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Electric Propulsion for JPL Missions

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Since the success of the DS1 mission, electric propulsion (EP) has moved from the laboratory to application on many present and proposed JPL missions. For JPL spacecraft, EP has three major uses. The first, as successfully demonstrated on DS1, is prime on-board propulsion that provides the ΔV required to allow relatively small spacecraft accomplish challenging deep space explorations to distant bodies. The second major use is to provide the low thrust for precision formation flying required by long-baseline interferometry spacecraft. The third application is for large, high power spacecraft potentially powered by nuclear reactors or hundreds of kilowatt solar arrays. These spacecraft could be used for major explorations of outer planets and their moons, or ferrying cargo to support manned exploration of the moon or Mars. The EP technologies for near term missions range from micro-Newton colloid thrusters on the ST-7 formation flying spacecraft to ten's of kilowatt thrusters for the potential high power missions, and their associated subsystems including propellant tanks, flow controllers, gimbals, and digital controllers. The next JPL spacecraft with electric propulsion, Dawn, has three NSTAR thrusters for prime propulsion and is being prepared for launch next year. The other EP flight project presently ongoing at JPL is ST-7, which will demonstrate colloid thrusters for precision formation flying. Focused technology is being developed in support of potential near-term missions including studies of thruster plume interactions with science payloads, electric thruster life validation by test and analysis, and technologies to extend thruster life. Other activities include EP technology development for future missions, ranging from miniature ion thrusters (MIXI) for formation flying to very high Isp, ion thrusters (NEXIS and Herakles), 2-stage Hall thrusters (VHITAL), lithium-fed Lorentz force accelerator (ALFA^2) and Nuclear-Electric Pulsed Inductive Thruster (NuPIT) for future high-power exploration missions.

I. Introduction

SINCE the success of the DS1 mission,[1] electric propulsion (EP) has moved from the laboratory to application on many present and proposed JPL missions. For JPL spacecraft, EP has three major uses. The first, as successfully demonstrated on DS1, is prime on-board propulsion that provides the delta-v required to allow relatively small spacecraft accomplish challenging deep space explorations to distant bodies. The second major use is to provide the low thrust for precision formation flying required by long-baseline interferometry spacecraft. The third application is for large, high power spacecraft potentially powered by nuclear reactors or hundreds of kilowatt solar arrays. These spacecraft could be used for major explorations of outer planets and their moons, or ferrying cargo to support manned exploration of the moon or Mars. In this paper we briefly describe each of these mission areas and identify some of the activities underway to support them. References are given to other papers in this conference that describe the activities in much greater technical detail.

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II. Dawn and Potential Other Discovery Missions

The Discovery Program is designed to accomplish frequent, high-quality planetary science investigations, using innovative and efficient management approaches. The Program’s prime objective is to enhance our understanding of the solar system as it is today and of solar system formation and history. In the process, it seeks to contain total mission cost and development time, and improve performance through the use of validated new technology and through commitment to, and control of, design, development and operations costs. Discovery missions are selected competitively and cover a wide range of scientific goals and destinations. Presently, the Dawn Discovery mission uses solar electric propulsion, as do some concepts for future Discovery missions.

A. Dawn

The Dawn Project[2] is designed to yield a significant increase in the understanding of the conditions and process acting at the solar system’s earliest epoch by examining the geophysical properties of two complementary bodies, (1) Ceres and (4) Vesta. The science investigations will use panchromatic and multispectral imagery; visible, infrared, γ-ray, and neutron spectrometry; and gravimetry. To acquire these data, the project will send a spacecraft (Figure 1) to orbit both bodies. Dawn will be the first mission to orbit a main belt asteroid and the first to orbit two extraterrestrial (and non-solar) bodies.

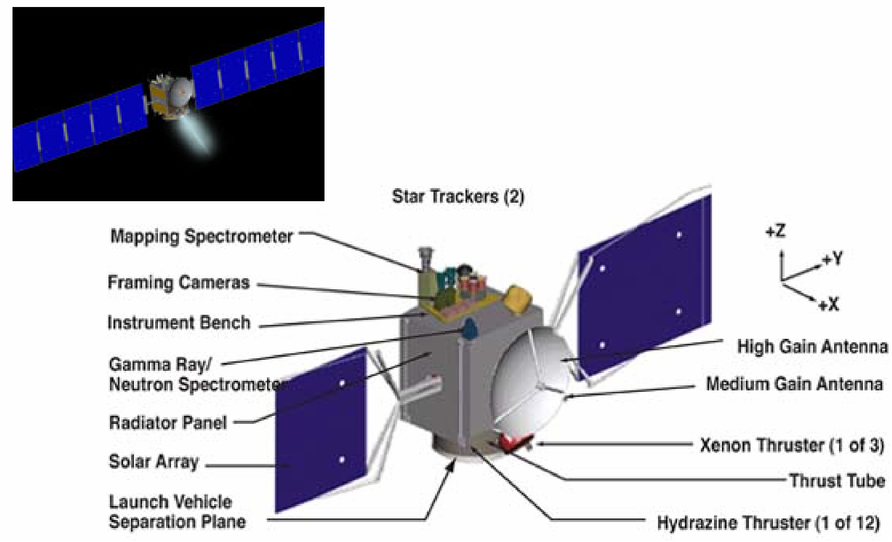
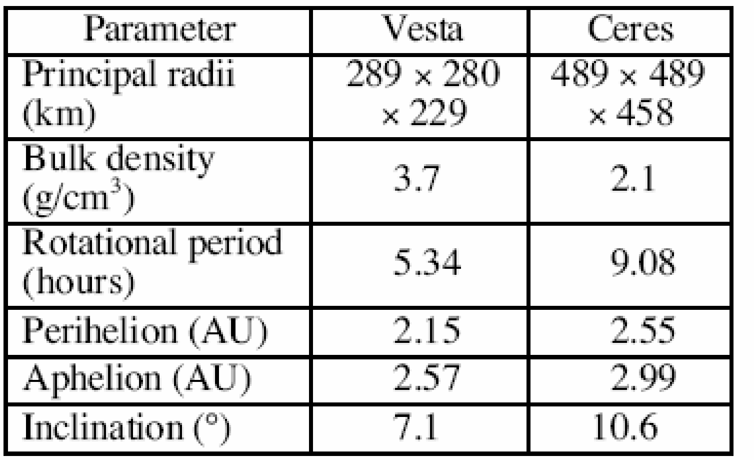


Figure 1. The Dawn Spacecraft.

The accretion of bodies during the earliest stages of the solar system led to the growth of planets. Jupiter’s gravity is believed to have interfered with this process, thus depriving the region between it and Mars of a single planet and leaving instead a belt of protoplanets. Collisions during the subsequent 4.5 billion years have reduced the size and increased the number of the asteroids, and complex dynamics have caused some of the fragments to be transported from the asteroid belt to elsewhere in the solar system. For example, (433) Eros, which was studied in detail by the Discovery Program’s Near Earth Asteroid Rendezvous Shoemaker mission, appears to be homogeneous, likely a fragment of a larger body. Eros is approximately 30 km × 13 km × 13 km. Vesta and Ceres are the two most massive asteroids, and they are far larger than the other asteroids visited by spacecraft. Both have survived largely intact through the collisional history of the solar system. They preserve retrievable records of the physical and chemical conditions during the solar system’ s early planet-forming epoch. Some of their relevant characteristics are in Table 1.

Table 1. Physical and orbital characteristics of Vesta and Ceres. (AU is astronomical unit.)



Parameter	Vesta	Ceres
Principal radii (km)	289 × 280 × 229	489 × 489 × 458
Bulk density (g/cm^3)	3.7	2.1
Rotational period (hours)	5.34	9.08
Perihelion (AU)	2.15	2.55
Aphelion (AU)	2.57	2.99
Inclination (°)	7.1	10.6

The Dawn ion propulsion system (IPS) (J. Brophy [3]) is an expanded version of the system operated extensively on Deep Space 1 (DS1). The Xe tank, titanium overwrapped with composite, has a capacity of 450 kg, and to provide high reliability in expending that much propellant, the spacecraft carries 3 NSTAR ion thrusters. The thruster design is qualified for a throughput of about 150 kg. Each 30-cm-diameter thruster is mounted to a 2-axis gimbal to allow for migration of the flight system’s center of mass during the mission and to allow the attitude control system (ACS) to use the IPS to control attitude when the IPS is thrusting. The system includes 2 sets of interface and control electronics and 2 power processing units, although no more than 1 thruster will be operated at a time. At its maximum throttle level, with an input power of 2.6 kW, the thrust is 92 mN. Throttling is achieved by balancing thruster electrical parameters and Xe feed system parameters; and at the lowest input power, 0.5 kW, the thrust is 19 mN. The specific impulse ranges from 3200 s to 1900 s. Because of Dawn’ s uniquely high Δv requirements, when the flight system is at Ceres, at a heliocentric range of 3 AU, the electrical power system (EPS) has to provide sufficient power to operate the IPS. Therefore, the spacecraft has 2 large solar arrays, which together provide 10.3 kW at 1 AU and 1.3 kW at their end of life at 3 AU. Each 18-m2 array uses InGaP/ InGaAs/Ge triple-junction cells.

B. Potential Future Discovery Missions

Two other potential strawman Discovery missions that are candidates for electric propulsion are described below. The destinations are generic, but are similar to current and proposed Discovery class missions that utilize electric propulsion. An analysis of these missions and a generic Dawn-like mission is reported by David Oh.[4]

Considered first is a Near Earth Asteroid sample return mission. The spacecraft launches directly to a positive C_3 Earth escape trajectory and uses SEP to rendezvous with the asteroid Nereus. It remains in the asteroid’s vicinity for 90 days before using SEP to return to Earth and conduct a flyby as it releases the sample for direct entry. The basic characteristics of this mission are shown in Table 2.

Table 2. Near Earth Asteroid Sample Return Mission Characteristics

Near Earth Asteroid Sample Return	
Target Body	Nereus
Launch Vehicle	Delta 2925
Power System	6 kW solar array at 1 AU
Bus Power	300 W
Duration	3.3 years
ΔV	4.5 to 6.5 km/s
Launch Year	2007/08
Ion/Hall Thruster Duty Cycle	90%
Launch and Rendezvous Dates	Selected by Optimizer
Optimization Method	SEPTOP

The second mission considered is a rendezvous mission with an active short period comet. The spacecraft launches directly to an Earth escape trajectory and uses SEP to rendezvous and orbit the comet Kopff. The structure of this mission is somewhat similar to concept for the comet Odyssey mission.[5] The basic characteristics of this mission are shown in Table 3.

Table 3. Comet Rendezvous Mission characteristics.

Comet Rendezvous	
Target Body	Kopff
Launch Vehicle	Delta 2925
Power System	9 kW solar array at 1 AU
Bus Power	250 W
Duration	3.8 years
ΔV	8.1 to 8.9 km/s
Launch Year	2006
Ion/Hall Thruster Duty Cycle	90%
Launch and Rendezvous Dates	Selected by Optimizer
Optimization Method	SEPTOP

C. Technology Development to Support Future SEP Missions

At JPL there is an active program to develop electric propulsion technology that improves the system performance and life, and reduces the system costs compared with the present NSTAR based system. A program to develop longer life carbon-carbon grids for the NSTAR thruster recently completed a 1000 hour wear test [J. Snyder[6]] as well a summary of the completed post test analysis of the NSTAR Extended Life Test [A. Sengupta[7]]. JPL is also assisting NASA/GRC in developing the NEXT 40 cm thruster for future, high power SEP missions [D. Vaughan,[8] J. Anderson,[9] R. Kuharski, *et. al.*[10]]. Much of the JPL efforts focus on modeling and measuring the basic physics of ion thruster operation [I. Katz,[11] I. Mikellides,[12] R. Wirz,[13] K. Jameson,[14] R. Kolasinski,[15]]. Much of this work is applicable to ion and Hall-Effect thrusters across all power levels.

III. ST7 and Potential Future Distributed Formation Flying Missions

NASA's goal is to take the concept of formation flying to an even higher level. It is developing the technology to fly multiple spacecraft in such perfect harmony that they become a single instrument-bigger and better than could be launched ready-made from Earth. Formation flying is a critical element in

NASA's search for Earthlike planets. Very low thrust, low noise, electric thrusters are a perfect match for the precision positioning requirements of spacecraft formations. Colloid thruster will be flown as part of the ST7 New Millenium Program, and two potential future missions, LISA and TPF will both use electric thrusters to maintain spacecraft formations.

A. Space Technology 7 (ST7)

Space Technology 7 (ST7) will flight test the Disturbance Reduction System (DRS), demonstrating that a solid body can float freely in space completely undisturbed. The DRS enhanced position measurement and control technologies will then be applied to follow-on missions well into the 21st century. The Laser Interferometer Space Antenna (LISA), a gravitational-wave observatory planned for launch in 2011, will be the first of such missions.

For NMP validation, and in preparation for the LISA mission, the DRS will fly on the European Space Agency's LISA Pathfinder. Onboard, the DRS will undergo rigorous in-space testing for a period of 90 days. During this time, the DRS primary goals are to validate a) improved sensor technology performance and b) nanometer spacecraft position control to an accuracy of a few millionths of a millimeter.

The DRS is based on the concept of freely floating test masses contained within a spacecraft that shields the test masses from external forces. Ideally, the test masses will follow a trajectory determined only by the local gravitational field. The spacecraft position must be continuously adjusted to stay centered about the test masses. In this way, the spacecraft essentially flies in formation with the test masses.

The DRS consists of an instrument package and clusters of micro Newton thrusters as shown in Figure 2. The instrument package includes a laser interferometer subsystem and the gravitational reference sensor (GRS) subsystem. Each GRS (GRS1 and GRS2) contains a freely falling test mass.

Interferometers continuously bounce laser beams between the GRS test masses, to measure their separation in distances as tiny as a fraction of an atom. The interferometers will also verify that the test masses are free from acceleration. To accomplish such tiny measurements, the DRS measures the capacitance of "floating" cubes of blended gold and platinum, each inside a box. Changes in the capacitive-position signals starts software that fires the micro Newton thrusters. In this way, spacecraft position is controlled. The thrusters, mounted in clusters at four points on the spacecraft perimeter, will counteract both external and internal pressures on the test masses. While in orbit, the strongest external force on the ST7 spacecraft will be from sunlight, which will be equal to one-hundredth the weight of a postage stamp.

Internal disturbances such as gravity from the spacecraft itself will be countered by the thrusters as well. This is achieved by "drag-free" control of spacecraft position, using the micro Newton thrusters and the capacitive measurement method.

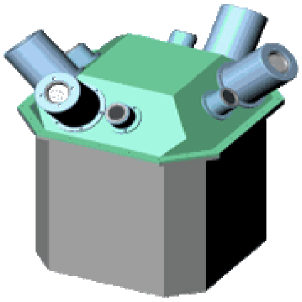


Figure 2. Micro Newton thrusters.

The DRS micro Newton thrusters consist of a colloidal fluid that is fed through a needle by a pressurizing system. At the tip of the needle, a high electrical field is applied. This causes droplets to form and to be ejected from the tip of the needle. The droplets are spontaneously ionized and accelerated by high voltage, to generate variable thrust in the desired range.

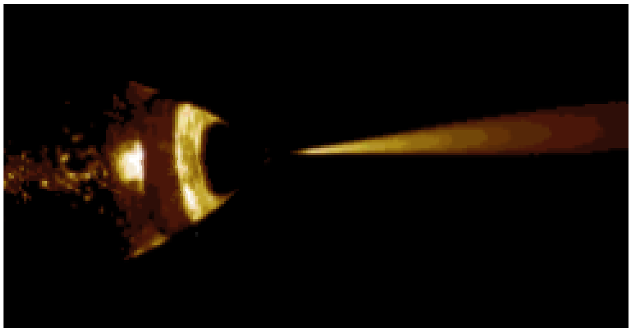


Figure 3 A colloid thruster electrospray of charged droplets.

Precise changes in thrust can be achieved by changes to the accelerating voltage. A cathode is included to emit electrons, which keeps the spacecraft neutral. This prevents the spacecraft from becoming negatively charged by the continual ejection of positively-charged droplets.

Eight colloidal thrusters are mounted in clusters at four points on the host spacecraft's perimeter. The thrusters generate enough thrust to control the spacecraft in the required six degrees of freedom. They will counteract both external and internal pressures on the test masses. The thruster will balance the strongest external force on the ST7 spacecraft that from sunlight, which will be equal to one-hundredth the weight of a postage stamp.

B. The Laser Interferometer Space Antenna (LISA)

How did the Universe begin? Does time have a beginning and an end? Does space have edges? These are the questions we've struggled to answer for centuries. Science and technology have now reached the point where answers to these questions are finally within our grasp. The Laser Interferometer Space Antenna (LISA) may supply some of these answers as the mission studies the mergers of supermassive black holes, tests Einstein's Theory of General Relativity, probes the early Universe, and searches for gravitational waves——the primary objective.

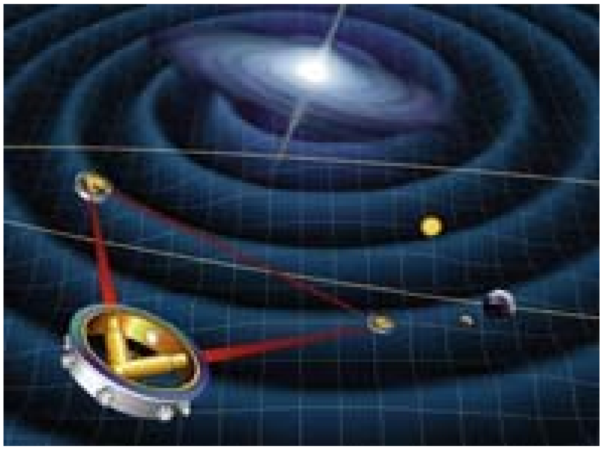


Figure 4. Artist's concept of the LISA mission.

As the first dedicated space-based gravitational wave observatory, LISA (Figure 4) will detect waves generated by binaries within our Galaxy, the Milky Way, and by massive black holes in distant galaxies. Although gravitational wave searches in space have previously been made, they were conducted for short periods by planetary missions that had other primary science objectives. Some current missions are using microwave Doppler tracking to search for gravitational waves. However, LISA will use an advanced system of laser interferometry for detecting and measuring them. And, LISA will directly detect the existence of gravitational waves, rather than inferring it from the motion of celestial bodies, as has been done previously. Additionally, LISA will make its observations in a low-frequency band that ground-based detectors can't achieve. Note that this difference in frequency bands makes LISA and ground detectors complementary rather than competitive. This range of frequencies is similar to the various types of wavelengths applied in astronomy, such as ultraviolet and infrared. Each provides different information.

In space, LISA won't be affected by the environmental noise that affects ground detectors on Earth's surface. Due to earthquakes and other vibrations, ground detectors can only make observations at frequencies above 1 hertz. However, other environmental factors *will* impact LISA. Such factors include the drift of the spacecraft, charging of the test masses, and buffeting by the solar wind. Making these small disturbances negligible is a technological challenge of the mission. Meeting this challenge will help to ensure the detection of gravitational waves.

LISA is jointly sponsored by the European Space Agency (ESA), as a Cornerstone mission in ESA's Cosmic Vision Programme, and NASA's Astronomy and Astrophysics Division, as part of the Structure and Evolution of the Universe 2003 roadmap, "Beyond Einstein: From the Big Bang to Black Holes." This program studies the building blocks of our own existence at the most basic level**:** the matter, energy, space, and time that make up the Universe. LISA is one of the program's Great Observatories.

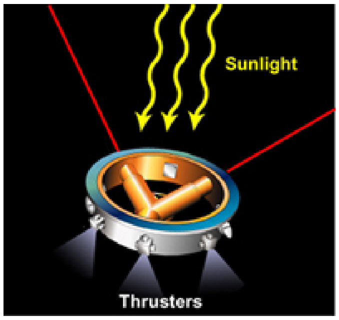


Figure 5. External disturbance by sunlight is counteracted by micronewton thrusters.

LISA's spacecraft positions must be precisely controlled to follow the motion of the test masses. LISA's micronewton thrusters provide the very small thrust needed to keep each spacecraft centered about its test mass (Figure 5). They perform attitude and position control of the spacecraft. The thruster development effort is described by J. Ziemer and S. Merkowitz.[16]

C. Terrestrial Planet Finder (TPF)

Terrestrial Planet Finder, NASA's first space-based mission to directly observe planets outside our own solar system, will rely on formation flying for one of its two observatories (Figure 6). Five separate spacecraft will work together to function as a single huge telescope. They will create an instrument powerful enough to distinguish the faint light of small Earthlike planets from the much brighter light of the stars they orbit.

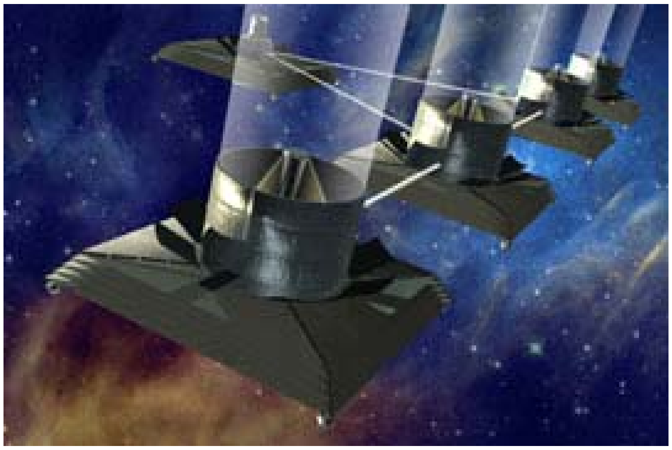


Figure 6. Terrestrial Planet Finder a formation-flying infrared interferometer.

Terrestrial Planet Finder (TPF) is a suite of two complementary observatories that will study all aspects of planets outside our solar system: from their formation and development in disks of dust and gas around newly forming stars to the presence and features of those planets orbiting the nearest stars; from the numbers at various sizes and places to their suitability as an abode for life.

By combining the high sensitivity of space telescopes with revolutionary imaging technologies, the TPF observatories will measure the size, temperature, and placement of planets as small as the Earth in the habitable zones of distant solar systems. In addition, TPF's spectroscopy will allow atmospheric chemists and biologists to use the relative amounts of gases like carbon dioxide, water vapor, ozone and methane to find whether a planet someday could or even now does support life. Our understanding of the properties of terrestrial planets will be scientifically most valuable within a broader framework that includes the properties of all planetary system constituents, including both gas giant and terrestrial planets and debris disks. Some of this information, such as the properties of debris disks and the masses and orbital properties of gas giant planets, will become available with currently planned space or ground-based facilities. However, the spectral characterization of most giant planets will require observations with TPF. TPF's ability to carry out a program of comparative planet studies across a range of planetary masses and orbital locations in a large number of new solar systems is by itself an important scientific motivation for the mission.

TPF's mission will not be limited to the detection and study of distant planets. An observatory with the power to detect an Earth orbiting a nearby star will also be able to collect important new data on many targets of general astrophysical interest. Efforts underway at JPL to develop thrusters suitable for TPF are described by R. Wirz.[17]

IV. Potential Future High Power Electric Propulsion Missions

A. Prometheus

In support of the peaceful robotic and human exploration of the solar system, Prometheus, the Nuclear Systems Development program, is developing technologies and conducting advanced studies in the areas of radioisotope and nuclear reactor power systems and electric propulsion. One objective of Prometheus is to develop and demonstrate that a nuclear reactor-powered spacecraft can be operated safely and reliably in deep space on long duration missions**.** Prometheus 1 (Figure 7) is the first proposed mission to take advantage of these revolutionary capabilities under development.

Figure 7. Artist's conception of the Prometheus 1 spacecraft.

Scientific investigations conducted by NASA's Galileo spacecraft provide strong evidence that three planet-sized moons of Jupiter -- Callisto, Ganymede and Europa -- may harbor vast saltwater oceans beneath their icy surfaces. These findings rank among the major scientific discoveries of the Space Age because liquid water is one of the three key ingredients for sustaining life, as we know it, on Earth. To investigate further, NASA has been developing plans for an ambitious mission to orbit each of these moons for extensive investigations of their makeup, their history, and their potential for sustaining life. The proposed mission, called Prometheus 1, would also raise NASA's capability for space exploration to a revolutionary new level by pioneering the use of electric propulsion powered by a nuclear reactor. These technologies would not only make it possible to consider a mission to orbit three of the moons of Jupiter, one after the other at a very close range, but they would also open the rest of the outer solar system to detailed exploration in later missions.

The spacecraft may be propelled by ion thrusters [T. Randolph[18]]. NASA's Deep Space 1 mission, which successfully demonstrated ion propulsion for interplanetary travel, drew electricity for its thrusters from solar panels. Prometheus One, as a more heavily instrumented craft traveling farther from the Sun, may power its ion thrusters with a nuclear reactor and a system for converting the reactor's thermal energy to electricity. The spacecraft's power system could give the craft more than 100 times as much power as a non-fission system of comparable weight.

JPL in partnership with NASA/GRC has had an extensive program to develop the electric thruster technology and the live validation methodologies needed for long duration NEP missions, such as Prometheus I and succeeding missions. Most of the JPL effort centered on the successful development and testing of the 65 cm NEXIS thruster [J.E. Polk,[19] J.S Beatty,[20] J.S. Snyder[21]], efforts to understand the basic life limiting thruster physics [I. Katz,[22] A. Sengupta,[23] I. Mikellides,[24] R. Wirz,[25] K. Jameson,[26] D. Goebel,[27] D. Goebel,[28] R. Kolasinski,[29,30,31]] and predicting ion thruster plume impacts on the spacecraft [M. Mandell[32]]. Dan Goebel of JPL was also the design lead on the joint JPL and NASA/GRC team planning the Herakles thruster for Prometheus 1 [M. Patterson[33]].

B. High-Power Electric Propulsion Mission Applications

Missions further in the future will need even higher power thrusters. Some possible missions are described below (for more detail the reader is referred to R. Frisbee[34]).

1. *Robotic Science Missions*

Electric propulsion offers significant mass savings and potential flight time reductions compared to chemical propulsion for robotic science missions. Of particular interest are missions to the outer planets (Jupiter and beyond), where nuclear electric propulsion (NEP) with system power levels of 100s of kWe to MW-class vehicles at Isp's of 5000 – 9000 seconds enable such very high delta-V missions.

2. *Lunar and Mars Missions*

Previous and recent studies provide examples of the benefits of high power electric propulsion for cargo missions in support of human exploration. Megawatt-class solar-electric propulsion (SEP) or NEP vehicles with near-term technology could deliver 10s of MT of cargo to the Moon or Mars with substantially lower mass than a chemical system. Later-term advanced power systems with low specific masses could utilize high-power EP to enable piloted human Mars missions with high-energy transfers for faster round-trip times than are achievable by chemical propulsion.

3. *Other Applications*

A high power electric propulsion infrastructure could be of significant value to future commercial space applications. For example, a near-term reusable SEP orbit transfer vehicle for raising heavy payloads from LEO to GEO operating at a few 100 kWe could significantly reduce the mass which must be delivered to LEO.

Figure 8. Left: Cutaway view of the Advanced Lithium-Fed, Applied-field Lorentz Force Accelerator (ALFA^2) design. Middle: The Very High Specific Impulse Thruster with Anode Layer (VHITAL). Right: The Pulsed Inductive Thruster (PIT).

There are several research efforts at JPL supporting Electric Propulsion technologies for advanced High Power Missions including the Advanced Lithium-Fed, Applied-field Lorentz Force Accelerator (ALFA^2 - Figure 8 left), the Very High Specific Impulse Thruster with Anode Layer (VHITAL) [C. Marrese-Reading[35] - Figure 8 middle], the Nuclear-Electric Pulsed Inductive Thruster (NuPIT - Figure 8 right) [R. Frisbee[36]] and the Variable Isp High Power Ion Thruster [D. Goebel[37]].

V. Summary

At JPL, electric propulsion technology efforts are mission driven. Potential missions range from near-term spacecraft to near-by asteroids to far-term nuclear power spacecraft to distant planets. Electric thrusters may be the primary on-board propulsion, as in the Discovery missions, or it may be used for precision formation flying, as in LISA. All the missions support the NASA goals to explore the Universe and search for life.

Acknowledgments

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