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Use of Mini-Mag Orion and superconducting coils for near-term interstellar transportation

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Abstract

Interstellar transportation to nearby star systems over periods shorter than the human lifetime requires speeds in the range of 0.1–0.15 c and relatively high accelerations. These speeds are not attainable using rockets, even with advanced fusion engines because at these velocities, the energy density of the spacecraft approaches the energy density of the fuel. Anti-matter engines are theoretically possible but current physical limitations would have to be suspended to get the mass densities required. Interstellar ramjets have not proven practicable, so this leaves beamed momentum propulsion or a continuously fueled Mag-Orion system as the remaining candidates. However, deceleration is also a major issue, but part of the Mini-Mag Orion approach assists in solving this problem. This paper reviews the state of the art from a Phases I and II SBIT between Sandia National Laboratories and Andrews Space, applying our results to near-term interstellar travel.

A 1000 T crewed spacecraft and propulsion system dry mass at .1 c contains $\sim 9\times10^{21}$ J. The author has generated technology requirements elsewhere for use of fission power reactors and conventional Brayton cycle machinery to propel a spacecraft using electric propulsion. Here we replace the electric power conversion, radiators, power generators and electric thrusters with a Mini-Mag Orion fission–fusion hybrid. Only a small fraction of fission fuel is actually carried with the spacecraft, the remainder of the propellant (macro-particles of fissionable material with a D-T core) is beamed to the spacecraft, and the total beam energy requirement for an interstellar probe mission is roughly 10^{20} J, which would require the complete fissioning of 1000 ton of Uranium assuming 35% power plant efficiency. This is roughly equivalent to a recurring cost per flight of 3.0 billion dollars in reactor grade enriched uranium using today's prices. Therefore, interstellar flight is an expensive proposition, but not unaffordable, if the nonrecurring costs of building the power plant can be minimized.

1. Introduction

Interstellar travel is difficult, but not impossible. The technology to launch slow Interstellar exploration missions, total delta velocities (ΔVs) of a few hundreds of kilometers per second, has been demonstrated in laboratories. One answer to the famous Fermi paradox is that no civilization ever launches colony ships because the colonists are always waiting for faster transportation! Alternatively, given that a colony ship is feasible, and given the growth of global capital, it seems as though such a global enterprise might become desirable. The first criteria for a colony ship is that it with resultant kinetic energies of the order of 10^{15} J/kg. Not surprisingly, the second criteria for a successful interstellar mission is cost effective energy generation and an

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efficient means of converting raw energy into a propulsive mechanism. In other papers, several candidate propulsion systems theoretically capable of delivering probes and colony ships to nearby star systems were analyzed. Here we concentrate on variations of the Mini-Mag Orion concept as providing the propulsive means.

Rockets have limited ΔV capability because they must carry their entire source of energy and propellant. Therefore, they must be able to complete a rendezvous with a target star system within the life of the average colonist, assuming a target demographic life expectancy of 100 years. There must be sufficient time for training prior to commencing the trip and sufficient time for exploiting the new world upon arrival. If one assumes twenty years for each of these segments, then a travel time of 60 years is a realistic planning value. Assuming relative short acceleration and deceleration times, star systems within 6–9 LY might be accessible. Achieving such parameters may be very difficult, but still possible, and the colony ship must be accelerated to a significant fraction of the speed of light, high energy densities and very high exhaust velocities. The original Project Orion was an effort to develop a rocket propulsion system using successive explosions of small nuclear bombs. The Mini-Mag Orion design adds two important aspects to the family of Orion concepts: first, the use of magnetic compression of the fissile targets enables the utilization of much smaller explosions (50–200 GJ yield vs. 20,000 GJ), which are triggered by an external device, and thus cannot be projected as a potential weapon. This addresses the political concerns with the original Orion family of designs, and also dramatically reduces the requirements on the damping mechanism needed to convert the energy generated by the explosion into forward momentum of the spacecraft.

Secondly, utilizing smaller yield explosions allowed for the replacement of the large superconducting ring with a more sophisticated assembly of several coils, arranged into a nozzle like configuration. This modification addresses the technical difficulty of in-space assembly of the spacecraft's propulsion system, and allows for much improved control over the hardening of the coil assembly against both the space environment and the debris produced by the explosions.

Improved integration of the momentum exchange and energy generation components of the propulsion system can also be realized. The major components in the MMO system are shown in Fig. 1, and discussed in the following sections.

1.1. *Mini-Mag Orion: breakthrough propulsion*

Human exploration of star systems requires spacecraft with "breakthrough" propulsion systems capable of generating tens of kilometers per second of delta velocity while carrying large (> 100 ton) payloads.

1.2. *Recent experimental and analytical progress in Mini-Mag Orion*

1.2.1. *Z-Pinch implosions: magnetic compression physics*

At the heart of the MMO concept is the idea of compressing initially sub-critical fission assemblies by use of an imploding Z-pinch. This enables the lower yield values, external triggering of the fission reaction, and reduces the severity of the environment in which the engine has to operate. The program included the analysis of solid, high Z material compression, paired with the experimental verification/calibration of the analysis [2]. A series of experiments compressing hollow, solid-density cylinders of Aluminum and Gold was conducted in late September 2002. The authors recently concluded that adding a D–T fusion driver would enhance fractional fission yield, requiring less fissionable material and enhancing the delivered specific impulse. This enhances the MMO concept's ability to meet the demands of an interstellar mission. Below is a synopsis of the experimental results. We will expand these results to show applicability to the interstellar mission.

1.2.2. *Neutron transport analysis: exotic fission materials*

The specific composition of the fissile material in the compression target has a large impact on the requirement for maximum compression needed to achieve criticality. The MMO program has investigated a variety of fissile materials regarding the applicability to the MMO concept, and performed neutron transport analyses to determine total yield, burnup fractions, and required amounts of neutron reflectors and initiation neutron sources [3]. The design settled on a baseline calling for the use of a hollow sphere of ^{245}Cm with an additional layer of Beryllium as a neutron reflector. An external neutron source is required and a variety of options (including D/T fusion ignition diodes) were evaluated.

1.2.3. *Pulse units: Low Mass Transmission Lines (LMTL)*

The ratio of the energetic yield released by the fission reaction, and amount of material vaporized and expelled in each pulse is of critical importance when trying to achieve the very high exhaust velocities (>200–$300\,\mathrm{km/s}$) needed for efficient interstellar travel. The MMO program has investigated the possibility of LMTL fabricated from Mylar. Experiments were performed on the Sandia National Laboratory Saturn machine. Results indicate that transmission lines weighing as little as 2 kg may be sufficient to deliver the required currents into the Z-pinch used to drive the MMO compression.

If one were to completely convert the energy available from fission into directed momentum, the fission fragments would achieve a velocity of $\sim 9.8\times10^6\,\mathrm{m/s}$, which is less than the final desired velocity of $3\times10^7\,\mathrm{m/s}$. Even adding in fusion energy, which we assume to be small due to a low coupling factor for most of the energy, would increase this to $\sim 1.1\times10^7\,\mathrm{m/s}$. To this energy we can add some energy from the fusion reaction, most of whose energy is present in the form of 14 MeV neutrons that dramatically enhances the fission yield. However, we estimate that 10% of the fusion energy will couple well with the internal plasma.

1.2.4. Magnetic nozzle design

The efficient conversion of the energy transferred into the plasma by the fission reaction into forward momentum of the spacecraft is another critical aspect of the MMO system. The MMO program has developed tools to analyze multi-coil magnetic nozzle configurations, and assessed a variety of designs for propulsive efficiency at minimum mass and power requirements. Both particle trajectory based models and MHD based fluid models were utilized in the investigation of the magnetic nozzle.

1.2.5. Power system: pulsed/continuous power generation

Driving the magnetic compression implosion at high repetition rates (1 Hz) and the level of reliability needed for a crewed system requires the use of large, redundant pulsed power supplies. During nominal operation a small fraction of the energy ($<1\%$) produced by the fission reaction is recycled to recharge the pulse power banks. In addition, a steady-state power supply is also needed to initially charge the system, or restart the engine in the case of a misfire. The MMO program has investigated a number of power storage technologies and determined a baseline design for both pulsed and continues power systems.

1.2.6. Engine design: feed system & nozzle/engine dynamics

The mechanical design of an engine capable of repetitively discharging the pulse units at rates of up to 1 Hz is also a formidable engineering task. The MMO program has investigated several options and developed a baseline engine design that combines operational simplicity, a minimum of moving components, and built-in redundancy to enable system fail-operational capabilities.

1.2.7. Thermal management: waste heat disposal

Any electrical space system operating on mega-watt power levels faces significant challenges in the removal of waste heat from the spacecraft. The thermal management system (TMS) of a high specific impulse spacecraft can account for a large fraction (up to 30%) of the vehicle's dry-mass. As a part of the MMO program, an analysis of the waste heat removal requirements of the MMO concept was conducted.

1.2.8. Conclusions

The Mini-Mag Orion program made significant progress towards establishing the Mini-Mag Orion concept as a basis for interstellar transportation. The main concept risk factors have been identified, and appropriate experimental and analytical tasks have been performed throughout the program to study these issues, to the degree possible under the program scope and funding. A follow-on program is being proposed to extend the experimental work originally started under this SBIR program.

The physics of imploding high-z solids was investigated, indicating that it is possible to achieve criticality in initially sub-critical assemblies of fissile materials. A 1-D compression model has been developed which was utilized in system scaling. Unfortunately, Z-pinch compressions are Rayleigh–Taylor unstable, and these instabilities are difficult to model. To reduce the effect of these instabilities, it is feasible to compress the geometries at factors of less than three per stage.

The first experiment investigating Low Mass Transmission Lines (LMTL) on the SNL Saturn machine has been successfully concluded with data favorable to the Mini-Mag Orion concept. The second experiment investigated the area of high-z solid material compression by the use of imploding z-pinches, and was conducted on the SNL z-machine in late September 2002. While only two of three planned implosions could be performed in the allotted time-slot, the two shots both resulted in some useful data on the behavior of solids when compressed in a magnetic field. The MMO team successfully fielded a previously untested diagnostic using bent-crystals and a terawatt scale X-ray source as a backlighter, which allowed for the capture of imagery close to the occurrence of peak compression during the implosion. Shock breakout data was also utilized to capture pressure evolution during the implosion. While the experiment was not successful in capturing sufficient data on each individual shot to determine a final density achieved in the compression, the experiment successfully demonstrated the experimental technique developed by the team; laying the foundation for further experimentation.

A trade study of various fission material targets was conducted and ^{245}Cm selected as the baseline compression target. A neutronics analysis indicates that a 10% burn up fraction can be expected, with 60+ generations of neutrons (sufficient for prompt criticality) produced if the target is compressed to a critical ρ of 65 g/cm^2.

2. Toward interstellar travel

2.1. Concept description

The Mini-Mag Orion interstellar spacecraft is shown conceptually in Figs. 1 and 2.

In order to place the MMO concept into perspective, we note that several studies have been accomplished evaluating interstellar travel with more-or-less conventional technologies. The late Dr. Robert Forward in his papers on interstellar lightsail [1,2] missions postulated a 7200-GW laser to accelerate his 785 ton unmanned probe and a 75,000,000-GW laser to accelerate his 78,500 ton manned vehicle. Lenard proposed an extension of Timberwind reactor technology and highly advanced power conversion and heat rejection technologies to electrically propel a NEP vehicle to nearby star systems within 65 year timeframes [3]. Andrews [4] performed a review of various technologies to propose a Sail-Beam concept, a variant of which is employed in this study. The possible venues for interstellar travel, but more specifically, interstellar rendezvous missions appear to fall into three primary categories: 1. momentum exchange, where all of the propulsive momentum is provided by devices, (lasers, particle beams, e.g.) in the Earth's solar system; 2. energy transfer devices, which send propulsive material to the spacecraft, which then uses that material for its own mass transfer, or 3. on-board propulsion technologies, where all of the propellant is carried by the spacecraft, such as anti-matter propulsion. Andrews indicates that all the concepts in group 3 are either impractical or do not fall into the category of today's physics. We note there that gargantuan laser devices, such as postulated by Forward probably cannot be construed to fall within today's physics either. Lenard has provided an initial insight into energy transfer devices, which actually send materials via macro-particle accelerators to the spacecraft, which then uses that material as propellant in a fission reaction. The initial work cited here looked at nuclear electric propulsion, which required enormous electrical power generation, massive electric thrusters and collected huge quantities of uranium for deceleration.

The approach here is conceptually shown in Fig. 3. As recalled from the recapitulation of MMO progress, it is noted that the fission–fusion pellet requires a conductive sheath to carry the compression current. It turns out that this fits in nicely with the proposed Sail-Beam concept.

To put our concept into perspective, it is first necessary to construct a strawman space system. Based upon our fission–fusion system, we construct the following parameters:

Parameter	Value	Units
Mission ΔV	30,000	m/s
Specific impulse	128,955	s
Payload mass	200,000	kg
Ignition mass	812,000	kg
Rho-r	65	g/cm^2
Compression ratio (Density)	30	n/d
Peak compression current	80	MA
Yield	89.1	TJ
Thrust	2623	kN
Thrust	589,470	Ibs
Power (Ave.)	22.27	TW
Alpha (specific power)	6.89×10^6	W/kg
Maximum acceleration	.42	g
Average acceleration	.335	g
Acceleration time	8.95×10^6	s

This presumes a pulse repetition frequency of approximately .25 Hz, which seems to be a reasonable re-feed time for the Z-pinch device. In the above assumptions, we believe that due to the fusion driver, 90% of the ^{245}Cm pellet is fissioned, and that all of the .1 g of DT is fused. Based on ^{238}U fusion neutron spectrum

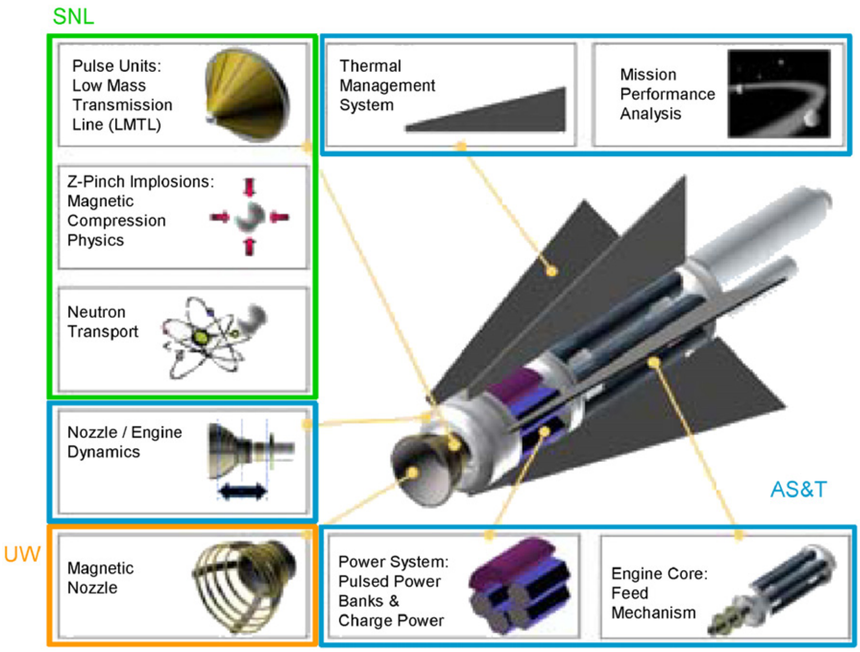

Fig. 1. Components of Mini-Mag Orion.

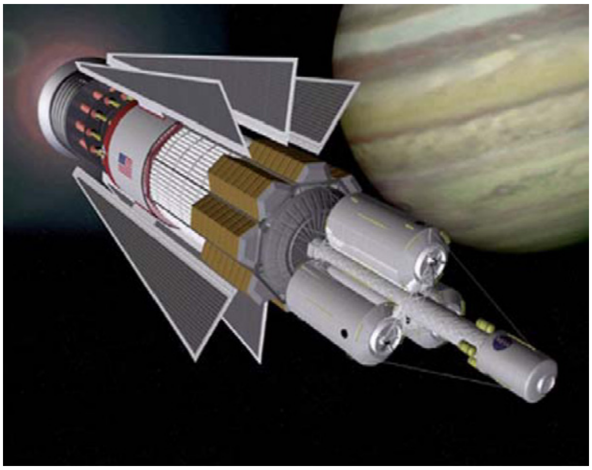

Fig. 2. Interstellar Mini-Mag Orion concept.

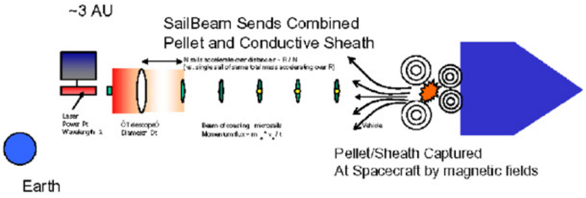

Fig. 3. Mini-Mag Orion pellet-sheath sail-beam concept.

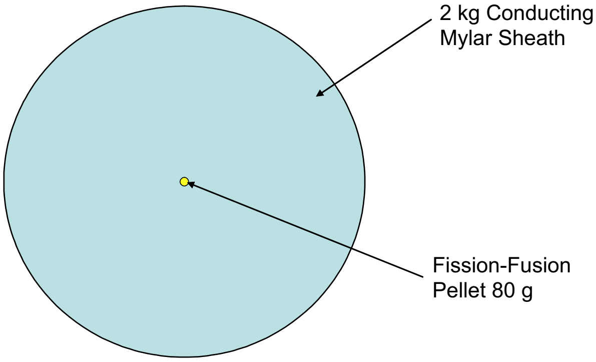

Fig. 4. Mylar sheath with embedded pellet.

neutron yield, this should be close to the correct ratio. The 2.0 kg Mylar sheath does not participate in either reaction, but contributes to the total mass that is expelled from the MMO interstellar rocket. A concept of the sheath-pellet combination is shown in Fig. 4.

In order to capture the pellet sheath combination, the arrival velocity at the spacecraft needs to be carefully controlled. Any velocity above about 1 km/s will destroy the pellet-sheath combination, so velocity control of $\sim$ a part in 10^4 will be required. Additionally, acceleration forces on the sheath will need to be below the yield strength of the Mylar sheath with the embedded pellet since the pellet density is significantly greater than the

Mylar density. One can estimate the maximum acceleration to which the sheath-pellet combination can be subject without tearing the pellet from the sheath. Assuming that the sheath has a tensile strength of 5×10^8 Pa and the pellet is 3 cm in diameter, then:

$$\frac{\mathrm{gm}}{A} = \frac{2\Delta t}{r}. \tag{2.1}$$

Putting in expected parameters in the equation yields at possible acceleration of 300 g, well in excess of what would be required to accelerate the sheath to meet the spacecraft, and well within capability to decelerate the pellet-sheath combination at the spacecraft.

Unlike other concepts, the primary motive force in the MMO hybrid acquires its accelerating force from the fission–fusion combination. As mentioned earlier, the final specific impulse is a function of energy release, energy coupling and total mass. The propellant velocity can be estimated as

$$v = \sqrt{\frac{2\cdot\xi\cdot\eta\cdot m_{\text{f–f}}\cdot 9\times10^{16}}{M_t}}, \tag{2.2}$$

where ξ and η are the mass to energy conversion and energy coupling efficiencies, (taken as .0011 and 1), $m_{\text{f–f}}$ is the mass of the fission–fussion material in the pellet and M_t is the mass of the pellet and sheath. Using these values, we obtain a specific impulse of $\sim$ 128,955 s. The impulse from a single explosion is

$$\begin{aligned} I = M_t\cdot v &= 2.08\cdot 1,289,550 \\ &= 2.68\times10^6 Nt - s. \end{aligned} \tag{2.3}$$

This impulse occurs at the rate of 1 every second. Given the above exhaust velocities the density of fission fragment material should be too low to represent a hazard to incoming pellet-sheath combinations

$$\rho = \frac{M_t}{1.33\cdot\pi\cdot(vt)^3}. \tag{2.4}$$

Since $vt \sim 1.2\times10^8$ cm then the density is $\sim$ 10–100 particles/cm^3.

2.2. Power requirements to accelerate pellet-sheath elements

Power requirements to accelerate the pellet-sheath elements to reach the spacecraft can be calculated. Since the velocity to which the sheaths must be accelerated is only slightly greater than the spacecraft velocity, we can estimate the energy in the compressive units and integrate over velocity to get total energy. The total energy to accelerate the units is 9×10^{21} J. The power required can also be evaluated, and this results in an average accelerating power requirements of approximately 1.005×10^{15} W, or 1000 TW.

However, coupling of the laser to the Sail-Beam is not perfect, although several variations have been proposed. One variant, first proposed by Kare [5], uses the momentum of a high-power laser beam to accelerate a stream of small, very low-mass microsails to high velocity. The stream of microsails transfer their momentum to a much larger mission vehicle, as shown in Fig. 3. Unlike conventional laser sails, Sail-Beam is not limited by diffraction, and was invented to transmit momentum to a distant spacecraft. Although and can transmit momentum over an arbitrarily large distance, it is our objective to propel a solid mass to a velocity that closely matches that of the spacecraft. Laser acceleration of microsails is made (comparatively) practical by the use of low-absorption quarter-wavelength-thick dielectric sails, as proposed by Landis [6], which avoid the thermal limitations on laser flux, and thus accelerations, that apply to metallic sails. However, our system is limited by the acceleration that the Mylar sheath can withstand when accelerating the dense pellet. So, any of these will work. While speculative, one can presume that coupling efficiencies will be high, > 80%, and that at 300 g acceleration, even accelerating the pellet element to .1 c will only require a distance of about 1 AU.

Over this distance, the laser beam should still retain sufficient beam resolution to not waste more than 50% of the overall energy. We can safely assume that the acceleration process will be approximately 40% efficient, thus, the power required is $\sim$ 2.5 TW. This is quite low compared to other options, so the concept of a MMO-driven colony ship is favorable when compared to momentum transfer only approaches.

2.3. Deceleration: the canonical issue

While accelerating to a sizable fraction of the speed of light is a daunting task, deceleration is a yet more challenging task. The reason is that no realistic scenario to provide the gravy-train approach to either momentum transfer or pellet energy transfer at distances of 4 + light years seems within known physics. We are therefore challenged with either sending sufficient numbers of pellet-sheath elements so that the spacecraft can decelerate with on-board energy, or to come up with some other innovative concept.

2.3.1. Fueling at departure point

One option is to provide all necessary propellant at the departure location. If the specific power and specific

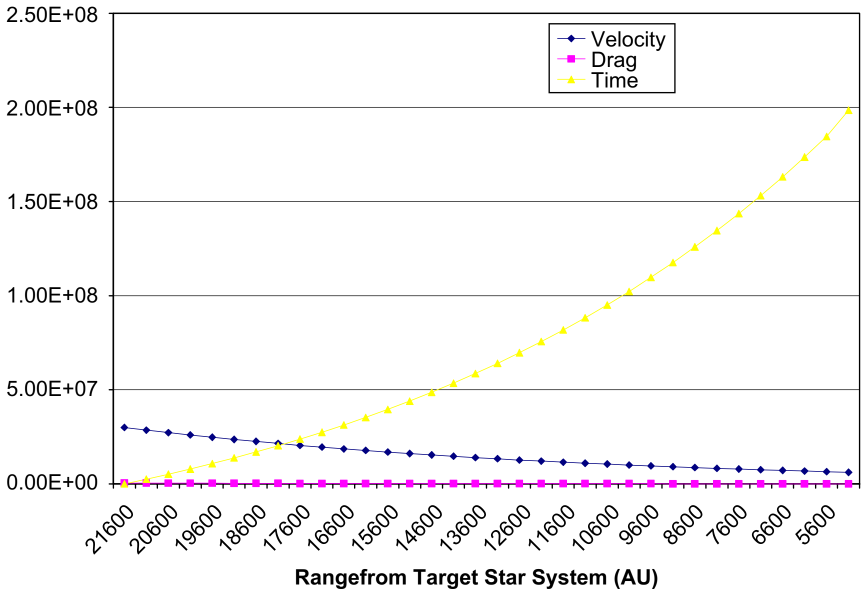

Fig. 5. Deceleration regime in interstellar space.

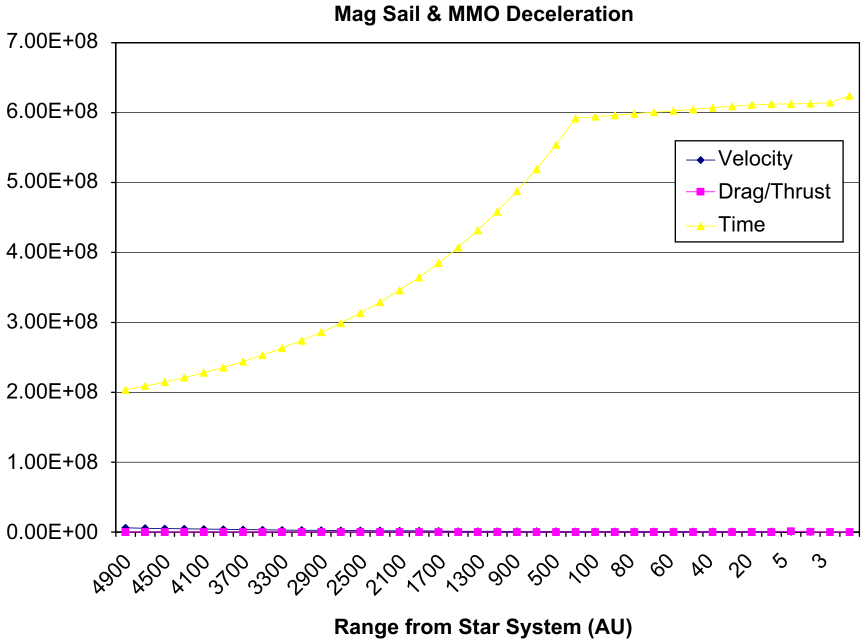

Fig. 6. Near-star system deceleration profile.

impulse is sufficiently high, this is a potential approach. However, for our MMO concept, it is not particularly feasible. For example, our specific power is certainly high enough, but our specific impulse is dictated by the pellet-sheath combination, which limits the Isp to 128,955 s. While this may seem like a prodigious specific impulse, the ratio of spacecraft speed .1 c to $g * \text{Isp}$ is 23. This means that the deceleration propellant must be e^{23} times the spacecraft mass, which is an unworkable solution.

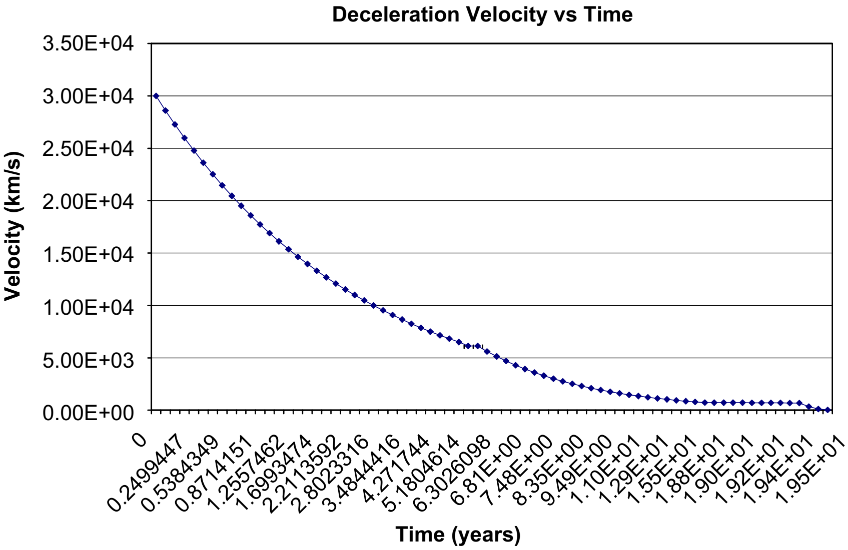

Fig. 7. Overall deceleration profile.

2.3.2. *Mag Sail deceleration*

In 2003 both Andrews and Lenard postulated using a large superconducting ring to intercept charge particles in interstellar space to slow the spacecraft down from high speeds. Additionally, the solar wind emanating from a star system provides an additional source of charged particles that can interact with the magnetic field. Deceleration can actually begin a sizable distance from the target star system. The following two charts indicate deceleration, velocity and time as a function of distance from the target star system. In this case the first phase of the deceleration starts at 21600 AU with a two-turn superconducting carbon nano tube reinforced loop. This loop captures the charged interstellar medium and deflects it to decelerate the spacecraft. This initial hoop size is 500 km in radius and carries 1,000,000 A of current. The spacecraft decelerates from .1 c to 6300 km/s by the time the spacecraft reaches 5000 AU. This will be quite a light show, so if there are any intelligent life forms with an observing system, they should be able to see the arrival.

This region is shown in Fig. 5. At 500 AU the Mag Sail is allowed to unfurl to a single loop of superconducting wire with twice the operating radius, but half the current. This results in a slight uptick in drag forces, hence deceleration and is shown in Fig. 6. Deceleration using the Mag Sail continues until the spacecraft reaches approximately 100 AU, where for purposes of display, the resolution of the distance is changed from 100 AU increments to 10 AU increments.

At ∼ 5 AU the spacecraft velocity is 692 km/s and the MMO engine begins firing at a rate of once every 2 s. At 4 AU the engine fires once every 12 s, and at 3 AU it fires once every 2 min. By this time the spacecraft reaches 2 AU, it is traveling ∼ 30 km/s, or approximately orbital velocity for that point in a sol-like star system. The overall deceleration profile is shown in Fig. 7.

3. Conclusion

A combination of several different variants of interstellar travel were investigated and analyzed. In this approach, we use the Mini-Mag Orion concept to provide high thrust acceleration of a spacecraft to .1 c. High velocities are feasible, but as an initial investigation, we wanted to establish a parameter space that was compelling without being unrealistically challenging. We discovered that unlike most momentum exchange or transfer concepts, the concept of accelerating the propellant (fission–fusion pellets and current sheath) dramatically reduced power requirements from the departing star system. It also reduced the timeframe over which the acceleration and power had to be provided. This makes the impact on the star system less demanding and therefore more likely. Decelerating is a major challenge and is not feasible by carrying onboard propellant for the Mini-Mag Orion concept. Use of the Mag Sail concept provides essentially “free” deceleration, although power to charge the superconducting loops must be provided. At the end of the journey, the Mini-Mag Orion engine must once again be used to decelerate to orbital velocity within the star system.

Major technical challenge include the continued requirement to understand the Z-pinch type compression process and to complete more experiments. The authors are preparing a supplemental SBIR proposal to accomplish just that.

While quite futuristic in approach, we believe the Mini-Mag Orion concept is extremely promising for interstellar travel if breakthrough propulsion does not bear fruit in the next 50 years or so. The seminal result of this paper is that we are not stuck in this solar system, even if breakthrough physics does not yield a new propulsion system. We note that none of the concepts mentioned here are not extant at some nascent level of investigation. Substantial maturing of technology is required, but no breakthroughs in physics are required.

Assuming that breakthrough physics does not yield a new propulsion concept, we are certainly on the verge of a new biology. We should reasonably expect that human lifespans could, at some point in the future, achieve antediluvian proportions. Given our former fractional time breakout, this means that a crew could ostensibly travel for 600 years and still be in their prime at the destination. This would mean that humanity could populate the galaxy in 60–90 LY spheres. Given the sophistication of humans and robots at that time, we could expect a new Diaspora to occur every 4000 to 5000 years. In a million years, half the galaxy could be inhabited.

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