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Honors University Physics II

Lab L1

April 9, 2011

Analysis and Comparison of Solar Sails, Ion Drives and Traditional Rockets

The future of space propulsion systems will be completely different from methods used in the past few decades. Because of space agencies such as NASA focusing on exploration missions that delve deeper into the solar system and beyond, a comparison of potential space propulsion systems must be made to choose the best overall option for such missions. Solar sails, ion drives, and traditional chemical propellant rockets can be compared on the basis of efficiency of design through specific impulse, energy efficiency, power supply and lifetime.

Before each system can be compared, the essential physics involved in each must be explained so that the system can be fully understood. The solar sail is actually a very challenging class of future spacecraft to implement. The basic idea of the solar sail is to utilize the momentum gained from the pressure exerted from photons due to sunlight on a reflective sail. This idea is nothing new, but the technological capability to implement such a design has become more possible in recent years (Block 2010). To determine a numerical value of this pressure, the solar constant S (approximately 1.366 $\mathrm{kW/m^2}$) at a distance 1 AU from the sun is divided by the speed of light c (3×10^8 m/s). The solar constant S is the amount of incoming solar electromagnetic radiation per unit area on a surface normal to the incident radiation (Glover 2001). This gives

$$P = \frac{S}{c}$$

where P is the pressure exerted on the sail. This yields a pressure of 4.56 x 10^{-6} Pa which is multiplied by 2 when the surface the photons collide with is reflecting ideally (Block 2010). Currently, the foils of the sail can be covered with an ultrathin metallic coating that isn't exactly the ideal, but functions as a sufficient mirror. In this way, the light pressure from the sun onto the sail is about 9µPa (Block 2010). This value will decrease by a function $1/d^2$ where d is the distance from the sun as d increases. For example, if the spacecraft was near Mercury, the pressure exerted on the sale would be an order of magnitude higher than if near Earth. On the other side of the situation such as distances beyond Jupiter the pressure becomes virtually negligible because of multiplication by the function of inverse distance squared.

The main concern with a solar sail is divided into two parameters. The first is the size of the solar sail itself. The solar sail must be big enough that the photons coming from the sun provide a pressure that culminates in a propelling force that is non-negligible. The other parameter is the total mass of the spacecraft. Because this pressure is so small, the mass of the spacecraft must be as small as feasibly possible to allow for a non-negligible acceleration of the spacecraft due to the solar propelling force (Block 2010). This ratio of total mass to sail size in past decades was in the range of 50 to 80 g/m^2, depending on mechanisms, payload assumed, and bus structure, but might be minimized to a range closer to about 20 g/m^2 with certain recent designs (Block 2010). Figure 1 shows what a solar sail should look like in space.

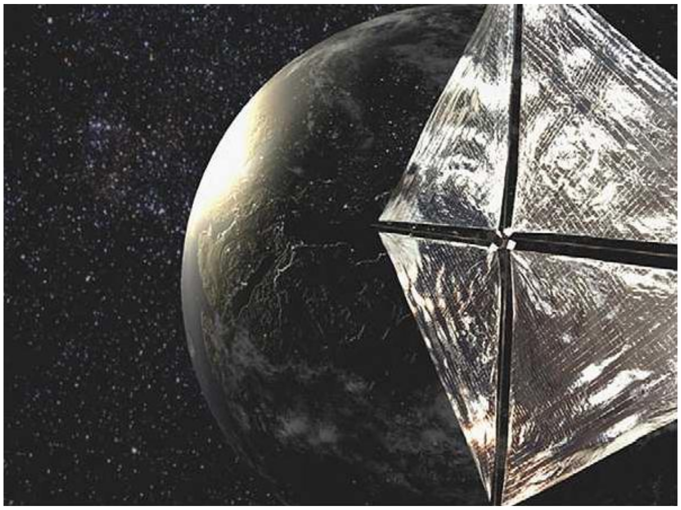


Figure 1. Basic solar sail concept, courtesy of Block.

Another important subject to be understood before direct comparison of propulsion systems is the physics behind ion propulsion. To begin, an ion is defined as an atom or molecule that has been electrically charged, and it follows that ionization is defined as the process of electrically charging an atom or molecule by adding or removing electrons (NASA 2008). An ion that has gained one or more electrons is defined negative and one that has lost one or more electrons is said to be positive. A gas is “ionized” if some or all the atoms or molecules composing the gas have been converted into ions. Plasma, the fourth state of matter, is an electrically neutral gas where all the charges contained add up to zero, including all atoms, electrons, and ions. The reason that plasma is relevant to ion drives is because it has the properties of a gas and at the same time is affected by electric and magnetic fields and further still is a good conductor of electricity (NASA 2008). Those properties make plasma fundamental to all electric propulsion where the electric and/or magnetic fields push electrically charged ions and electrons to achieve thrust for a vehicle.

Ionization is typically obtained through one of two methods. The first is called electron bombardment. This is the traditional method for ionizing propellant atoms in an ion thruster. The process of electron bombardment involves shooting an electron at a propellant atom, releasing a second electron in addition to the original electron and the now positive ion (previously neutral atom) (NASA 2008). The other method is called electron cyclotron resonance (ECR). This involves high-frequency radiation often in the form of microwaves along with a high magnetic field that are combined in order to heat the electrons of the propellant atoms and cause them to break free creating a plasma from which ions can be extracted (NASA 2008).

Current ion thrusters use inert gasses as their propellant, usually xenon. Xenon is a gas that is chemically inert, colorless, odorless, and tasteless. Starting from the downstream end of the thruster, the inert gas is injected from its container and flows toward the upstream end of the thruster so that the amount of time that the propellant is in the chamber is at a maximum (NASA 2008). The electrons of conventional ion thrusters are generated from a hollow cathode called a discharge cathode. This cathode (basically an electron gun) is located in the center of the upstream end of the thruster. From the discharge cathode, the electrons flow out and are attracted to the discharge chamber walls that have been charged by the thruster’s power supply to a high positive potential, since opposite charges attract one another (NASA 2008). The propellant that was injected into the upstream end is ionized from these electrons coming from the discharge cathode through electron bombardment. The discharge chamber walls contain high-strength magnets that change the direction of the approaching attracted electrons by their magnetic fields. The reason that the electrons are even manipulated to be attracted to the chamber walls in the first place is to increase the amount of time that electrons and propellant atoms are in the chamber so that the chance for ionization of the propellant atoms is maximized (NASA 2008). This allows ionization in the ion thruster to be very efficient.

As the ions continue down the discharge chamber, they are accelerated by electrostatic forces. The source for these forces are electrodes located in the downstream end of the chamber (NASA 2008). These electrodes (also named ion optics or grids) have thousands of apertures along the same axis that act as a lens, electrically focusing ions through the electrodes. An example of such a thruster is NASA's Ion Thruster, which uses a two-electrode system to direct the electrons in the desired direction. The upstream electrode (screen grid) is charged highly positive, while the downstream electrode (accelerator grid) is charged highly negative so that the ions which begin in the upstream area are attracted to the negatively charged accelerator grid (NASA 2008). In this manner, the ions flow out of the discharge chamber in the form of thousands of ion jets that form a stream called an ion beam. The force that exists between the upstream ions being attracted to the accelerator grid is what causes the primary thrust force for the propulsion system. Figure 2 shows a diagram of an ion thruster in operation.

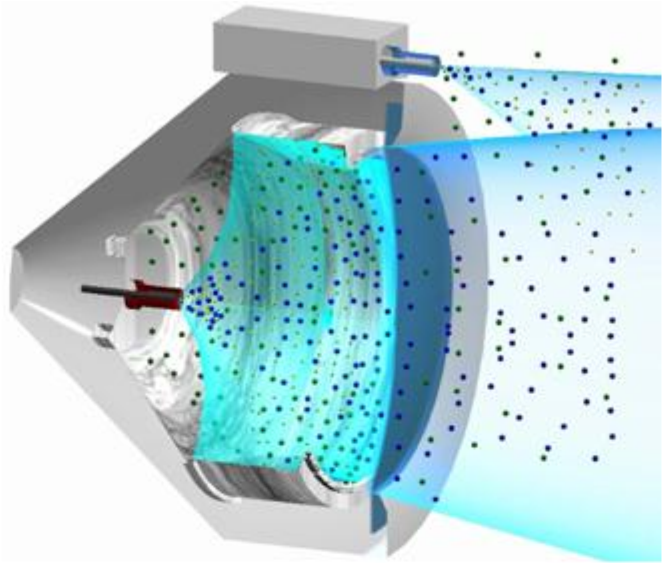


Figure 2, courtesy of NASA

The velocity of the ion beam can be controlled using the amount of voltage that is run through the optics focusing the ions (NASA 2008). One of the primary differences between conventional chemical rockets and ion thrusters is that the chemical rocket's top speed is limited to the thermal capability of the exhaust rocket nozzle, while the only variable limiting the ion thruster' stop speed is voltage run through the optics which is theoretically unlimited. Since the ion thruster must have an overall neutral charge, an equal amount of negative charge is released from a second hollow cathode (also called a neutralizer) can be seen on the top of the downstream section of the thruster in Figure 2 in order to balance the large amount of positive ions being released (NASA 2008).

The last propulsion system that must be understood before direct comparison is that of traditional rocket propulsion. Rocket propulsion typically divides into two basic groups known as liquid propellant rocket engines and solid propellant rocket engines. Liquid propellant rocket engines use pressure to move the liquid fuel from its container into the combustion chamber where the propellants react through combustion of the fuel with an oxidizer to form very hot gasses (Sutton 2001). These gasses are accelerated and shot out at a high velocity through the nozzle at the end of the engine which creates a thrusting force on the engine mount by Newton's third law of motion and results in momentum for the rocket. The nozzle that the gas flows through has a constriction in it called the throat followed by a conical section as can be seen in Figure 3 (Sutton 2001). This type of engine may use a bipropellant consisting of a liquid fuel like kerosene and a liquid oxidizer like liquid oxygen. Otherwise a monopropellant, which is one liquid with both fuel and oxidizing elements that decompose into a hot gas when catalyzed, may be used (Sutton 2001). Pump-fed liquid rocket engines such as the one in Figure 3 are the type used by space launch systems that require large thrusts and therefore more propellant.

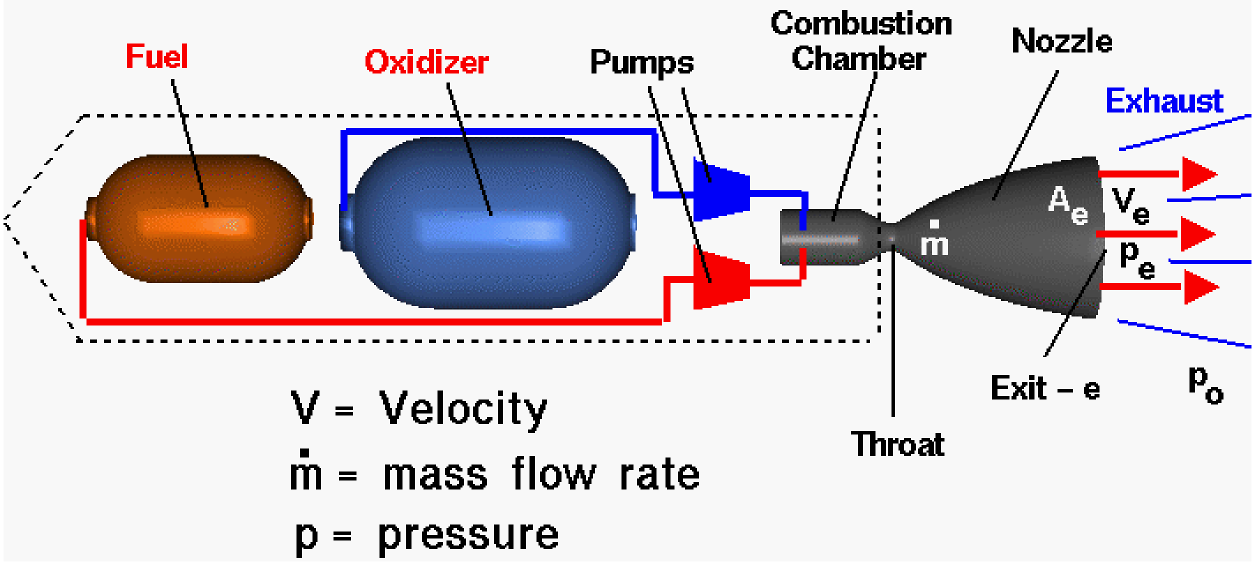


Figure 3. Liquid propellant rocket engine, courtesy of NASA

Solid propellant rocket engines are the other main type of conventional rocket motor. In this propulsion system, the propellant is a solid mixture of the fuel and oxidizer that is packed into a cylindrical shape fitting the inside of the container. A hole in the cylinder is left to serve as the combustion chamber. Once ignited, the solid propellant mixture will burn at a predetermined rate on the inside of the exposed combustion chamber (Sutton 2001). In Figure 4, the part of the propellant that is burning is labeled as the flame front. This internal cavity created by the flame front will grow as the solid mixture propellant is consumed in the combustion, which results in a high temperature and high pressure gas that is accelerated through the nozzle to produce thrust (Sutton 2001). The actual amount of gas that results from combustion depends on the area of the flame front. Different hole shapes can be used to control the change in thrust for the rocket, depending on what is required (NASA 2008). The specific design of the nozzle can change the total thrust produced by the engine. The smallest cross-sectional area of the nozzle is known as the throat, as labeled on Figures 3 and 4. The hot gas is choked at the throat so that the engine has a Mach number of 1 (Mach number is the object speed divided by the speed of sound), and the mass flow rate ($\dot{m}$) is completely determined by the area of the throat (NASA 2008).

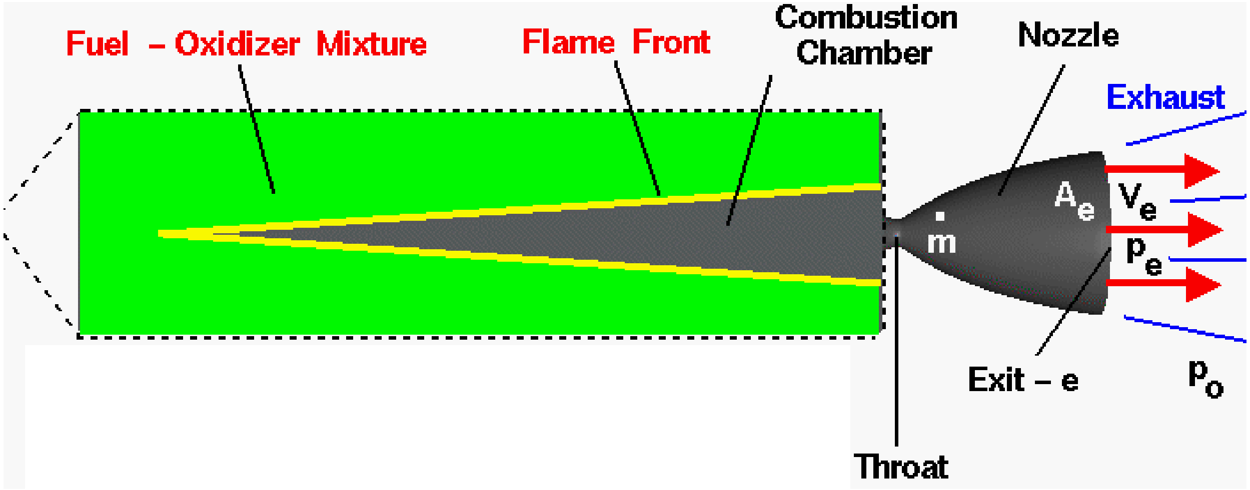


Figure 4. Solid propellant rocket engine, courtesy of NASA

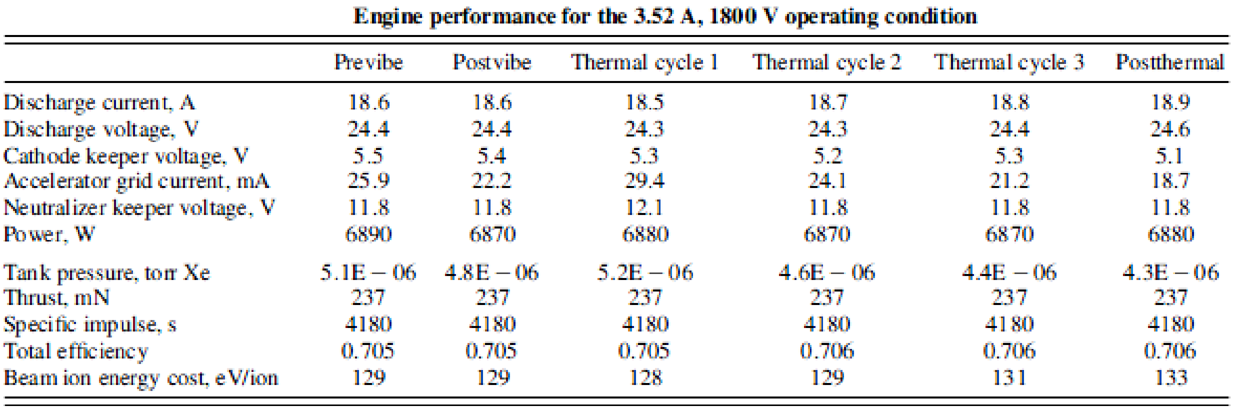
The thrust given by either a solid or liquid propellant rocket engine is given by the thrust (*F*) equation,

$$F = \dot{m}V_e + (p_e - p_o)A_e$$

where V_e is the exit velocity, p_e is the exit pressure, p_o is the initial stream pressure of the gas, and A_e is the cross-sectional area ratio of the throat to the exit of the nozzle (NASA 2008).

Now that all three of the propulsion systems have been described, they can be compared on several parameters to find which is most ideal for a given situation. These parameters include efficiency of design through specific impulse, energy efficiency, power source and lifetime.

The three propulsions system can first be compared through their specific impulse and total efficiency. For the ion thruster, data used is from NASA's Evolutionary Xenon Ion Thruster environmental test prototype, which was subject to several tests include vibration and thermal tests.



Engine performance for the 3.52 A, 1800 V operating condition

	Previbe	Postvibe	Thermal cycle 1	Thermal cycle 2	Thermal cycle 3	Postthermal
Discharge current, A	18.6	18.6	18.5	18.7	18.8	18.9
Discharge voltage, V	24.4	24.4	24.3	24.3	24.4	24.6
Cathode keeper voltage, V	5.5	5.4	5.3	5.2	5.3	5.1
Accelerator grid current, mA	25.9	22.2	29.4	24.1	21.2	18.7
Neutralizer keeper voltage, V	11.8	11.8	12.1	11.8	11.8	11.8
Power, W	6890	6870	6880	6870	6870	6880
Tank pressure, torr Xe	5.1E − 06	4.8E − 06	5.2E − 06	4.6E − 06	4.4E − 06	4.3E − 06
Thrust, mN	237	237	237	237	237	237
Specific impulse, s	4180	4180	4180	4180	4180	4180
Total efficiency	0.705	0.705	0.705	0.706	0.706	0.706
Beam ion energy cost, eV/ion	129	129	128	129	131	133

Figure 5. Test performance of ion thruster, courtesy of Snyder

As can be seen from Figure 5, the specific impulse for this model of an ion thruster was 4180s, and the total efficiency was at maximum 70.6%. A test was conducted from a NASA funded group that ran a 900 hour test at 5.7kW. This group projected the xenon thruster lifetime to be greater than 30,000 hours, or about 3.6 years (Rawlin 1990). For traditional rockets, a high specific impulse or value of exhaust velocity is obtained from high combustion temperatures produced by low average molecular weight of reaction products or large heat of reaction (Sutton 2001). For an aluminized ammonium perchlorate propellant, the average specific impulse between 5 different chamber pressures was 270s (Sutton 2001). Because of the difference in specific impulse, ion propulsion will result in significant propellant-mass advantages for many applications including north-south stationkeeping (NSSK) satellites in geosynchronous orbit, orbit raising and maneuvering, as well as planet to planet spaceflight (Beattie 1989). Figure 6 demonstrates the direct comparison of the two propulsion systems.

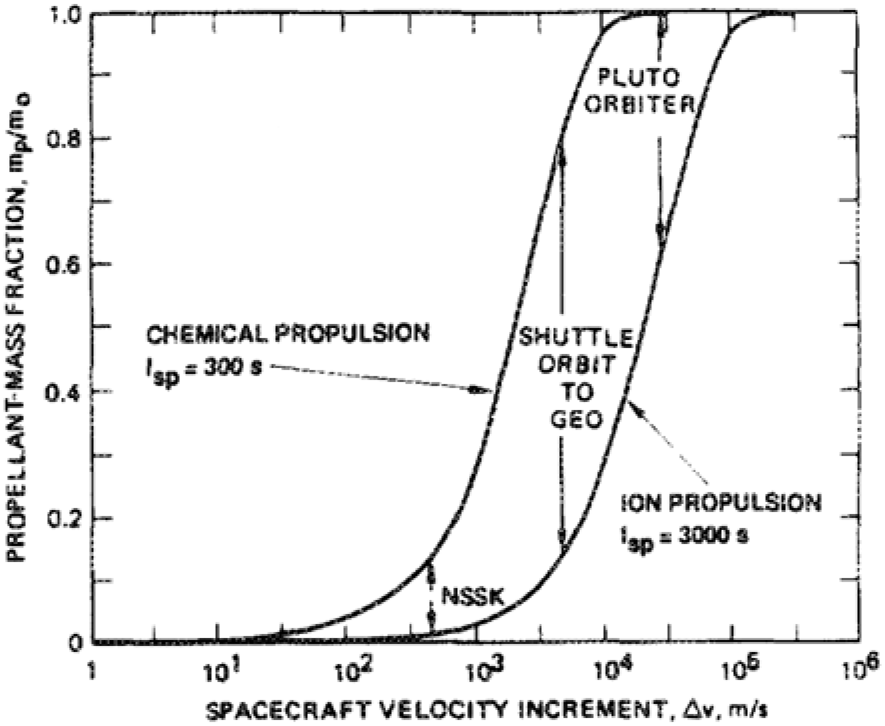


Figure 6. Ion propulsion advantage over chemical propulsion, courtesy of Beattie

Due to the nature of the solar sail, discussion of thrust and specific impulse is less relevant since it merely builds up momentum from the sun's photons over time. One of the prime advantages to using a solar sail is the power supply. Since the solar sail relies purely on the sun's solar radiation, there is virtually no other propellant needed onboard making propellant supply unlimited. The ion propulsion also has a long lifetime as previously stated relative to the short burst of flame that a conventional liquid or solid rocket engine will yield.

Also, it should be apparent that the three types of propulsion systems in consideration are more suitable towards certain types of missions. For example, the solar sail has a very low acceleration, but over time builds up with more momentum from the solar radiation and has a high top speed which would be ideal for deep space missions. However, ion propulsion numerically overpowers the solar sail and traditional chemical rockets when compared by specific impulse. This would make ion propulsion ideal for missions requiring large amounts of thrust needed quickly, or larger thrusts for longer periods of time.

Another component for comparison is engine stability and limitation. One of the disadvantages of using conventional liquid or solid propellant rocket engines is the constant risk of an explosion. This risk is completely absent from an engine using a solar sail or ion drive, since there is no combustion within the basic physics of those two designs. As previously mentioned, the conventional rocket’s top speed is limited by the thermal capabilities of the exhaust nozzle while the only variable limiting the ion thruster’s top speed is the theoretically unlimited voltage run through the optics.

All three of the propulsion systems that have been discussed can be used as a means for different ends. The solar sail is ideal for deep space missions where a low beginning acceleration moves the spacecraft as it continually speeds up from the sun’s solar radiation hitting the sail. The ion drive is a powerful engine utilizing the acceleration of ions that can deliver a much larger specific impulse than the conventional rocket engine. The conventional rocket engine is still a useful propulsion system but because of its heavy propellant that is consumed so quickly and may explode in the process, compared to its contenders it simply must be put at the bottom of the list. As research continues on solar sails and ion drives, even better propulsion systems will be engineered to meet the demands of space exploration.

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