SELECTED CHALLENGES IN SPACE ION PHYSICS RESEARCH AND TECHNOLOGY

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Abstract: Ion physics in outer space and on-board is under short consideration. We focus on ionization, desorption, ion sputtering, mass-to-charge analysis, particle acceleration and trapped motion in electromagnetic field, electrical propulsion, and so on. A brief analysis of ion mass spectrometry physical background, technologies, and applications in space is provided. Several specific challenging cases present actual tasks of ion technology and mass-spectrometry in space.

Keywords: Space, Jet Thrust, Ionization, Desorption, Sputtering, Mass Spectrometry.

Introduction

Space activities and applications are vital to our society's growth and development. Space research aims to foster a cost-effective, competitive, and innovative space industry, and advanced research community as well. In this context, space policy is an instrument responding to social, economic and strategic types of need. Space ion physics is basic scientific research carried out using novel technologies and scientific equipment in outer space. That includes the use of space technology for a broad spectrum of research and technology fields, including Earth science, materials science, life science, electric propulsion, technical developments, and ion physics. The scientific objectives of expeditions to Planets of Solar system and small objects in space are to study their surface, subsurface and atmosphere, as well as the interaction with the interplanetary medium. Comets and asteroids carry interstellar materials pivotal to understanding prebiotic molecules that could have initiated life on Earth. About one third of the molecules detected in the interstellar medium or circumstellar shells are complex ones, containing six or more atoms. Using electric energy is especially important because it can be produced on-board by means of the solar radiation conversion. In that content, electrical Hall and ion-based thrusters both have been successfully used for primary propulsion in both deep-space scientific missions and satellite station control. On-board mass-spectrometry (MS) in outer space is most powerful analytical tool for materials science in general, and for investigation of any kind of remote substance like solid state, gases and solutions, in form of atoms and molecules particularly.

Ion Physics and Jet Engines

According to the fundamental laws of nature, the jet propulsion apparatus can be realized by ejecting an expendable material agent in the form of combination of electromagnetic field irradiation and massive matter ejection. The required technologies are initiation of reactions by means of electrical energy, effective operation in vacuum conditions with appropriate expendable substances, and production of accelerated particle beams leaving the jet into free space, and originated from the mentioned substances (agents). The ion beam exiting the thruster is often called the thruster plume, and the characteristics of this plume are important in how the exhaust particles interact with the spacecraft. The plume from a thruster typically has a complex structure. This material can deposit on spacecraft surfaces, which can change surface properties such as emissivity, transparency, etc. Electric thrusters propel the spacecraft using the same basic principle as chemical rockets — accelerating mass and ejecting it from the vehicle. The ejected mass from electric thrusters, however, is primarily in the form of energetic charged particles. Electric thrusters provide exhaust velocities higher than those available from gas jets or chemical rockets. For explanation of modern thrusters operation, it is required to describe the fundamental physics of these devices. This is a task requiring basic knowledge of plasma physics, ion accelerators, cathodes, electrical discharges, high voltage, gas dynamics, and many other technologies. The total efficiency is the jet power produced by the thrust beam divided by the electrical power in the system. Electric thrusters are generally described in terms of the acceleration method used to produce the thrust. These methods can be separated into three categories: electro thermal, electrostatic and electromagnetic. Ion thrusters employ a variety of plasma generation techniques to ionize a large fraction of the propellant. Ion thrusters feature the highest efficiency. Electrostatic thruster of Hall type utilizes a cross-field discharge described by the Hall effect to generate plasma. Such thruster efficiency and specific impulse are somewhat less than that achievable in the ion thrusters, but the thrust at a given power is higher and the device is much simpler and requires fewer power supplies to operate. The most well-known Russian SPT-100 Hall thruster operates nominally at electrical power of 1.35 kW. This thruster includes a redundant hollow cathode to increase the reliability and features a lifetime in excess of 9000 hours. There are many other types of electric propulsion thrusters: electro thermal resistojets and arcjets, electrospray/field emission, pulsed plasma, magneto plasma dynamic, and many others [1].

Indeed, the electromagnetic field radiation reactive force produces mechanical pressure on an *open* resonator, or antenna, as predicted by A. Einstein in 1906, demonstrated experimentally by P.N. Lebedev, and confirmed theoretically elsewhere based on Maxwell's equations in a framework of classical electrodynamics on the conductor boundary [2–5]. However, it is impossible to create a sufficient momentum thrust by means of electromagnetic field with an *open* empty inner volume of a microwave cavity. The maximum pressure force produced by electromagnetic field equals approximately to $|F_{EMF}| \approx 2W / V_g$, where W is a radiation power expanded freely into space, V_g is the group velocity of the wave (which has a value close to the speed of light). The coefficient of 2 appears when the wave incidents from outer space and is re-irradiated back. Excessive input power, approximately 150 MW, is required for notable acceleration values produced by 1N of force. Recently, the idea has appeared for an “EM Drive” which generates a small amount of thrust simply by bouncing microwaves in closed interior volume of a cone-shaped copper chamber. These approach and view are based on an erroneous assumption that, in the steady state excitation regime, a closed cavity, continuously irradiated by microwave power flow, can convert it into unbalanced force and kinetic energy of the motion of closed mechanical system. Of course, such closed system generates zero radiation of radio frequency power into space; therefore, the jet thrust must vanish [6]. There are no reasons to support the attractive EM Drive concept. There is no serious theoretical explanation for how such an engine might work, and not all possible sources of experimental error were under critical consideration in the article [7]. To put it briefly, such artifacts could be caused by a) radio frequency non-uniform heating of the chamber and b) infrared radiation pressure acting from outer volume on hot walls.

The challenging tasks in the field of ion physics and electrical propulsion could be presented by a novel design of high quality long-life thrusters, their optimum design, protected from any secondary negative effects; selection and preparation of expendable substances; 2D/3D computer modeling of a plume; the practical implementation of desorption and sputtering of the outboard solid-state substances [6]. Other possible applications might involve materials preparation, chemical reactions and building procedures by means of ion technologies on planets' surfaces.

Space Mass-Spectrometry

In the human practice on Earth's surface, vacuum mass-spectrometry (MS) is extremely effective, high sensitive and almost universal analytical tool, having wide spread in science, technology, medicine, and many others applications. MS is based on a great deal of fundamental knowledge in any kind of sample collection, ionization, desorption, ion sputtering, principles of charge particles motion in electromagnetic fields in vacuum chambers, determination of ion trajectory, design, and parameters of data acquisition systems, and information technologies. Further, practical MS requires specific experience of applications and "know-how" as well. In outer space missions, MS keeps its outstanding analytical features, so we can expand our knowledge and understanding of universe positively [8]. The space programs include MS for both environmental monitoring and as a tool in on-board medical experiments. Several examples could confirm this idea. The lower atmosphere MS were flown on the USA Pioneer Venus and on the USSR Venera 11 and 12 landers. One upper atmosphere MS was on the Pioneer Venus and one on the Pioneer Venus Orbiter. The last three Apollo flights to the moon carried magnetic MS to detect the presence of an atmosphere and to determine its composition. MS experiments carried by spacecraft Giotto (Europe), Vega 1 and Vega 2 (USSR), determined the abundances and the chemical, elemental and isotopic composition of the gases and low-energy ions in the coma of Halley’s Comet. The Cassini mission to Saturn launched in October 1997 was equipped by MS designed to identify and measure chemicals in Titan's atmosphere. By means of Viking 1, Viking 2 and The Phoenix spacecraft landed on Mars, a number of MS programs were realized there. The Ion Mass Analyzer of Mars Express Orbiter mission was an improved version of the ion mass spectrographs TICS/Freja, IMIS/Mars-96 and IMI/Nozomi and a copy of Rosetta’s ICA instrument [8]. An ion MS measured relative abundances of collected ion samples from the ionosphere. Gas Analyzer MS was built for use on Shuttle's biomedical laboratory missions that flew between 1989 and 1995. However, space MS applications require some different approaches to hardware design, sample collection, its processing and analysis, data storage, and utilization. Specific conditions include weight and power limitations, high acceleration and acoustic vibrations during launch, extreme temperature variations and ionizing radiation, remote telecommunications. It is essential that all ionization and detection processes are clear, stable and long-life. Micro-scale size MS are optimal required for space applications with small orbital satellites and deep missions as well, e.g. for the chemical composition and biomarker exploration of planets, asteroids and comets. Hybrid and tandem MS look like emerging promising device for future study of complex molecules in space.

Conclusion

Ion physics, technology, and mass spectrometry reveal great opportunities in the field of modern and future space investigations. Selected challenges here require a novel design of both ion-based propulsion and ion mass-spectrometry hardware, implementation of advanced ionization, desorption, and ion sputtering schemes, wider using of any natural resources, available in space expeditions.

References

1. Dan M. Goebel and Ira Katz. Fundamentals of Electric Propulsion: Ion and Hall Thrusters //JPL Space Science and Technology Series, Jet

Propulsion Laboratory, California Institute of Technology. March 2008. 486p.
2. Einstein A. The principle of conservation of the center of gravity movement and the inertia of energy. Ann. Phys. 20, 627-633, 1906
3. Lebedew, P. Über die ponderomotorische Wirkung der Wellen auf ruhende Resonatoren. III. Akustische Hohlresonatoren. - Leipzig, 1897 - 20 S. - (Annalen der Physik und Chemie. Neue Folge. Bd. 62).
4. Von Peter Lebedew. Über die ponderomotorische Wirkung der Wellen auf ruhende Resonatoren. II. Hydrodynamische Oscillationsresonatoren // Annalen der Physik und Chemie. Neue Folge. Bd. 59. 1896. - Leipzig: Johann Ambrosius Barth (Arthur Meiner), 1896. - 18 S
5. Griffiths, David J. (2007), Introduction to Electrodynamics, 3rd Edition; Pearson Education – Problem 9.10.
6. Tsybin, O.Y., Makarov, S.B., Ostapenko, O.N. Jet engine with electromagnetic field excitation of expendable solid-state material // 2016. Acta Astronautica, 129, pp. 211-213. doi:10.1016/j.actaastro.2016.08.022
7. Harold White, Paul March, James Lawrence, a.o. Measurement of Impulsive Thrust from a Closed Radio-Frequency Cavity in Vacuum // Journal of Propulsion and Power, Vol. 33, No. 4, July–August 2017, p.830-841. doi: 10.2514/1.B36120
8. Hoffman, John. H., Griffin, Timothy P., Limero, Thomas., Arkin, C. Richard. Space Applications of Mass Spectrometry. NASA Technical Reports. Chapter 31. February 01, 2010. 130 p. Document ID 20100039433.

CESIUM ATOMIC CLOCK FOR GLONASS SATELLITE NAVIGATIONAL SYSTEM

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Abstract: One of the essential elements of satellite navigation system is an atomic clock. The proper operation of any navigation system depends on the performance of atomic clock. Several directions of modernization of the cesium atomic clocks are considered. New design of the frequency