Design of a Hydrogen-Powered Interstellar Ion Engine

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Electrostatic ion engines are some of the only modern day engines theoretically capable of traversing the vast distances between the stars in a reasonable amount of time based on criteria developed in this paper. While most ion engines use Xenon as a propellant, interstellar ion engines must use Hydrogen collected from interstellar space due to the amount of fuel required for such a journey. This paper describes the theory behind electrostatic ion propulsion and discusses a theoretical design for an interstellar ion engine optimized for using Hydrogen as a propellant, including a mechanism for collecting fuel along the way. Subsequent analysis of the engine's performance shows it is not suitable for interstellar travel.

Nomenclature

A	=	Ion engine exhaust area (m^2)
A_c	=	Interstellar Hydrogen collector area (m^2)
a	=	Interstellar spacecraft acceleration (m/s^2)
E	=	Electric field between accelerator grids (V/m)
E_{ion}	=	Energy required to ionize a propellant atom including losses (eV)
F	=	Ion engine thrust (N)
j	=	Ion beam current (A)
$\dot{m}$	=	Mass flow rate of ions through the ion engine (kg/s)
$\dot{m}_c$	=	Mass flow rate of interstellar Hydrogen through collector (kg/s)
M	=	Mass of ionized Hydrogen (kg)
M_0	=	Initial mass of the interstellar spacecraft (kg)
M_f	=	Initial mass of the fuel carried on-board interstellar spacecraft (kg)
M_s	=	Mass of the interstellar spacecraft at a point in time (kg)
P_E	=	Power required/available to the ion engine (W)
q	=	Elementary charge (C)
v_e	=	Ion exhaust velocity (m/s)
V_b	=	Voltage across the accelerator grids (V)
V_f	=	Final interstellar spacecraft velocity (m/s)
V_s	=	Velocity of the interstellar spacecraft at a point in time (kg)
x	=	Spacing between the accelerator grids (m)
ε_0	=	Permittivity of free space (F/m)
ρ	=	Density of Hydrogen in interstellar space (atom/m^3)

I. Introduction

THE distances between stars is vast. The closest star to our sun is Proxima Centauri, some 4.3 light years distant[2]. A light year is the distance light travels in a year, about 9.5 x 10^{12} km, at 300,000 km/s. A spacecraft travelling at the speed of light takes 4.3 years to get to Proxima Centauri. By contrast, the fastest spacecraft ever built, Voyager 1, has a velocity of only 17 km/s [3]. If it was on a trajectory towards our closest neighbor star, the probe would arrive in about 77,000 years. A true interstellar spacecraft requires a much more powerful thruster in order to reduce the travel time between stars. Also, this thruster must be durable, operating continuously for extremely long periods of time. This paper surveys current thruster technology and then proposes and analyzes a potential design for interstellar travel.

Developing a more powerful engine requires an understanding of engine thruster operation. Fundamentally, a thruster utilizes on Newton's Second and Third Laws of motion. It provides a force, or thrust, on a spacecraft of mass M_s, resulting in an increase in velocity. This thrust comes from the discharge of propellant in a direction opposite the direction of travel. A relationship between spacecraft velocity V_s, mass M_s, propellant exhaust velocity v_e, and mass M_f is obtained by conserving linear momentum:

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$$M_sV_s = (V_s + dV_s)(M_s - dM_f) + dM_f(V_s - v_e) \quad (1)$$

Expanding and simplifying terms gives:

$$M_s dV_s = v_e dM_f \quad (2)$$

Since dM_f is the same as loss in spacecraft mass $-dM_s$, the above equation can be rewritten:

$$M_s dV_s = -v_e dM_s \quad (3)$$

Separating terms and integrating:

$$\int_0^{V_f} \frac{dV_s}{v_e} = -\int_{M_0+M_f}^{M_0} \frac{dM_s}{M_s} \quad (4)$$

V_f is the final spacecraft velocity and M_0 is the initial spacecraft mass without fuel. Carrying out the integration yields Tsiolkovsky's Rocket equation:

$$V_f = v_e ln \frac{M_0 + M_f}{M_0} \quad (5)$$

From this equation it can be seen that to increase the velocity V_f of an interstellar spacecraft (or any high-velocity spacecraft for that matter), an increase in exhaust velocity v_e, propellant mass M_f, or both is necessary. The question arises on which is most efficient. v_e varies linearly with V_f while M_f varies logarithmically. This means a linear change in v_e results in the same change in V_f while an exponential change in M_f is necessary for the same V_f. This is shown in Figs. 1 and 2. Clearly exhaust velocity is the more important characteristic for a powerful interstellar engine. Just how large should v_e be? Less demanding interplanetary missions (up to 4 x 10^9 km, or 4 light *hours*) require exhaust velocities of about 10 km/s [4]. Therefore, interstellar missions must require much higher ones, though a threshold has not been defined. An order of magnitude higher v_e, or about 100 km/s seems reasonable. The first criterion an interstellar engine must fulfill is that its exhaust velocity v_e is on the order of 100 km/s.

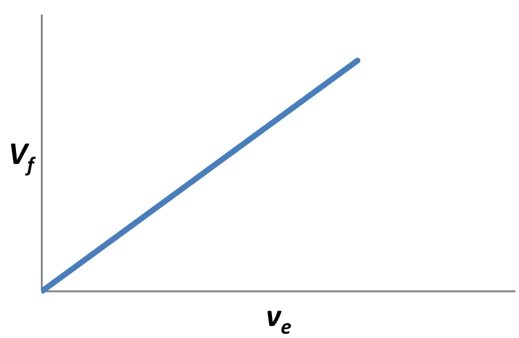

Figure 1. Spacecraft velocity varies linearly with exhaust velocity.

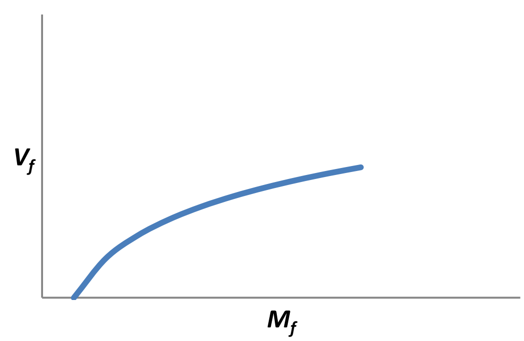

Figure 2. Final velocity varies logarithmically with fuel mass.

The critical factor in an interstellar engine is durability. The engine must operate continuously for extremely long periods of time. As calculated earlier, Voyager 1 would take nearly 77,000 years to reach our nearest neighboring star. An interstellar engine does not have to operate as long however, because Voyager 1 is not accelerating (it is coasting due to a gravity assist from Jupiter[5]). Assuming a constant engine acceleration of 0.5 m/s^2 and neglecting relativistic effects, the time to travel 4.3 light years to Proxima Centauri is just under 13 years. Therefore, the second criterion an interstellar engine must fulfill is an operational lifetime on the order of decades (not millennia).

II. Candidate Engines

A number of engine thrusters are available today, but hardly any meet the developed criteria of v_e ~ 100 km/s and decades-long operational lifetime. While chemical rocket engines most certainly do not pass, electric thrusters appear the most promising, although only one satisfies the criteria, albeit just barely.

A. Chemical Rocket Engines

Chemical engines burn propellant in a chemical reaction. The reaction produces hot gases which are expanded through a nozzle, generating thrust. The traditional chemical engines that power most rockets and spacecraft nowadays are not suitable for interstellar spacecraft. They have an extremely low v_e of between 2 and 5 km/s, limited by the amount of energy released by the chemical reaction. Chemical rockets also have short burn times, on the order of minutes, so continuous acceleration for long periods of time is not possible. Additionally, the mass of the fuel is prohibitively large. Reaching Proxima Centauri in 13 years requires more than 10^{17} kg of propellant.

B. Electric Thrusters

Electric thrusters accelerate propellant using electricity, so they have no theoretical limit to their v_e other than the speed of light, provided sufficient power is available and the engine can operate with that amount of energy[6]. In practice, v_e is limited by the amount of power available to accelerate the propellant. As long as power is provided and the accelerating mechanism does not break down, electric thrusters can operate for very long periods of time. They are the best candidates for interstellar engines. There are three kinds of these: electrothermal, electromagnetic, and electrostatic[7].

1. *Electrothermal Thrusters*

   Electrothermal thrusters (Fig. 3[8]) heat the propellant electrically and pass the hot gas through a nozzle, generating thrust. There are two kinds of these thrusters: Resistojets and Arcjets. Both are not suitable as interstellar engines and fail the criteria. Resistojets use a high-resistance wire with current passing through it to heat the propellant. This method has a fundamental limit on the amount of heat that can be transferred to the propellant though, and under ideal conditions, the maximum v_e is only 10 km/s [9]. Arcjets on the other hand pass electricity directly through the propellant to heat it up. v_e can be as high as 20 km/s, but requires a large amount of electric power[10]. Also, both of these thrusters only have lifetimes on the order of months[11].

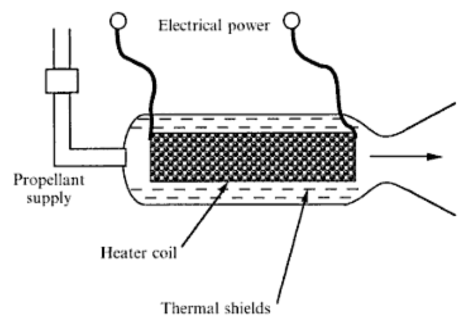

Figure 3. Schematic of an electrothermal thruster. *Propellant is heated electrically and accelerated through a nozzle, generating thrust.*

2. *Electromagnetic Thrusters*

   Electromagnetic thrusters (Fig. 4[12]) ionize propellant, generating plasma, and accelerate it using electric and magnetic fields (Lorentz force). Two kinds of electromagnetic thrusters are Hall Effect and Magnetoplasmadynamic (MPD) thrusters. Hall Effect thrusters use the Hall Effect to generate plasma while MPDs use high current arcs. Both are also unsuitable for being interstellar engines. Hall Effect thrusters can only operate for around a year[13] and MPDs only last about a month[14]. Both have v_e of between 15 km/s and 25 km/s [15].

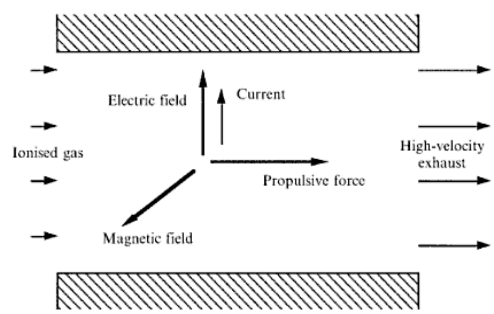

Figure 4. Principle of an electromagnetic thruster. *Propellant is ionized and the resulting plasma is accelerated using electric and magnetic fields.*

3. *Electrostatic Thrusters*

   Like their electromagnetic counterparts, electrostatic thrusters use an ionized propellant, but accelerate it using only an electric field. The electrostatic thruster appears satisfy the interstellar engine criteria. Its v_e is between 50 km/s and 100 km/s [16] and has an operational lifetime exceeding 10 years[17]. According to Turner, "most manned, interplanetary missions have been studied or planned around … [electrostatic] propulsion" [18]. This is an indication that electrostatic thrusters have a chance of succeeding in interstellar missions.

The following table summarizes candidate interstellar engines.

Table 1 Candidate interstellar engines.

Thruster Type	v_e, km/s	Lifetime
Chemical	2-5	Minutes
Electrothermal	10-20	Months
Electromagnetic	15-25	Months
Electrostatic	50-100	Years

Judging from the previously defined criteria for an interstellar engine (v_e of ~100 km/s and operational lifetime on the order of decades), electrostatic, or ion thrusters, appear to be the only thrusters to satisfy the criteria. They are the focus of the remainder of this paper.

III. Ion Thruster Fundamentals

An ion thruster consists of three parts: the ionizer, accelerator, and neutralizer. The ionizer takes the neutral propellant gas and strips electrons from it, producing ions. The accelerator takes the resulting charged particles and feeds them through a chamber containing an electric field, causing the ions to accelerate out the back of the thruster and producing thrust. The neutralizer recombines the charged ion stream with the stripped electrons, negating the buildup of a negative charge inside the spacecraft. This is all shown in Fig. 5[19] below.

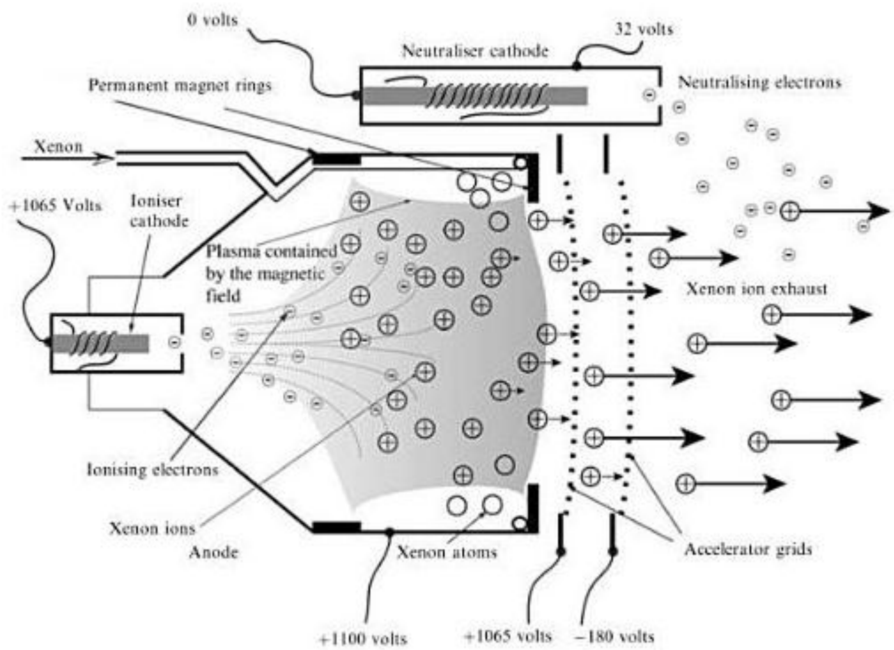

Figure 5. A schematic diagram of the NASA NSTAR ion engine, as used on Deep Space 1. *Propellant is ionized and accelerated through an electric field between two grids. The exhaust is neutralized with electrons to prevent the build-up of charge over time.*

A. Ionizer

Ionization of the propellant gas typically occurs through an electron bombardment process. The neutral gas molecules enter the ionization chamber with negligible velocity. The combination of a radial electric field and weak magnetic field in the chamber causes electrons emitted by a central cathode to accelerate outwards at tens of eV in a spiral path and crash into the neutral gas molecules, ionizing them[20]. The spiral path maximizes the probability of collisions and is crucial for high ionization efficiency, because the energy going into producing ions is not contributing directly to engine thrust[21].

B. Accelerator

The ions drift from the ionization chamber into the acceleration chamber. The chamber is composed of three electrically charged grids. The first two grids have a high potential across them, creating a strong electric field[22]. Ions passing through this electric field gain energy and exit the second grid at high velocity, generating thrust. There is a limit to the number of ions that can flow through the accelerator however, called the Space Charge Limit. As the number of positive ions increases, the accelerating field is shielded more and more. When the charge of the ions leaving the chamber matches the charge of the grid potential, the accelerating field drops to zero[23]. The maximum ion current *j* per unit area *A* defined by the Space Charge Limit is given by[24]:

$$\frac{j}{A} = \frac{4\varepsilon_0}{9}\sqrt{\frac{2q}{M}\frac{E^3}{x}} \tag{6}$$

E is the strength of the electric field between the grids, *x* is the spacing between the grids, *M* is the mass of a propellant ion, *q* is the elementary charge, and ε_0 is the permittivity of free space. The maximum *E* and minimum *x* are limited by electrode breakdown (arc discharge) between the high-voltage grids, which can result in damage to either or both of the grids. Studies have shown that electric fields in Molybdenum grids should not exceed 40 kV/cm, 23 kV/cm for Carbon-carbon composite grids, and 20 kV/cm for Pyrolytic Graphite grids[25]. Similarly, grid spacings of no less than 0.5mm are necessary[26]. For a given *j* the mass flow of ions per unit area is:

$$\frac{\dot{m}}{A} = j\frac{M}{q} \tag{7}$$

The thrust *F* per unit area from the beam current is:

$$\frac{F}{A} = \dot{m}v_e \tag{8}$$

where

$$v_e = \sqrt{\frac{2qV_b}{M}} \tag{9}$$

V_b is the voltage between the two grids ($V_b = E\,x$). Combining (6) through (9) gives:

$$\frac{F}{A} = \frac{8}{9}\varepsilon_0\left(\frac{V_b}{x}\right)^2 = \frac{8}{9}\varepsilon_0 E^2 \tag{10}$$

Thrust is independent of the propellant type (at the Space Charge Limit); it only depends on the strength of the electric field between the accelerator grids. The consequence is an upper-bound on achievable thrust.

The third grid of the chamber has a higher potential than the second and slows down the ions a little bit, but prevents any electrons from the neutralizer "leaking backwards" and damaging the ionizer[27].

The electrical schematic of the grid configuration is shown in Fig. 6[28].

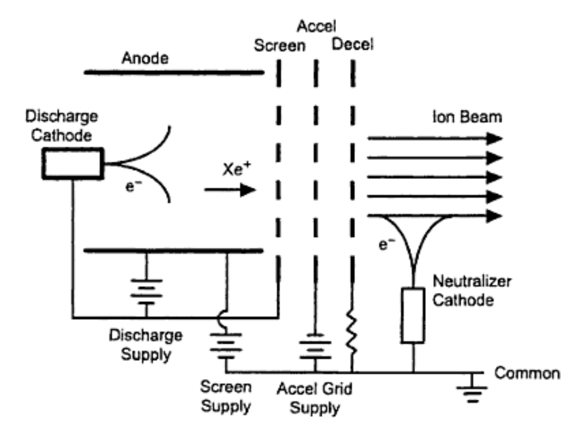

Figure 6. Electrical schematic of an ion thruster.

C. Neutralizer

The neutralizer emits electrons into the positive ion beam at the back of the thruster. If this is not done, the spacecraft rapidly acquires a negative charge over time, impeding and eventually negating thrust.

D. Propellant

Despite the fact (10) shows that thrust is independent of propellant type, the choice of propellant for an ion engine is very important. Recall that in practice, electric thrusters are limited by the power available to them. Consider the power to thrust ratio[29]:

$$\frac{P_E}{F} = \frac{M{v_e}^2 + 2E_{ion}}{2Mv_e} \tag{11}$$

E_{ion} is the energy required to create an ion. When E_{ion} is small compared to Mv_e^2, the (11) reduces to:

$$\frac{P_E}{F} = \frac{1}{2}v_e \tag{12}$$

This says the power required per unit thrust scales linearly with exhaust velocity. In order to minimize the power required, the exhaust velocity must be lowered. For a given V_b, minimizing v_e requires propellants with a small charge-to-mass ratio q/M, as seen in (9). Therefore, for a thruster operating at the Space Charge Limit, it is advantageous to use propellants with low ionization energy and a low charge-to-mass ratio. Xenon has both of these properties. Its ionization energy is 12.13 eV and its atomic mass is 131.29 amu (2.18 x 10^{-25} kg).

When it comes to an interstellar engine, there is really only one practical propellant: Hydrogen, not Xenon. To see this, recall Tsiolkovsky's rocket equation (5). A mass ratio MR can be defined:

$$MR = \frac{M_0 + M_f}{M_0} \tag{13}$$

Rewriting (5) and solving for MR gives:

$$MR = e^{V_f/v_e} \tag{14}$$

For interstellar missions, V_r must be large. In order to achieve a final velocity V_f = 400 km/s for v_e = 100 km/s, MR = 54.6. For a 1000 kg spacecraft, the amount of fuel required is about 53,600 kg. Even at this velocity it takes 3,220 years to reach Proxima Centauri. Exponentially more propellant is required for shorter trips. Obtaining tens of thousands of kilograms of rare Xenon is no small feat, nor is it cheap. Presently, Xenon costs $1700 per kg with only 59,000 kg of it being produced per year[30]. Even if such a mass could be gathered of Xenon or any other element, launching it into space from the Earth is quite expensive, considering it costs about $22000 per kilogram of material to fly into Earth orbit. The most attractive fuel source is one that is obtained during the interstellar journey. Such a source is Hydrogen, accounting for around 75% of the known mass in the universe and just sitting out in space, waiting to be harvested. An interstellar ion engine will run on Hydrogen. Since most ion engines are designed to run on Xenon, a new design is needed. This paper will focus on a preliminary one.

IV. Design

The primary difference between an ion engine running on Xenon and an interstellar ion engine running on Hydrogen is in the accelerator design. The ionizer and neutralizer need no modification because the ionization energies of the two propellants are similar and the ion currents at the Space Charge Limit are identical. The accelerator design needs to be optimized for a Hydrogen propellant within the constraints of the power available. The most appropriate power source for powering an ion engine is a small nuclear reactor. NASA's Prometheus program introduced the SAFE-400 (Safe Affordable Fission Engine) for spacecraft in long-duration missions[31]. It can produce 100kW of electric power, so the power required P_E for this engine design must be 100kW or less. Also, a device for collecting enough interstellar Hydrogen to provide constant, maximum thrust must be designed. Finally, a method of storing excess Hydrogen collected is explored. The majority of the design focuses on optimum accelerator and collector design.

A. Ionizer

Atomic hydrogen has an ionization energy of 13.6 eV compared to Xenon's 12.13 eV. Because the two are so similar, a standard electron bombardment ionizer from existing ion engine models is used. Losses during the ionization process increase the actual energy used to create an ion up to about 500 eV with 80% ionization efficiency[32].

B. Accelerator

As mentioned earlier, the minimum spacing between grids x is 0.5 mm with current grid technology. The maximum power available to the engine P_E is 100 kW and the energy required in the ionizer to ionize the propellant atoms E_{ion} is 500 eV. Applying accelerator theory with grid spacings of 0.5 mm and 1 mm respectively yields the following plot of thrust versus grid diameter (Fig. 7). Additional data is presented in Tables 2 and 3. The plot for grid spacing x of 5 mm is not displayed because an impractically large grid diameter is necessary to produce a decent amount of thrust. This is seen in Table 4.

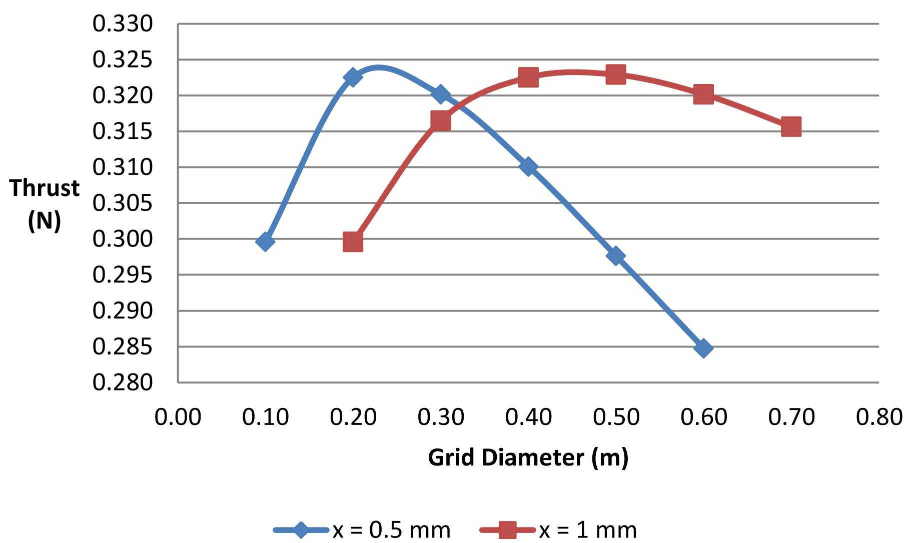

Figure 7. Thrust for a given Grid Diameter. *Thrust is limited by the power available to the engine for a given ion exhaust exit area. This plot is for a 100 kW power supply that uses 500 eV to ionize a propellant atom.*

Table 2 Thrust versus Grid Diameter Data for x = 0.5 mm.

Grid Diameter (m)	0.1	0.2	0.3	0.4	0.5	0.6
E (kV/cm)	22.0	11.4	7.59	5.60	4.39	3.58
v_e (km/s)	419	331	269	232	205	185
F (N)	0.29959	0.32250	0.32015	0.31008	0.29762	0.28476

Table 3 Thrust versus Grid Diameter Data for x = 1 mm.

Grid Diameter (m)	0.2	0.3	0.4	0.5	0.6	0.7
E (kV/cm)	11.0	7.54	5.71	4.57	3.79	3.23
v_e (km/s)	459	380	331	296	269	249
F (N)	0.29959	0.31650	0.32250	0.32289	0.32015	0.31563

Table 4 Thrust versus Grid Diameter Data for x = 5 mm.

Grid Diameter (m)	0.5	1.0	5.0	10	25	50
E (kV/cm)	2.77	1.57	0.408	0.220	0.0914	0.0439
v_e (km/s)	1630	1230	625	459	296	205
F (N)	0.11855	0.15319	0.25706	0.29959	0.32289	0.29762

For a grid spacing of 0.5 mm, the optimal grid diameter, or exhaust area A is 0.23 m. This gives a maximum thrust of 0.32321 N. The electric field of 9.94 kV/cm necessary is well below electrode breakdown thresholds for any of the Molybdenum, Carbon-carbon, and Pyrolotic Graphite grids (40 kV/cm, 23 kV/cm, and 20 kV/cm respectively). As a result, any grid technology may be used. There is no difference in thrust for the optimum grid diameter for a 1 mm grid spacing as opposed to the 0.5 mm or 5 mm spacings; the difference lies only in the size of the engine.

C. Neutralizer

Since the neutralizer structure is not dependent on the propellant type, and the ion current is the same for any propellant in the Space Charge Limit, a standard neutralizer is used.

D. Collector

Collecting enough Hydrogen to power the engine is not easy. The local density ρ of interstellar Hydrogen is about 10^5 atoms per cubic meter[33]. For a collector of area A_c, the mass flow of propellant through it is:

$$\dot{m}_c = \rho M A_c V_s \quad (15)$$

At steady state, the mass flow rate of ions through the collector is the same as the mass flow through the engine:

$$\dot{m}_c = \dot{m} \quad (16)$$

At the space charge limit, $\dot{m}$ = 1.05 x 10^{-6} kg/s. For a V_s of 400 km/s, the A_c required for steady state acceleration is 1.6 x 10^{10} km^2. The diameter of such a collector is about 140 km! A physical "scoop", or funnel, of this size is far too massive to construct out of even the lightest materials known. A scoop 150 km in diameter and 1 mm thick constructed from a material with density 1 mg/cm^3 has a mass of nearly 20 million kilograms, 10 times more massive than a Space Shuttle.

A more reasonable type of collector is a magnetic one, called a toroidal ramscoop. Fig. 8 shows the ramscoop proposed by Cassenti in 1991[34]. Superconducting wire is wound around the circumference of the torus, and current passing through the wire creates a magnetic field, pushing incoming ions towards the center of the scoop for collection. The nice property superconductors have is that they can hold large direct currents (DC) for extraordinary periods of time with no power loss because they effectively have zero resistance[35]. After the initial "charge-up" from low Earth orbit, the ramscoop does not draw power (or draws just trace amounts of it) from the spacecraft power supply and remains operational during the interstellar journey. One advantage the magnetic scoop has over a physical one is that it can provide a decelerating force if the spacecraft ever needed to reduce its velocity. This is done by reversing the current in the wire; incoming interstellar Hydrogen is deflected instead of collected. At high velocities, this method of deceleration is very efficient[36].

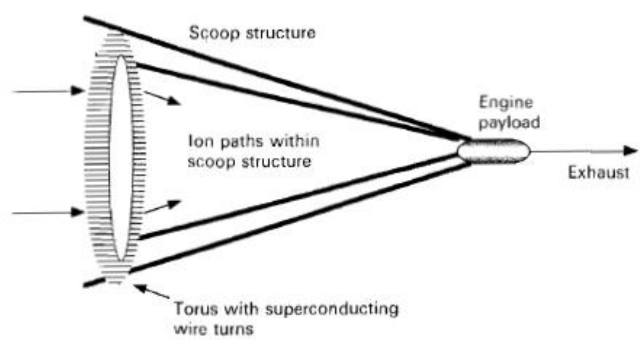

Figure 8. A toroidal ramscoop concept for collecting interstellar Hydrogen. *A giant magnetic field attracts and funnels charged ions to the spacecraft for collection.*

The 140 km diameter scoop calculated earlier is arguably too large in size to construct, but may be feasible. Cassenti himself imagined an 800 km diameter toroidal ramscoop[37]. That configuration only needs a steady state V_s of 12.5 km/s for self-sufficient operation, but has an estimated mass of a few hundred thousand kilograms[38]! The acceleration from the engine's maximum thrust F of 0.32321 N is on the order of 10^{-6} m/s^2. Starting from low-Earth orbit at V_s = 10 km/s, it would take nearly 80 years to reach V_s = 12.5 km/s. The 140 km diameter ramscoop is more than 5 times smaller, but needs 25 times more time to reach steady state (roughly 2000 years). Fig. 9 below shows approximate travel times necessary to achieve steady state operation for a given collector diameter.

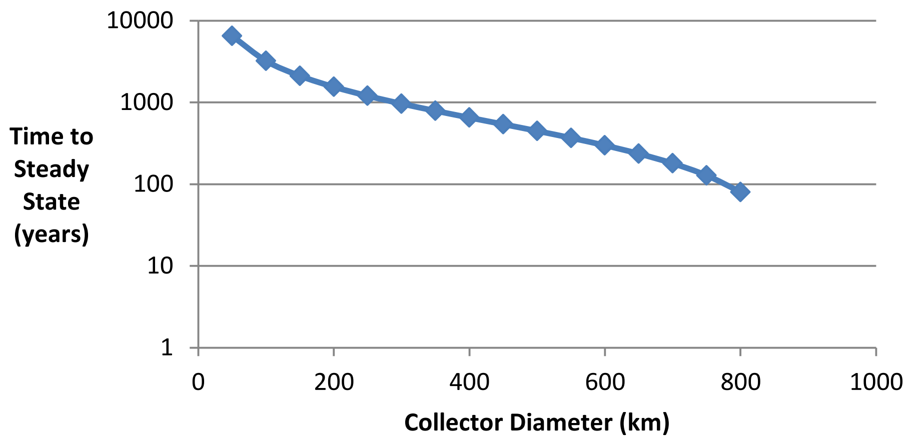

Figure 9. Time to self-sufficient operation from initial V_s = 10 km/s for a given collector diameter. *A significant amount of time is necessary to reach self-sufficiency from low-Earth orbit without external forces.*

It becomes clear that steady state acceleration is likely not attainable during the life of the engine without an external force like gravity assist from a planet. A gravity assist can increase the velocity of a spacecraft by up to 2 times the velocity of the moving planet[39]. Jupiter orbits 7.5 x 10^8 km from the Sun at about 13 km/s, so a change in V_s of 13 km/s from 10 km/s to 23 km/s is not unreasonable. Conservation of energy states V_s decreases over time as the spacecraft travels farther from the Sun. In the limit the spacecraft escapes the Sun's influence, its velocity is given by[40]:

$$V_f = \sqrt{V_s^2 - 2GM_{sun}\left(\frac{1}{R_s}\right)} \tag{17}$$

M_{sun} is the mass of the Sun, G is the constant of gravitation, and R_s is the planet's distance from the Sun. For initial V_s = 23 km/s, V_f = 13.2 km/s, enough velocity for steady state acceleration of the 800 km diameter collector. Therefore, the interstellar ion engine needs something like a gravity assist to operate.

E. Hydrogen Storage

Over the course of an interstellar spacecraft's journey, the craft enters regions of higher and lower than average Hydrogen density. If the density in a region is too low, steady state operation ceases and acceleration drops. For this reason it is advantageous to store excess Hydrogen collected for use in situations of need. Hydrogen has a boiling point of -253ºC and the temperature in space is -270ºC, so no additional power is needed to keep the storage tanks refrigerated. A year's worth of Hydrogen reserve fuel is only 33 kg at full engine power. Since liquid Hydrogen is stored at 72 kg/m^3, only about half a cubic meter, or 500 L is required.

F. Final Configuration

Based on the information presented in the previous sections, the parameters of the Hydrogen-powered interstellar ion engine design are presented in Table 5 below.

Table 5 Engine Parameters.

Parameter	Value
P_E (kW)	100
x (m)	0.0005
A (m^2)	0.04155
E (kV/cm)	9.94
v_e (km/s)	308
$\dot{m}$ (kg/s)	1.05 x 10^{-6}
F (N)	0.32321

V. Analysis

There are three different engine configurations. One has a self-sufficient collector so no fuel needs to be carried by the spacecraft. Another has no collector so all fuel must be carried on-board. The last has a smaller, non-self-sufficient collector and needs to carry some on-board fuel. Unfortunately, all three configurations cannot complete an interstellar journey due to engine failure at some point during the long journey.

A. With Self-Sufficient Collector

A self-powered engine that constantly accelerates sounds too good to be true; it is. Assume Matloff's "few hundred thousand kilograms" toroidal ramscoop mass is about 3 x 10^5 kg. Take the scoop's diameter to be Cassenti's 800 km. Then assume the gravity assist from Jupiter gives the spacecraft a solar system escape velocity of 13.2 km/s. $\dot{m}_c$ is given by (15) and $a = F / M_s$. The approximate initial spacecraft parameters are in Table 6. It would take just over 8600 years to reach Proxima Centauri given this configuration. In order to decrease the travel time, a must be increased. The only way to do this is to lower M_s since F is fixed. Lowering M_s lowers A_c, in turn lowering $\dot{m}_c$. The lowest $\dot{m}_c$ can go is $\dot{m}$ (for steady state operation). From (15), the minimum A_c is about 4.67 x 10^5 km^2, or about 771 km in diameter. If M_s varies linearly with collector diameter, the minimum M_s is 2.89 x 10^5 kg. a is now 1.12 x 10^{-6}, with a travel time of just under 8200 years; not much improvement. Fig. 10 shows how trip duration varies with initial V_s using (15) and the method described above. Since ion engines have an operational lifetime on the order of decades, the initial V_s must be around a very unreasonable 100000 km/s to complete the trip. It is clear that a self-sufficient interstellar ion engine cannot survive the length of an interstellar journey.

Table 6 Self-sufficient spacecraft parameters.

Parameter	Value
M_s (kg)	~3 x 10^5
A_c (km^2)	~5 x 10^5
V_s (km/s)	13.2
$\dot{m}_c$ (kg/s)	~1.1 x 10^{-6}
a (m/s^2)	~10^{-6}

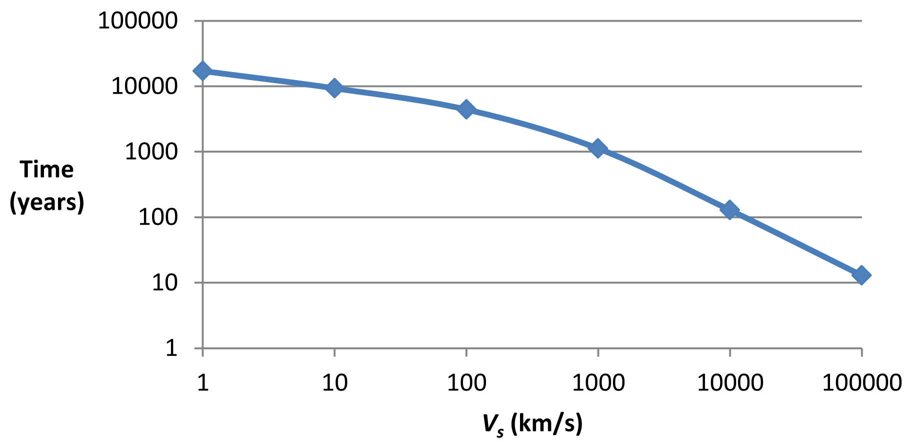

Figure 10. Interstellar trip duration from a given initial V_s for a self-sufficient engine. *Interstellar travel, even with a self-sufficient engine, takes a substantial amount of time with realistic initial velocities.*

B. Without Collector

An engine without the massive collector still suffers from the operational lifetime limit. An interstellar spacecraft with no collector must carry all the fuel for its journey on-board. Determining how much is necessary for a given trip duration is not easy because the spacecraft's acceleration will change over time as fuel is consumed. Instead of doing any complicated calculations, assume the spacecraft carries only its power supply, a 1200 kg nuclear reactor. a is maximized at 2.7 x 10^{-4} m/s^2 and V_s is still 13.2 km/s. The resulting travel time is 550 years, still too long for an ion engine. Fig. 11 shows how travel time varies with V_s assuming M_s is fixed at 1200 kg. The same result is obtained as with the self-sufficient engine, namely that V_s must be prohibitively high. Including the mass of the fuel now, the more fuel carried on board (increasing M_s), the smaller a is, and the

Table 7 Non-collecting spacecraft parameters.

Parameter	Value
M_s (kg)	1200
A_c (km^2)	0
V_s (km/s)	13.2
$\dot{m}_c$ (kg/s)	0
a (m/s^2)	2.7 x 10^{-4}

longer the trip will take. An interstellar spacecraft that supplies its own fuel also cannot survive the length of an interstellar journey.

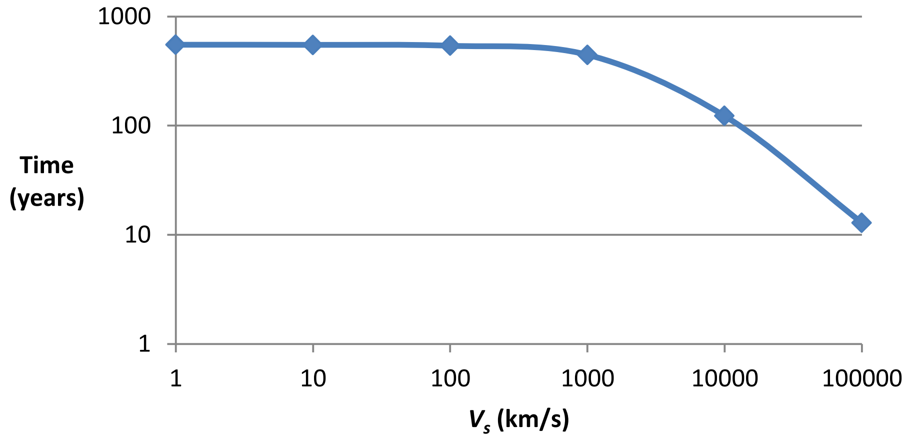

Figure 11. Interstellar trip duration from a given initial V_s for a non-self-sufficient engine. *In the ideal, but impossible case where the mass of the fuel carried by the spacecraft is zero, interstellar travel time is still prohibitively long.*

C. With Non-Self-Sufficient Collector

It is reasonable to assume that based on the two previous configurations, this configuration also will not survive the interstellar journey because of the mass of the collector and the fuel carried.

VI. Conclusion

A design for a Hydrogen-powered interstellar ion engine was presented. Analysis of the engine showed it was not capable of making an interstellar journey to our nearest star Proxima Centauri, some 4.3 light years away. The primary reason was the engine's low thrust to mass ratio. Accelerations on the order of 10^{-6} m/s^2 were expected. Such low accelerations resulted in travel times of millennia, greatly exceeding the operational lifetimes of modern ion engines. Although this form of electrostatic propulsion meets the previously developed criteria for interstellar engines (high exhaust velocity and long operational lifetime), this particular ion engine is unsuitable for interstellar travel.

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