AIMStar: Antimatter Initiated Microfusion For Pre-cursor Interstellar Missions

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Abstract. We address the challenge of delivering a scientific payload to 10,000 A.U. in 50 years. This mission may be viewed as a pre-cursor to later missions to Alpha Centauri and beyond. We consider a small, nuclear fusion engine sparked by clouds of antiprotons, and describe the principle and operation of the engine and mission parameters. An R&D program currently in progress is discussed.

INTRODUCTION

The interstellar medium provides several clues to the evolution of the solar system, yet it cannot be fully exploited. Mewaldt[1] states that a "termination shock" of the interstellar wind at approximately 80 AU limits earth-based scientific investigation of high-energy particles and magnetic fields beyond this point. Moreover, speculation about the existence of Brown Dwarves in the Oort Cloud at 10,000 AU, also difficult to detect from ground-based sources, has piqued interest concerning the sun's formation as well as the mass of the solar system and ultimately the universe.

An interstellar scientific payload can answer three unresolved issues: (1) the precise location of the shock and the magnitude of the magnetic fields beyond; (2) composition of high-energy particles and plasma in the interstellar medium; and (3) the presence of Brown Dwarves and other clumps of matter not previously detected. To accomplish its goal, a space probe must not only carry the desired scientific equipment, but must also reach the Oort Cloud within a certain period of time to enrich our knowledge. Until now, failure of meeting the latter of these conditions has held interstellar exploration to a dream.

The challenge of developing a means to travel to the stars in the life span of a human being is long-standing. In their book Mirror Matter , Forward and Davis[2] review several proposed concepts, including rockets utilizing nuclear fusion reactions or antimatter annihilation, as well as rocketless systems such as laser-pushed lightsails. More recently, particle-pushed magsails[3] and solar sails[4] have been proposed as another example of rocketless propulsion. A comprehensive review of fusion rocket concepts has been presented recently by Frisbee.[4]

Each concept faces fundamental technological problems. For example, fusion rockets require massive (several hundred tonnes) high powered "drivers", being either a laser or particle beam array (ICF systems) or a magnetic torus or mirror (MCF systems). Antimatter systems generally call for quantities of antimatter far in excess of current or conceivable future production capabilities. Rocketless systems require intense high power laser or particle beams with exceptional focusing requirements, etc.

We have developed a new concept, called Antimatter Initiated Microfusion (AIM), which is a hybrid of nuclear fusion and antimatter technologies. Any system designed for deep space missions must meet the following criteria: (1) high specific power: $\alpha > 1$ kW/kg; (2) high exhaust velocities: $v_{ex}(max) = 10^4$ km/s; and (3) continuous power with near zero maintenance for several years. The following sections describe the AIMStar concept and expected performance for stellar missions.

SPARKING THE FUSION BURN

Physicists have been working for fifty years in an attempt to "spark" fusion fuel into a significant burn. ICF experiments use short pulses of intense laser or particle beams to compress and heat targets by ablation of surrounding materials. Using intense magnetic fields, MCF experiments attempt to continuously compress and heat fusion fuel into a burn. In general, results to date have been measurable, but unfortunately incomplete, burns of the target material. Inefficient coupling of beams to the target and plasma instabilities have been largely responsible for the failure for full ignition.

These experiments have generally attempted fusion of hydrogen isotopes deuterium (D) and tritium (T), which has a low ignition temperature. The fusion reaction:

$$D + T \; 6 \; n(14.1\ \text{MeV}) + \alpha(3.5\ \text{MeV}), \qquad (1)$$

presents serious problems for space applications: (1) large amounts of radioactive tritium are required. From space transportation safety considerations, this requires special shielding; (2) the neutrons require absorbers if their energy is to be used to heat propellant, and (3) if not fully shielded, the neutrons will cause severe radiation damage to the engine and payload. In all, the additional weight required may be at least 1 tonne, which would be intolerable for a small, fast stellar probe. Therefore, for this study we have considered DHe^3 fusion:

$$D + He^3 \; 6 \; p(14.7\ \text{MeV}) + \alpha(3.6\ \text{MeV}), \qquad (2)$$

which is aneutronic provided the fuel is burned at a sufficiently high temperature so that the competing $D + D$ 6 $n + He^3$ fusion rate is insignificant. We therefore hereafter illustrate AIMStar performance characteristics using DHe^3 as the fusion fuel.

We propose to inject small fusion fuel droplets into a cloud of antiprotons confined in a very small volume within a reaction Penning trap. The reaction trap (Figure 1) is roughly the size of a shoebox, weighing perhaps 10 kg. It is fed 10^{11} antiprotons on a periodic basis from a portable trap (not shown) positioned about 1 meter away on axis, safe from fusion debris. Radial confinement within a 0.8 cm maximum diameter orbit is provided by a 20T axial magnetic field. Axial trapping of the 2 cm long cloud of antiprotons within a 10 keV space charge electric potential on the electrodes is shown in Figure 2.

The key ingredient for heating of the 42 ng DHe^3 liquid droplet (Figure 2) is antiproton-induced fission fragments which have a range of 45 μm in the droplet. In order to spark the microfusion process, $5H10^8$ antiprotons are annihilated in a 2% molar admixture of a pre- or actinide metal, such as Pb^{208} or U^{238}, with the DHe^3. Annihilation takes place on the surface of the antiproton cloud, pealing back 0.5% of the cloud. The power density released by the fission fragments into the DHe^3 is about $5H10^{13}$ W/cm^3, fully ionizing the D and He^3 atoms. This is roughly comparable to a 1 kJ, 1 ns laser depositing its energy over a 200 μm ICF target, a system much too massive for driving a small space probe.

We note that it has been shown recently that the fission fragments from antiproton-induced fission are not radioactive,[5] so there is no concern of accumulative radioactive contamination of the engine and spacecraft as the engine burns.

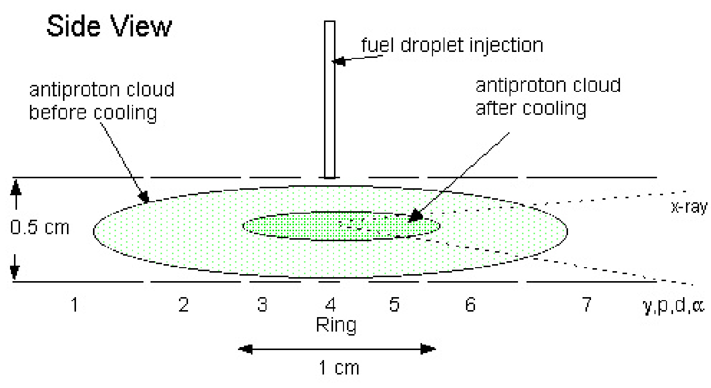

FIGURE 1. Expanded side view of the AIMStar reaction trap.

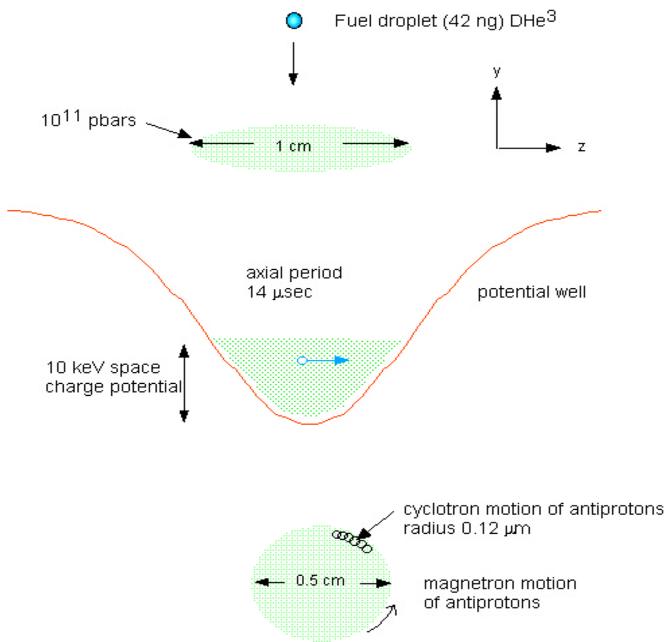

FIGURE 2. Fuel injection cycle, showing fuel droplet and confined antiproton cloud (side and end view).

The heating of the plasma takes place in 1 ns, and is confined in the center of the trap by application of a weak nested well potential (Figure 3). Antiprotons, as well as ionized electrons, are stored off trap center for use in subsequent cycles of the engine.

Transverse profiles of the antiprotons are shown in Figures 2 and 3, before and after injection of the fuel droplet, respectively. The antiprotons and D^+, He^{++} ions are confined by magnetic cyclotron and magnetron forces, which along with the axial electric force comprise a set of three fundamental harmonic forces in a Penning trap.

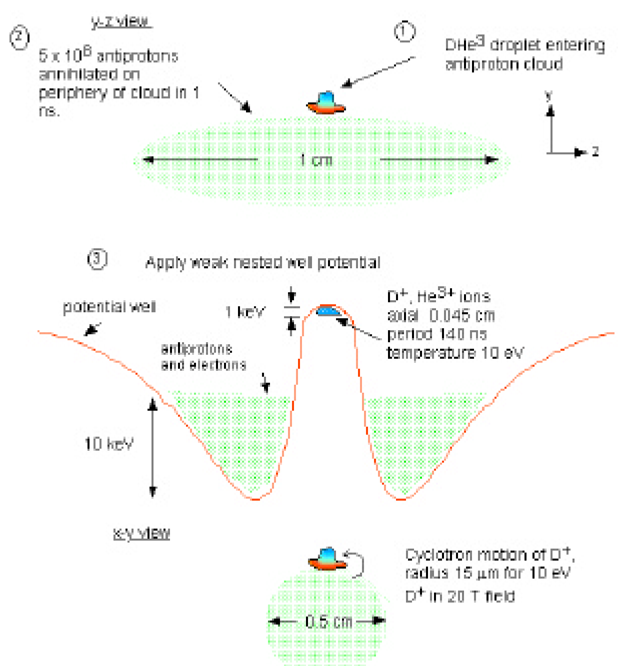

FIGURE 3. Fuel heating cycle, showing antiproton annihilation and confinement of D^+,H^+ ions, antiporton and electrons in a weak nested potential (side and end views).

COMPRESSING THE FUEL TO A FULL BURN

In order to compress the fully ionized DHe^3 droplet to high density and temperature sufficient to start a fusion burn, we apply a strong nested well potential as shown in Figure 4. The application of a 600 kV potential, which presents a new and important challenge to Penning trap operation, results in a 100 keV ion plasma with density $n = 6H10^{17}$ ions/cm^3, which when combined with a $\tau = 20$ ms lifetime satisfies Lawson's criterion ($n\tau > 5H10^{15}$ s/cm^3) for a full fusion burn. Because the kinetic pressure of the plasma under these conditions exceeds the magnetic pressure, a question which must be best answered experimentally arises as to the lifetime of the plasma against this instability.

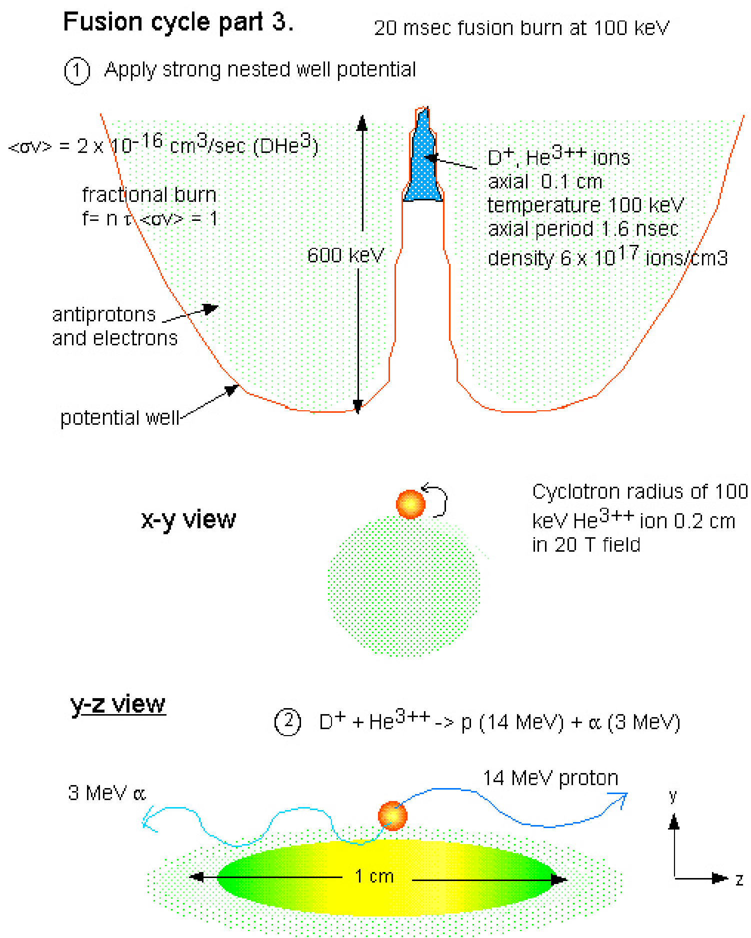

FIGURE 4. Fuel burn cycle, showing D^+,He^{++} ion compression to high density conditions over a 20 msec period, by application of a strong nested potential (side and end view)

Antiprotons not consumed in the original ionization of the droplet await later use, trapped in the wings of the potential well. Upon completion of the burn, the potential is returned to its original configuration (Figure 1), minus 0.5% of the original load of 10^{11} antiprotons. The four cycle process is repeated 50 times, followed by one cycle used to load another 10^{11} antiprotons from the storage trap into the reaction trap. The duty factor of the reaction trap is 99.5%, and delivers 0.75 MW (15 kJ/20 ms cycle) of continuous power in the form of protons and alpha particles.

SPECIAL CHALLENGES

The techniques described above are required to establish conditions for a complete fusion burn. They present two identifiable challenges in technology. First, the requisite density ($6H10^{17}$ ions/cm^3) shown in Figure 4 exceeds the Brillouin space charge limit by several orders of magnitude. This we propose to mitigate by dynamic injection and manipulation of electrons in the ion cloud, following the prescription outlined by Ordonez.[6] This technique has been generally applied in other electromagnetic fusion ion confinement schemes, for example by Bussard,[7] Krall[8] and Barnes et al.[9]

Second, injection of 600 kV of high voltage onto electrode gaps in the trap presents special problems associated with breakdown and stability. However, the resultant fields (1200 kV/cm) are not far beyond proposed fields (600 kV/cm) in other current and similar applications of traps, such as that of Barnes et al.[9] This work will bear watching as we approach experimental tests of our proposed system.

SPACECRAFT DESIGN

A preliminary design of the AIMStar spacecraft is shown in Figure 5. The reaction traps, antiproton storage, and engine are located to the aft of the vessel in a special "booster rocket" used only to accelerate the payload (shown at right) to a velocity of ~ 0.003c. At time of burnout the booster engine separates, leaving only the payload that is fully expanded into the form seen in Figure 6. Separation of the booster is important to permit communications with Earth.

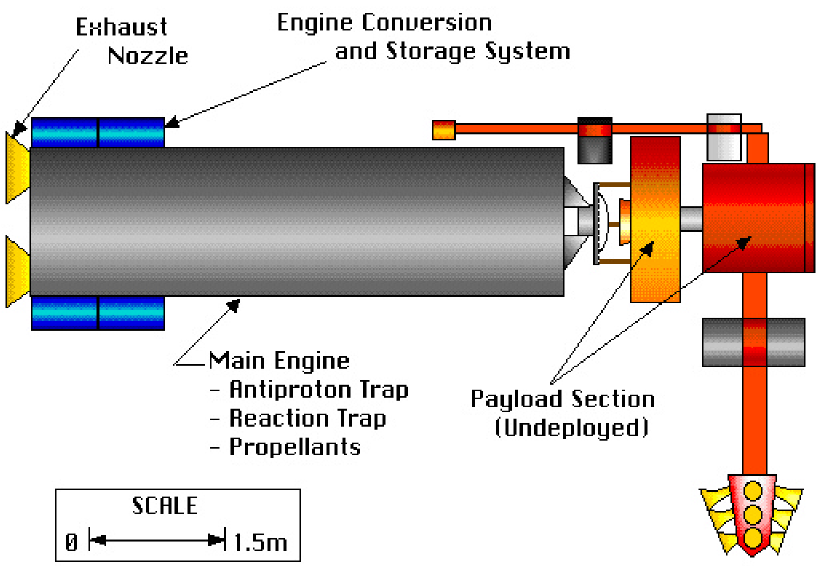

FIGURE 5. Profile of the AIMStar spacecraft.

Figure 6 describes the general locations of the various subsystems, as well as the scientific apparatus used for the mission. The magnetometer, found farthest from the central hub, is used to examine magnetic fields of the interstellar medium and determine the location of the termination shock discussed previously. A near-infrared spectrometer is used to examine Brown Dwarves in the Oort Cloud, and the optical imager serves a dual-purpose to detect large clumps of cold matter and to tell the spectrometer where to point. The astrophysics package, containing an ion-mass spectrometer, investigates high-energy matter and plasma contained within the interstellar medium.

Assuming that Ka-band will be employed on the Deep Space Network by 2030, a 100 bps data rate at 10,000 AU can be achieved by use of an 8m parabolic antenna. This requires 780W of power, which can be acquired through the use of RTG's envisioned for the future (AMTEC's).

MISSION ANALYSIS

We have developed a 50 year, pre-cursor mission to 10,000 A.U. (Table I). For comparison, we include parameters for both DHe^3 and DT fusion-driven systems. The DT system has lower ignition temperatures, but presents problems associated with containment of 14 MeV neutrons and tritium. We are presently designing a chamber in which the energy of protons and alpha particles from the fusion reactions is transferred to hydrogen propellant. The numbers in Table I assume 100% energy

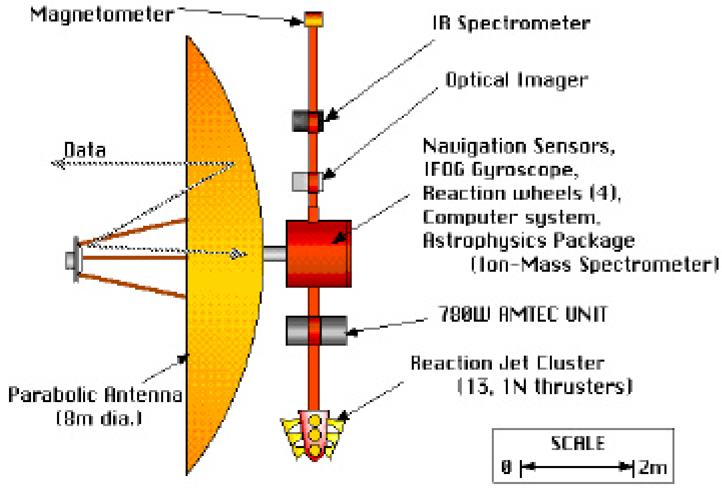

FIGURE 6. Profile of the AIMStar payload sections.

transfer efficiency, which is of course not realistic, and will be updated as our work progresses.

We see that the parameters under the assumptions stated above meet the minimum expectations for deep space missions outlined earlier. Further, the antiproton requirements are modest. Therefore, we believe that further work and defining experiments should be carried out on this very promising technology.

TABLE I. AIMStar 50 year Mission to 10,000 A.U.

	DT	**DHe^3**
ΔV	956 km/s	956 km/s
V_e	5.98 H 10^5 m/s	5.98 H 10^5 m/s
I_{sp}	61,000 s	61,000 s
Power	33 MW	0.75 MW
Thrust	55.2 N	1.25 N
dm/dt	9.22 H 10^{-5} kg/s	2.09 H 10^{-6} kg/s
t_b	0.50 yr = 6 mo.	22 yr
Distance @ burnout	37 AU	1635 AU
α_{ave}	30.5 kW/kg	0.69 kW/kg
N_{pbar}	130 μg	28.5 μg

1) $\Delta V/V_{ex} = 1.6$ for energy optimization (from rocket eq. this fixes payload to total mass ratio = 0.2);
2) 361 kg dry mass, 1444 kg propellant.

RESEARCH AND DEVELOPMENT PROGRAM

In collaboration with Penn State, Synergistic Technologies, Inc. (STI) is developing an Antimatter Plasma Gun (APG) under a NASA STTR Phase I award. We can foresee that the APG has potentially important near term applications as an ion thruster, and in a scaled up version as a spark or ignitor of nuclear fusion reactions to drive fast, interstellar probes. The technical objectives of this activity are to design and confirm computationally the specifications and applicability of the APG to important plasma applications technologies, and especially ion thrusters for near-term space propulsion.

As discussed earlier in this paper, the APG would utilize simultaneous double-well, nested confinement of negatively and positively charged particles in a Penning trap of cylindrical geometry. The negatively charged species is antiprotons, which are an extraordinarily high energy density and compact source for heating and ionization of neutral atoms when confined in a trap. Partially ionized positive ions created by antiproton annihilation with these atoms are captured and stored in the trap, along with the remaining antiprotons (and electrons resulting from the ionization process). Questions to be addressed in this research include: Can the positively charged ions be captured, along with the remaining antiprotons and ionization electrons, in separate wells by application of a double-well, nested electric potential? What vacuum is required to sustain storage for up to about one second, before injection of more atoms?

Radial confinement of the particles would be provided by an axial magnetic field, perhaps as much as 2-5 T. Can this field be provided by permanent magnets? If not, would a hot or cold electromagnet be the next best choice?

The positive ions would be extracted from the trap in the form of a bright, low emittance beam ready for applications. What configuration of extraction potentials on the trap electrodes are required to provide a well-defined beam of 1 keV energy, for example? Can the beam be extracted in very short pulses, and with what duty factor? Whata ion current is expected?

The HiPAT trap[10] presently under development at MSFC will serve as a storage facility for 10^{12} antiprotons. Initially, up to 10% of these antiprotons would be transferred from HiPAT to the APG. This number defines the approximate space charge limit for a non-neutral plasma cloud of antiprotons in an APG magnetic field. This process would be repeated with a periodicity which depends on the desired duty factor of beam delivery by the APG. Can the transfer be done efficiently, and what electrostatic lens configurations are required?

As indicated above, a small droplet of neutral atomic matter, e.g. LiH / U, would be injected into the antiproton cloud. What physical mechanism is required for a stable and repeatable injection of droplets of about 100 ng mass at a rate of about 1 Hz?

The high density cloud of positively charged ions and electrons created by the antiproton annihilation form a neutral plasma of temperature 1-10 eV. When the double-well, nested electrostatic potential configuration is placed on the trap electrodes, confining the positive ions in the center of the trap, the remaining antiprotons and electrons are pushed to confining wells at the ends of the trap. In order to achieve the highest possible density of ions, it is desirable to recirculate electrons from the outer wells back through the central well. What are the electric fields and frequencies required for dynamic manipulation of the mobile electrons form the outer wells to the central well and back, such that a load of positive ions many orders of magnitude above the space charge limit for a non-neutral plasma remains trapped?

This process of injection of neutral atoms is repeated, perhaps every one second, accompanied by injection at a slower rate of more antiprotons from HiPAT into the APG. Each injection of atoms will consume about 0.1% of the antiprotons in the APG. Allowing for a storage time of order one second per injection, the full 10^{12} fill of antiprotons in HiPAT will support plasma formation for approximately 3-4 hours with 100% duty factor, 30-40 hours with 10% duty factor, etc., depending on specific beam requirements.

Because of the extremely high power density imparted to the plasma by antiprotons, i.e. about 1.9×10^{14} W / cc, the APG can be compact and light of weight, making it an ideal portable plasma gun. Unlike other devices currently used for low temperature plasma research, its compactness and cost could make the APG widely available to universities, small-to-medium sized businesses, and government research laboratories for a myriad of applications.

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