New Dawn for
ELECTRIC ROCKETS

Efficient electric plasma engines are propelling the next generation of space probes to the outer solar system   **By Edgar Y. Choueiri**

KEY CONCEPTS

- Conventional rockets generate thrust by burning chemical fuel. Electric rockets propel space vehicles by applying electric or electromagnetic fields to clouds of charged particles, or plasmas, to accelerate them.

- Although electric rockets offer much lower thrust levels than their chemical cousins, they can eventually enable spacecraft to reach greater speeds for the same amount of propellant.

- Electric rockets' high-speed capabilities and their efficient use of propellant make them valuable for deep-space missions.

—*The Editors*

Alone amid the cosmic blackness, NASA's Dawn space probe speeds beyond the orbit of Mars toward the asteroid belt. Launched to search for insights into the birth of the solar system, the robotic spacecraft is on its way to study the asteroids Vesta and Ceres, two of the largest remnants of the planetary embryos that collided and combined some 4.57 billion years ago to form today's planets.
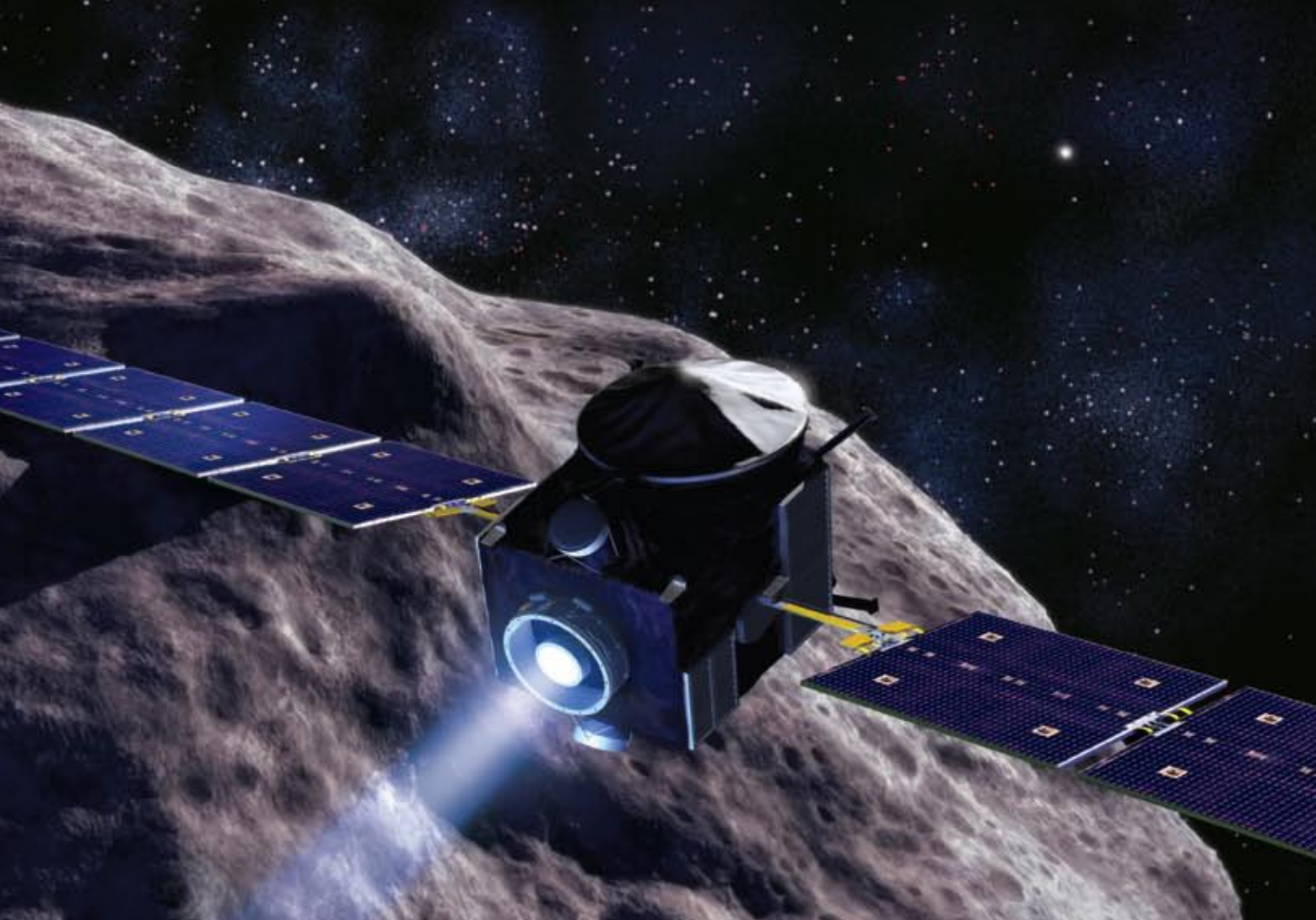
But the goals of the mission are not all that make this flight notable. Dawn, which took off in September 2007, is powered by a kind of space propulsion technology that is starting to take center stage for long-distance missions—a plasma rocket engine. Such engines, now being developed in several advanced forms, generate thrust by electrically producing and manipulating ionized gas propellants rather than by burn-

ing liquid or solid chemical fuels, as conventional rockets do.

Dawn's mission designers at the NASA Jet Propulsion Laboratory selected a plasma engine as the probe's rocket system because it is highly efficient, requiring only one tenth of the fuel that a chemical rocket motor would have needed to reach the asteroid belt. If project planners had chosen to install a traditional engine, the vehicle would have been able to reach either Vesta or Ceres, but not both.

Indeed, electric rockets, as the engines are also known, are quickly becoming the best option for sending probes to far-off targets. Recent successes made possible by electric propulsion include a visit by NASA's Deep Space 1 vehicle to a comet, a bonus journey that was made feasible by propellant that was left over after the spacecraft had ac-

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complished its primary goal. Plasma engines have also provided propulsion for an attempted landing on an asteroid by the Japanese Hayabusa probe, as well as a trip to the moon by the European Space Agency's SMART-1 spacecraft. In light of the technology's demonstrated advantages, deep-space mission planners in the U.S., Europe and Japan are opting to employ plasma drives for future missions that will explore the outer planets, search for extrasolar, Earth-like planets and use the void of space as a laboratory in which to study fundamental physics.

A Long Time Coming

Although plasma thrusters are only now making their way into long-range spacecraft, the technology has been under development for that purpose for some time and is already used for other tasks in space.

As early as the first decade of the 20th century, rocket pioneers speculated about using electricity to power spacecraft. But the late Ernst Stuhlinger—a member of Wernher von Braun's legendary team of German rocket scientists that spearheaded the U.S. space program—finally

turned the concept into a practical technology in the mid-1950s. A few years later engineers at the NASA Glenn Research Center (then known as Lewis) built the first operating electric rocket. That engine made a suborbital flight in 1964 onboard Space Electric Rocket Test 1, operating for half an hour before the craft fell back to Earth.

In the meantime, researchers in the former Soviet Union worked independently on concepts for electric rockets. Since the 1970s mission planners have selected the technology because it can save propellant while performing such tasks as maintaining the attitude and orbital position of telecommunications satellites in geosynchronous orbit.

Rocket Realities

The benefits afforded by plasma engines become most striking in light of the drawbacks of conventional rockets. When people imagine a ship streaking through the dark void toward a distant planet, they usually envision it trailing a long, fiery plume from its nozzles. Yet the truth is altogether different: expeditions to the outer solar system have been mostly rocketless affairs,
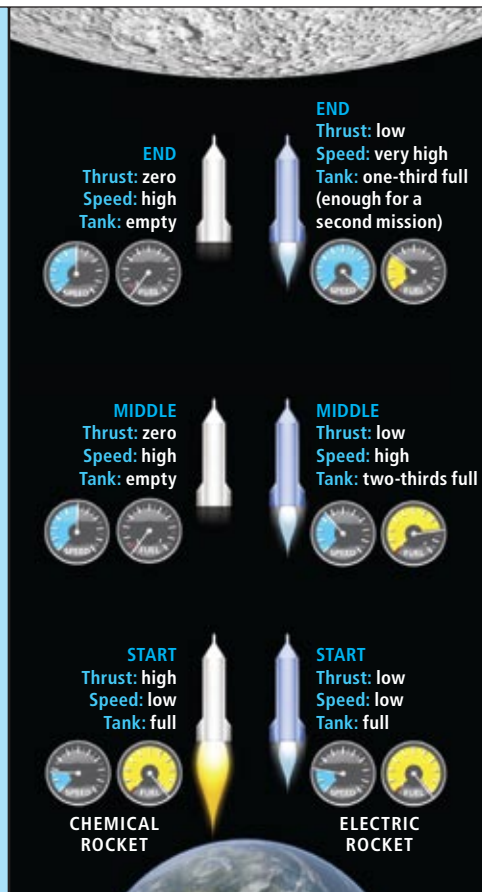
NASA'S DAWN SPACE PROBE, which is propelled by an electric rocket called an ion thruster, nears the asteroid Vesta in this artist's conception. Vesta is its initial survey target; the asteroid Ceres, its second destination, floats in the far distance in the image (*bright spot at upper right*). A conventional chemical rocket engine would be able to carry enough fuel to reach only one of these asteroids.

Chemical vs. Electric Rockets

Chemical and electric propulsion systems are suited to different kinds of missions. Chemical rockets (*left*) produce large amounts of thrust quickly, so they can accelerate to high speeds rapidly, although they burn copious quantities of fuel to do so. These characteristics make them appropriate for relatively short-range trips.

Electric rockets (*right*), which use a plasma (ionized gas) as propellant, generate much less thrust, but their extremely frugal consumption of propellant allows them to operate for much longer periods. And in the frictionless environment of space, a small force applied over time can eventually achieve similarly high or greater speeds. These features make plasma rockets well equipped for deep-space missions to multiple targets.

END
Thrust: zero
Speed: high
Tank: empty

END
Thrust: low
Speed: very high
Tank: one-third full (enough for a second mission)

MIDDLE
Thrust: zero
Speed: high
Tank: empty

MIDDLE
Thrust: low
Speed: high
Tank: two-thirds full

START
Thrust: high
Speed: low
Tank: full

START
Thrust: low
Speed: low
Tank: full

CHEMICAL ROCKET

ELECTRIC ROCKET

[THE AUTHOR]

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motor would typically have no fuel left for braking. Such a probe would need the ability to fire its rocket so that it could slow enough to achieve orbit around its target and thus conduct extended scientific observations. Unable to brake, it would be limited to just a fleeting encounter with the object it aimed to study. Indeed, after a trip of more than nine years, New Horizons, a NASA deep-space probe launched in 2006, will get only a brief encounter of not more than a single Earth day with its ultimate object of study, the recently demoted "dwarf planet" Pluto.

The Rocket Equation

For those who wonder why engineers have been unable to come up with ways to send enough chemical fuel into space to avoid such difficulties for long missions, let me clarify the immense hurdles they face. The explanation derives from what is called the rocket equation, a formula used by mission planners to calculate the mass of propellant required for a given mission. Russian scientist Konstantin E. Tsiolkovsky, one of the fathers of rocketry and spaceflight, first introduced this basic formula in 1903.

In plain English, the rocket equation states the intuitive fact that the faster you throw propellant out from a spacecraft, the less you need to execute a rocket-borne maneuver. Think of a baseball pitcher (a rocket motor) with a bucket of baseballs (propellant) standing on a skateboard (a spacecraft). The faster the pitcher flings the balls rearward (that is, the higher the exhaust speed), the faster the vehicle will be traveling in the opposite direction when the last ball is thrown—or, equivalently, the fewer baseballs (less propellant) the pitcher would have to hurl to raise the skateboard's speed by a desired amount at any given time. Scientists call this incremental increase of the skateboard's velocity "delta-v."

In more specific terms, the equation relates the mass of propellant required by a rocket to carry out a particular mission in outer space to two key velocities: the velocity at which the rocket's exhaust will be ejected from the vehicle and the mission's delta-v—how much the vehicle's velocity will increase as a result of the exhaust's ejection. Delta-v corresponds to the energy a craft must expend to alter its inertial motion and execute a desired space maneuver. For a given rocket technology (that is, one that produces a given rocket exhaust speed), the rocket equation translates the delta-v for a desired mission into the mass of propellant required to complete it.

because most of the fuel is typically expended in the first few minutes of operation, leaving the spacecraft to coast the rest of the way to its goal. True, chemical rockets do launch all spacecraft from Earth's surface and can make midcourse corrections. But they are impractical for powering deep-space explorations because they would require huge quantities of fuel—too much to be lifted into orbit practically and affordably. Placing a pound (0.45 kilogram) of anything into Earth orbit costs as much as $10,000.

To achieve the necessary trajectories and high speeds for lengthy, high-precision journeys without additional fuel, many deep-space probes of the past have had to spend time—often years—detouring out of their way to planets or moons that provided gravitational kicks able to accelerate them in the desired direction (slingshot moves called gravity-assist maneuvers). Such circuitous flight paths limit missions to relatively small launch windows; only blasting off within a certain short time frame will ensure a precision swing past a cosmic body serving as a gravitational booster.

Even worse, after years of travel toward its destination, a vehicle with a chemical rocket

The delta-v metric can therefore be thought of as a kind of "price tag" of a mission, because the cost of conducting one is typically dominated by the cost of launching the needed propellant.

Conventional chemical rockets achieve only low exhaust velocities (three to four kilometers per second, or km/s). This feature alone makes them problematic to use. Also, the exponential nature of the rocket equation dictates that the fraction of the vehicle's initial mass that is composed of fuel—the "propellant mass fraction"—grows exponentially with delta-v. Hence, the fuel needed for the high delta-v required for a deep-space mission could take up almost all the starting mass of the spacecraft, leaving little room for anything else.

Consider a couple of examples: To travel to Mars from low-Earth orbit requires a delta-v of about 4.5 km/s. The rocket equation says that a conventional chemical rocket would require that more than two thirds of the spacecraft's mass be propellant to carry out such an interplanetary transfer. For more ambitious trips—such as expeditions to the outer planets, which have delta-v requirements that range from 35 to 70 km/s—chemical rockets would need to be more than 99.98 percent fuel. That configuration would leave no space for other hardware or useful payloads. As probes journey farther out into the solar system, chemical rockets become increasingly useless—unless engineers can find a way to significantly raise their exhaust speeds.

So far that goal has proved very difficult to accomplish because generating ultrahigh exhaust speeds demands extremely high fuel combustion temperatures. The ability to reach the needed temperatures is limited both by the amount of energy that can be released by known chemical reactions and by the melting point of the rocket's walls.

The Plasma Solution

Plasma propulsion systems, in contrast, offer much greater exhaust speeds. Instead of burning chemical fuel to generate thrust, the plasma engine accelerates plasmas—clouds of electrically charged atoms or molecules—to very high velocities. A plasma is produced by adding energy to a gas, for instance, by radiating it with lasers, microwaves or radio-frequency waves or by subjecting it to strong electric fields. The extra energy liberates electrons from the atoms or molecules of the gas, leaving the latter with a positive charge and the former free to move freely in the gas, which makes the ionized gas a far better electrical conductor than copper metal. Because plasmas contain charged particles, whose motion is strongly affected by electric and magnetic fields, application of electric or electromagnetic fields to a plasma can accelerate its constituents and send them out the back of a vehicle as thrust-producing exhaust. The necessary fields can be generated by electrodes and magnets, using induction by external antennas or wire coils, or by driving electric currents through the plasma.

The electric power for creating and accelerating the plasmas typically comes from solar panels that collect energy from the sun. But deep-space vehicles going past Mars must rely on nuclear power sources, because solar energy gets too weak at long distances from the sun. Today's small robotic probes use thermoelectric devices heated by the decay of a nuclear isotope, but the more ambitious missions of the future would need nuclear fission (or even fusion) reactors. Any nuclear reactor would be activated only after the vessel reached a stable orbit at a safe distance from Earth. Its fuel would be secured in an inert state during liftoff.

Three kinds of plasma propulsion systems have matured enough to be employed on long-distance missions. The one in most use—and the kind powering Dawn—is the ion drive.

The Ion Drive

The ion engine, one of the more successful electric propulsion concepts, traces its roots to the ideas of American rocketry pioneer Robert H. Goddard, formed when he was still a graduate student at Worcester Polytechnic Institute a century ago. Ion engines are able to achieve exhaust velocities ranging from 20 to 50 km/s [*see box on next page*].

In its most common incarnation, the ion engine gets its electric power from photovoltaic panels. It is a squat cylinder, not much larger than a bucket, that is set astern. Inside the bucket, xenon gas from the propellant tank flows into an ionization chamber where an electromagnetic field tears electrons off the xenon gas atoms to create a plasma. The plasma's positive ions are then extracted and accelerated to high speeds through the action of an electric field that is applied between two electrode grids. Each positive ion in the field feels the strong tug of the aft-mounted, negatively charged electrode and therefore accelerates rearward.

The positive ions in the exhaust leave a spacecraft with a net negative charge, which, if left to

EARLY HISTORY OF ELECTRIC ROCKETS

1903: Konstantin E. Tsiolkovsky derives the "rocket equation," which is widely used to calculate fuel consumption for space missions. In 1911 he speculates that electric fields could accelerate charged particles to produce rocket thrust.

1906: Robert H. Goddard conceives of electrostatic acceleration of charged particles for rocket propulsion. He invents and patents a precursor to the ion engine in 1917.

1954: Ernst Stuhlinger figures out how to optimize the performance of the electric ion rocket engine.

1962: Work by researchers in the Soviet Union, Europe and the U.S. leads to the first published description of the Hall thruster, a more powerful class of plasma rocket.

1962: Adriano Ducati discovers the mechanism behind the magneto-plasmadynamic thruster, the most powerful type of plasma rocket.

1964: NASA's SERT I spacecraft conducts the first successful flight test of an ion engine in space.

1972: The Soviet Meteor satellite carries out the initial spaceflight of a Hall thruster.

1999: NASA's Jet Propulsion Laboratory's Deep Space 1 demonstrates the first use of an ion engine as the main propulsion system on a spacecraft that escapes Earth's gravitation from orbit.

ROBERT H. GODDARD, circa 1935

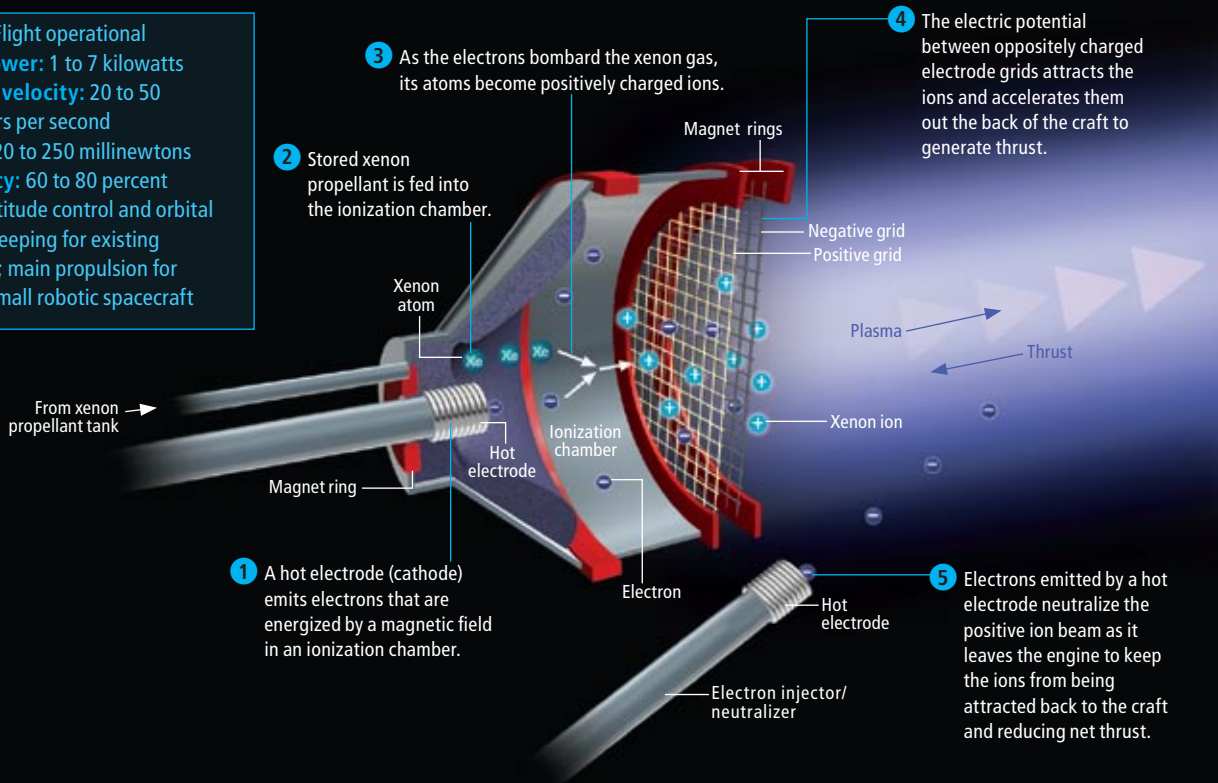# The Proven Plasma Propulsion Workhorse

This engine type creates a plasma propellant by bombarding a neutral gas with electrons emitted from a hot electric filament. The resulting positive ions are then extracted from the plasma and accelerated out the back of the craft by an electric field that is created by applying a high voltage between two electrode grids. The ion exhaust generates thrust in the opposite direction.

Status: Flight operational
Input power: 1 to 7 kilowatts
Exhaust velocity: 20 to 50 kilometers per second
Thrust: 20 to 250 millinewtons
Efficiency: 60 to 80 percent
Uses: Attitude control and orbital station-keeping for existing satellites; main propulsion for current small robotic spacecraft

3 As the electrons bombard the xenon gas, its atoms become positively charged ions.

2 Stored xenon propellant is fed into the ionization chamber.

4 The electric potential between oppositely charged electrode grids attracts the ions and accelerates them out the back of the craft to generate thrust.

Magnet rings

Negative grid

Positive grid

Xenon atom

Plasma

Thrust

From xenon propellant tank

Xenon ion

Hot electrode

Ionization chamber

Magnet ring

1 A hot electrode (cathode) emits electrons that are energized by a magnetic field in an ionization chamber.

Electron

Hot electrode

Electron injector/ neutralizer

5 Electrons emitted by a hot electrode neutralize the positive ion beam as it leaves the engine to keep the ions from being attracted back to the craft and reducing net thrust.

ION THRUSTER, which is 40 centimeters in diameter, was test-fired inside a laboratory vacuum chamber. Charged xenon atoms account for the blue color of the exhaust plume.

build up, would attract the ions back to the spacecraft, thus canceling out the thrust. To avoid this problem, an external electron source (a negative cathode or an electron gun) injects electrons into the positive flow to electrically neutralize it, which leaves the spacecraft neutral.

Dozens of ion drives are currently operating on commercial spacecraft—mostly communications satellites in geosynchronous orbit for orbital "station-keeping" and attitude control. They were selected because they save millions of dollars per spacecraft by greatly shrinking the mass of propellant that would be required for chemical propulsion.

At the end of the 20th century, Deep Space 1 became the world's first spacecraft using an electric propulsion system to escape Earth's gravitation from orbit. The probe then accelerated by about 4.3 km/s, while consuming less than 74 kilograms of xenon propellant (about the mass of an untapped beer keg), to fly through the dusty tail of the comet Borrelly. This is the highest velocity increment gained via propulsion (as opposed to gravity assists) by any spacecraft to date. Dawn should soon break that record by adding 10 km/s to its velocity. Engineers at the Jet Propulsion Laboratory have recently demonstrated ion drives able to function flawlessly for more than three years of continuous operation.

A plasma rocket's performance is determined not only by the speed of the exhaust particles but also by its thrust density, which is the amount of thrust force an engine produces per unit area of its exhaust aperture. Ion engines and similar electrostatic thrusters suffer from a major shortcoming, called space-charge limitation, that severely reduces their thrust density: as the positive ions pass between the electrostatic grids in an ion engine, a positive charge inevitably builds up in this region. This buildup limits the attainable electric field to drive the acceleration.

Because of this phenomenon, Deep Space 1's ion engine produces a thrust force that is roughly equivalent to the weight of a single sheet of paper—hardly the thundering rocket engine of sci-fi movies and more akin to a car that takes two days to accelerate from zero to 60 miles per

hour. As long as one is willing to wait long enough (typically, many months), though, these engines can eventually attain the high delta-vs needed for distant journeys. That feat is possible because in the vacuum of space, which offers no resistance, even a tiny push, if constantly applied, will lead to high propulsion speeds.

The Hall Thruster

A plasma propulsion system called the Hall thruster [*see box at right*] avoids the space-charge limitation and can therefore accelerate a vessel to high speeds more quickly (by way of its greater thrust density) than a comparably sized ion engine can. This technology has been gaining acceptance in the West since the early 1990s, after three decades of steady development in the former Soviet Union. The Hall thruster will soon be ready to take on long-range missions.

The system relies on a fundamental effect discovered in 1879 by Edwin H. Hall, then a physics graduate student at Johns Hopkins University. Hall showed that when electric and magnetic fields are set perpendicular to each other inside a conductor, an electric current (called the Hall current) flows in a direction that is perpendicular to both fields.

In a Hall thruster a plasma is produced when an electric discharge between an internal positive anode and a negative cathode situated outside the device tears through a neutral gas inside the device. The resulting plasma fluid is then accelerated out of the cylindrical engine by the Lorentz force, which results from the interaction of an applied radial magnetic field and an electric current (in this case, the Hall current) that flows in an azimuthal direction—that is, in a circular "orbit" around the central anode. The Hall current is caused by the electron's motion in the magnetic and electric fields. Depending on the available power, exhaust velocities can range from 10 to more than 50 km/s.

This form of electric rocket avoids a space-charge buildup by accelerating the entire plasma (of both positive ions and negative electrons), with the result that its thrust density and thus its thrust force (and so its potential delta-v) is many times that of an ion engine of the same size. More than 200 Hall thrusters have been flown on satellites in Earth orbit. And it was a Hall thruster that the European Space Agency used to efficiently propel its SMART-1 spacecraft frugally to the moon.

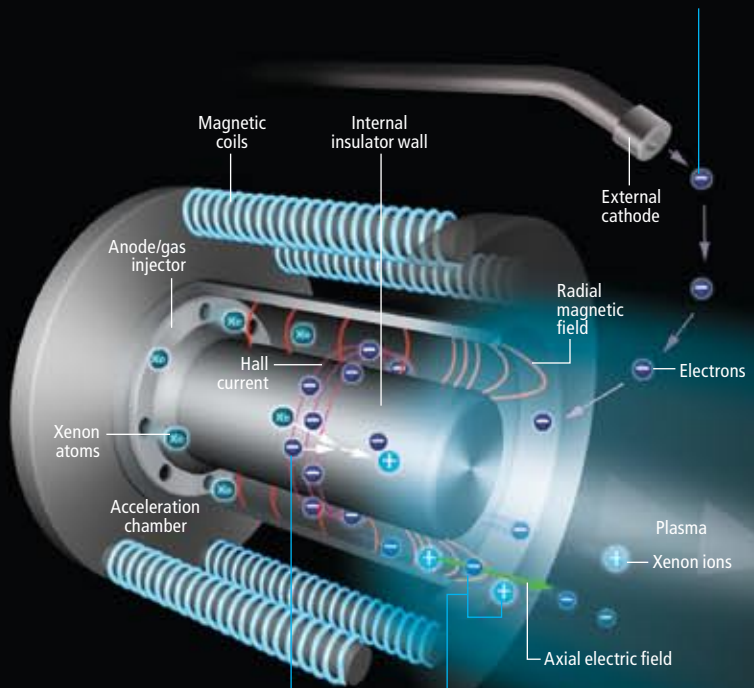Engineers are now trying to scale up today's

[HALL THRUSTER]

The Latest Plasma Engine Contender

This device generates propulsion by crossing a so-called Hall current and a radial magnetic field, which causes electrons to circle around the device's axis. These electrons tear electrons from xenon atoms, producing xenon ions, and an electric field parallel to the axis accelerates the ions downstream. The density of propulsive force produced by a Hall thruster is greater than that of an ion engine because its exhaust contains both positive ions and electrons, which avoids the buildup of positive charge that can limit the strength of an accelerating electric field.

1 An electric potential established between an external negative cathode and internal positive anode creates a mostly axial electric field inside the acceleration chamber.

2 As the cathode heats up, it emits electrons. Some of the electrons drift upstream toward the anode. When the electrons enter the chamber, a radial magnetic field and the axial electric field cause them to whirl around the axis of the thruster as a "Hall current."

Magnetic coils

Internal insulator wall

Anode/gas injector

External cathode

Radial magnetic field

Hall current

Electrons

Xenon atoms

Plasma

Acceleration chamber

Xenon ions

Axial electric field

3 Xenon gas propellant feeds through the positive anode injector into the annular acceleration chamber, where the whirling electrons collide with the xenon atoms, turning them into positive ions.

4 The plasma (containing both positive ions and electrons) is accelerated sternward by the electromagnetic forces resulting from the interaction between the predominantly radial magnetic field and the Hall current.

Status: Flight operational
Input power: 1.35 to 10 kilowatts
Exhaust velocity: 10 to 50 kilometers per second
Thrust: 40 to 600 millinewtons
Efficiency: 45 to 60 percent
Uses: Satellite attitude control and station-keeping; used as main propulsion for medium-size robotic spacecraft

$10,000

is roughly what it costs to send a pound (0.45 kilogram) of payload into Earth orbit with conventional rocket boosters. This high price tag is one reason engineers go to great lengths to shave as much mass from spacecraft as is feasible. The fuel and its storage tank are the heaviest parts of a vehicle powered by a chemical rocket.

rather small Hall thrusters so that they can handle higher amounts of power to generate greater exhaust speeds and thrust levels. The work also aims to extend their operating lifetimes to the multiyear durations needed for deep-space exploration.

Scientists at the Princeton Plasma Physics Laboratory have taken a step toward these goals by implanting segmented electrodes in the walls of a Hall thruster. The electrodes shape the internal electric field in a way that helps to focus the plasma into a thin exhaust beam. This design reduces the useless nonaxial component of thrust and improves the system's operating lifetime by keep-

ing the plasma beam away from the thruster walls. German engineers have achieved similar results using specially shaped magnetic fields. Researchers at Stanford University have meanwhile shown that lining the walls with tough, synthetic-polycrystalline diamond substantially boosts the device's resistance to plasma erosion. Such improvements will eventually make Hall thrusters suitable for deep-space missions.

Next-Generation Thruster

One way to further raise the thrust density of plasma propulsion is to increase the total amount of plasma that is accelerated in the engine. But as the plasma density in a Hall thruster is raised, electrons collide more frequently with atoms and ions, which makes it more difficult for the electrons to carry the Hall current needed for acceleration. An alternative known as the magnetoplasmadynamic thruster (MPDT) allows for a denser plasma by forgoing the Hall current in favor of a current component that is mostly aligned with the electric field [*see box at left*] and far less prone than the Hall current to disruption by atomic collisions.

In general, an MPDT consists of a central cathode sitting within a larger cylindrical anode. A gas, typically lithium, is pumped into the annular space between the cathode and the anode. There it is ionized by an electric current flowing radially from the cathode to the anode. This current induces an azimuthal magnetic field (one that encircles the central cathode), which interacts with the same current that induced it to generate the thrust-producing Lorentz force.

A single MPD engine about the size of an average household pail can process about a million watts of electric power from a solar or nuclear source into thrust (enough to energize more than 10,000 standard lightbulbs), which is substantially larger than the maximum power limits of ion or Hall thrusters of the same size. An MPDT can produce exhaust velocities from 15 to 60 km/s. It truly is the little engine that could.

This design also offers the advantage of throttling; its exhaust speed and thrust can be easily adjusted by varying the electric current level or the flow rate of the propellant. Throttling allows a mission planner to alter a spacecraft's engine thrust and exhaust velocity as needed to optimize its trajectory.
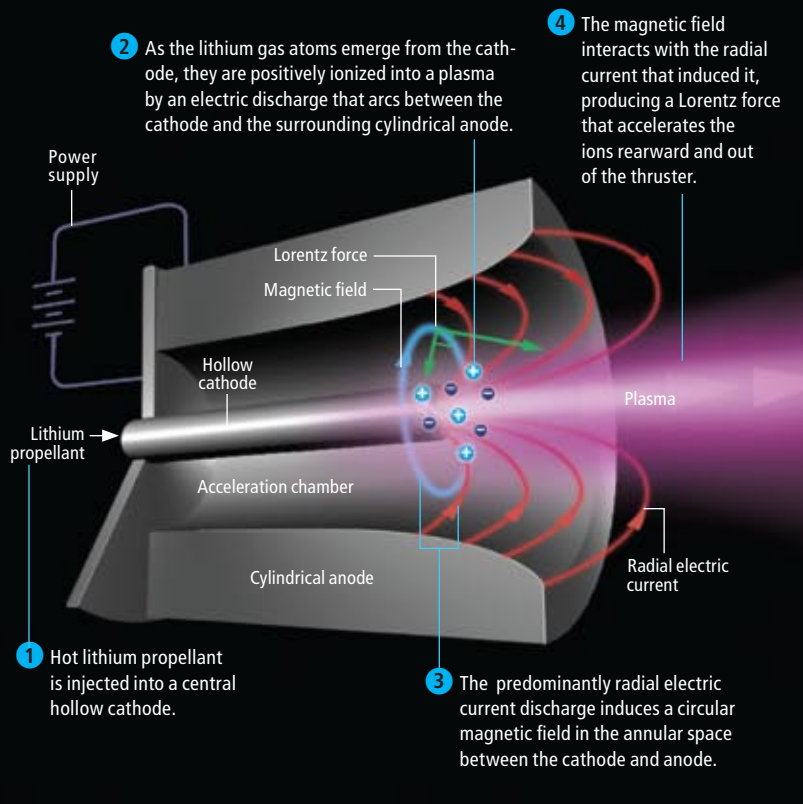
Intensive research on mechanisms that hamper the performance and lifetimes of MPD devices, such as electrode erosion, plasma instabilities

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[MAGNETOPLASMADYNAMIC THRUSTER]

The Future of Plasma Propulsion

An MPDT relies on the Lorentz electromagnetic force to accelerate the plasma to produce thrust. The Lorentz force (*green arrows*), which is mainly along the axis, is created by the interaction of a mostly radial electric current pattern (*red lines*) with a concentric magnetic field (*blue circle*).
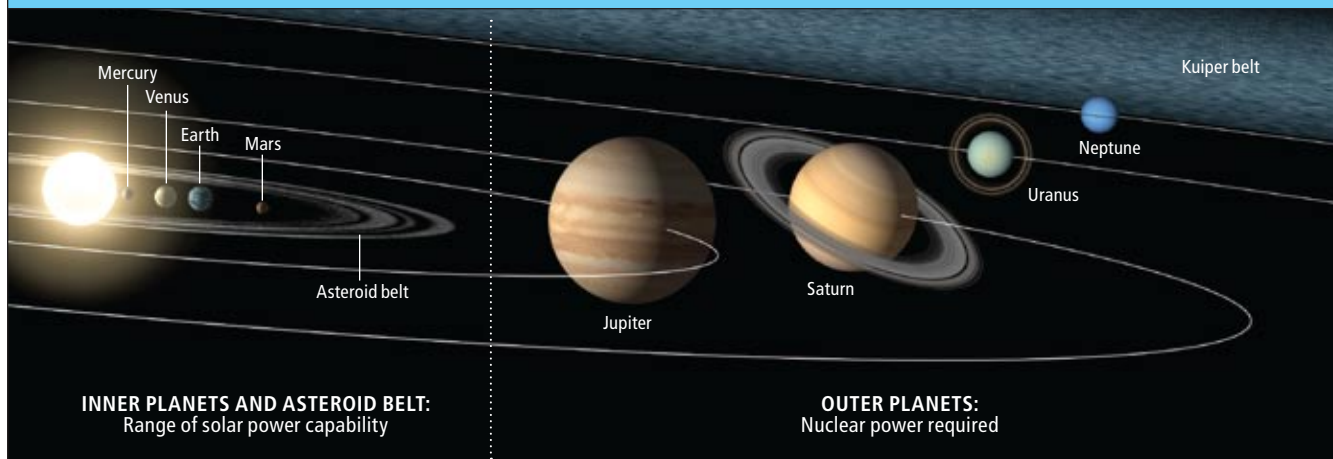
Status: Flight-tested but not yet operational
Input power: 100 to 500 kilowatts
Exhaust velocity: 15 to 60 kilometers per second
Thrust: 2.5 to 25 newtons
Efficiency: 40 to 60 percent
Uses: Main propulsion for heavy cargo and piloted spacecraft; under development

2 As the lithium gas atoms emerge from the cathode, they are positively ionized into a plasma by an electric discharge that arcs between the cathode and the surrounding cylindrical anode.

4 The magnetic field interacts with the radial current that induced it, producing a Lorentz force that accelerates the ions rearward and out of the thruster.

Power supply

Lorentz force

Magnetic field

Hollow cathode

Lithium propellant

Acceleration chamber

Cylindrical anode

Plasma

Radial electric current

1 Hot lithium propellant is injected into a central hollow cathode.

3 The predominantly radial electric current discharge induces a circular magnetic field in the annular space between the cathode and anode.

Solar and Nuclear Energy for Electric Rockets

For trips to the inner solar system, where the sun's rays are strong, sufficient electric power can be provided to plasma rocket engines by solar cells. But trips to the outer planets of the solar system would generally require nuclear power sources. A large, heavy craft would need a nuclear reactor, but a smaller, lighter one might get by with a thermo-electric power-generation device heated by the decay of radioisotopes.

Mercury
Venus
Earth
Mars
Asteroid belt
Jupiter
Saturn
Uranus
Neptune
Kuiper belt

INNER PLANETS AND ASTEROID BELT:
Range of solar power capability

OUTER PLANETS:
Nuclear power required

and power dissipation in the plasma, has led to new, high-performance engines that rely on lithium and barium vapors for propellants. These elements ionize easily, yield lower internal energy losses in the plasma and help to keep the cathode cooler. The adoption of these liquid-metal propellants and an unusual cathode design that contains channels that alter how the electric current interacts with its surface has resulted in substantially less erosion of the cathode. These innovations are leading to more reliable MPDTs.

A team of academic and NASA researchers has recently completed the design of a state-of-the-art lithium-fed MPDT called α^2, which could potentially drive a nuclear-powered vessel hauling heavy cargo and people to the moon and Mars as well as robotic missions to the outer planets.

The Tortoise Wins

Ion, Hall and MPD thrusters are but three variants of electric plasma rocket technology, albeit the most mature. During the past few decades researchers have developed many other promising related concepts to various degrees of readiness. Some are pulsed engines that operate intermittently; others run continuously. Some generate plasmas through electrode-based electric discharge; others use coil-based magnetic induction or antenna-generated radiation. The mechanisms they apply to accelerate plasmas vary as well: some use Lorentz forces; others accelerate the plasmas by entraining them in magnetically produced current sheets or in traveling electromagnetic waves. One type even aims to exhaust the plasma through invisible "rocket nozzles" composed of magnetic fields.

In all cases, plasma rockets will get up to speed more slowly than conventional rockets. And yet, in what has been called the "slower but faster paradox," they can often make their way to distant destinations more quickly by ultimately reaching higher spacecraft velocities than standard propulsion systems can using the same mass of propellant. They thus avoid time-consuming detours for gravity boosts. Much as the fabled slow and steady tortoise beats out the intermittently sprinting hare, in the marathon flights that will become increasingly common in the coming era of deep-space exploration, the tortoise wins.

So far the most advanced designs could impart a delta-v of 100 km/s—much too slow to take a spacecraft to the far-off stars but plenty enough to visit the outer planets in a reasonable amount of time. One particularly exciting deep-space mission that has been proposed would return samples from Saturn's largest moon, Titan, which space scientists believe has an atmosphere that is very similar to Earth's eons ago.

A sample from Titan's surface would offer researchers a rare chance to search for signs of chemical precursors to life. The mission would be impossible with chemical propulsion. And, with no in-course propulsion, the journey would require multiple planetary gravity assists, adding more than three years to the total trip time. A probe fitted with "the little plasma engine that could" would be able to do the job in a significantly shorter period. ∎

➥ **MORE TO EXPLORE**

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DON DIXON