ANTIMATTER DRIVEN SAIL FOR DEEP SPACE MISSIONS

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Abstract

The ultimate goal of this project is to identify and investigate an exploration architecture that would allow a light-weight instrument package to be sent to another stellar system. Due to the difficulty inherent in an interstellar mission, we have examined an architecture for a less demanding mission; sending a probe to the Kuiper Belt in a transit time of 10 years. Missions to deep space will require specific impulses greater than 6000 seconds in order to accomplish the mission within the career lifetime of an individual. Only two technologies available to mankind offer such performance; fusion and antimatter. Fusion has proven unattainable despite forty years of research and billion of dollars. Antimatter, alternatively, reacts with uranium 98% of the time in a well-described manner. However, development of a suitable propulsion system based on antimatter has not been shown until now. Our system analysis indicates that a 10 kg instrument payload could be sent to 250 AU in 10 years using 30 milligrams of antihydrogen. In addition, preliminary calculations also show that 17 grams of antihydrogen could send a similar probe to the next star, Alpha Centauri, in 40 years. We have designed a very straightforward system that will produce a variable specific impulse with a maximum of near one million seconds. The concept is one that can be throttled, that can be steered, and that can be demonstrated within the next two years. In this paper we identify the components of the system architecture that will be needed to perform a mission to the Kuiper Belt.

VISION

Sometime around 20 years in the future, humanity will want to send unmanned scientific spacecraft outside of the solar system to the hydrogen wall at the interface between the heliosphere and interstellar medium [1]. At approximately the same distance from the sun are the gravitation lens focal point of the sun and the low-density Kuiper comet belt. Approximately 10-100x further out is the Oort cloud, and yet another 10-100x further away is our nearest stellar neighbor, Alpha Centauri, that is 4.3 light-years away. Figure 1 contains a NASA/JPL slide showing these features on a logarithmic axis.

Based on current trends, the scientific instrumentation for such an unmanned probe is estimated to have a mass of approximately 10 kg. This leaves the spacecraft designers with a goal of creating propulsion and power systems that have masses comparable to the instrumentation. Based on this study, a roadmap toward the design and implementation of low mass systems is conceivable and, given 20 years, practical. In fact, the first stage of funding required to develop this idea has started.

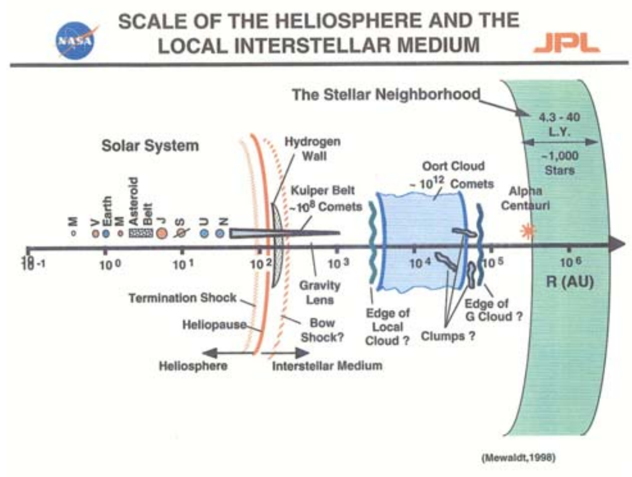

Figure 1: Solar system and interstellar features of intense interest for future scientific unmanned space missions.

SPACECRAFT OVERVIEW

Figure 1 contains a schematic representation of the proposed antimatter driven spacecraft [2]. There are four basic sections of the spacecraft, with the 10 kg instrumentation package at the rear, either attached rigidly to the body of the spacecraft or towed via tether a few kilometers behind and away from the pion and neutron flux from annihilations and fissions occurring at the sail in the front of the spacecraft.

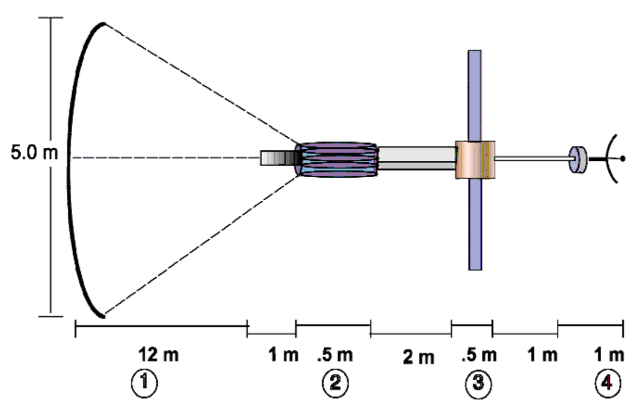

Figure 2: Proposed antimatter driven spacecraft. The primary subsystems are (1) a uranium coated carbon sail, (2) solid H2bar crystal storage units, (3) an antiproton driven electrical power supply, and (4) a 10 kg instrument package.

The basic nuclear physics behind this concept is the fact that antimatter incident on the surface of an uranium foil has a 98% probability of inducing a fission event [3].

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In undergoing fission it is found that two fragments of approximately palladium-111 are emitted back-to-back with a total energy of approximately 190 MeV. The velocity of the fission products is 1.39×10^7 m/s and the mass is 1.85×10^{-25} kg/atom. This velocity would equate to a specific impulse of 1.4 million seconds. In addition, there are numerous penetrating particles emitted such as high energy neutrons, gamma rays, and pions.

Imagine a cloud of antihydrogen drifting onto a thin uranium foil. On average, half of the fission fragments will have trajectories outside of the foil. These fragments do nothing other than carry away kinetic energy and reduce the overall energy efficiency of the concept. On the other hand, the other fission fragment enters the foil and is stopped via dE/dx. Because the incoming fission fragment can have any angle within 2π steradians, the forward momentum transfer is on average half of the per-fragment momentum. To stop a fission fragment propagating normal to the foil surface, the surface would have to be approximately 5.5 microns thick. In principle any material can be used as a backing layer to the uranium foil to provide this stopping power. Note that toward the end of life of the foil, its thickness will be much reduced and a high-strength, high melting point material is desired. We have chosen carbon for these reasons (fig. 3). A minimum thickness of 15 microns is required for dE/dx.

One possible enhancement might be to accelerate the incident antiprotons toward the uranium surface such that the stopping range of the antiprotons is well within the surface. It has been hypothesized that an annihilation event below the surface may create a cloud of ejecta which would increase the momentum transfer into the sail. An antiproton kinetic energy of 100 keV, easily created by electrostatically biasing the sail with respect to the antihydrogen container, would stop the antiprotons approximately 355 nm below the surface. The disadvantage of this concept is that more of the uranium in the sail is consumed, forcing the thickness for a mission to the Kuiper belt of 293 microns. Assuming a 5 m diameter sail, this gives the sail a mass of slightly over 100 kg. Though significantly heavier than the mass of the instrumentation, this is much lower than traditional ideas.

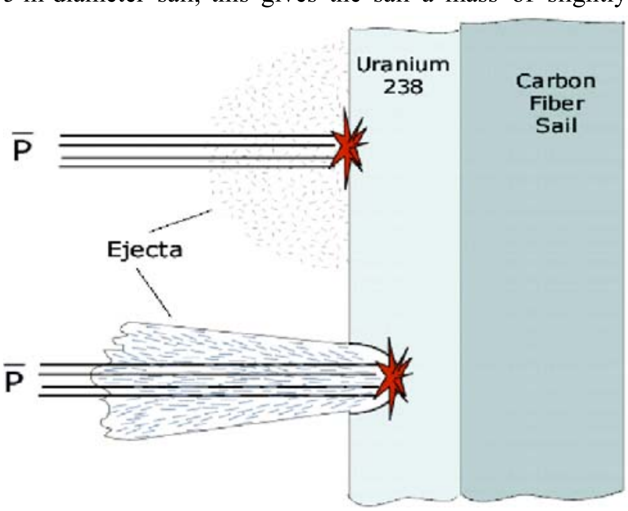

Figure 3: Depiction of the effect of annihilations on the sail as a function of incident antiproton kinetic energy.

The advantage of this scenario is that it reduces the specific impulse of the drive, increasing the energy efficiency of the concept and reducing the number of antiprotons required. Figure 4 contains the results of a calculation showing the change in antiproton consumption as a function of the number of un-fissioned uranium atoms ejected per antiproton annihilation (N_{at}). The experimental characterization of this mass ejecta effect, if existent, is the focus of the next phase of the experimental development effort for this technology.

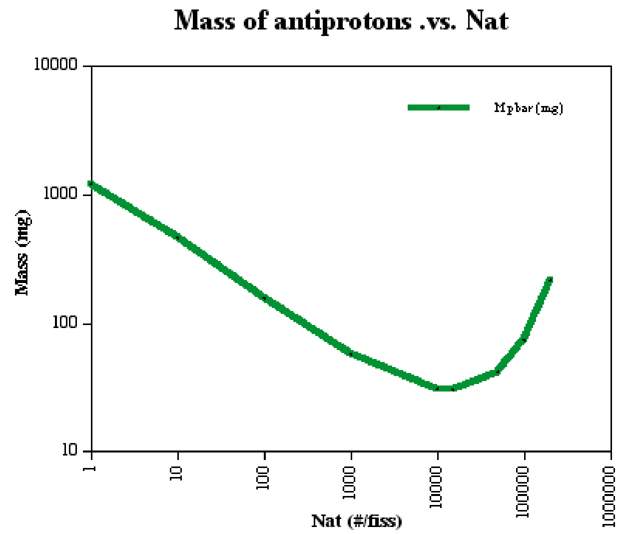

Figure 4: Calculation of the effect of the stored antimatter mass required for this mission scenario as a function of the number of uranium atoms ejected per annihilation.

Because the number of antiprotons required for this mission is roughly 2×10^{22}, space charge forces prevent their storage in that form. At a minimum, antihydrogen molecules must be formed. Because of the vapor pressure of solid hydrogen, very low cryogenic temperatures must be preserved.

The antihydrogen storage system is held 12 m away from the sail via four tethers. The storage system is envisioned to be an array of small chips resembling integrated circuit chips. Each chip, however, is not an electronic unit but contains a series of tunnels etched in a silicon substrate. Each tunnel is a sequence of electrodes. Each electrode pair forms a cell that contains a single pellet of solid antihydrogen. The operational scenario is similar to that of CCD chips, wherein charge is transported from one well to the next in a bucket-brigade manner. Each pellet holds approximately 10^{15} antihydrogen atoms and a charge of roughly 10^{-11} coulombs. Each tunnel holds 67 cells. There are 100 tunnels per 4 cm long chip. Thus, each chip holds 1.6×10^{19} antihydrogen atoms. There are roughly 2000 chips in the storage assembly. Total number of antihydrogen atoms is 1.8×10^{22} or 30.45 milligrams. The entire mass of the storage unit is about 9 kg.

The generation of onboard power is also accomplished using antiprotons. The industry-standard radioisotope thermoelectric generator used in the Voyager through Cassini missions has a specific mass at 194 kg/kw. We assumed a power requirement of 400 W based on the specifications for the Voyager spacecraft [4]. Again using antiproton annihilation on uranium nuclei, we now use the trajectory of fission fragments through a scintillator material, wavelength matched to photovoltaics, to generate power. The overall efficiency of such a unit is estimated to be 4.4%. Thus, around $2x10^{14}$ antiprotons per second are needed for the 400 W of electrical power. Dominated by the demands of signal transmissions to Earth, the power is generated on demand when communications back to Earth are desired. A waste-heat radiator is composed of two sheets, diametrically opposed, with the edges facing the sail. The sheets, designed as fins with a roughly triangular cross section, have a total surface area of $3.5\ m^2$. The radiator temperature is 620 C. The power unit mass is around 6.4 kg. Thus, the specific mass of the unit is 16 kg/kw.

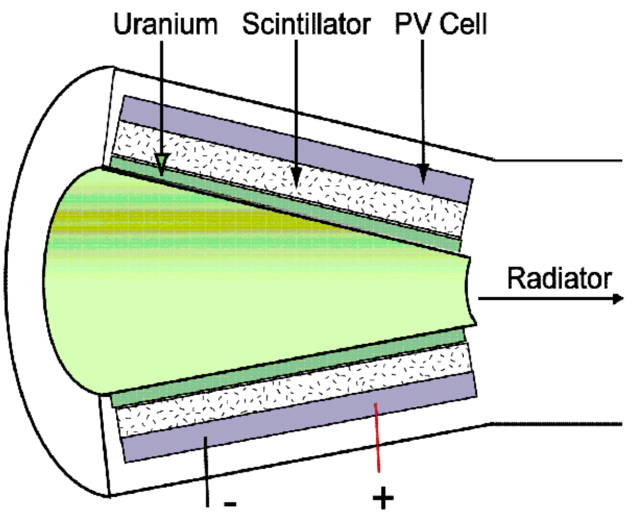

Figure 5: Schematic representation of the antiproton-based power generation system envisioned for anticipated missions. Instead of generating thrust, the fission fragments excite photons in the scintillator wavelength matched to the photovoltaic cells.

ANTIPROTON PRODUCTION

At present the Fermi National Accelerator Laboratory is capable of producing 10^{11} antiprotons per hour for a traditional total of 4450 hours per year. If every antiproton generated in a year was formed into antihydrogen and stored on board such an unmanned spacecraft, roughly $4.5x10^{14}$ antihydrogen atoms would be stored. This is enough to generate 400 W for two seconds, or 1 part in 40 million of the total antihydrogen inventory. At the present time, enough antiprotons are generated to perform millisecond type thrust tests. In order to reach the inventories of antiprotons needed for missions such as the one envisioned in this paper, it will be necessary to greatly increase the rate of antiproton production.

Basically, there are two ways to increase the antiproton production rate. The first is to put more protons on the antiproton production target. The limitations to this method are heating of the target and the cost of accelerating antiprotons. The second way is to increase the efficiency of antiproton production. At present, the Fermi production efficiency is 15 antiprotons for every million protons on target. An internal memo [5] suggests that an efficiency of even 1% is possible if a thin target is used and protons pass through the target repeatedly.

The present method of antiproton capture and cooling is optimized for the production of low emittance beams for use in colliding particle beam physics. Removing the resultant longitudinal and transverse emittance limitation imposed by this usage, a modified accelerator complex that decelerates and captures antiprotons without intermediate cooling can be readily envisioned. The design of such an accelerator complex is presently underway. In all, an increase in antiproton production rate of approximately 10,000x is envisioned in 10 years.

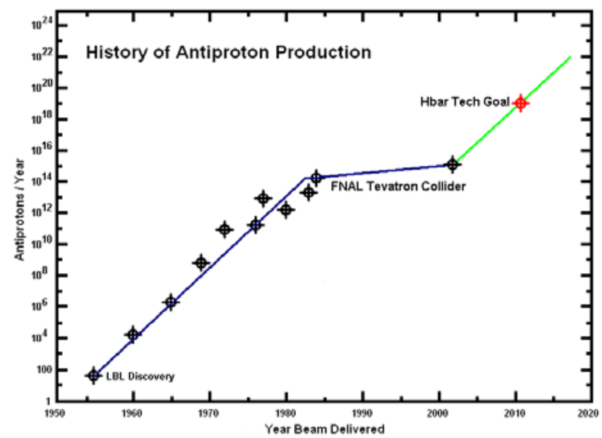

Figure 6: History and projection of record global antiproton production rates. The blue line in the center of the graph represents the recent Fermi National Accelerator Laboratory (FNAL) increases in production over the course of almost 20 years. The green line to the right indicates the goal of Hbar Technologies, LLC.

ACKNOWLEDGEMENTS

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