RESEARCH INTRODUCTION

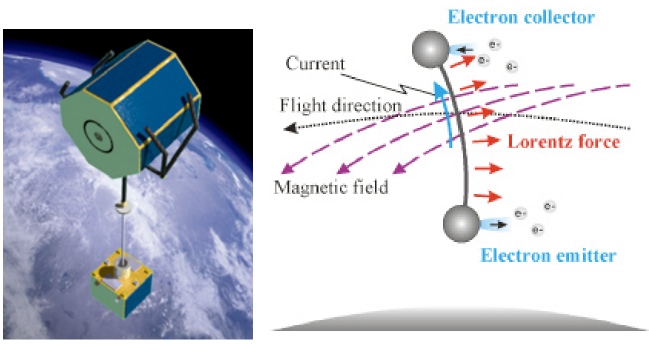
Simple electron emitters for space

Demand for electron sources in space

Asteroid explorer "Hayabusa" returned to Earth on June 13, 2010 after a seven-year space flight using "ion engines" (refer to p. 07). With an electric propulsion system, such as an ion engine, an electron source (neutralizer) for electrically neutralizing expelled positive ions is indispensable.

With outer space in a plasma state, where the thin gas is ionized into positively charged ions and electrons, and under the added influence of various high-energy particles as well as ultraviolet rays, artificial satellites may become electrically charged. If there is a high potential difference between the parts of a satellite due to this "electrical charge", an electrical discharge occurs, resulting in the equipment becoming damaged or malfunctioning. In order to avoid this problem, an electron source can be used to emit the accumulated electrons and relax the charge condition.

Many spent man-made objects (space debris), such as satellites that have completed their missions, are floating in Earth's orbit. At JAXA, we are continuing research and development on a servicing satellite (fig. 1) for reducing space debris, and an electron source is vital to the electrodynamic tether, which is a unique propulsion system for this satellite.



Electromotive force (EMF) is induced along the conductive tether by crossing the geomagnetic field. If electrons are emitted from one end and collected at another end of the tether, electric current is driven through the tether by EMF. The interaction between the geomagnetic field and the tether current generates Lorentz force against the orbital motion.

Fig.1 Principle of the electrodynamic tether and debris removal system

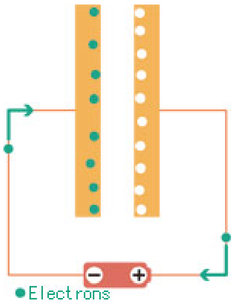
Simple mechanism of electron emission

Electrons can be produced by applying heat to a material. Electrons can also be extracted electrically. Considering the thermal load on spacecraft, it is desirable to realize a "field emission cathode" (FEC).

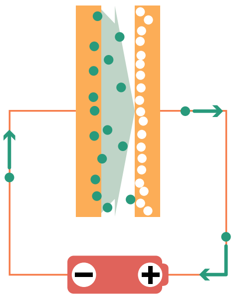
When an electrical field is applied between two parallel electrodes, electrons (free electrons) flow from the electrode with the lower electric potential to that with the higher one. (Fig. 2a) If the electrical field is further increased, a phenomenon occurs called "quantum tunneling", where accumulated electrons are emitted. (Fig. 2b) If there are pointed structures on the emitting side, the electrons are more easily emitted since a high electrical field can be achieved, even if the electrical potential difference is small. (Fig. 2c) In other words, how finely the structure is made becomes key.

In 1991, material composed of carbon atoms and having the minute size of a diameter between one nanometer (one-billionth of a meter) and tens of nanometers and of a length of a few micrometers (one-millionth of a meter), called "carbon nanotubes", was discovered. Carbon nanotubes have the property of easily emitting electrons from the tube end when an electrical field is applied. Our study is based on this simple mechanism of electron emission using carbon nanotubes.

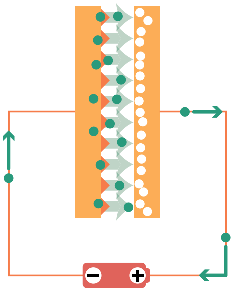
In field emission cathodes, electron flow into the gate should be reduced because flow means power loss and



a When an electrical field is applied between two electrodes, electrons flow from the electrode with the lower electric potential to that with the higher one.

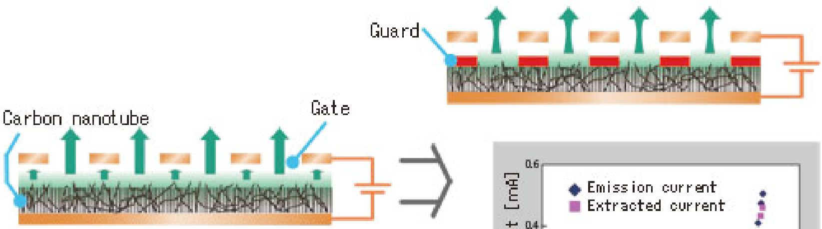


b If a high electrical field is applied, accumulated electrons are emitted from the electrode (quantum tunneling).



c If there are pointed structures on the emitting side, a high electrical field can be achieved with a low voltage difference and quantum tunneling occurs.

Fig.2 Quantum tunneling



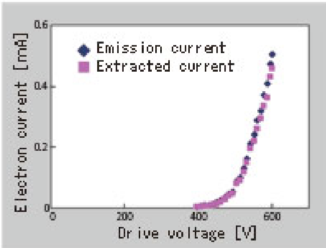


Fig.3 Field emission

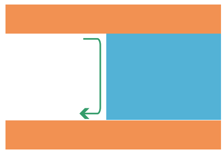
may cause electrode deformation due to thermal stress. Therefore, we have taken the approach of reducing the loss current by placing a guard on the cathode. (Fig. 3) This has made it clear that electrons can be obtained more efficiently than with conventional technology.

Currently, we are conducting research and development with the aim of performing a demonstration test in space of an electrodynamic tether equipped with an electron source developed based on this method.

Aiming at higher efficiency

In order for a large amount of electrons to be emitted under a low voltage, reducing the distance between the electrodes would be effective. Although a space currently remains between the electrodes because of the metal screws, a method of sandwiching insulating material between the electrodes (layering method) is considered effective in reducing the spacing between electrodes and simplifying the construction. However, if the spacing between electrodes is too small, a phenomenon called "creeping discharge" occurs, where electricity flows along the surface of the sandwiched material. (Fig. 4a) Therefore, we believe that we can curb creeping discharge by making the insulator film as thin as possible and constructing it in multiple layers. (Fig. 4b)

a If something is sandwiched between the electrodes, even if it is an insulating material, a "creeping discharge" occurs, where electrons move along the surface (current flows).



b We believe this "creeping discharge" can be prevented if the insulating material sandwiched between the electrodes has a multi-layer construction or a rough surface.

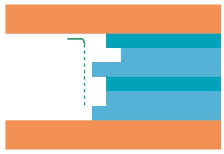


Fig.4 Preventing a creeping discharge by layering

Figure 5 shows the results achieved with the layering method. In comparison with the method where a space is maintained between electrodes (fig. 3), the required voltage can be significantly reduced, making this an effective low-voltage method. However, we can see that only half the total of emitted electrons is extracted through the gate. We believe this is due to misalignment of the electrodes. We are now studying methods to improve the electron extraction efficiency, such as the sophistication of the assembling technique and the application of other nanocarbon materials.

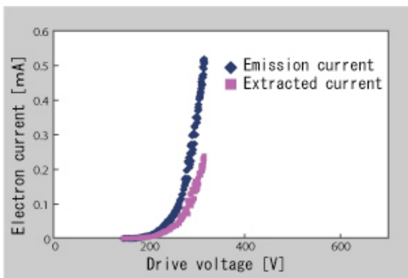


Fig. 5: Electron emission resulting from the layering method

[**Innovative Technology Research Center**]

(From left) Kouji Matsumoto, Yasushi Ookawa, Satomi Kawamoto, Syoiji Kitamura.

RESEARCH INTRODUCTION

Moving smoothly in any environment

Lubricants also used in space mechanisms

A heavy object placed on the floor does not move, even if it is pushed or pulled. (Fig. 1, left) Now, place that same object on top of round rods arranged side by side. This time, when the object is pushed, it can easily be moved. (Fig. 1, right) In this case, the rods assume the role of lubricant.

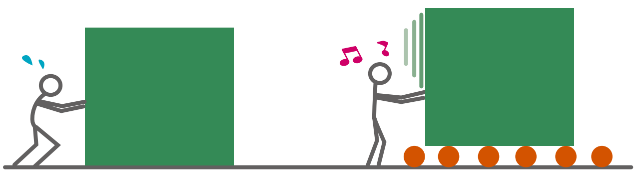
In mechanisms assembled from various parts, such as gears, lubricants are essential for smooth operation and minimizing friction between the parts. This is also true in space. Both "liquid lubricants" and "solid lubricants" are used in space. As liquid lubricants, oils and greases are used in the same way as on the ground. However, in a special environment such as a vacuum or zero gravity, use of a lubricant with a low evaporation rate is mandatory, and an appropriate supply amount and method must be devised. As solid lubricants, soft metals, molybdenum disulfide or polymer materials, such as PTFE, are mainly used, because they display a low friction coefficient in a vacuum. The solid lubricants reduce friction by creating a lubricating film on the surface of the parts, resulting in smooth movement..

Low Earth orbit-the low vacuum of space

Artificial satellites, such as earth observation satellites, are operating at altitudes called a "low Earth orbit", which is within the area around Earth to an altitude of 2,000 km. The International Space Station (ISS), where astronauts from various countries live for long periods of time to perform experiments and observations, is being constructed in a low Earth orbit at an altitude of 400 km. In a low Earth orbit, the environment is a low vacuum , and there are large amounts of ultraviolet rays. The oxygen has become atomic oxygen, where bonds between atoms have been broken, and there is a lot of contamination(*) in this environment. Even in this harsh environment, lubricants must fulfill their role properly.

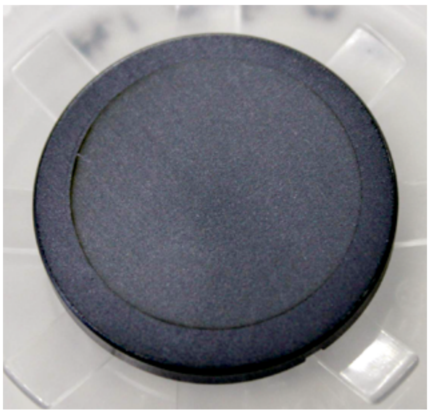
From October 2001 to August 2005, three sets of experimental apparatuses mounted with materials, including solid lubricants, used in various spacecraft were placed on the Russian Service Module of the ISS, and space exposure experiments were performed with each set retrieved after a fixed period of time. (Refer to "Sora to Sora", no. 14.)

After similar space exposure experiments were conducted for about 8 months on the exposed facility of the Japanese experiment module (JEM) "Kibo" on the ISS, the experimental apparatuses returned to Earth in April 2010 with Astronaut Yamazaki. Compared with the rear location of the Russian Service Module on the ISS, relative to the direction of travel, JEM is at the front, where the environment has very little contamination. By comparing the experiment results, we expect that we will be able to understand the effects of a space environment, such as contamination, on materials, including lubricants, used in



Even an object that does not yield whether it is pushed or pulled (left) moves smoothly when round rods are placed between it and the floor to reduce friction (right).

Fig.1 Concept of lubricants



By comparing the results of the space exposure experiments and the results of the ground experiments, we believe the most appropriate method for the ground simulation test can be obtained.

Fig.2 Solid lubricant used in the space exposure experiment with JEM space. Currently, we are in the process of analyzing, on the ground, the various tested materials from the JEM exposure experiment. Performing experiments in space is not easy.

Therefore, in order to evaluate the effect of the space environment, solid lubricants are being exposed to atomic oxygen and ultraviolet rays on the ground, and their conditions are being evaluated. Atomic oxygen and ultraviolet rays are assumed to be a major cause of lubricant degradation. Since silicon-based materials have been recognized as one cause of contamination, they were applied to the surface of solid lubricants, and assessment testing simulating the space environment is being performed. By comparing the results of these ground experiments and the results of exposure experiments performed in space, we believe we will be able to assess the method for the most appropriate ground simulation test. (Fig. 2).

Moon dust appearing to be quite troublesome

The surface of the moon is covered with a fine dust called "regolith". We are concerned about whether the lubricant will function properly and the machine will operate if regolith, which is different from dust on the ground, enters mechanical components. Therefore, we are performing ground experiments with sand that simulates regolith (regolith simulant).

Figure 3 shows an illustration of the concept of the experiment. The regolith simulant is inserted between a roller and a surface with the solid lubricant applied, and then the roller is rotated and pressed on the surface with the simulant between them. In this experiment, the solid lubricant is assessed to determine how it is affected by the regolith. In this case, we have determined that conventional solid lubricants are immediately worn by

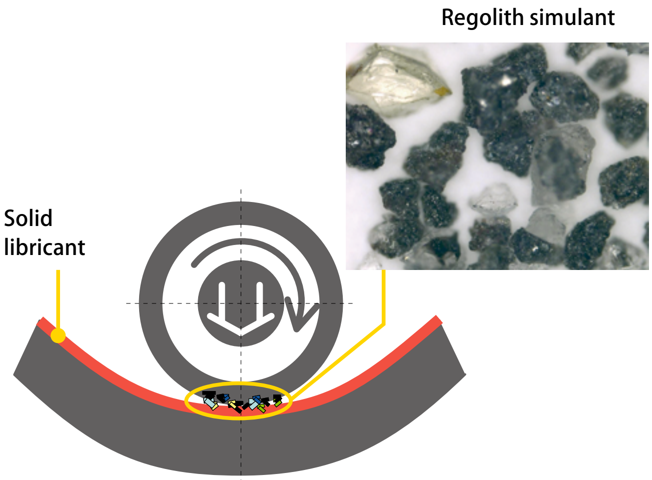


Fig.2 Numerical analysis results

regolith. Therefore, we are performing assessment testing to determine if harder and tougher materials, such as composite materials of ceramics and polymers, can be used as new lubricants.

The surface of the moon is an extremely harsh thermal environment, as compared to that of Earth; for example, there are areas that are not exposed to the rays of the sun all year round. Using the space tribology testing facilities (Refer to here), we are continuing assessment testing in environments of extremely low temperatures in order to study how solid lubricants function in such thermal environments.

(*) Contamination : In the same way that the water in a cup left standing naturally evaporates, gaseous molecules are gradually emitted from the surface of a spacecraft exposed to space. These gaseous molecules, called outgassing, drift near the spacecraft shortly after being emitted and attach to sensors, cameras and solar panels, resulting in contamination. Contamination impairs the sensitivity and performance of satellite instruments.

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Ion engines

■ Various propulsion systems used in spacecraft

On September 11, 2010, the first quasi-zenith satellite, "Michibiki", was launched by an H-IIA launch vehicle from the Tanegashima Space Center. In order to defy gravity and move the man-made satellite into space, a propulsion system able to achieve a large thrust was needed. The H-IIA advances through the counterforce to the expulsion of expanded gas obtained when fuel (liquid hydrogen) and an oxidizing agent (liquid oxygen) are mixed and ignited. A propulsion system that uses energy from chemical combustion in this way is called a "chemical propulsion system". (Fig. 1a)

In contrast to a chemical propulsion system, a propulsion system that achieves thrust through physical force is called a "non-chemical propulsion system". There are various types of non-chemical propulsion systems. For example, the small solar-powered sail demonstrator "IKAROS", launched on May 21, 2010, advances by means of a "solar sail propulsion system", which deploys a micro-thin solar sail that seizes the pressure from sunlight. (Fig. 1b)

Asteroid explorer "Hayabusa", which returned to Earth on June 13, 2010, was equipped with an "ion engine" providing thrust through electrical force.

■ Mechanism of an ion engine

An ion engine consists of a "discharge chamber", where ions are generated, an "ion accelerator", which accelerates those ions, and a "neutralizer", which emits electrons. (Fig. 2)

The discharge chamber is filled with atoms, such as xenon, which are bombarded with electrons and converted into cations. In a grid system, the appropriate electric potential is provided to accelerate the cations, which are expelled downstream. As a counterforce to this, thrust can be achieved.

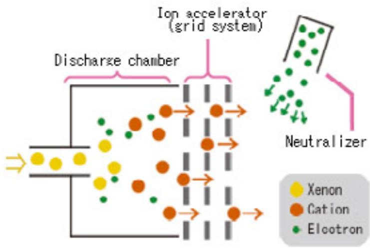


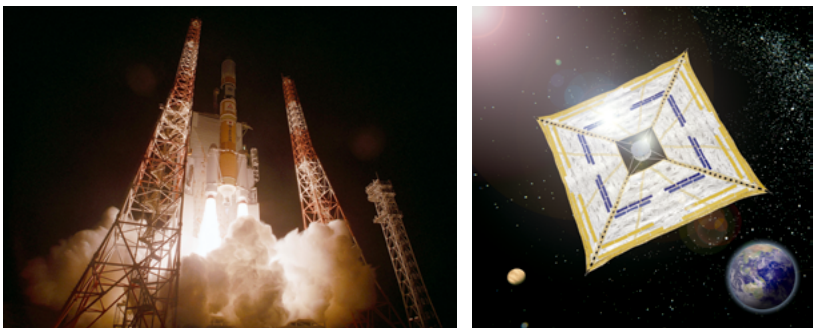
Fig.2 Principle of the ion engine

The role of the neutralizer is to maintain the spacecraft's electrical neutrality by emitting into space electrons equivalent to the expelled cations. By neutralizing expelled ions, it also has the function of allowing the spacecraft to stay in space in a stable plasma state.

■ High fuel efficiency of ion engines

Thrust is determined as "the amount of propellant expelled in 1 second × the exhaust velocity of the propellant". In other words, if the exhaust velocity is increased, the amount of propellant necessary to achieve the same thrust decreases. Since the exhaust velocity in a chemical propulsion system is determined according to the amount of chemical energy that the propellant has, there are limits on this velocity. Because of the electrical force of the ion engine, an exhaust velocity of at least 10 times that achieved with chemical energy is possible.

To achieve the same thrust, a higher exhaust velocity can minimize propellant consumption, making these "fuel-efficient engines". Since they can operate longer than a chemical propulsion system with the same amount of propellant, we believe that spacecraft can move at high speeds by expelling propellant for a long period of time and even be able to travel to the outer edges of distant solar systems. However, since the generated thrust is not very large, it cannot be used for the large sudden thrust necessary to defy gravity and launch satellites.



a　H-IIA launch vehicle
Rising high into the sky while producing a thunderous roar. This launch vehicle is a representative of the chemical propulsion system.

b　IKAROS
Advancing toward Venus with the large, ultra-thin sail (20 m square and 0.0075 mm thick) deployed and gathering pressure from sunlight.

Fig.1 Various space propulsion systems