had advanced sufficiently so that the triple junction cells on the single array still generated almost 2 kW of power, enough to power the seven scientific instruments needed to map the Moon including a radar, spectrometer, and neutron detector.

After the failure of the solar array structure on Mars Global Surveyor, a different approach was taken for the **Mars Climate Orbiter**. As shown in Figure 6c, a single solar array was designed to do double duty as the generator of primary power and also as a drag shield during aerobraking. During cruise, the array was deployed perpendicularly from the spacecraft bus to capture solar energy. During aerobraking, the array was oriented perpendicular to the direction of travel such that its surface area is used to slow the spacecraft. During this phase, primary spacecraft power was provided by batteries. Although Mars Climate Orbiter failed to achieve its mission, the failure was not caused by the solar arrays and the follow-on mission, **Mars Odyssey**, adopted the same design for the solar power system as shown in Figure 6d. While the solar array design was the same for Mars Climate Orbiter,[[41]](#endnote-41) a more conservative aerobraking profile was adopted to allow for dust storms and wider atmospheric variations.[[42]](#endnote-42)

**3.2 Single, Fixed Panels**

The **Deep Impact** mission rendezvoused with comet Tempel 1 and released an impactor to expose materials on the comets surface. To avoid deposition of ice and debris on the solar array, the array was mounted on one side of the spacecraft as shown in Figure 6e, and the spacecraft was oriented to keep the array directly opposite the comet upon impact. After observing the ejecta, the spacecraft continued on as an extended mission to flyby a second comet, Hartley 2, and was renamed **EPOXI**.

While Earth-orbiting telescopes are not representative of typical planetary science missions, the 2009 **Kepler** mission is exploring planets that orbit stars outside of our galaxy (Figure 6f), and **NEOWISE,** theextended mission for the Wide-Field Infrared Survey Explorer (**WISE**) astrophysics mission, is studying the distribution of asteroids near Earth. Typical of other space-based telescopes, they orbit the Earth, and operate by pointing at one point in space for an extended duration, and need to point neither towards the Earth nor towards the Sun. This configuration results in one side of the spacecraft continuously pointing to the Sun, so one solar panel on that side is the most efficient design as shown in Figure 6g. These solar arrays are mounted with a gap between the array and the spacecraft to provide a thermal break so they are not technically body-mounted, but are nonetheless similar in the simplicity of the solar panel design.

**4.0 Missions Using Body-Mounted Solar Arrays**

The initial phase of U.S. solar powered solar system exploration concluded with the 1978 launches of the **Pioneer 12 and 13** to Venus. Both of these spacecraft went “back to the future” with body mounted solar cells as shown in Figure 7a. Pioneer 13 dropped four probes that descended through the dense Venusian atmosphere to the surface of Venus while Pioneer 12 served as an orbiting data relay station. Both were based on the same design to reduce cost, and the absence of protruding solar arrays enabled Pioneer 13 to descend to about 110 km altitude while acquiring atmospheric data and releasing its large and three small probes. The first mission to fly past a comet was International Comet Explorer (**ICE**), the extended mission of the heliophysics International Sun-Earth Explorer (**ISEE-3**), and employing a very similar design as Pioneer 12/13 as shown in Figure 7b.

In 1998 the **Lunar Prospector** mission carried five instruments to measure gamma rays, electrons, neutrons, alpha particles, and the magnetic field at the Moon. None of these instruments required imaging, and each needed to be mounted far from the electrically noisy spacecraft bus. The design solution to carry these instruments was to mount them on radial booms while keeping the solar panels mounted on the spacecraft surface. This also enabled the use of relatively low-cost spin stabilization attitude control since the arrays did not need to be kept pointing at the Sun. After 19 months of lunar orbit, Prospector intentionally impacted the Moon to create a dust cloud that was studied from Earth. The penetrating cone shown in Figure 7c was used to increase the penetration depth.

Selected as a Discovery mission just after **Stardust**, the 2002 Comet Nucleus Tour (**CONTOUR**) mission was designed to analyze material flowing from comets Encke, Schwassmann-Wachmann-3, and d’Arrest, taking it on a path ranging 0.75 to 1.5 AU from the Sun. Like Stardust, CONTOUR used a Whipple shield to protect the spacecraft from high velocity particle impacts, but unlike Stardust the solar panels on CONTOUR were mounted directly on the body of the spacecraft to offer additional protection (Figure 7d). As was the case for **Lunar Prospector**, this allowed for spin-stabilization during the mission’s long cruise periods, reducing both spacecraft operations and Deep Space Network tracking costs. Of note was the mission’s first use of an indirect launch mode to reduce launch costs, maintaining an elliptical Earth orbit for several weeks before injecting into the heliocentric orbit needed for its first comet encounter.

The 2009 Lunar Atmosphere and Dust Environment Explorer (**LADEE**) employed a body-mounted solar panel configuration as shown in Figure 7e for its mission to impact the Moon. Like **DART**, LADEE was originally considered as a rideshare mission and a key objective was to keep costs down. The spacecraft design was based on the Modular Common Spacecraft Bus developed by the NASA Ames Research Center to provide a nominally off-the-shelf spacecraft bus for multiple lunar missions. Thirty panels of silicon solar cells generated 295 W, and the body-mounted design simplified the spacecraft by eliminating deployment and articulation mechanisms, and spin stabilization simplified thermal design by eliminating hot and cold sides.

**4.1 Cruisers**

As described in Section 2.2.2, the design of the spacecraft used to deliver landed assets is simple. The cruise stages for **Mars Pathfinder, Mars Exploration Rover, Mars Science Laboratory,** and **Mars 2020** used body mounted solar panels mounted directly to the aft end of the transit vehicle as shown in Figures 8a-d, providing power for avionics and communications during transit in an economical design.

**4.2 Rovers**

The tiny **Sojourner** rover on **Mars Pathfinder**, the first to operate on another planet, was designed to be low cost, and its design was accordingly simple (Figure 8e). A single solar panel affixed to the entire upper surface of the vehicle accommodated over 200 GaAs/Ge cells on the 0.22 m2 panel to generate 35 W of electrical power at noon on Mars, roughly equivalent to the power generated by the AIMP lunar orbiter. While not traversing, excess electrical energy from the solar array was used to resistively heat a warm electronics box, although three radioisotope heater units provided the main source of nighttime warmth.

The solar panels on the **Spirit** and **Opportunity** rovers flown on the 2003 Mars Exploration Rover mission folded out to extend beyond the surface of the rover chassis as shown in Figure 8f and stayed in a fixed horizontal position. They provided roughly 140 W at Mars noon, supplying power to acquire imagery and spectroscopic measurements of the Mars surface. Opportunity holds the current planetary roving record of 45 km over its 14 year life.

The Mars 2020 mission delivered the tiny **Ingenuity** helicopter in addition to the nuclear-powered Perseverance rover. Ingenuity is the first aircraft to sustain controlled flight on another planet. It is powered by a single solar panel mounted on the top of its rotor as shown in Figure 8g. Because low mass is so critical to flight in the thin atmosphere at Mars, Ingenuity is the first spacecraft to be powered solely by inverted metamorphic solar cells which provide high efficiency energy conversion (32%) on a flexible, low mass substrate. In addition, the solar panel served a dual use as the reflector for a monopole omnidirectional antenna used for the helicopter to communicate with Perseverence.[[43]](#endnote-43)

The Volatiles Investigating Polar Exploration Rover (**VIPER**) is scheduled for a 2023 launch to map out water ice deposits directly from the ground in the lunar South Pole. Its solar arrays are mounted on the vertical sides of the rover to capture sunlight that rises at most 10° above the horizon (Figure 8h).[[44]](#endnote-44)

**5.0 Rideshare Missions**

The final class of planetary science missions are those that ride as secondary missions, sharing a launch vehicle with another, primary, mission. These are listed in Table 4 and shown in Figure 9. Although not technically deep space missions, four CubeSat missions studied topics of interest to planetary sciences. **GENE-SAT**, **Pharma-SAT**, and **O/OREOS** studied the effects of the space environment on organic matter to understand how life may survive elsewhere in the Solar System. **Q-PACE** was designed to study how particles adhere and fragment in zero-gravity to better understand the formation of planets and planetary ring systems. All four of these spacecraft were low-cost CubeSats employing body mounted solar panels, harkening back to the earliest spacecraft.

However, rideshares are not new and both Apollo 15 and 16 carried 35 kg lunar orbiters known as the Particles and Fields Subsatellites **(PFS-1** and **PFS-2)** to measure magnetic fields, lunar gravity variations, and proton and electron flux densities. They were manually deployed by the Apollo astronauts, and used body-mounted solar panels as shown in Figure 9e, just as CubeSats often do today.

The Lunar Crater Observation and Sensing Satellite (**LCROSS**) mission flew as a rideshare to the Moon with the LADEE mission. LCROSS’ innovative design incorporated the launch vehicle’s secondary payload adapter ring as its primary structure, with its fuel tank mounted within the ring and all of its subsystems mounted to the ring’s six ports. One of these ports was allocated for the solar panel as shown in Figure 9f. This single wing was oriented to the Sun during the cruise phase. The primary objective of LCROSS was to observe ejecta created by the impact of the launch vehicle’s upper stage into the Moon to determine the presence or absence of water ice in permanently shadowed regions.[[45]](#endnote-45)

Similarly, the twin **MarCO** spacecraft were rideshares with InSight to Mars. Each 6U CubeSat followed the same ballistic trajectory as InSight, and were used to image the Insight landing. Also like the other rideshares described in this section, MarCo was designed to maximize the use of commercially available subsystems and components. Commercially available solar panels deployed in the two-wing, single-panel per wing orientation shown in Figure 9g were used.

**LunaH-Map** will orbit the Moon after delivery there by Artemis-1 in 2021. It will use electric thrusters to enter into a highly elliptical orbit with a low periapse at the South Pole to map out concentrations of hydrogen. To power the thrusters and on-board neutron spectrometer the commercially available multi-panel solar arrays were used as shown in Figure 9h.

In contrast, **Janus** and **Lunar Trailblazer** are under development to independently arrive at their destination via a rideshare with a primary mission headed to a different location. The twin Janus spacecraft will visit asteroids 1996 FG3 and 1991 VH, respectively, after sharing a launch with the Psyche mission that will use electric propulsion to visit its eponymous asteroid. Similarly, Lunar Trailblazer will get itself to lunar orbit after sharing a launch with the IMAP mission headed to the Sun-Earth L1 point to study the Sun. Both Janus and Lunar Trailblazer will employ twin, gimbaled solar arrays, although the designs may not be fixed at the time of this writing.

**6.0 Future Trends**

The missions described above show the increasing use of solar power in regions that are ever more inhospitable to photovoltaics: in high or low temperature, high radiation, low intensity, and dusty environments with long periods of eclipse. Research into photovoltaics capable of operations in the low intensity, high temperature, caustic environment of the Venus atmosphere[[46]](#endnote-46) [[47]](#endnote-47) could enable very long duration missions to understand atmospheric and geological processes on Earth’s nearest planetary neighbor. Progress in concentrator technology such as the reflectors to be demonstrated on DART coupled with IMM cells hold the promise for efficient solar array usage out to Saturn[[48]](#endnote-48), especially when coupled with the flexible blanket arrays used on Lucy and DART. These arrays can be scaled to provide up to 150 kW at 1AU to enable the delivery of large payloads to Mars for human exploration,[[49]](#endnote-49) which should in turn should be ample for missions to Saturn and even beyond. Just as the solar arrays on OSIRIS-REx tilted out of the way of asteroid Bennu and Mars Global Surveyor’s arrays tilted back to provide aerodynamic stability, more controllability of solar arrays may be used to, for instance, fully retract an array for close approach to a surface,[[50]](#endnote-50) or increased structural dynamic control for precise interactions with planetary atmospheres, further blurring the distinction between aerodynamics and astrodynamics begun with Mars Global Surveyor and Maven.

The development of photovoltaics optimized for the solar spectrum at individual planetary bodies such as Mars or Titan could increase capabilities at those locations.[[51]](#endnote-51) Novel configurations such as vertical solar arrays or a network of tent-like panels could provide power for polar rovers and infrastructure for in-situ resource utilization. [[52]](#endnote-52) And while it seems that losses would preclude the efficient use of power beaming, it is possible that solar arrays could be mounted on surface assets stationed in permanently dark regions to receive power from orbiting lasers.[[53]](#endnote-53)

Rideshare missions also may dramatically change the way planetary science missions are conducted. As the small spacecraft industry evolves, the use of commercial-off-the-shelf components, including solar arrays, could reduce mission costs and allow for a more frequent cadence of small planetary science missions. While it seems that the most efficient solar cells will still be used to reduce overall costs, it may be that low efficiency cells with ultra-low manufacturing costs could contribute to reduced mission costs to enable very low-cost deep space rideshare missions.

**7.0 Conclusion**

Conventional wisdom once held that solar arrays are not for use far from the Sun, in high radiation environments, near the poles on planetary surfaces, for missions that span long nights or often are exposed to dust, or in a subsurface application. Except for the latter (never say never, lightpipes maybe?), these barriers have been broken down. Juno, Europa Clipper, and Lucy are solar powered missions to Jupiter, surmounting its low intensity, low temperature, and (for Juno and Clipper) high radiation environment. Mars Polar Lander and Phoenix each took a different approach to solar power at the Mars south pole, and VIPER plans to use side-mounted solar panels at the southern lunar pole. InSight is taking seismic measurements during the days and nights on Mars, and continues to operate after heavy dust storms like Opportunity did before, relying on natural dust dispersion from winds.

The achievements of these spectacular missions are grounded in the solar array designs of the past. The earliest spacecraft progressed from simple body-mounted cells, to fixed fold-out panels or paddles, ending up in little over a decade with the deployable and gimbaled multi-panel wings that are often used today. While this gimbled design is now nearly ubiquitous in commercial telecommunications satellites, unique mission requirements drive unique solutions for deep space planetary science missions. Even as we extend the use of solar arrays deeper into the Solar System, echoes of these early designs persist and all robotic US planetary science missions have employed some variant on these themes, employing unique variations as mission requirements demanded. Solar arrays became larger as their use at distances from the Sun has increased, and in a modern twist, the recent emergence of low-cost rideshare missions have roughly mirrored the progression of solar array designs on those earliest spacecraft, starting again with body-mounted cells and now emerging with gimbaled wings.

As shown by the missions described in this chapter, solar arrays have enabled the robotic exploration of the solar system and the space environment, and the reach of solar powered missions continues to increase. Advances in solar cells and array structures promise to enable missions low into the atmosphere of Venus and perhaps out to Saturn and even beyond. By harnessing the power of the Sun, missions can last a very long time as evidenced by the 14 year operation of the Opportunity rover on Mars, and NASA’s oldest surviving spacecraft, Pioneer 6, launched in 1965.

In addition to providing primary power, solar arrays have been tasked with additional spacecraft functions. Surveyor 1’s mast-mounted solar panel provided shadowing for thermal control of its lunar lander spacecraft; the Mars Exploration Rover landers supported off-ramps for the Spirit and Opportunity rovers; and Maven’s gull-wings provided aerodynamic control in the Mars atmosphere. Beginning with Mariner 3, spacecraft have been designed so the solar arrays help to balance solar radiation pressure, and Mariner 10 relied on this feature to control the spacecraft to minimize propellant usage. Solar arrays have been used as critical drag shields for aerobraking on Mars Global Surveyor and Mars Reconnaissance Orbiter, and several, beginning with Mars Global Surveyor, used their solar array structures to position magnetometers far from their electromagnetically-noisy spacecraft bus.

The future of solar-powered exploration of our Solar System has never been brighter.

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**TABLE 1: BODY-MOUNTED MISSIONS**

|  |  |  |
| --- | --- | --- |
| **Destination** | **Mission (Body Mounted)** | **Year** |
| **The Moon** |  |  |
| Lunar orbit | Lunar Prospector | 1998 |
| Lunar orbit | LADEE | 2013 |
| LEO | NRL’s Vanguard 1 | 1958 |
| Solar orbit | Pioneer 6 – 9 | 1965 - 68 |
| Venus orbiter  | Pioneer 12 | 1978 |
| Venus Multiprobe bus | Pioneer 13 | 1978 |
| Comet tour | ISEE-3/ICE | 1978 |
| NEO | Contour | 2002 |
| **Mars** |  |  |
| Mars | Mars Pathfinder: Cruiser | 1996 |
| Mars surface | Mars Pathfinder: Sojourner | 1996 |
| Mars | MER: Cruiser | 2003 |
| Mars surface | MER: Spirit/Opportunity | 2003 |
| Mars | MSL: Cruiser | 2011 |
| Mars | Mars 2020: Cruiser | 2020 |
| Mars surface | Mars 2020: Ingenuity | 2020 |

**TABLE 2: MULTI-WING MISSIONS**

|  |  |  |  |
| --- | --- | --- | --- |
| **Design Destination** | **Mission (Symmetric Deployed)** | **Configuration** | **Year \*=failed** |
| **The Moon** |  |  |  |
| Lunar orbit | Pioneer P-Series  | 4 fixed paddles | 1959\* |
| HE Earth orbit | Ranger 1-9 | 2 fixed wing | 1961-65 |
| HE Earth orbit | AIMP D (Explorer 33) | 4 fixed wing | 1966 |
| Lunar orbit | Lunar Orbiter 1-5 | 4 fixed wing | 1966-67 |
| Lunar orbit | AIMP E (Explorer 35) | 4 fixed paddles | 1967 |
| Lunar orbit | Clementine | 2 wing | 1994 |
| Lunar orbit | GRAIL A&B | 2 fixed wing | 2011 |
| Venus flyby | Pioneer 5 | 4 fixed paddles | 1960 |
| Venus flyby | Mariner 1&2 | 2 fixed wing | 1962 |
| Venus flyby | Mariner 5 | 4 fixed wing | 1967 |
| Venus/Mercury flyby | Mariner 10 | 2 wing | 1973 |
| Venus orbit | Magellan | 2 wing | 1989 |
| 433 Eros rendezvous | NEAR Shoemaker | 4 fixed wing | 1996 |
| 9969 Braille | Deep Space 1 | 2 wing | 1998 |
| Wild 2 | Stardust | 2 fixed wing | 1999 |
| Sun-Earth L1 | Genesis | 2 fixed wing | 2001 |
| Mercury orbit | MESSENGER | 2 wing | 2004 |
| NEA (Bennu) | OSIRIS-REx | 2 wing\* | 2016 |
| NEA (Didymos) | DART | 2 wing\* | 2022 p |
| **Mars** |  |  |  |
| Mars flyby | Mariner 3&4, 6&7 | 4 wing | 1964, 1969 |
| Mars orbit | Mariner 8&9 | 4 wing | 1971 |
| Mars orbit | Viking 1&2 | 4 wing | 1975 |
| Mars orbit | Mars Global Surveyor | 2 wing\* | 1996 |
| Mars surface | Mars Pathfinder: Lander | 3-fixed wing | 1996 |
| Mars | Mars Polar Lander: Cruiser | 2 fixed paddles | 1999\* |
| Mars surface | Mars Polar Lander | 2 fixed wing\* | 1999\* |
| Mars orbit | MRO | 2 wing\* | 2005 |
| Mars | Phoenix: Cruiser | 2 fixed paddles | 2007 |
| Mars surface | Phoenix: Lander | 2 fixed wing\* | 2007 |
| Mars orbit | Maven | 2 wing\* | 2013 |
| Mars | Insight: Cruiser | 2 fixed wing | 2018 |
| Mars surface | Insight: Lander\* | 2 fixed wing\* | 2018 |
| Main Asteroid Belt | Dawn | 2 wing | 2007 |
| Jupiter | Juno | 3 wing\* | 2011 |
| Jupiter system | Lucy | 2 wing\* | 2021 (est) |
| Main Asteroid Belt | Psyche | 2 wing\* | 2022 (est) |
| Europa | Europa Clipper\* | 2 wing | 2025 (est) |

\*denotes unique configuration described section 5.0.

**TABLE 3: SINGLE-PANEL MISSIONS**

|  |  |  |
| --- | --- | --- |
| **Destination** | **Mission (single panel)** | **Year** |
| **The Moon** |  |  |
| Lunar surface | Surveyor lander 1-7 | 1966, 67, 68 |
| Lunar orbit | LRO | 2009 |
| **Mars** |  |  |
| Mars orbit | Mars Observer | 1992\* |
| Mars orbit | Mars Climate Orbiter | 1998\* |
| Mars orbit | Mars Odyssey | 2001 |
| **Earth Orbit** |  |  |
| Earth orbit | Deep Impact/EPOXI | 2005 |
| Earth orbit | Kepler | 2009 |
| Earth Orbit | NEOWISE | 2009 |

**TABLE 4: RIDESHARE MISSIONS**

|  |  |  |  |
| --- | --- | --- | --- |
| **Destination** | **Mission (Rideshare)** | **Config** | **Launch Year** |
| **LEO** |  |  |  |
| LEO | GENE-SAT (CSLI?) | Body-Mount | 2006 |
| LEO | Pharma-SAT (CSLI?) | Body-Mount | 2009 |
| LEO | O/OREOS (CSLI?) | Body-Mount | 2010 |
| LEO | Q-PACE (CSLI) | Body-Mount | 2021 |
| **The Moon** |  |  |  |
| Lunar orbit | PFS 1&2 (Apollo 15&16) | Body-Mount | 1971, 1972 |
| Lunar impact | LCROSS (LADEE) | Body-Mount | 2009 |
| Lunar orbit | LunaH-Map (EM-1) | 2-wing | 2021 p |
| Lunar orbit | Lunar Trailblazer (IMAP) | 2-wing | 2025 p |
| **Near-Earth** |  |  |  |
| 1996 FG3 1991 VH | Janus A (Psyche) Janus B (Psyche) | 2-wing 2-wing | 2022 p 2022 p |
| **Mars** |  |  |  |
| Mars flyby | MarCO A&B (Insight) | 2-wing | 2018 |

**REFERENCES**

1. Geoffrey A. Landis et al., “Mars Solar Power,” NASA/TM—2004-213367, November 2004. Presented at the AIAA 2nd International Energy Conversion Engineering Conference, August 16-19, 2004, Providence, RI. [↑](#endnote-ref-1)
2. The Boeing Company, “Lunar Orbiter I: Extended-Mission Spacecraft Subsystem Performance,” NASA CR-870, September 1967. [↑](#endnote-ref-2)
3. James A. Dunne and Eric Burgess, “The Voyage of Mariner 10,” Chapter 4, NASA SP-424, 1978. [↑](#endnote-ref-3)
4. Ibid, Chapter 8 (Dunne & Burgess) [↑](#endnote-ref-4)
5. NASA, “Mariner 1,” NASA Space Science Data Coordinated Archive, Version 5.1.9, April 27, 2021. [https://nssdc.gsfc.nasa.gov/nmc/spacecraft/display.action?id=MARIN1#](https://nssdc.gsfc.nasa.gov/nmc/spacecraft/display.action?id=MARIN1) [↑](#endnote-ref-5)
6. John R. Scull, “Guidance and Control of the Mariner Planetary Spacecraft,” IFAC Symposium on “Automatic Control in the Peaceful Uses of Space,” Vol.2, Issue 1, page 11, June 21-24, 1965, Stavanger, Norway. [↑](#endnote-ref-6)
7. NASA, “Mariner 10,” NASA Space Science Data Coordinated Archive. <https://nssdc.gsfc.nasa.gov/nmc/spacecraft/display.action?id=1973-085A> Version 5.1.9, April 27, 2021. [↑](#endnote-ref-7)
8. Burgess, op. cit. Figure 4.5. [↑](#endnote-ref-8)
9. NASA Ames Research Center, “Science Instrument Survey,” NASA TM-108628, May 1973. [↑](#endnote-ref-9)
10. R.J. Parks, “Surveyor 1 Mission Report Part 1. Mission Description and Performance,” Technical Report No. 32-1023, page 39, August 31, 1966. [↑](#endnote-ref-10)
11. Ibid, page 23. (Parks 1966) [↑](#endnote-ref-11)
12. Richard G. Goldman, Guy S. Gurski, and William H. Hawersaat, “Description of the SERT II Spacecraft and Mission,” NASA Technical Memorandum TM X-52862, 1970. [↑](#endnote-ref-12)
13. William R. Corliss, “The Interplanetary Pioneers,” NASA SP-279, 1972. [↑](#endnote-ref-13)
14. NASA JPL, “Magellan Mission to Venus: Chapter 4: The Magellan Spacecraft,” <https://www2.jpl.nasa.gov/magellan/guide4.html>, Accessed September 19,2021. [↑](#endnote-ref-14)
15. Ibid, Chapter 5. (Young 1990) [↑](#endnote-ref-15)
16. Carolynn Young, “The Magellan Venus Explorer’s Guide,” Chapter 4, JPL Publication 90-24, August 1990. https://www2.jpl.nasa.gov/magellan/guide [↑](#endnote-ref-16)
17. R. Dobson, et al., “GaAs/Ge solar panels for the SAMPEX program,” AIAA Aerospace Design Conference, Irvine CA, Feb 3, 1992. AIAA-92-1063. [↑](#endnote-ref-17)
18. David M. Murphy, “The Scarlet Solar Array: Technology Validation and Flight Results,” <https://www.yumpu.com/en/document/view/35962023/the-scarlet-solar-array-pds-small-bodies-node> Accessed May 2, 2021. [↑](#endnote-ref-18)
19. “Deep Space 1 Ion Propulsion System Operation Sequence and Status,” <https://www.nasa.gov/centers/glenn/about/history/ds1opseq.html> Page updated May 21, 2008. Accessed May 2, 2021. [↑](#endnote-ref-19)
20. Navid S. Fatemi et al., “Performance of High-Efficiency Advanced Triple-Junction Solar Panels for the LILT Mission Dawn,” IEEE Photovoltaic Specialists Conference, February 2005. [↑](#endnote-ref-20)
21. Maria T. Zuber, C.T. Russell., “GRAIL: Mapping the Moon’s Interior,” Space Science Reviews, Vol. 178, Issue 1, 2013. [↑](#endnote-ref-21)
22. Steve Gasner et al., “The Stardust Solar Array,” Proceedings of the 3rd World Conference on Photovoltaic Energy Conversion, 2003. [↑](#endnote-ref-22)
23. Alliant Techsystems, “ATK Ultraflex Solar Arrays Deploy and Provide Critical Power to the Mars Phoenix Lander,” SpaceRef, May 26, 2008. <http://www.spaceref.com/news/viewpr.html?pid=25506> Accessed May 2, 2021. [↑](#endnote-ref-23)
24. Paul. M. Stella et al., “Multijunction Solar Cell Technology for Mars Surface Applications,” IEEE Photovoltaics Specialists Conference, June 2006. [↑](#endnote-ref-24)
25. Paul M. Stella et al., “Mars Global Surveyor (MGS) High Temperature Survival Solar Array,” 25th Photovoltaic Specialists Conference, p. 283, May 13-17, 1996, Washington, D.C. [↑](#endnote-ref-25)
26. Stella 1996 op. cit., p. 286. [↑](#endnote-ref-26)
27. NASA, “Mars Global Surveyor: An Explanation of How Aerobraking Works,” <https://mars.nasa.gov/mgs/confrm/aerobexp.html> Accessed May 2, 2021. [↑](#endnote-ref-27)
28. NASA, Mars Reconnaissance Orbiter: Electrical Power,” <https://mars.nasa.gov/mro/mission/spacecraft/parts/electricalpower> Accessed May 2, 2021. [↑](#endnote-ref-28)
29. NASA, “MAVEN Press Kit,” November, 2013. <https://mars.nasa.gov/files/resources/MAVEN_PressKit_Final.pdf>

Accessed May 2, 2021. [↑](#endnote-ref-29)
30. G. Dakermanji, J. Jenkins, and C.J. Ercol, “The MESSENGER Spacecraft Solar Array Design and Early Mission Performance,” IEEE 4th World Conference on Photovoltaic Energy, Waikoloa, HI, May 7-12, 2006. [↑](#endnote-ref-30)
31. C. Jack Ercol, George Dakermanji, and Bihn Le, “The MESSENGER Spacecraft Power Subsystem Thermal Design and Early Mission Performance,” p. 6, AIAA 2006-4144, 4th International Energy Conversion Engineering Conference and Exhibit (IECEC), June 26-29, 2006, San Diego, CA. [↑](#endnote-ref-31)
32. Geoffrey A. Landis, et al., “Power System Design for the Solar Probe+ Mission,” paper AIAA-2008-5712, 6th AIAA International Energy Conversion Engineering Conference, Cleveland OH, July 28-30, 2008. [↑](#endnote-ref-32)
33. NASA, NASA, “Juno’s Solar Cells Ready to Light Up Jupiter Mission,” July 15, 2011. <https://www.nasa.gov/mission_pages/juno/launch/Juno_solarpower.html> Updated August 7, 2017. Accessed May 2, 2021. [↑](#endnote-ref-33)
34. NASA, “Juno Spacecraft Information,” <https://spaceflight101.com/juno/spacecraft-information> Accessed May 2, 2021. [↑](#endnote-ref-34)
35. J.E.P. Connerney et al., “The Juno Magnetic Field Investigation,” p. 56, Space Science Review, Vol. 213 pp. 39-138. February 14, 2017. [↑](#endnote-ref-35)
36. Martin Kroon et al., “Solar Arrays for Jupiter Missions Europa Clipper and Juice,” Space Power Workshop, April 2, 2019 [↑](#endnote-ref-36)
37. Stephen Clark, “Scientists optimistic planetary probes won’t face coronavirus launch delays,” Spaceflight Now, April 29, 2020. <https://spaceflightnow.com/2020/04/29/scientists-optimistic-planetary-probes-wont-face-coronavirus-related-launch-delays> Accessed May 2, 2021. [↑](#endnote-ref-37)
38. E. Gaddy, “Transformational Solar Array Final Report,” NASA Contractor Report, April 26, 2017. <https://ntrs.nasa.gov/api/citations/20170010684/downloads/20170010684.pdf> Accessed May 2, 2021. [↑](#endnote-ref-38)
39. RCA Astro-Electronics, “Mars Observer: Phase 0 Safety Review Data Package TG-27886,” NASA Contractor Report CR-180526, November 17, 1986. [↑](#endnote-ref-39)
40. Mars Observer Mission Failure Investigation Board, “Mars Observer Mission Failure Board Report: Volume 1,” Dec. 31, 1993. [↑](#endnote-ref-40)
41. Mark A. Johnson, William H. Willcockson, “Mars Odyssey Aerobraking: The First Step Towards Autonomous Aerobraking Operations,” IEEEAC paper #1169, Vol. 8-3503, January 10, 2003. [↑](#endnote-ref-41)
42. John C. Smith and Julia L. Bell, “2001 Mars Odyssey Aerobraking,” AIAA 2002-4532, AIAA/AAS Astrodynamics Specialist Conference, August 5-8, 2002, Monterey, CA. [↑](#endnote-ref-42)
43. James L. Green, “Talking to Ingenuity and Other Space Robots, with Nacer Chahat,” Gravity Assist Podcast, Season 5, Episode 2, April 23, 2021. [↑](#endnote-ref-43)
44. NASA, “VIPER’s Mission Operations,” <https://www.nasa.gov/viper/lunar-operations> Updated Feb 9, 2021. Accessed May 2, 2021. [↑](#endnote-ref-44)
45. Kimberly Ennico et al., “The Lunar Crater Observation and Sensing Satellite (LCROSS) Payload Development and Performance in Flight,” Space Sci Rev (2012) 167:23-69. February 19, 2011. [↑](#endnote-ref-45)
46. Jonathan Grandidier et al., "Low-Intensity High-Temperature (LIHT) Solar Cells for Venus Atmosphere," IEEE Journal of Photovoltaics, vol. 8, pp. 1621-1626, 2018. [↑](#endnote-ref-46)
47. Geoffrey A. Landis and Emily Haag, “Analysis of Solar Cell Efficiency for Venus Atmosphere and Surface Missions” paper AIAA-2013-4028, AIAA 11th International Energy Conversion Engineering Conference, San Jose CA, July 15-17 2013.. [↑](#endnote-ref-47)
48. Andreea Boca et al., “A Data-Driven Evaluation of the Viability of Solar Arrays at Saturn,” IEEE Journal of Photovoltaics, vol. 7, no. 4, pp. 1159-1164, July 2017. [↑](#endnote-ref-48)
49. Carolyn R. Mercer et al., “Solar Electric Propulsion Concepts for Human Space Exploration,” NASA TM-2016-218921, AIAA-2015-4521, AIAA Space 2015 Conference, Pasadena CA, August 31-September 2, 2015. [↑](#endnote-ref-49)
50. James Moore, “Simple Reliable Retractable Lunar Lander Solar Array,” NASA SBIR Contract 80NSSC19C0621, 2019. [↑](#endnote-ref-50)
51. Rao Surampudi et al., “Solar Power Technologies for Future Planetary Science Missions,” JPL D-101316, December 2017. [↑](#endnote-ref-51)
52. Geoffrey A. Landis et al., “Mars Solar Power,” NASA/TM—2004-213367, November 2004. Presented at the AIAA 2nd International Energy Conversion Engineering Conference, August 16-19, 2004, Providence, RI. [↑](#endnote-ref-52)
53. Jonathan Grandidier et al., “Laser Power Beaming for Lunar Night and Permanently Shadowed Regions,” Whitepaper #302 submitted to the Planetary Science and Astrobiology Decadal Survey 2023-2032. Published by the Bulletin of the AAS, March 18, 2021. [↑](#endnote-ref-53)