Relativistic Spaceflight and the Catalytic Nuclear Ramjet

By Daniel P. Whitmire, Center for Nuclear Studies, University of Texas at Austin, Austin, TX 78712, USA

Author address as of April 2009: The University of Louisiana - Lafayette, Department of Physics 44210, Lafayette, LA 70504, <whitmire@louisiana.edu>

Abstract

The interstellar ramjet concept allows us, at least hypothetically, to get around the mass-ratio limit inherent with relativistic fuel-carrying rockets. The required ramjet energy must be extracted from the nuclear reserves of the interstellar hydrogen (interstellar deuterium is too scarce). Unfortunately, the usual PPI chain for converting hydrogen to helium is hopelessly slow due to the minute weak interaction cross section of the reaction $p + p \rightarrow {}^2D + e^+ + \nu$ at essentially any energy. It is shown here that this problem can be avoided, in principle, by exploiting a proton burning catalytic cycle. The best known catalytic cycle is the CNO Bi-Cycle occurring in sufficiently hot main sequence stars. The catalyst "fuel" may be carried on board the ship since it is not depleted, and the ultimate source of energy is the interstellar hydrogen. It is shown that with potentially realistic parameters the energy requirements for a ramjet accelerating at 1*g* to near luminal velocities can be met with either the "hot" CNO Bi-Cycle or the Ne-Na cycle. Some of the formidable technological problems associated with a conventional heavy ion fusion reactor are briefly discussed. It is not absolutely necessary that a conventional plasma reactor model be used; for example a laser fusion reactor or a large scale Migma-type reactor (if technologically possible) might be employed. The problem of interstellar drag is considered and a model is suggested in which the incident proton's kinetic energy is stored in the electric field between charged grids and returned to the exhaust particles after the relevant nuclear reactions are completed. Such a combination of electric and magnetic fields would make less severe other suggested limitations to the ramjet's performance. The problem of ionizing the interstellar medium directly in front of the ramjet when operating in non-HII regions of space is also discussed. It is shown that laser ionization is energetically possible for interstellar number densities ≥10 cm^{-3}; however, since the laser also tends to sweep the interstellar matter out of the ramjet's path, more quantitative study is necessary before the method can be considered feasible at any density. The possibility of using a thin stripper foil, placed over the intake cross section, to ionize the interstellar medium is suggested. This method has the advantage of efficiently ionizing the interstellar matter independent of density.

Introduction

The physical limitations to relativistic spaceflight by vehicles that carry their own fuel are well known.[1,2,3,4] If chemical or nuclear energy is employed, the ratio of fuel mass to payload mass becomes prohibitively large as $V_{max} \rightarrow c$. Even if a means were found to obtain 100% conversion of mass to energy, only moderately relativistic ships could be realistically considered. Though technological details such as the particle exhaust velocity affect the exact value of the initial to final mass ratio, the limit depends essentially only on the conservation of energy and momentum and is therefore fundamental. One alternative to the fuel-carrying relativistic rocket is a ship that is pushed by a terrestrial or solar system based laser.[5] The advantage is that the large mass necessary for accelerating the vehicle would not have to be taken along. Unfortunately, in the rest frame of the ship the photon momentum is red shifted and there is a decrease in intensity with increasing velocity.[6] The resulting decrease in efficiency represents a serious physical restriction on this type of propulsion.

At present the only remotely promising model for a relativistic spacecraft is the interstellar ramjet, first considered quantitatively by Bussard.[7] As the name indicates, the ship extracts its fuel from the interstellar medium in analogy with its terrestrial counterpart; the fundamental problem of carrying fuel along is thus avoided in principle. However, several objections have been raised concerning the ultimate potential performance of the ramjet.[8,9,10,11] Perhaps the most serious conceptual difficulty is that the proton burning PPI cycle is far too slow. The chain consists of the following sequence of reactions:

$$p + p \rightarrow {}^2D + e^+ + \nu$$
$${}^2D + p \rightarrow {}^3He + \gamma$$
$${}^3He + {}^3He \rightarrow {}^4He + 2p$$

It is the first proton burning reaction to occur in main sequence stars and accounts for the long lifetimes of these stars. The net result of a cycle is the conversion of four protons into a ^{4}He nucleus with the release of 19.53 MeV of potentially usable energy plus 0.263 MeV in neutrino losses (the complete conversion of a quantity of hydrogen to helium requires the first two reactions in the chain to occur twice as often as the third). The weak interaction $p + p \rightarrow {}^2D + e^+ + \nu$ cross section, at essentially any temperature, is hopelessly small and could never be used for propulsion power (we show this quantitatively later).

The deuterium exoergic reactions

$${}^2D + {}^2D \begin{cases} \nearrow {}^3He + n \\ \searrow T + p \end{cases}$$

have cross sections that are typically 10^{24} times greater than the $p + p \rightarrow {}^2D + e^+ + \nu$ cross section; unfortunately, even using the most optimistic estimate of the abundance of 2D in the interstellar medium, the magnetic scoop cross section would have to be prohibitively large. The ramjet is thus limited to burning the interstellar hydrogen for fuel.

This problem was recognized in Bussard's original work, but no viable alternative to the PPI chain has yet been suggested. Here we show that the problem of the slow PPI rate can be resolved in principle by exploiting a proton burning catalytic cycle similar to the well known CNO Bi-Cycle occurring in sufficiently hot main sequence stars. The catalyst "fuel" can be taken along since it is not depleted, but the ultimate source of energy is the inters teller hydrogen. The slowest links in the catalytic chains will be found to be 10^{18} - 10^{19} times faster than the PPI rate at an ion temperature of 86 keV and number density of 5 x 10^{19} cm^{-3}.

In addition to the ramjet energy source, the important problems of interstellar drag and ionization of the interstellar medium in non-HII regions of space is discussed.

The Interstellar Ramjet Reviewed

A major technological obstacle in the operation of an interstellar ramjet is the enormous (by present standards) cross section of the magnetic intake scoop necessary to maintain an acceleration of 1*g*, say. Assuming hydrogen can be burned at the necessary rate the ramjet proper acceleration a, is:[7]

$$a_s = M_H c^2 \eta \alpha \frac{n_0}{M_s} \quad (\beta \gg \alpha\eta) \quad (1)$$

Here β is the ramjet velocity (divided by c) relative to the interstellar medium, η is an efficiency parameter, A is the scoop cross section, M is the ship mass, n_0 the (proper) number density of fuel in the interstellar medium, and α is the fraction of mass converted into potentially usable energy. In calculating α care must be taken to subtract out the neutrino energy. Because of neutrino losses α will in general depend on the actual nuclear reactions rather than just the initial minus final nuclear masses. For example, the fusion of a given quantity of hydrogen to helium by PPI gives $\alpha = 0.0070$ while CNO fusion gives $\alpha = 0.0067$. Setting $a_s = 980$ cm/sec^2, $\alpha = 0.007$, $\eta = 1$, $M_s = 10^9$ g, and $n_0 = 10^3$ cm^{-3}, A is fixed at $\approx 10^4$ km^2 corresponding to a circular radius of 56 km (or ≈35 miles). The mean number density in interstellar space is ≈1-10 atoms/cm^3, requiring scoop radii of 1900-500 km respectively. Therefore, independent of other restrictions, nuclear powered ramjets may require nebular regions of space for take-offs if accelerations greater than 1*g* are desired. However, once the desired velocity is obtained in a nebula runway, it will be maintained and even increased as the ship moves into less dense regions of space. This is evident from Equation 1 since so long as $n_0 \neq 0$ acceleration will continue (but at less than 1*g*). Nebulae are also required for stopping interstellar ramjets since deceleration requires as much energy as acceleration.

It does not seem likely that a ramjet could accelerate or decelerate in the solar neighborhood and unfortunately there is no sufficiently dense nearby nebula. The ship could of course be conventionally propelled to the nearest nebula, but at considerable cost in time. However, technologies lying within or near a dense nebula would have no such constraints. A chief motivation in the study of interstellar ramjets or other interstellar spacecraft models should be the realization that similar extraterrestrial spacecraft may be observable from earth, provided we know where to look and (at least qualitatively) what to look for. As noted above, dense nebulae offer a natural runway for accelerating interstellar ramjets. To determine the observational properties of a ramjet it is necessary to know how the ship interacts with the interstellar medium, the quantity and spectral distribution of radiation emitted, whether the fusion reactor is pulsed (as in contemporary machines) or continuous (as in current concepts for eventual fusion power systems), and the kind of nuclear reactions that can power the spacecraft.

The Catalytic Ramjet

It has been implicitly assumed in the above discussion, as in Bussard's original paper,[7] that the ramjet fusion reactor is somehow capable of burning hydrogen to helium at the *necessary rate* to maintain 1*g* acceleration. We have already noted that the PPI chain is not capable of generating the necessary power. For a given magnetic scoop cross section A, it is evident from Equation 1 that the acceleration depends linearly on the interstellar fuel number density no. Hence for a deuterium reactor the acceleration is reduced by the factor $(\alpha_D\eta_D/\alpha_H\eta_H) = 0.14(\eta_D/\eta_H)$ over what it would be if hydrogen could be used as fuel. If the products of ^{2}D + ^{2}D further interact. to make ^{4}He then $\alpha \approx 0.0064$ rather than the value 0.001 used here. The ratio η_D/η_H is not known in general and may vary considerably in the interstellar medium if deuterium does not have a primordial origin. The terrestrial value of η_D/η_H is = 10^{-4}, but a recent measurement[12] gives an interstellar ratio (near one star at least) of ~10^{-5}. This means that for a given acceleration and mass a deuterium powered ramjet requires a scoop cross section 10^6 times greater than a proton burning ramjet with the same mass and efficiency parameter. Since A for a proton burning ramjet accelerating at 1*g* is already quite large, there seems little hope for a deuterium burning ramjet unless the η_D/η_H ratio turns out to be anomalously high in certain regions of the galaxy. Other charge particle reactions such as p + D, D + ^{3}He, D + T, etc. can also be ruled out because of low interstellar abundances. The tritium would in fact have to be made first by D + D.

The problem is to be able to use the interstellar hydrogen as fuel, but somehow avoid the impossibly slow $p + p \rightarrow {}^2D + e^+ + \nu$ *rate*. This can, in fact, be done by exploiting a catalytic nuclear reaction chain. As the name suggests, one element in the cycle acts only as a catalyst and after completion of the cycle is returned to the plasma. *The catalyst fuel is not depleted and can therefore be carried along in the ship.* The best known proton burning catalytic chain is the CNO Bi-Cycle occurring in sufficiently hot main sequence stars.[13] At ion temperatures and densities to be considered here (86 keV and 5×10^{-9} cm^{-3}) the usual CNO Bi-Cycle is modified and the so-called "hot" CNO Bi-Cycle is operative.[14] In the hot Bi-Cycle the reaction $^{13}N(p,\gamma)^{14}O$ is faster than the usual beta decay $^{13}N \rightarrow {}^{13}C + e^+ + \nu$, but the end products of the chain are essentially the same. The hot CNO catalytic Bi-Cycle consists of the following reaction chain:

$$^{12}C + p \rightarrow {}^{13}N + \gamma$$
$$^{13}N + p \rightarrow {}^{14}O + \gamma$$
$$^{14}O \rightarrow {}^{14}N + e^+ + v$$
$$^{14}N + p \rightarrow {}^{15}O + \gamma$$
$$^{15}O \rightarrow {}^{15}N + e^+ + v$$
$$^{15}N + p \rightarrow {}^{12}C + \alpha$$

with weaker branches $^{13}N(e^+ \nu)\ {}^{13}C(p,\gamma)\ {}^{14}N$, the usual CNO branch, and $^{15}N(p,\gamma)\ {}^{16}O(p,\gamma)\ {}^{17}F(e^+ \nu)\ {}^{17}O(p,\alpha)\ {}^{14}N$. Another proton catalytic cycle is the Ne-Na chain:

$$^{20}Ne + p \rightarrow {}^{21}Na + \gamma$$
$$^{21}Na \rightarrow {}^{21}Ne + e^+ + v$$
$$^{21}Ne + p \rightarrow {}^{22}Na + \gamma$$
$$^{22}Na + p \rightarrow {}^{23}Mg + \gamma$$
$$^{23}Mg \rightarrow {}^{23}Na + e^+ + v$$
$$^{23}Na + p \rightarrow {}^{20}Ne + \alpha$$

In these cycles the slowest reaction rates (the quantity $<\sigma v>$ below) are ~10^{18} and 10^{19} (respectively) times greater than the $p + p \rightarrow {}^2D + e^+ + \nu$ reaction rate at $T_{ion} = 86$ keV = 10^9 °K.

Other proton catalytic cycles involving nuclei with higher Z may be possible, but at ion temperatures of 86 keV their cross sections will be dominated by the Coulomb barrier and hence the corresponding reaction rate will be much lower than the above chains. Radiation losses become significant when nuclei with $Z > 2$ are present in a fusion reactor and this problem will be discussed after the relevant thermonuclear reaction rates are determined.

In all calculations an ion temperature of 86.2 keV = 10^9 °K will be used. This temperature is typical of ramjet fusion ion temperatures used by other authors and is presumably within the capability of future technology. At $T_{ion} \geq 86.2$ keV there will be some leakage out of either catalytic cycle, however, this can be tolerated since the interstellar abundance of ^{12}C and ^{16}O is quite significant (these nuclei are most abundant next to H and ^4He). The interstellar abundance of ^{20}Ne is also expected to be high. We assume that the interstellar medium has been enriched over its primordial abundance. (This will certainly be true of nebulous regions.) The ramjet reactor can thus afford to leak some of its initial on-board catalyst fuel. The fuel used as a hot CNO catalyst can be any element in the chain since at $T_{ion} \approx 86.2$ keV the entire Bi-Cycle will rapidly come into equilibrium anyway (several $^{12}C(p,\gamma)$ lifetimes are probably sufficient). At equilibrium in the hot CNO Bi-Cycle the ^{14}N abundance will be greatest since the $^{14}N(p,\gamma)$ rate is the slowest. At equilibrium in the Ne-Na cycle the ^{20}Ne abundance will predominate. Since cycle times are determined essentially by the $^{14}N(p,\gamma)$ and $^{20}Ne(p,\gamma)$ rates respectively, it is sufficient to consider only $<\sigma v>$ for these rates.

The thermonuclear reaction rate for a given reaction is defined as the number of particles/cm^3-sec undergoing the nuclear reaction: it is given by

$$r_{ab} = n_a n_b \langle \sigma v \rangle_{ab} \quad (2)$$

where n_a and n_b are the respective reactor number densities of the reacting nuclei, and $<\sigma v>$ is the product of cross section (as a function of velocity) times the relative velocity averaged over a Maxwell-Boltzmann distribution of velocities. If nuclear species *a* and *b* are identical, Equation 2 is multiplied by a factor of 1/2. To compare rates it is convenient to consider only the temperature dependence of r_{ab}, therefore the quantity $<\sigma v>$, the reaction rate per pair of interacting particles, is normally quoted.

Despite the fact that the CNO and Ne-Na cycles are 10^8 to 10^9 times faster than the PPI chain at T_{ion} = 86 keV, it remains to be shown that this is sufficient. We first determine how many hydrogen atoms must be burned per second to maintain a given acceleration and then calculate the reactor parameters necessary in order that the reactor burn hydrogen at this same rate. The number *dN* of protons scooped up in ship time dt_s, is

$$dN = c\beta\gamma n_0 A(dt_s) \quad (3)$$

where n_o is the proper interstellar number density and $\gamma = (1 - \beta^2)^{-1/2}$. For a given on-board acceleration a_s, *A* can be found from Equation 1 and substituted into Equation 3, giving

$$\left(\frac{dN}{dt_s}\right)_{in} = \left[\frac{\beta\gamma}{cM_H\alpha\eta}\right] \quad (\beta \gg \alpha\eta) \quad (4)$$

This is the number of protons that must be burned to helium per second in order that a given ship acceleration a_s be maintained. Taking $\beta = 1$, $\gamma = 10$, $a_s = 1g$, $M_s = 10^9$ g, $\alpha = 0.0067$, and $\eta = 1$, this corresponds to an energy generation of 1.2×10^{17} W.

The number of reactions per second in a spherical fusion reactor of radius *L* is, from Equation 2,

$$\left(\frac{dN}{dt_s}\right)_{burned} = n_a n_b \langle\sigma v\rangle_{ab} \frac{4\pi L^3}{3} \quad (5)$$

and we require that

$$\left(\frac{dN}{dt_s}\right)_{burned} = \left(\frac{dN}{dt_s}\right)_{in} \quad (6)$$

or

$$n_a n_b L^3 = \left(\frac{3\beta\gamma}{4\pi c M_{H\alpha\eta}}\right)\frac{a_s M_s}{\langle\sigma v\rangle_{ab}} \quad (7)$$

Taking the above ship parameters

$$n_a n_b L^3 = \frac{6.6x10^{27}}{\langle\sigma v\rangle_{ab}} \quad (8)$$

A semi-empirical extrapolation gives the following rate for $p + p \rightarrow {}^2D + e^+ + v$ [16]

$$\langle\sigma v\rangle = \frac{7.0x10^{-39}}{T_9^{2/3}}\exp\left[\frac{-3.38}{T_9^{1/3}}\right] \quad (9)$$
$$\left(1 + 0.123T_9^{1/3} + 1.09T_9^{2/3} + 0.938T_9\right)cm^3\sec^{-1}$$

where T_9 is the ion temperature in 10^9 °K. For $T_9 = 1$ = 86.2 keV, Equation 9 gives $<\sigma v>_{pp} = 6.6 \times 10^{-39}$ cm^3-sec^{-1} and from Equation 8, $n_H^2 L^3 = 10^{66}$. Taking $n_H = 5 \times 10^{19}$ cm^{-3} the required reactor radius is $L = 7.35 \times 10^8$ cm = 4.6×10^3 miles! Of course the mass of a reactor with this dimension would be much greater than our assumed 10^9 *g*. Hence, it is physically impossible to accelerate any object at 1 g to near luminal velocities using the PPI chain.

A semi-empirical extrapolation of the $^{14}N(p,\gamma)$ and ^{20}N e(p,γ) reaction rates gives[16]

$$\langle\sigma v\rangle_{N-P} = \frac{7.0x10^{-17}}{T_9^{2/3}}\exp\left[\frac{-15.228}{T_9^{1/3}} - 0.825x10^{-2}T_9^2\right]$$
$$x\left(1 + 0.027T_9^{1/3}\right) + \frac{3.8x10^{-21}}{T_9^{3/2}}\exp\left[\frac{-3.01}{T_9}\right]$$
$$+\frac{1.04x10^{-19}}{T_9^{3/2}}\exp\left[\frac{-11.476}{T_9}\right] + \frac{8.5x10^{-18}}{T_9^{3/2}}\exp\left[\frac{-28.147}{T_9}\right] \quad (10)$$

and

$$\langle\sigma v\rangle_{Ne-P} = \frac{1.56x10^{-17}}{T_9^{2/3}}\exp\left[\frac{-19.447}{T_9^{1/3}} - 4.48T_9^2\right]$$
$$x\left(1 + 2.14x10^{-2}T_9^{1/3} - 0.427T_9^{3/2} - 6.4x10^{-2}T_9\right)$$
$$+\frac{2.73x10^{-19}}{T_9^{2/3}}\exp\left[\frac{-4.381}{T_9}\right] + 1.6x10^{-20}\exp\left[\frac{-10.598}{T_9}\right] \quad (11)$$

At $T_9 = 1$, $<\sigma v>_{N\text{-}P} = 2.1 \times 10^{-22}$ cm^3-sec^{-1} and $<\sigma v>_{Ne\text{-}P} = 3 \times 10^{-21}$ cm^3-sec^{-1}. Assuming equal hydrogen and catalytic fuel number densities of $n_a = n_b = 5 \times 10^{19}$ cm^{-1} gives L_{CNO} = 19 m and $L_{Ne\text{-}Na}$ = 9.6 m. The minimum plasma confining magnetic field can be estimated by equating the magnetic energy density to twice the kinetic energy density,

$$\frac{B^2}{8\pi} = 2nkT_{ion} \quad (12)$$

With our assumed temperature and number density, $B = 1.8 \times 10^7$ Gauss which is considerably greater than current laboratory magnetic fields but perhaps within the range of an advanced technology. We conclude that the "hot" CNO Bi-Cycle and the Ne-Na catalytic cycle are theoretically capable of generating sufficient power to accelerate a ship of mass 10^9 g at 1*g* to near luminal velocities with potentially realistic reactor parameters. The reactor parameters necessary for the Ne-Na cycle are T_{ion} = 86 keV, $n = 5 \times 10^{19}$ cm^{-3}, $B = 1.8 \times 10^7$ G and L = 9.6 m. Another possible set of reactor parameters is $n = 1.5 \times 10^{21}$ cm$^{-3} \approx n_{air}$, $B \approx 8 \times 10^7$ G, and L = 1.5 m.

Bremsstrahlung and cyclotron radiation losses normally become critical in a reactor when nuclei of charge $Z > 2$ are present in the plasma. A straightforward calculation indicates that radiation energy losses at $T_{electron}$ = 86.2 keV are greater than energy production for either catalytic cycle. However, the radiation losses are due to accelerating electrons and in a heavy ion reactor a steady state will exist in which the electron temperature will be considerably less than the ion temperature.[9] At the reactor densities and dimensions considered here, $n \approx 5 \times 10^{19}$ cm^{-3} and $L \approx 10$ m, some of the cyclotron and bremsstrahlung radiation will be reabsorbed. On the other hand, too much interaction between the radiation and matter will tend to bring the electron and ion temperatures into equilibrium and create a radiation pressure that must be taken into account. A radiation contribution to the pressure would in turn require a stronger confining magnetic field. Since the plasma is not in thermodynamic equilibrium the mean charge state of a heavy ion is not that obtained from an equilibrium calculation. For a given ion temperature, the actual charge state may be less than the equilibrium value. This will lower the effective nuclear Z and considerably reduce the bremsstrahlung power losses, though it is difficult to estimate this effect quantitatively without detailed knowledge of the reactor system.

There are no practical fusion reactors of any kind at present and the prospects for a workable heavy ion reactor with our assumed parameters are more remote. Nonetheless, the difficulty seems to be of a technological rather than fundamental nature. Other means of obtaining energy from the catalytic fusion of interstellar hydrogen can be imagined. A pulsed laser fusion reactor or a large scale catalytic Migma-type reactor,[15] if technologically possible, might be employed. (These reactors would not significantly enhance the PPI rate however.) The important point is that the catalytic proton burning model is at least theoretically capable of using the interstellar hydrogen to generate the power required for acceleration at 1*g* to relativistic velocities.

Interstellar Drag

We turn now to another conceptual problem facing relativistic spaceflight, that of interstellar drag or momentum loss to the interstellar medium. The problem can be appreciated by imagining oneself in the ship's frame of reference. Suppose the ship's velocity is $\beta = 0.5$. We observe 150 MeV protons exchanging momentum with the ship's magnetic field; but the field is coupled to the ship so this is equivalent to head-on collisions with the ship itself. The protons are stopped in the fusion reactor where they undergo nuclear reactions. Suppose, for example, α-particles are expelled out the exhaust giving the ship its forward thrust. The most exoergic fusion reaction will not yield more than several MeV per α-particle of usable energy.[16] Therefore, if the ship's velocity is greater than a few percent the speed of light it loses momentum in the process.

The incident proton kinetic energy and momentum can be recovered, in principle, by employing charged grids (or nets) as illustrated in Figure 1. The direction of the electric field $\vec{E}$ is shown in four regions; the arrows indicate the direction of the electric force on a positive charge and the diagonal lines represent the magnetic scoop boundary. The electric field $\vec{E}$ is essentially zero in regions A and D, but once the positively charged proton arrives in region B its motion is retarded. The proton's energy is lowered from ~BeV, say, to ≤100 keV prior to entering the reactor mouth. Its kinetic energy is stored, for the time being, in the electric field of the forward capacitor. Note that due to its greatly reduced momentum the proton can now be funneled into the reactor with a much weaker axial magnetic field. When the reaction product (an α-particle, say) emerges in region C it is electrostatically accelerated to an energy equal to the kinetic energy loss of four incident protons plus the nuclear energy released in the relevant (p,α) reaction. The mass of an α-particle is ≈ (1-α) times that of four protons, therefore for the same kinetic energy the α-particle will possess slightly less momentum.

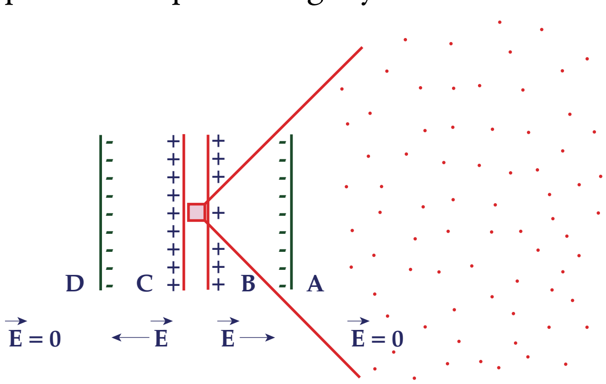

Figure 1 — Schematic representation of a drag-free interstellar ramjet

Nonetheless, it can be shown that this momentum loss is always less than the gain from the relevant nuclear reaction (α ~ 0.007 and E_α ~ MeV) so long as all the incident kinetic energy is stored and recovered efficiently. The ship is now essentially drag-free since an incident proton will recover its original kinetic energy and momentum even if there is no exoergic reaction.

The required magnitude of the capacitor electric field E can be estimated in the following way. An incident proton of kinetic energy E_k must essentially be stopped, therefore the potential energy drop V across the forward grids must be

$$V = E_k = eEl_1 \quad (13)$$

where l_1 is the forward capacitor grid separation distance. Suppose we want a ship time dilation factor of γ = 10, then $E_k \approx 9M_pc^2 \approx$ BeV and

$$E(volts/meter) = \frac{9x10^9}{l_1(meters)} \quad (14)$$

For l_1 = 10 km (~6 miles), E = 9 x 10^5 V/m. For fixed l, the field E could be varied in flight according to the ship's velocity. In maintaining the necessary grid charge, work must be done in bringing up new charges to the plate; but since there are no net energy losses in decelerating and accelerating the interstellar protons, the energy necessary can easily be supplied by the fusion reactor itself with our assumed energy generation of 1.25 x 10^{17} W. To avoid undesirable fringe effects the grid dimension should be comparable to l_1, i.e. 1-10 km. The grid dimensions are still relatively small compared to the magnetic intake cross section A. As the incident protons are slowed between the forward grids, a steady state condition will exist in which the plasma number density increases toward the reactor.

The combination of electric and magnetic fields similar to that shown in Figure 1 make less severe the minimum mass and intake fraction problems[8,9] since much weaker axial magnetic fields are required. The model should also help reduce magnetic scoop synchrotron radiation losses since the incident protons and electrons are decelerated and accelerated primarily in a linear direction. With electric fields of ~10^6 V/m there is no minimum mass stress limit analogous to the one for the magnetic field.[8]

The mass of the grids (nets) must of course be included in M_s.

Ionization of the Interstellar Medium

If the ramjet accelerates in other than HII regions of space, the ship itself must ionize the interstellar hydrogen in front of it. It has been suggested[8] that to accomplish this one merely needs to shine a light in front of the ramjet. It takes only ~13 eV of the ship's energy to ionize a single hydrogen atom, whereas the same atom returns ~MeV in the subsequent nuclear reaction; hence, it would appear that the ship could easily supply the required energy. We note first that to be efficient the light must be a laser, otherwise too many divergent photons will be wasted. A difficulty with the laser ionization method is that the laser will, in addition to ionizing the interstellar medium, tend to sweep the ions out of the ramjet's path. Presumably the laser will create an HII region of temperature ~10^4 °K. The corresponding ion thermal velocity is = 1.6×10^6 cm/sec; thus only atoms ionized a small distance in front of the ramjet can be utilized. This distance depends on the scoop cross section and ship velocity; for a cross section radius of 56 km and $\beta = 1$, the cutoff distance is ~10^{11} cm. The UV photons that go on to ionize atoms further away are wasted. If more than 10^5 13-eV photons are required per usable hydrogen atom, then the laser ionization method will not be energetically feasible. The hydrogen ionization cross section σ_H at 13 eV is ~ 10^{-17} cm^3 and the mean free path is $(\sigma_H n)^{-1} = 10^{14}$ cm for $n = 10^3$ cm^{-3}. Hence, the fraction of UV photons that ionize a usable hydrogen atom is $1 - \exp[-10^{11}/10^{14}] = 1 - \exp[-10^{-3}] \approx 10^{-3}$. Thus the method is energetically possible for interstellar number densities ≥ 10 cm^{-3}. However, the laser will tend to sweep away the interstellar matter at distances $\geq 10^{11}$ cm, thereby reducing n. In order that the laser ionization method be energetically possible it must be shown quantitatively that the number density seen by the ramjet is > 10 cm^{-3}. This question will be taken up in detail elsewhere.

In addition to the possibility of laser ionization, the interstellar hydrogen in non-HII regions of space can be ionized by a thin stripper foil placed over the intake area A. This method of ionization has the advantage of being independent of the interstellar number density; thus it would be applicable in regions where $n_o < 10$ cm^{-3}. If $\gamma >> 1$ a thin foil will strip the electrons from the incident hydrogen atoms, yet retain only a small amount of the proton's kinetic energy. The incident proton velocity will determine how thin the foil has to be. The stopping power (dE/dx) of an ion passing through solid matter varies inversely with energy; therefore the greater the incident proton energy the less ion energy lost to the foil.[17] Stripper foils are often used for this purpose in the positive terminals of Tandem Van de Graaff accelerators where negative ions must be stripped of their electrons prior to entering the second stage of acceleration. The energy lost to the foil by the ions and electrons will be radiated away and there will be negligible heating of the foil. To obtain a physical feeling for the amount of deterioration of a foil (or any other physical structure) traveling through interstellar space at relativistic velocities, it is instructive to calculate the maximum current flowing through 1 cm^2 of foil area. Assuming $n_o = 10^3$ cm^{-3} and $\beta = 1$ the current per cm^2 is

$$\frac{1}{(area)}\frac{dQ}{dt} = \gamma p_e c \approx \gamma p_e c = \gamma e c n_0 = 4.8 \gamma mA / cm^2 \tag{15}$$

where ρ_e is the space frame charge density ($\rho_e \approx e n_o$). Even for $\gamma = 100$ there is less than a milliamp of current flowing through each cm^2 of plate (less than a micro-amp for $n_o = 1$ cm^{-3}). We conclude that for $\gamma >> 1$ the foil (and forward grid) will not suffer undue deterioration from the interstellar hydrogen (at least) or extract excessive energy from the incident protons.

The major drawback with this method of ionizing the interstellar hydrogen is the additional mass required. The foil must be strong (thick) enough to support its weight against 1*g* acceleration. If it is to cover the entire scoop cross section then the foil mass (using present materials) may be greater than our assumed ship mass of 10^9 g. It might be worth noting however, that recent advancements in material technology[18] have produced materials (composite fibers) well over an order of magnitude stronger per unit mass than existed when the ramjet was first. suggested. An original objection to the ramjet concept was that the ship must be too tenuous; but this criticism was based on calculations using strengths per unit mass comparable to steel. The ramjet as a hold must still be quite tenuous even by today's standards, but it can no longer be dismissed outright on this objection alone.

Concluding Remarks

We have shown that with our assumed parameters the catalytic "hot" CNO Bi-Cycle and the Ne-Na cycle are theoretically capable of generating energy at a rate sufficient to accelerate an interstellar ramjet at 19 to near luminal velocities ($\gamma \geq 1$). Although the catalyst fuel is carried along it is not depleted and *the interstellar hydrogen is the ultimate source of energy.* The minute $p + p \rightarrow {}^2D + e^+ + \nu$ rate is thus bypassed in the conversion of $4H \rightarrow He$. Taking $M_s = 10^9$ g (2.2 million pounds), $n_o = 10^3$ cm^{-3} in an HII region, and $a_o = 980$ cm-sec^{-2}, the following parameters are required: magnetic intake cross section radius $r_o = (A/\pi)^{1/2} = 56$ km (35 miles), reactor radius $L = 9.6$ m, reactor number density $n = 5 \times 10^{19}$ cm^{-3}, reactor ion temperature $T_{ion} = 86.2$ keV (due to plasma radiation losses it is also assumed that $T_{electron} << T_{ion}$) and reactor magnetic field $B = 1.8 \times 10^7$ G. The reactor parameters depend essentially only on the assumed ship acceleration a_s, β, and M_s. These parameters can be played off against one another to some degree; for example n and B can be decreased (increased) if L^3 is increased (decreased) proportionately. In regions of space where $n_o >> 10^3$ cm^{-3} the technological constraints on the ramjet's performance become much less severe. The spacial extent of these dense regions will in general be less than a light year, thereby requiring ramjet accelerations greater than 1*g*.

We have considered one possible method of recovering the lost energy and linear momentum of the protons when these particles are brought (essentially) to rest in the fusion reactor. The drag-free model is in principle capable of storing and returning the proton energy and momentum efficiently. Efficiency is very important if large γ's are to be obtained. This is because a fractional loss in incident energy and momentum must be made up at the expense of the nuclear energy released. In the ship frame this energy is constant, but a given fraction of the incident energy increases in absolute value with γ.

The problem of ionizing the interstellar medium directly in front of the ramjet when operating in other than HII regions of space is discussed. It was shown that laser ionization is energetically possible for number densities >> 10 cm^{-3}, but that the laser also swept matter away from the ship's path thereby reducing the number density seen by the ramjet. A more quantitative analysis of this method is necessary before it can be considered feasible. The possibility of using a thin stripper foil to ionize the interstellar matter was considered. This method has the advantage of efficiently ionizing the interstellar medium independent of density.

The physical problems related to relativistic spaceflight with an interstellar ramjet are formidable. Here we have only touched upon some of the more fundamental difficulties facing the interstellar ramjet, and clearly much more quantitative study is required before the ramjet concept can be considered technologically possible. On the other hand, it would be premature to discount the fusion ramjet as a potentially viable means of relativistic interstellar spaceflight, especially for technological civilizations within or sufficiently close to nebular regions of the galaxy.

Acknowledgments

I thank Dr. Richard G. Couch for pointing out that the CNO Bi-Cycle might burn interstellar hydrogen at a faster rate than PPI, and Doctors Robert W. Bussard, W. Rory Coker, Albert A. Jackson IV, and David P. Wright for helpful discussions. This work was supported in part by the U.S. National Science Foundation and the Robert A. Welch Foundation.

Publication History

Received 3 December 1973; revised 29 April 1974.

Reformatted and color illustration added in May 2009 by Mark Duncan.

References

[1] J. Ackeret; Zur Theorie der Raketen, He/vet. Physica. Acta 19, 103-112 (1946); English translation by L. Gilbert, in Journal British Interplanetary Society 6, 116--123 (1947).

[2] L. R. Shepherd; Interstellar Spaceflight, in Realities of Space Travel, Leonard J. Carter (editor), pp. 395-416, McGraw-Hill, New York (1957).

[3] Von Hoerner Sebastian; The General Limits of Space Travel, in Interstellar Communication, Alastair G. W. Cameron, (editor), pp. 144-159, Benjamin, New York (1963).

[4] Edward Purcell; Radioastronomy and Communication Through Space, in Interstellar Communication, Alastair G. W. Cameron, (editor), pp. 133-143, Benjamin, New York (1963).

[5] George Marx; Interstellar vehicle propelled by terrestrial laser beam, Nature 211, 22-23 (1966). doi: 10.1038/211022a0

[6] J. L. Redding, Interstellar vehicle propelled by terrestrial laser beam, Nature 212,588-589 (1967). doi:10.1038/213588a0

[7] Robert W. Bussard; Galactic matter and interstellar flight, Astronautica Acta 6, 179-194 (1960).

[8] J. F. Fishback; Relativistic interstellar spaceflight, Astronautica Acta 15, 25-35 (1969).

[9] Anthony R. Martin; Magnetic intake limitations on interstellar ramjets, Astronautica Acta 18, 1-10 (1973).

[10] Anthony R. Martin; Structural limitations on interstellar spaceflight, Spaceflight 16, 353-357 (1972).

[11] Anthony R. Martin; Some limitations of the interstellar ramjet, Spaceflight 14, 21-25 (1972).

[12] J. H. Black and A. A. Dalgarno; The cosmic abundance of deuterium, Astrophysical Journal 184, 101-104 (1973).

[13] Donald D. Clayton; Principles of Stellar Evolution and Nucleosynthesis, p. 303, McGraw-Hill, New York (1968). ISBN 0226109534

[14] J. Audouze, J. Truran, and B. Zimmerman, Hot CNO-Ne cycle burning, I: Thermonuclear evolution at constant temperature and density, Astrophysical Journal 493-516 (1973).

[15] Dietrick E. Thomsen — Physical Science Editor; Science News 103, 392-393 (June 16, 1973).

[16] William A. Fowler, Georgeanne R. Caughlan, and Barbara A. Zimmerman; "Thermonuclear Reaction Rates, II," Annual Review Astronomy and Astrophysics 13, 69-112 (1975).

[17] Jerry B. Marion and F. C. Young; Nuclear Reaction Analysis, pp. 14-15, Elsevier, New York (1968).

[18] Richard F. Post and Stephen F. Post; Flywheels, Scientific American 229 (December 1973).