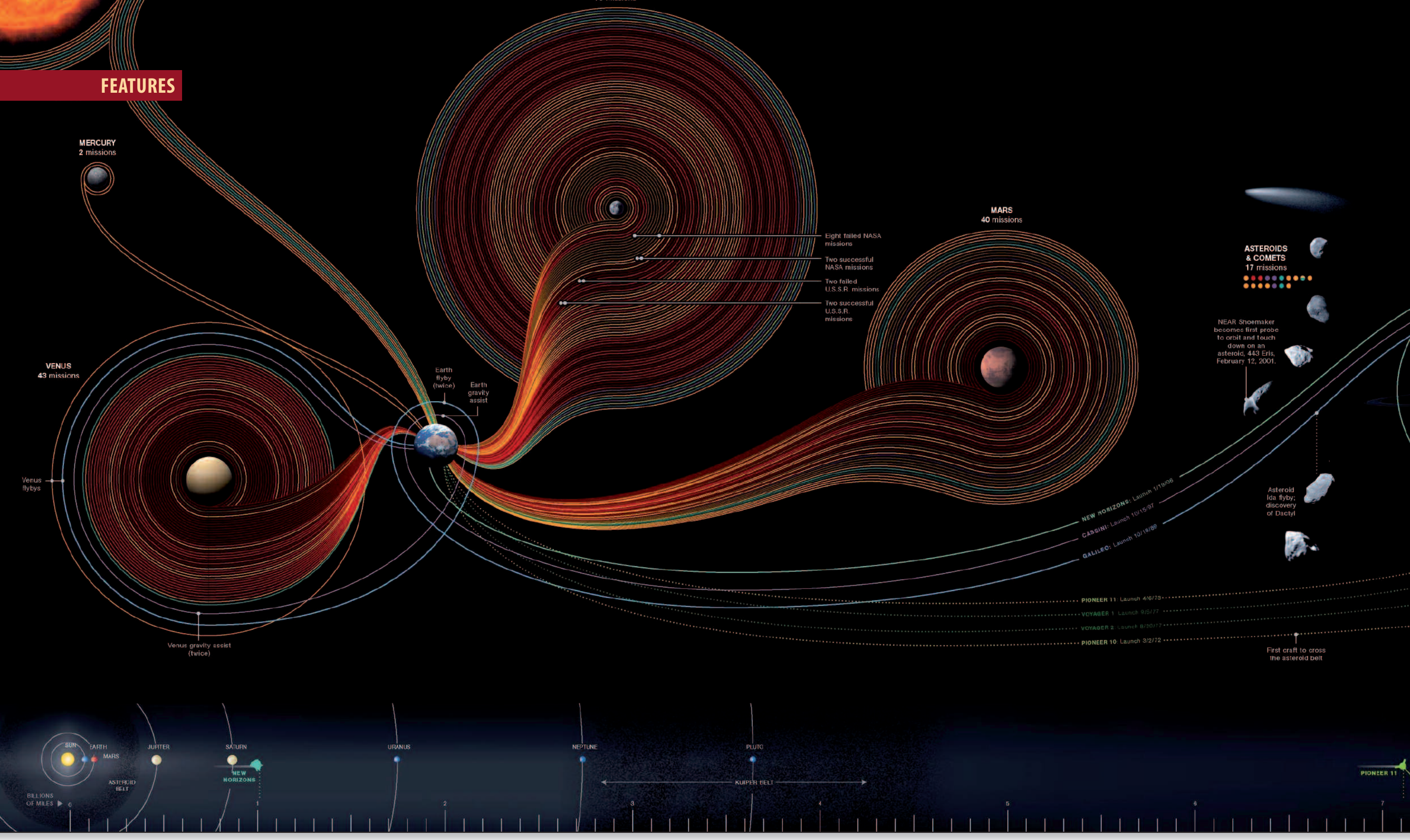

▲ Image created by graphic designers Sean McNaughton and Samuel Velasco for National Geographic.

Space Exploration Technologies

PEGASES a new promising electric propulsion concept

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Space represents a unique vantage point for both exploring the universe and looking down onto our own planet, enabling major discoveries with regard to our origins and the environment we live in. To observe, communicate and explore, we need technologies that can control our movement in space. This article will give a short introduction into spacecraft propulsion and present a new promising electric propulsion technology.

Above is an artistic illustration of all the space missions carried out since the 1950s, and it shows our relatively short history in exploration and observation from space. We have done more than 70 missions to the moon, 9 to the sun, 40 missions to Mars, and several other missions to the far- reaching planets and their moons. Pioneer, launched in the 70s, was the first human- made spacecraft to cross the asteroid belt, and Voyager the first spacecraft to approach Uranus and Neptune. Voyager is now in the interstellar space (beyond the boundary of our Solar System), and more than 30 years after its launch it still transmits data back to earth.

How to move in space?

To allow exploration and observation in space, we need a control of the spacecraft position in space. On earth, friction and gravitation forces help us moving. In space these forces are negligible or non-existing: So how do objects move by pushing on nothing?
Isaac Newton gave the answer as early as in 1687 when he published the laws of motion, where the third law states that every action has an equal and opposite reaction. The Russian physicist Konstantin E. Tsiolkovsky (1857-1935) was one of the early pioneers in space rocketry and used Newton's laws to derive what we now refer to as the rocket equation:

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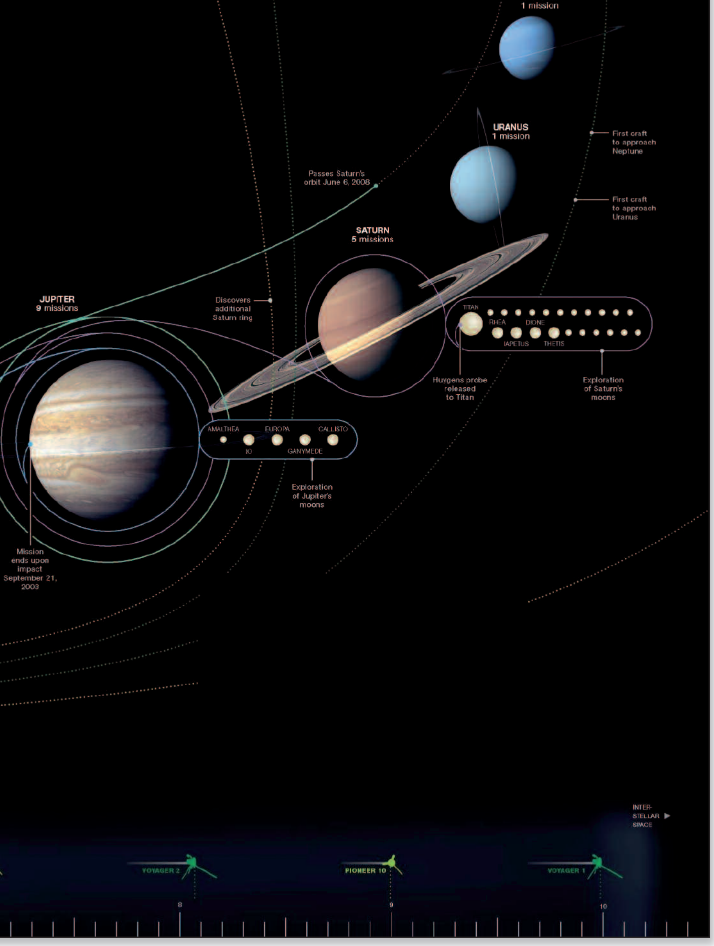


$$T = m\frac{dv}{dt} = -\frac{dm}{dt}v_g$$

It shows that the force T (called thrust in the space community) acting on the spacecraft equals the rate of change of the spacecraft mass (dm/dt) times the velocity v_g of the ejected particles (v is the spacecraft speed).
The delivered thrust is one of the major performance values used to classify a thruster concept. There are many different ways to generate thrust. For example, a rocket uses a chemical reaction or combustion to give a large transfer of momentum to the propellant; the propellant then passes through a nozzle to accelerate the fluid to high velocities. A lot of mass is ejected during a very short period of time and even if the velocity of the ejected particles is not very high, the thrust values can reach up to hundreds of Mega-Newton. To escape earth, the thrust created by the propulsion system has to be bigger than the weight of the escaping body. Chemical propulsion, with its enormous thrust, is therefore very suitable for launching objects into space and is so far the only method to leave the Earth's gravitation field.

Specific Impulse and Propellant consumption

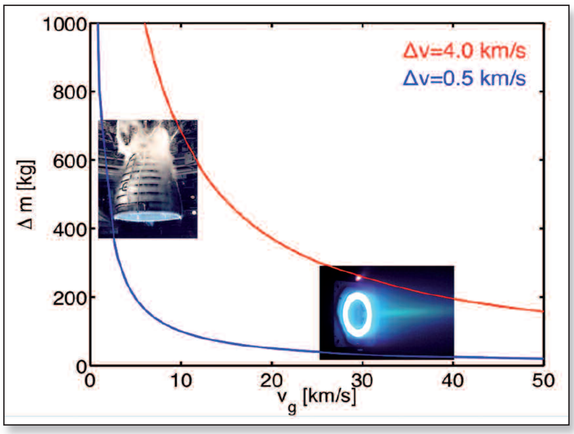
By integrating the rocket equation, we can find an expression for the required amount of propellant Δm, which also corresponds to the change in the spacecraft mass, as a function of the propellant velocity v_g. Figure 1 shows that high v_g leads to a strong reduction in the use of propellant. A thruster is therefore also evaluated depending on its propellant velocity, which in the space propulsion community is defined as the thruster's Specific Impulse $I_{sp} = v_g/g_0$, where g_0 is the gravitation at sea-level. The higher the I_{sp} the more propellant efficient is the system.

Chemical versus Electrical propulsion

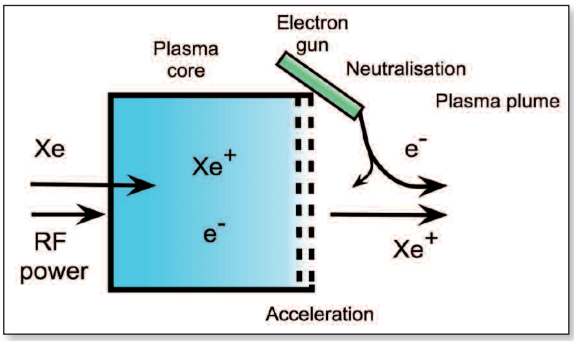
Electric propulsion (or plasma propulsion) offers very high v_g. Contrary to chemical propulsion the amount of ejected propellant is low. As a result, only low thrust values can be achieved. Typically, current electric propulsion systems offer an I_{sp} of around 3000 seconds and a thrust of a few hundreds of milliNewton, in comparison to chemical propulsion systems that have typically an I_{sp} of less than 400 seconds but thrust values that can vary from 10 Newton to several Mega-Newton. If we take the example of an interplanetary mission that will need a velocity change Δv of 0.5 km/s (figure 1), to achieve the same maneuver one could go from a propellant mass of around 300-400 kg to only 25 kg by choosing electric rather than chemical propulsion. Yet, the duration to achieve the maneuver is very different due to the thrust level. Launchers (huge rockets using chemical propulsion) are used to get a spacecraft up into space. In Europe, Ariane V is one of the biggest and most powerful on the market and can for example bring two satellites of around 2-5 ton into space. To use this launcher costs about 14000 euro per kg that are brought up to GEO orbit [1]. The 300 kg saved in using electric propulsion would correspond to a budget reduction of 4 million-euro.
One would therefore expect that all spacecrafts or space probes would be driven by electric propulsion when they are in space. The first mission that used electric propulsion as a unique propulsion system was launched in 1989 with the Deep Space I program. This mission was very successful and showed its huge potential. Despite this fact, only a few percent of the space probes, commercial and military satellites, use electric propulsion today. WHY?
One of the reasons is due to "political inertia": The decision makers in charge of the mission are not ready to take the risk of using new technology, as it might not work and therefore jeopardize the whole mission. Another more fundamental reason will be clarified below.

Principle of electric propulsion

Existing technologies for electric propulsion, illustrated in figure 2, uses electrostatic or electromagnetic fields to accelerate a beam of positively charged ions to generate thrust



◄ **FIG. 1:** Total propellant needed during a mission as a function of the ejected particle velocity. The example is given for a spacecraft with an initial mass of 2 ton. Δv is the total velocity change required for a certain mission; 4 km/s is required to change from Low earth orbits (LEO) to Geostationary orbits (GEO), while 0.5 km/s is more suitable for interplanetary missions.



▶ FIG. 2: Illustration of the existing electric propulsion concepts. High-density plasma is created, in which positive ions are accelerated and neutralized by electrons downstream of the acceleration stage. Usually Xenon is used, as it is heavy and therefore good for thrust and does not require much energy for ionization.

[2]. The ions are accelerated from a *high-density plasma*, consisting of positive ions, electrons and few neutrals. To ensure an efficient use of the propellant most of the ejected particles should be ions (and not neutrals).

In space, when a positive beam of ions leaves the thruster, the space vessel would charge negatively. This would lead to a charge separation and therefore an electric field that would cancel the acceleration field. To avoid this charge separation, the positive ion beam needs to be neutralized downstream of the acceleration stage. This is normally done by an electron gun feeding electrons into the positive stream. As a result a quasi-neutral beam leaves the thruster and provide thrust.

Two weak points in existing technologies

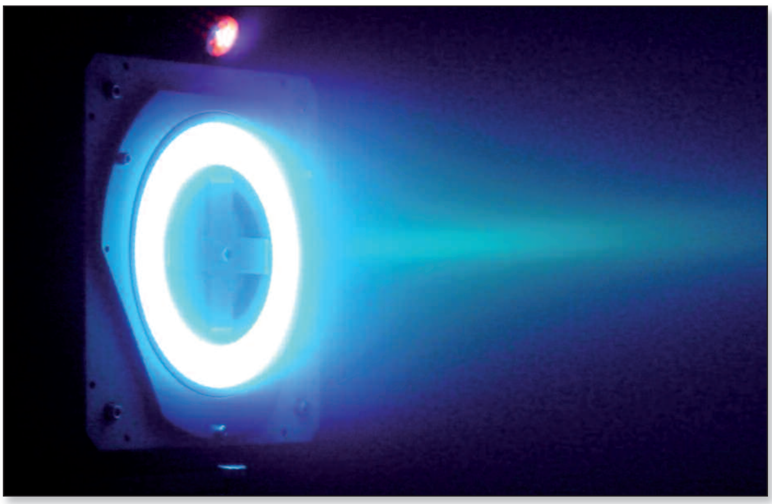
The lifetime and stability of the electron gun are very often critical, and might limit the lifetime of the thruster at high power operations. Much effort is put into improving these issues, and the evolution of the hollow cathode (the most advanced electron gun on the market) is improving rapidly.

The plasma plume outside the thruster, visible on figure 3, causes another more fundamental problem: The fast ions leaving the thruster have typically a speed around 20-40 km/s or larger. They escape from the spacecraft immediately. But some of these fast ions collide with the ejected neutrals before they escape, and in this collision they can exchange the charge. As a result a fast neutral escapes the thruster and a slow ion remains in the surrounding of the thruster. The plasma plume contains therefore the accelerated ions and neutrals from the thruster, the electrons ejected for neutralization, and the slow ions generated in the plume.

These slow ions can cause damage to the satellite/spacecraft. Since the spacecraft is typically not an equipotential surface these ions can backscatter which results in sputtering of the thruster itself, the solar panels and other external surfaces of the spacecraft.

This ion backscattering problem is probably the most reasonable argument for why electric propulsion is still not used excessively in the space industry. However, up to now there has been no mission failure due to ion-spacecraft interactions.

▼ FIG. 3: A picture of the PPSX®000-ML Hall-effect thruster operating in a test facility at the ICARE institute. The glowing plasma plume is beautiful, yet it can cause problems due to the slow ions backscattering towards the spacecraft. The electron gun is the red-glowing element on top of the thruster core.



PEGASES – a new promising concept for electric propulsion

With this in mind, we propose a new concept for electric propulsion [3-5]. This concept is called PEGASES and is an acronym for Plasma propulsion with Electronegative GASES. The concept is illustrated on figure 4.

Instead of accelerating only positive ions to provide thrust and use negatively charged electrons for neutralization downstream, in the PEGASES thruster both positively and negatively charged ions are accelerated and provide thrust. In this way the additional neutralization system is redundant and the issue related to the plasma plume is reduced. The PEGASES thruster operation can be separated into 3 stages:

Stage 1 is the ionization stage occurring in the plasma core (see figure 4). Here the external power is coupled to the electrons such that they get sufficient energy to ionize the gas and form the plasma. To be able to create both positively and negatively charged ions, the gas has to be electronegative. This means that the gas molecules have a high electron affinity and allow electrons to attach to the molecules, creating negatively charged ions. Electron attachment occurs when electrons of low energy collide with the neutral molecules. In contrast, if the electrons are more energetic the electron-molecule collision results in ionization. Electronegative gases are typically molecular gases containing halogens such as fluorine (F), chlorine (Cl), bromine (Br) or iodine (I).

Stage 2 is the electron filtering stage. Charged particles gyrate around magnetic field lines due to the Lorenz force. Since the electrons are much lighter than heavy ions, a magnetic field can be used to confine the electrons in the plasma core, but allow the ions (of opposite charge) to diffuse perpendicular to the field. The electrons can only move perpendicular to the field by collisions, and are therefore cooled down when diffusing in this direction. These colder electrons attach efficiently to neutrals forming negative ions. As a result the plasma in the PEGASES thruster is segregated into two regions, i) a plasma core comprising positive and negative ions and electrons and ii) an ion-ion plasma region comprising only positive and negative ions. The ion-ion plasma is a new type of plasma, and currently much research is done on the fundamental physics of these plasmas. The ion-ion region is the heart of the PEGASES thruster and is a distinctive feature of this new concept.

Stage 3 is the acceleration stage. Due to the formation of the ion-ion plasma it is possible to accelerate both types of ions for thrust. The acceleration is obtained, similar to classical gridded thrusters, by two or more parallel grids polarized to generate an acceleration field between them. In the PEGASES thruster, one of the grids is alternately biased, changing alternately the acceleration field. As a result consecutive bursts of positive and negative ions are extracted and accelerated out of the thruster, and both the positive and negative charges provide thrust.

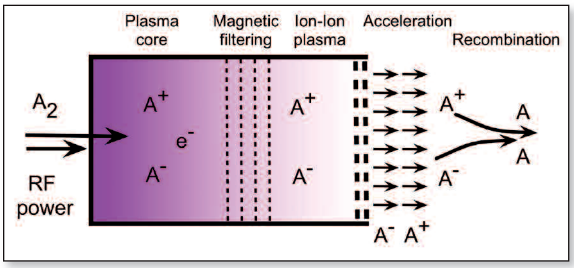
The PEGASES advantages

Since both positive and negative ions leave the thruster, there is no need for an additional neutralization system. This is a promising advantage for this innovative concept, but it is not the only advantage and probably not the most important one. As discussed above, with the current technologies a fraction of the plasma plume interacts with the spacecraft components. This plume exists because the recombination process between electrons and ions to form a neutral atom or molecule is a slow process, in particular between the fast ions and the neutralizing electrons. In the PEGASES thruster the only expelled charges are heavy ions, and their recombination process is often much faster than between electrons and ions. The plasma plume outside the PEGASES thruster will therefore transform quickly into a beam of fast neutrals with a significant reduction in the charge density. Remember that the problem with the plume is the creation of slow ions from collisions with neutrals. If the density of charged particles is reduced, also the production of slow ions will be significantly reduced and hence the backscattering problems will be solved.

Current state of the PEGASES development

The PEGASES concept was invented and patented at the Ecole Polytechnique in 2007 [3]. Since then a research team, comprising permanent researchers, post doctoral fellows, PhD students and engineers, have worked ambitiously towards a proof of concept [4,5].

Several prototypes for laboratory tests have been designed and built, and the results are promising for the future. The most recent prototype can be seen on figure 5. The estimated performances of power, mass and thrust efficiencies are comparable to the existing electric propulsion systems. The team aims to measure the thrust within the following year, and these results will show if PEGASES one day will fly in space. ■



◄ FIG. 4: Illustration of the innovative PEGASES concept, where both positive and negative ions are accelerated and used for thrust generation.

About the authors

Ane Aanesland, researcher at the CNRS, and in charge of the PEGASES project. PhD from the University of Tromsø, Norway, in 2004, and received a Marie Curie Intra European Fellowship in 2006. She was the EPS invited speaker at the ESCAMPIG in 2010.

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▼ FIG. 5: The PEGASES prototype, attached to a lager vacuum chamber in the LPP laboratory. Here the permanent magnets are positioned for optimal performance. Photo: P. Lavialle, Ecole Polytechnique.