The Future of Deep Space Flight Using Ion Propulsion

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As interest grows in establishing a human presence beyond the moon, there has also been an increasing need to research alternative propellants. Electric propulsion using ion thrusters may serve as an alternative to traditional chemical methods. Requiring less propellant, ion thrusters are becoming increasingly more popular in the aerospace industry. Since its first deep space flight in 1998, ion thrusters have been used in a variety of missions from keeping geostationary satellites in Earth's orbit to orbiting the protoplanets Vesta and Ceres. In recent years, NASA Evolutionary Xenon Thrusters (NEXT) and the Annular Ion Engine (AIE) have emerged as two of the major ion propulsion systems of the future. NEXT uses Xenon, the most common element utilized in ion propulsion, this is done to produce greater thrust and helps to reduce manufacturing cost and time. Because of this, NEXT operates at three times the power of previous ion propulsion systems and is tested to operate for six consecutive years. However, the newer AIE has the capability to exceed NEXT. AIE yields a beam area that is twice the size of NEXT's, reduces system complexity, and has a higher thrust-to-power ratio. This paper will explore how ion thrusters such as NEXT and AIE cost less and provide significantly more thrust than current chemical propulsion systems, along with the search for other propellants beyond ion propulsion. This paper will also explore the applications of these propulsion methods in terms of commercial and defense applications.

I. Nomenclature

AU	=	Astronomical Unit
EP	=	Electric Propulsion
kW	=	Kilowatts
mN	=	Milli-Newton

II. Introduction

The capabilities of spacecrafts have been in a constant state of evolution since the early days of the space program in the 1950s. Since launching the first satellite, sending the first person into space and then the moon, Mars has always been the next stop in mankind's cosmic journey. While Mars has become the coveted next mark, propulsion technology has struggled to keep up with the quickly growing desire to get to the red planet and beyond. Since the 1950's, most spacecraft have been powered using, effective yet limiting, chemical propellant. Chemical propellant can be broken up in to three different categories, liquid propellant, solid propellant, and a hybrid of the two. There are many specific types of propellants within these three categories which are well suited for a variety of different missions. For example, the very cold cryogenic propellant is very safe and high preforming yet isn't ideal for long term missions since keeping them cold for long periods of time is very difficult. Another example is the reliable hypergolic propellants which have no ignition system and is well suited for long term space flight, however, they're highly corrosive and dangerous to handle. Containing both an oxidizer and fuel, when ignited, solid

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propellant generates a lot of thrust and is easily stored for long duration missions, however it is difficult to control the specific amount of thrust produced. Taking a solid propellant and liquid or gas oxidizer, hybrid propellants take the best of both liquid and solid propellants, high thrust achieved by solid propellant and the controllability of liquid propellant. While chemical, solid, and hybrid propellants have been able to meet the needs of previous missions, it isn't ideal for long distance human space flight. It took Apollo 11 just over four days to get to the moon traveling at a speed of 24,200 miles an hour. Using that same technology, it would take approximately 122 months. However, there have been advancements in chemical propulsion that can get men to Mars in approximately 7 months. But looking beyond Mars to the moons of Jupiter and Saturn, chemical propulsion is just too expensive, massive, and slow. However, alternant propulsion methods provide a cheaper, lighter, and quicker solution. Interest in electric propulsion has grown rapidly in previous years. Electric propulsion can be split into to three different types; Hall-Effect propulsion, Thermal/Resistojet propulsion, and Ion propulsion, which is the focus of this paper.

III. How Ion Thrusters Work

Ion thrusters use electricity to ionize propellant and generate thrust. The propellant is ionized in a process called electron bombardment, where electrons with high energies bombard a neutral propellant atom, usually xenon, releasing electrons and generating positively charged ions. This whole process results in a negatively charged plasma; when mixed together with the positively charged ions, result in no overall charge. The electrons are kept in the chamber for future ionization and the positively charged ions are ejected through both a positive and negative grid. Once released, the create an ion beam which ejects the ions at 90 km/sec; significantly higher than fuel ejection in chemical thruster at 5 km/sec. Using ion thrusters also have a high fuel efficiency of 90% opposed to the 35% which chemical combustion fuels provide. This whole process is power by electricity generated from solar panels, meaning there is no need for a battery and reduces total weight. While the thrust generated by a single ion isn't significant, while it is measured in mili-newtons, the thrust is constant and can run for long periods of time over long distances.

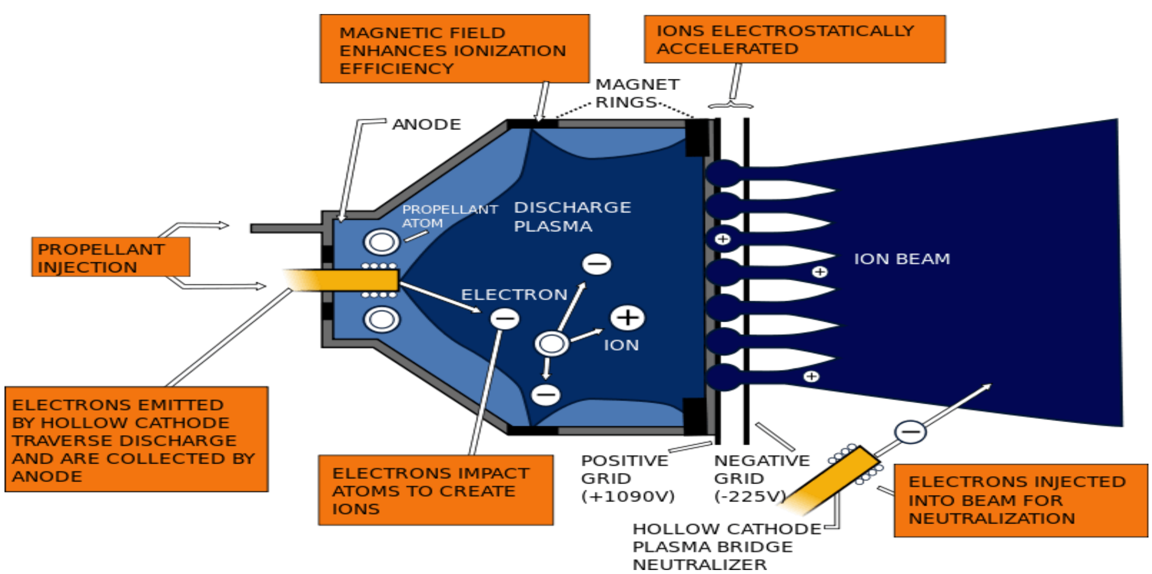

Image 1. Ion Thruster, NASA Glenn Research Center

The most used propellant atom is Xenon for its high atomic mass. Xenon is also easily ionized and results in a high level of thrust when ionized. Xenon is also an ideal propellant atom because it is easy to store on a spacecraft because of its density and inertness. While Xenon is the ideal element in ion propulsion, it is a relatively rare element given its abundance is only 10 ppb. Other relatively common elements such as Hydrogen and Carbon have an abundance of 750,000,000 ppb and 5,000,000 ppb respectively. Abundance is important to keep in mind when discussing ion propulsion because future applications of ion propulsion use atoms present where the spacecraft will be and harvest the elements from the space around it.

IV. Types of Ion Thrusters in Development

Since the realization chemical propellant wouldn't be sufficient to travel long distance with humans, ion propulsion has become more of a reality than a science fiction. Since the 1990s, a lot of research has gone into ion propulsion there have been a few different types of engines developed using ion thrusters. NASA Solar Technology Application Readiness, NSTAR, was the first, and only too date, ion thruster to fly. However, many more ion thrusters are currently in development based off of NSTAR's technology and are in various stages of testing and hopefully will be flown in the coming decades and will be the engine to take humans to Mars.

A. NASA Solar Technology Application Readiness

The earliest ion thruster developed was the NASA Solar Technology Application Readiness, NSTAR, which made its first flight October 1998 by Deep Space 1. After logging 8,000 hours of test hours in a vacuum chamber simulating deep space, the data was used to help design flight hardware. During the early weeks of the flight, the engine was fired up running for two continuous weeks, longer than any other deep space probe on any other propulsion system before. During those two weeks, the throttle levels were tested at various levels ranging from 6 to 90 with the max being 111. At 90, the thrusters seemed to be reaching their limits, using approximately 2.4 kW of power. Later in the mission, April 1999, Deep Space 1 completed a six week cycle of continuous thrust, resulting in a 650 mph speed increase. In contrast, using the traditional chemical propellant in the same six-week period, there would have only been a 50 mph speed increase. Also during that six-week period, only 5 kg of xenon was used. In contrast, if chemical propellant was used continuously for six-weeks, it would have used tons of propellant.

After proving its success in Deep Space 1, three ion thrusters using NSTAR were also used in the Dawn spacecraft, launching in 2007. NSTAR's thrusters allowed Dawn to travel to the protoplanets of Vesta and Ceres, being the first mission of its kind orbiting two objects in the asteroid belt between Mars and Jupiter. NSTAR is still proving its success today by keeping over 100 communication satellites in Earth's orbit. NSTAR was significant to ion propulsion development because it was used in deep space flight powered primarily by ion propulsion and it showcased how little propellant is required to achieve a desirable amount of thrust over a long period of time. NSTAR played a huge role in development of ion propulsion and paved the road for future ion propulsion.

B. NASA Evolutionary Xenon Technology

Currently, in development, the NASA Evolutionary Xenon Thruster, NEXT, is a new Xenon ion thruster in development that works at 3 times the power of its predecessor NSTAR and reduces trip time and cost. In testing, the thrusters worked continuously for 51,000 hours, approximately 6 years, proving that they can be used for long-duration missions. NEXT out preforms its predecessor NSTAR in virtually every aspect. NEXT is able to process 450 kg of propellant in its lifetime whereas NSTAR could only process 200 kg. The higher propellant throughput will lengthen the operational time of the thruster and allow for longer missions. NEXT also produces more thrust than NSTAR; NEXT's maximum thrust is 236 mN with maximum thruster power is 6.9 while NSTAR's maximum thrust was only 91 mN with maximum thruster power at 2.3 kW. NEXT's total impulse is also higher, upwards of 18 $x10^6$ N-sec, while NSTAR total impulse was only just above 5 $x10^6$ N-sec. The higher impulse and thrust allows for a higher change in velocity in flight.

NEXT has huge potential for future space operations. NEXT has the potential to operate upwards of 10 years and has a few potential missions lined up in the next few decades. Titan Saturn System Mission (TSSM) and Europa Jupiter System Mission (EJSM) are two mission concepts proposed by NASA and the ESA that would use NEXT's Ion Thrusters to explore Titan and Europa. TSSM will use Venus' gravity and 2 solar sails for the first portion of the mission. When using Venus' gravity and solar sails are no longer useful due to distance, approximately one AU, the Ion Thrusters will be utilized for the remainder of the mission. Each thruster will use approximately 225 kg of xenon, totaling 450 kg for the whole mission, which is well within the thrusters' capabilities. While EJSM is in earlier development than TSSM, it is likely to follow a very similar plan. The New Worlds Observer (NWO) mission is another potential mission in development yet is decades away from development. Through indirect detection techniques, more than 200 Earth-like planets have been discovered in other solar systems. NWO's objective is to study these planets and NEXT make NWO goal attainable. Another proposed implication of NEXT is to collect samples from comets and asteroids. In 2009, an Announcement of Opportunity for New Frontiers was released by NASA whose goal was to implicate NEXT into future mission proposals.

C. Annular Ion Engine

The newest ion engine in development is the Annular Ion Engine, AIE, which has the capability to outperform NEXT. AIE has the potential to produce a beam area twice as large as NEXT's and has the potential to reduce manufacturing cost and complexity while increasing performance. AIE's new design uses an annual discharge chamber with a pair of ion optics with a neutral cathode assembly in the center. This new design has many benefits such as an increase in power, thrust density, lifetime, and overall efficiency. AIE's maximum thrust power is 14 kW and its maximum thrust is upwards of 200 mN. AIE's maximum specific impulse is 5000 sec, and while no defined number for propellant throughput is available yet, tests show a significant increase in propellant throughput which result in a 10x longer lifespan than NEXT. While still in early stages of development, AIE shows promise to produce 100s of kW and travel longer and further than any other EP systems.

Figure 1. NSTAR, NEXT, AIE Performance Comparisons, NASA Glenn Research Center

Characteristic	NSTAR	NEXT	AIE
Max. Thruster Power (kW)	2.3	6.9	14
Max. Thrust (mN)	91	236	200+
Throttle Range (Max./Min.Thrust)	4.9	13.8	N/A
Max. Specific Impulse (sec)	3120	4190	5000
Total Impulse ($x10^6$ N-sec)	>5	>18	N/A
Propellant Throughput (kg)	200	450	N/A
Thrust Density (N/m^2)	N/A	2	>8

D. ESA's Air Breathing Ion Engine

The European Space Agency is currently working on a new ion engine which uses an air breathing engine. Instead of carrying electrons in a separate chamber to be used to ionize the neutral propellant in a second chamber, the new engine draws particles from the surrounding atmosphere which are then electrically changed and ejected, generating thrust. The design is relatively simple, using only coils and electrode, making it a safe system. While this design is relatively new, only being in development for a few years, it shows a lot of promise for the future. It is very flight weight and resourceful. By using atoms from the surrounding environment, there is no need to carry a propellant; that in combination of solar panels, the air breathing engine, in theory, they engine can run for very long periods time with very little resources. While the air breathing ion thrusters sounds like pure fiction now, just as ion thrusters overall did just a few decades ago, they are an emerging trend in aerospace right now.

V. Conclusion

Ion propulsion is a propulsion method which has been researched and tested to provide an alternative to chemical propellants aimed at making deep space flight feasible. Ion propulsion is a very good option to reduce flight time, mass, and increase speed. For example, Deep Space one, using only 5 kg of propellant, went record breaking speeds over record breaking amounts of time. There are many different engines in development that use ion thrusters and they are getting better each day. Ion propulsion has the capabilities to get humans beyond Mars and enable human deep space exploration.

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