

ELECTRIC PROPULSION OF **SPACECRAFT**



NASA/GRC

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The electrification of spacecraft could significantly extend the useful life of billion-dollar missions in outer space.

The worldwide effort to decarbonize energy systems has set the stage for an era of electrically driven mobility. Cars, buses, heavy trucks, and trains are increasingly switching to electrical propulsion. Drones are already in the air and plans are underway for electric flying taxis to revolutionize personal and on-demand transportation systems.¹ Denmark and Sweden are preparing to replace their domestic fleet of airplanes with fossil-fuel-free versions by 2030, when all-electric 186-seat passenger airplanes will enter into service. Before then, smaller, 100-seat Wright Spirit electric airplanes² are due out in 2026.

Electrical pump-feed rocket engines have also made their way into launch systems. Indeed, five years ago Rocket Lab used that technology to deliver to orbit a commercial payload of several satellites. Many small satellites already use electric propulsion thrusters in space, with SpaceX's Starlink constellation being the most prominent example. (See references 3 and 4 to learn more about thruster designs and applications on various types of spacecraft.)

Yet many more space assets—from small probes and satellites to large spacecraft—continue to rely on conventional chemical-based propulsion. For now, the electrification of in-space mobility systems lags behind that of Earth systems. But that may soon change.

Longer life means better value

Many electric propulsion systems intended for outer space have already been proved ef-

ficient and reliable.⁵ If implemented on future missions, those systems could extend the life of prominent, billion-dollar space programs. Examples abound of programs currently limited by chemical-propulsion capabilities. Launched in 2009 with only 12 kg of chemical fuel, the *Kepler* space telescope, illustrated in figure 1, had to stop its search for exoplanets after nine years in deep space because it no longer had hydrazine propellant. (The mission was renamed *K2* in 2014 after NASA had to stabilize the spacecraft's pointing.) *Kepler's* thrusters used that fuel to correct its drift and maintain the telescope's orientation toward a specific target and its data transmission to Earth.⁶ All other systems, including *Kepler's* solar-cell-based power, still operated normally.

Like the *Kepler* mission, the *Dawn* mission was forced to end when it depleted the chemical propellant used to orient its solar panels toward the Sun and its communication

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instruments toward Earth.⁷ *Dawn* (illustrated in figure 2) was launched in 2007 and cost nearly a half billion US dollars. It was NASA's first science mission to use solar-electric-powered ion thrusters (see box 1) and reach two of the largest objects in the asteroid belt—the dwarf planet Ceres and the proto-planet Vesta—to collect priceless data on the formation of our solar system.⁸

Dawn would have had to burn more than 6000 kg of on-board chemical propellant to reach and orbit those asteroids. Fortunately, it accomplished both by sending only 400 kg of xenon propellant through the electric thrusters. That design decision significantly reduced the size of the launch vehicle and the cost of the mission. Had the *Kepler* and *Dawn* missions been configured with an all-electric-propulsion system—either a modern ion or Hall thruster system, for instance—it's likely that both would still be able to continue their cutting-edge research into the next decade.

Although 10 years may seem like a long time for a spacecraft to operate, their financial costs typically are on the scale of billions of dollars. And their development spans many years; in fact, it often takes decades to design and build them. One of the most famous space-based systems, the *Hubble Space Telescope*, has been subject to five manned servicing missions since its launch in 1990. The last of those missions extended its life past 2020. But sending a service mission to refuel the *Kepler* space telescope is technologically out of the question—at least for now. As it follows an Earth-trailing trajectory, *Kepler* will reach the other side of the Sun by 2035, putting it effectively out of reach. For missions like *Kepler*, using more efficient electric thrusters would have been the most logical way to extend their lifetimes.

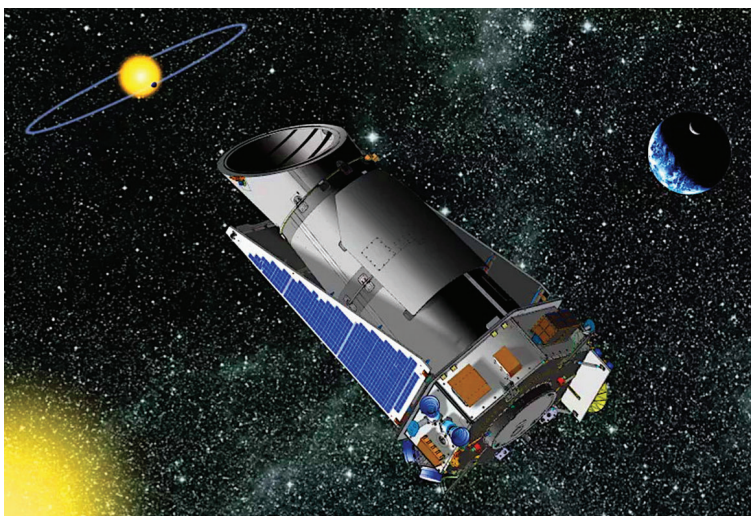


FIGURE 1. THE KEPLER SPACE TELESCOPE, shown here, ceased its operation in 2018 because it had run out of hydrazine propellant. As a result, *Kepler* could no longer point with the accuracy needed to continue its original mission. Electric propulsion systems would have avoided that problem. They consume much less propellant per unit thrust and produce much higher specific impulse. (Courtesy of NASA.)

Even for *Hubble*, its remaining hydrazine fuel is only sufficient to maintain target alignment for a few more years. Its hydrazine thrusters are also not powerful enough to raise *Hubble* from its orbit of 568 km, and the telescope could potentially spiral back to Earth by 2028. Importantly, *Hubble* uses reaction wheels and magnetic torquers—devices that interact with Earth's magnetic field but do not require any fuel—for orientation control. Even so, the devices are efficient only at low orbits, where the magnetic field is relatively strong. An efficient



FIGURE 2. DAWN was NASA's first deep-space mission that used electric propulsion to reach and orbit two bodies in the asteroid belt—Vesta and Ceres. The spacecraft's gridded ion thrusters used 400 kg of xenon to accomplish the mission. Chemical thrusters would have required more than 6 tons of additional fuel. (Courtesy of NASA.)

electric propulsion system capable of raising the orbit could have kept it active for several more years, perhaps long enough for the next generation of manned space systems to become available for another service mission.

Improved stability and control

Beyond the low fuel efficiency and other challenges intrinsic to chemical-based space thrusters, many proposed future missions cannot be realized using traditional, thermodynamics-based thrust systems.⁹ Colonizing Mars and establishing other distant outposts require fast and reliable transportation of large manned and cargo spacecraft over millions of kilometers. As with *Dawn*, using electric propulsion for those missions can potentially reduce the amount of propellant that has to be launched into space by nearly an order of magnitude.

On the other end of the spectrum in mission size is an emerging industry of ultrasmall spacecraft known as CubeSats. A few kilograms in size, they fly in formation or as constellations that require equally small thruster systems. Those systems must not only be efficient but also deliver thrust with unprecedented precision. That's also critical for space-based

observatories sensitive enough to capture faint signals, such as ripples in spacetime, and provide data to help solve other curiosities of the universe, including how the quantum vacuum works and the mysteries of repulsive gravity and negative energy.

China's Taiji mission and the European Space Agency's LISA (Laser Interferometer Space Antenna) mission are examples of formation-flying, network-based space observatories. To a large extent, their success will depend on the ability of individual satellite probes to maintain their position and orientation with respect to the source of a target signal and to each other while millions of kilometers apart.¹⁰

Both missions' satellites have drag-free control with ultrahigh precision and ultrastable operation that cannot be achieved by hydrazine thrusters. Other types of conventional thrusters, such as cold-gas systems, do not have the level of specific impulse and control needed to sustain for years the propulsion requirements of those systems. Not surprisingly, the recently launched *Taiji-1* powered by ultrasmall, high-precision electric thrusters, and *LISA Pathfinder*, shown in figure 3, demonstrated precision attitude control using an

Box 1. Electric propulsion thrusters for space missions

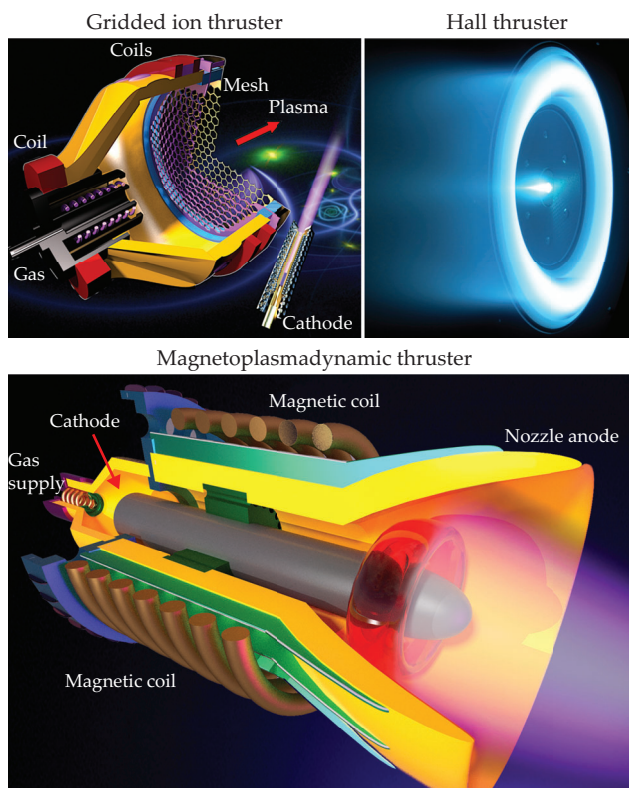
Space electric propulsion systems can be broadly classified as electrothermal, electrostatic, and electromagnetic. Each type of thruster fills an important niche, as the entire spectrum of electric propulsion technology spans five orders of magnitude in power and about two orders of magnitude in specific impulse—the exhaust velocity of the propellant.¹⁷

Electrothermal thrusters are the simplest system, using thermodynamic principles of gas acceleration in nozzles. As a result, they feature a relatively low specific impulse, though it is usually higher than that of corresponding chemical systems. Among electrostatic thrusters, two types are considered mature, space-proven technologies: the gridded ion thruster (top left, adapted from I. Levchenko et al., *Nat. Commun.* **9**, 879, 2018) and the Hall thruster (top right, courtesy of NASA). In the gridded ion thruster, propellant gas is ionized in a magnetized chamber and the ions are accelerated by two or more high-voltage (mesh) grids that provide thrust. A cathode mounted outside the thruster provides electrons to neutralize the ion beam and avoid charging the spacecraft.

In the Hall thruster—named after US physicist Edwin Hall—the propellant ionized in the annular channel is accelerated by crossed electric and magnetic fields to produce thrust. As in the case of the gridded ion thruster, a cathode is needed to ionize the propellant gas and to neutralize the ion beam. The cathode could be installed outside the chamber or in the center of the thruster. The Hall thruster includes several magnetic coils and an integrated magnetic circuit (neither of which are shown) to ensure that the magnetic field is properly oriented in the acceleration chamber.

In electromagnetic thrusters, the propellant is accelerated in the form of quasi-neutral plasma. That method stands in contrast to electrostatic thrusters, which accelerate ions or electrically charged particles. As a result, electromagnetic thrusters, unlike gridded ion thrusters, are not limited by electric space charge. Several types of electromagnetic thrusters are currently

under consideration. They include pulsed thrusters, magnetoplasmadynamic (MPD) thrusters, and helicon thrusters. Importantly, MPD thrusters, such as the one shown in the bottom image (adapted from I. Levchenko et al., *Phys. Plasmas* **27**, 020601, 2020), promise to generate high thrust at high power—up to 10^5 W—and hence could be considered for cargo and personal transportation missions to Mars.



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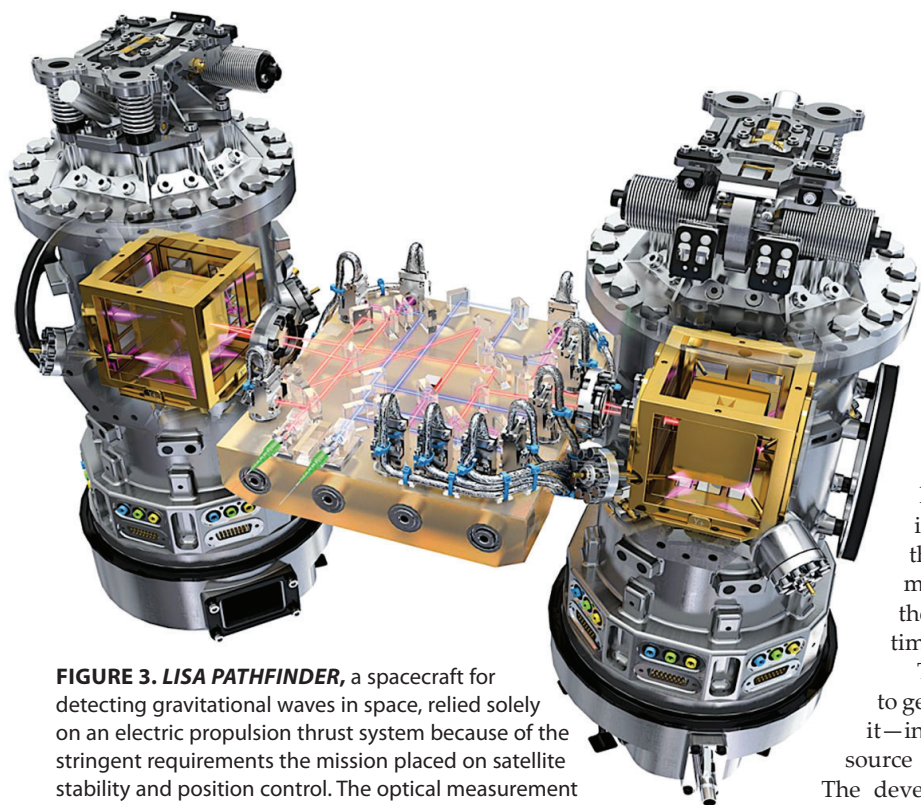


FIGURE 3. LISA PATHFINDER, a spacecraft for detecting gravitational waves in space, relied solely on an electric propulsion thrust system because of the stringent requirements the mission placed on satellite stability and position control. The optical measurement system comprises two gold/platinum test masses (gold cubes), each enclosed within an electrode housing in compact vacuum chambers. The optical bench of the laser interferometer is arranged between the test masses. (Image courtesy of the European Space Agency/Medialab.)

electric propulsion colloid-thruster system.¹¹ *LISA Pathfinder* was launched in 2015 and operated until 2017.

The unique demands of those new ambitious missions—and a significant increase in the population of small satellites during the past decade (see figure 4)—may provide the impetus necessary to drive wider electrification across all sizes of space-thrust platforms.

Barriers to adoption

The path to higher-efficiency, lower-cost missions is not without its challenges. Electric thrusters were first used roughly 60 years ago, but their use was limited until about 20 years ago by the lack of sufficient electrical power on spacecraft. Since that time, improvements in the efficiency and size of solar arrays have increased the power available on both communications satellites and deep-space spacecraft to more than 20 kW. NASA's next solar-electric mission, the Gateway space station, will include the Power and Propulsion Element (PPE), which will likely have a 60 kW solar array to power the transport of cargo to the Moon and ultimately to Mars. Ion and Hall thrusters now routinely run at power levels of 1.5–5 kW and are in development to run at 12.5 kW for the PPE and up to 20 kW for prototypes at NASA's Glenn Research Center, so power and thruster technology finally exists that can take advantage of electric power available in space.

Another issue is thruster lifetime and energy storage. The satellite communications industry has embraced electric

thrusters for on-orbit station-keeping of geostationary communications satellites because they reduce the amount of propellant needed by a factor of 5 to 10 to provide the required 15-year satellite life. But the application can handle only about an hour of thrusting per day.

Providing 5 kW of power, modern lithium-ion batteries have plenty of capacity to run electric thrusters in most station-keeping applications. One major benefit of the batteries is that they allow the thrusters to make the orbital adjustments required to insert a satellite into its assigned orbit. That orbit-raising function requires operating a thruster for hundreds to thousands of hours at a time. No other battery technology is currently available—or even foreseen—that can provide such energy. Likewise, for most propulsion applications in deep space, the thrusters must run for weeks to years at a time, with lifetimes in the tens of kilohours.

Thus all-electric spacecraft will need either to generate electric power on-board or to receive it—in a form known as beamed energy—from a source that may be millions of kilometers away.¹²

The development of compact, light, and efficient sources of electric energy on a spacecraft is far from trivial. Similarly, beaming energy across vast distances requires exceptional pointing precision to minimize losses and on-board infrastructure to convert an incoming beam of light into electrical energy.

Solar cells that use novel materials and advanced architectures currently represent the best and most widely used means of on-board energy generation. Even at their maximum output, however, conventional solar panels are unlikely to supply enough energy to meet all the energy needs of future satellites throughout the solar system. Simply increasing the size of the panels will increase a satellite's mass, can render it more cumbersome to maneuver, and may restrict the field of view for on-board instrumentation.

Despite plans to construct large solar arrays capable of delivering hundreds of kilowatts of power near Earth for cargo and manned missions, exploring deep space and remote planets using solar panels is infeasible. The reduction in available light to power the spacecraft becomes simply too significant as it moves away from the Sun. (See examples of Sun-powered electric-propulsion-driven deep-space missions in box 2.) Thus missions to deep space and remote planets would require sources of electric power other than solar cells.

The most obvious alternative source of power for deep-space missions is nuclear systems. Yet scaling down fission reactors to a realistic size and mass while maintaining low specific power—the electrical output power divided by the mass of the power system—has been difficult and expensive to achieve. Flying nuclear reactors seem unlikely anytime soon unless substantial investments are made to mature the technology for space applications and change public perception about its safety. The NASA SP-100 (space-reactor prototype) program was supposed to design a fission reactor to become a standard

deep-space power system, but it was canceled partly because of its high cost.

Other concepts based on thermonuclear fusion systems may provide solutions for high power in deep space and reduce the travel time of missions by nearly half. But developing them assumes that fusion technology can be perfected on the ground and transferred into space in a reasonable time and cost. One of the main motivations for research into nuclear power for space propulsion is the considerable energy-density gain that can be realized with nuclear fuel in place of conventional chemical combustion.¹³

Advanced propulsion systems using high-power solar arrays, beamed energy, or nuclear fusion could help to achieve NASA's plans for a manned Mars mission. The reduced travel times would effectively cut the harmful effects of space travel, such as radiation and weightlessness, on the crew. What's more, the ability of a nuclear engine to supply both power and propulsion makes it suitable for a broad range of space missions—robotic and manned.¹⁴

Apart from those energy issues, the high price of commonly used xenon propellant—currently more than \$2000 per kg—is also a problem. Not surprisingly, SpaceX's Starlink network uses krypton, which is not as efficient as xenon and requires much larger tanks to store the same mass, but it is much cheaper. Another approach is to use sublimating solid propellants such as iodine, which is predicted to make the whole system simpler and less expensive. Two of us (Levchenko and Bazaka) recently reported on the first demonstration in space of an iodine thruster designed by a team led by Trevor Lafleur and Dmytro Rafalskyi (see "For an efficient electric propulsion system, use iodine," PHYSICS TODAY online, 2 December

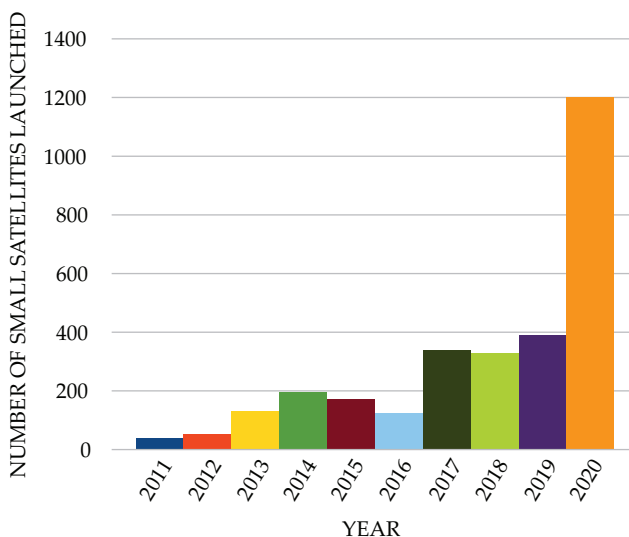


FIGURE 4. THE NUMBER of small satellites launched worldwide each year grew dramatically between 2011 and 2020. (Data are from E. B. Salas, "Number of small satellites launched worldwide 2011–2020," Statista, 2021.)

2021),¹⁵ and we expect further efforts to implement the solid propellant. The Massachusetts-based Busek company already sells iodine-propellant thrusters.

Another challenge for the wider adoption of electric propulsion platforms in deep-space missions is the obvious requirement for safety and reliability. That requirement sometimes warrants opting for simpler, well-proven systems at the expense

Box 2. Electric thrusters in deep space

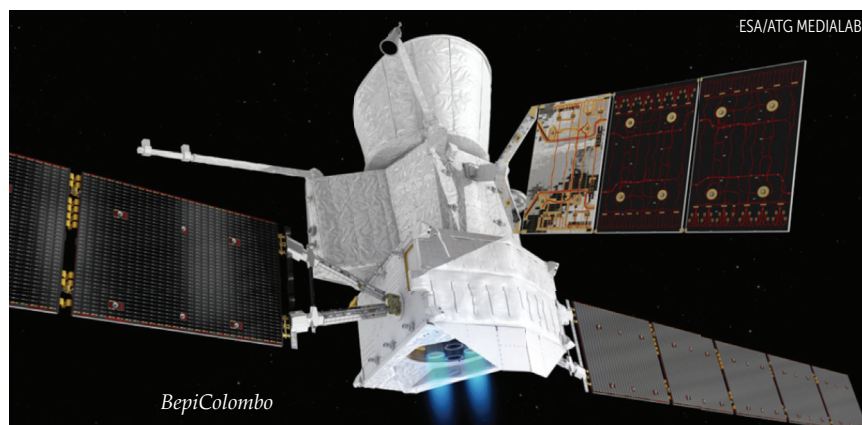
Like multiple-satellite systems, such as Starlink and OneWeb, which operate at low-Earth orbits, several deep-space missions are also using electric propulsion thrusters. One of them, the *Psyche* mission, is NASA's next deep-space science probe, designed to investigate a unique metal-rich asteroid about 200 km in diameter. The spacecraft is equipped with huge solar panels, each one 75 m² in area, that are capable of powering Hall thrusters 500 million km from the Sun. Scheduled for launch in the next two years, the mission will cruise through outer space for three to five years before looking deep into the history of terrestrial planets.

BepiColombo is a joint international mission between the European Space Agency (ESA) and the Japan Aerospace Exploration Agency (JAXA) that was launched in 2018. It is currently performing flybys of Mercury, which it will orbit starting in 2025 and begin a complex investigation using two orbiters, one built by ESA and the other by JAXA.

The interplanetary trip is supported by four gridded ion thrusters, each capable of consuming up to 4.5 kW of electric power supplied from two 14 m solar panels.

The Power and Propulsion Element is another example of a solar-powered electric propulsion system. With a total mass of 8 tons and 60 kW of electric power, it is scheduled to be launched in 2024 and will

operate as part of Gateway, a future international space station orbiting the Moon. The spacecraft's solar arrays will supply electric power to station equipment, and its Hall thrusters will deliver the system to lunar orbit and are capable of changing the station's orbit around the Moon. Testing near the Moon will determine whether similar systems could be used to explore Mars.



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of their efficiency and cost. Moreover, all deep-space missions go through years of design work. During that process, many trade-offs are made between various systems, including electric and chemical propulsion. To cite one example, for the *New Horizons* mission—the first probe to Pluto—scientists selected chemical systems for its onboard propulsion.

Where to from here?

Electric propulsion thrusters offer several exciting opportunities that have not been sufficiently embraced by current R&D communities. More work is needed in the following areas:

- Higher thrust efficiency produced by higher-power, long-lived electric thrusters to support planned manned expeditions and cargo missions to Mars and possibly other celestial objects.¹⁶ That goal requires developing the next generation of high-power ion and Hall thrusters and alternative electric thruster technologies, such as magnetoplasmadynamic thrusters, to provide the desired combination of high power, high specific impulse, low mass, and small size.

- Ultrahigh precision in controlling the thrust with ultralow noise for highly sensitive space astronomical observatories and for fine satellite control within formation-flying constellations.

- Ultracompact electric thrusters for controlling small satellites—particularly those with masses less than 10 kg—to make them capable of active maneuvering, formation flying, and orbit change.

- Alternative power sources in space beyond solar power, such as nuclear or beamed-power systems coupled to high-power electric propulsion systems.

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