Galactic Matter and Interstellar Flight

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Abstract

This paper describes a vehicle which uses the interstellar gas as a source of energy (by nuclear fusion) and as a working fluid. By this means high ship velocities and consequent short flight times can be attained in spite of the inadequacy of nucleon rearrangement reactions for interstellar flight by rocket. Study of the relativistic flight mechanics of this interstellar ramjet shows that maximum vehicle accelerations of the order of earth-gravity can be achieved with fusion-powered vehicles only if the frontal area loading density per unit interstellar gas density is 10^{-8} (gm/cm^2) per (reactive nucleon/cm^3) or less. Graphs are presented showing the theoretical performance of such ramjet ships.

1. Introduction

Characteristics of interstellar flight and the general prospects for its eventual attainment have been considered in some detail by several authors in recent years. In a pioneering paper, Ackeret[1] derived relativistically correct equations of motion for the powered flight of rocket vehicles. From these it was shown that an optimum distribution of propellant mass and empty (burnt) mass exists which will give a maximum velocity change, in the initial rest-frame, to the vehicle. To achieve this maximum velocity change, or maximum vehicle "characteristic" velocity in a vehicle powered by exothermic nuclear reactions involving nucleon rearrangements, Ackeret further showed that it would be necessary to use inert non-energy-generating matter as a considerable fraction of the total propellant mass in order to make optimum use of the nuclear energy. The third significant point established was that even for very energetic nuclear reactions, the maximum attainable vehicle velocity will always be limited to a rather small fraction (ca. 1/20) of the speed of light, and that the concurrent optimum propellant exhaust velocity is of the same order as the vehicle final velocity. This conclusion is a direct result of the fact that the fraction of nuclear mass converted into energy in rearrangement reactions is less than 1% of the initial mass for the most energetic known reactions. Of course this is not true for particle/anti-particle annihilation reactions. We will not consider these here as energy sources for interstellar flight, since the only presently known source of anti-particles is by pair production, which requires the expenditure of at least two rest mass energies, and considerably more if the initiating particle is accelerated to high energy in the laboratory rather than the reaction center-of-mass coordinate frame. Since considerable inert mass must be expelled and maximum attainable velocities are small relative to the speed of light, an optimum (as previously defined) interstellar rocket powered by conventional nuclear energy sources will require flight times of hundreds of years to reach even the nearest stars.

In a later paper, Shepherd [2] considered the problems and potential performance of such craft in some detail, and extended the analysis to include losses due to inefficiency in conversion of the source energy into exhaust jet energy. Shepherd also pointed out that, even if sufficiently energetic sources were available so that the vehicle could be accelerated to velocities close to the speed of light the acceleration time required to reach such velocity would be the order of hundreds of years, because of the present practical limitations of equipment size as a function of power handling capacity with present day power plant technology. Through an example of a typical vehicle for flight to the nearest stars he showed that vehicle accelerations must be limited to the order of 10^{-4} to 10^{-3} of earth gravity acceleration if propulsion is to be by nuclear/electric ion acceleration systems with specific masses of hundreds of kilograms per thermal megawatt. This level of propulsion plant performance is an order of magnitude better (lighter) than those currently proposed [3] for propulsion of inter-orbital vehicles in the solar system, however application of direct nuclear/electric conversion devices utilizing thermionic emission phenomena [4, 5] should eventually yield these lower specific masses.

In order to reduce interstellar flight times as measured by clocks on board the vehicle to the order of years rather than hundreds of years it is necessary that vehicle velocity be close to optical velocity and that acceleration from the initial rest state to this velocity take place in a time the order of years, or less.

In fundamental work on the subject, Sanger [6] and Peschka [26] has shown that accelerations the order of earth gravity (1 g_o) in the vehicle's rest-frame are required to achieve this desirable performance. As an illustration of the powerful effect of the Lorentz time-dilatation effect at near-optical velocities Sanger calculated that the center of our galaxy could be reached in 20 years and the entire known universe could be traversed in less than 42 years ship-time if a vehicle frame acceleration of 1 g_o could be maintained continuously. Similar results have been demonstrated more recently by Kooy [7] in a study of relativistic rocket motion. Assuming an adequate (unknown) energy source Sanger has considered in detail [8] the case of radiation propulsion by the ejection of photons produced from the conversion of matter into energy aboard the rocket vehicle. For photon rocket flight to the galactic center and through the universe, required mass-ratios were shown to be of order 10^8 and 10^{19}, respectively [26]. Applying the same basic arguments mentioned earlier for the ion propelled, low velocity interstellar vehicle, Shepherd [2] pointed out that the power plant specific mass must be extremely small and estimated that black-body radiator temperatures must be the order of 10^5 °K to achieve accelerations of 1 g_o by photon propulsion. In recent theoretical work on radiation leakage and absorption in light and heavy atom plasmas, Sanger [9] has shown that uranium plasmas at temperatures of 2×10^5 to 5×10^5 °K or hydrogen plasmas at about 3×10^4 °K could be used as radiators for photon propulsion. Temperatures of this sort could, in principle, be reached in the fissioning core of a large gaseous core reactor of the sort first discussed by Shepherd and Cleaver [10] and more lately by Safonov [11], Bell [12], Winterberg [13], Shepherd [14], and the present author [15], however the practical attainability of such temperatures is questionable at present. If lower temperatures are forced by requirements of wan cooling, for example, vehicle accelerations will drop drastically (since radiation pressure is proportional to T^4) below the 1 g_o needed for short acceleration times in interstellar flight.

In summary of the past work we see that two principal types of difficulty arise to thwart the theoretical achievement of short flight times (measured by clocks on the vehicle) in interstellar rocket flight. The first and most fundamental of these is that:

> 1) Known sources of nuclear energy from nuclear rearrangement reactions (i.e., fission, fusion, radioisotope decay) are very inadequate compared to the energy required to accelerate a vehicle to near-optic velocity.

The second objection is that:

> 2) Achievement of 1 g_o acceleration with the high exhaust velocities needed for optimum flight is so far beyond the present state of propulsion system engineering technology as to appear virtually impossible at the moment.

This second objection is not a fundamental one in that it is based on the inability of present-day power plant technology to produce the equipment needed for high acceleration interstellar propulsion systems. This objection will inevitably give way to the continued advance of modern technology; but the first objection, which is on basic physical grounds, will remain. The lack of an adequate source of energy is, at present, a fundamental physical limitation on interstellar flight of rocket vehicles. Until new and very much more energetic controllable reactions are found (and this seems improbable at the moment), efforts to solve the second, technological objection would seem to be fruitless. In the light of this dilemma, Shepherd [2], Spitzer [16], and others have considered as a possible solution the concept of interstellar travel involving flights of hundreds, perhaps thousands of years, with whole civilizations in microcosm rising and falling while in flight between planetary worlds. If we wish to avoid this aesthetically unattractive picture, yet cling to hope for interstellar travel, we must find a way to overcome the inadequate-energy-source objection cited above.

2. The Interstellar Ramjet

It is the purpose of this paper to discuss one method of doing this, by abandoning the interstellar rocket entirely, turning to the concept of an interstellar vehicle which does not carry any of the nuclear fuel or propellant mass needed for propulsion, but makes use of the matter spread diffusely throughout our galaxy for these purposes. By rough analogy with its atmospheric counterpart we call this an *interstellar ramjet*. Other possible types might include, vehicles which carry all of the nuclear fuel on board and only use swept-up galactic matter as inert diluent added to the propellant stream (analogous to the operation of ducted rockets in atmospheric flight) and all variations between these two extremes. Study of the performance of these fuel-carrying vehicles is deferred to a future paper.

No attempt is made to devise conceptual engineering approaches to the propulsion system design although some potentially applicable physical principles are discussed briefly. Propulsion system engineering technology falls under objection [2], previously cited, however we are interested here only in providing an answer to the energy objection [1]. To this extent the problems of short duration (from the traveler's standpoint) interstellar flight remain unsolved. Our principal interest is to determine the relation between flight time in the vehicle's rest frame of reference (hereafter called the ship-frame) and distance traveled in the fixed space-frame, as a function of vehicle initial velocity and overall design parameters.

As we have discussed, the acceleration capability will be determined by the engineering characteristics (i.e., operating temperatures, mass flow rates, structural masses, etc.) of the vehicle and its propulsion system. Detailed analysis of these is not within the scope of the present paper, and a simple gross parameter, the frontal area loading density, is used to relate acceleration to vehicle flight conditions. We limit consideration at the outset to one-dimensional rectilinear flight in field-free space of vehicles whose thrust and acceleration vectors are parallel. Parameters measured in the ship-frame are denoted by the subscript s; those in the space-frame (e.g., assumed fixed relative to the galactic center) by the subscript *o*.

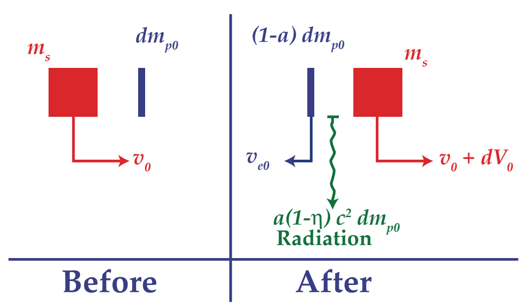

Figure 1 — Conditions before and after fusion reaction of an increment (dm_{p0}) of interstellar gas.

Consider the system sketched in Figure 1. Here we see a pure ramjet vehicle moving to the right with instantaneous velocity[1] v_o in the space-frame, with intake area A_o and constant rest-mass m_s, just before and just after swallowing, burning (by nuclear reaction), and expelling a small differential rest-mass dm_{po}, of galactic material. A fraction ex (following Shepherd's notation [2]) of this is converted into energy and $(1 - \alpha)\, dm_{po}$, is expelled from the vehicle with velocity v_{eo}, (chosen positive to the left) relative to the space-frame. The energy generated is converted into kinetic energy in the exhaust jet with an efficiency η, $(1 - \eta)$ being lost as thermal radiation transverse to the vehicle velocity vector. This conversion efficiency is a parameter in principle within the control of the propulsion system designer, since it is determined by the degree of irreversibility (thermal radiation, joule heating losses, etc.) characterizing the conversion process and equipment employed for propulsion. For our purposes it is considered as an arbitrary constant characterizing the propulsion plant performance.

Before burning, the system total energy (measured in the space-frame) is just:

$$E_{before} = \frac{m_s c^2}{\gamma_0} + c^2 dm_{p0} \quad (1)$$

and after burning, as described, the energy is distributed as:

$$E_{after} = \frac{m_s c^2}{\gamma_0 + d\gamma_0} + \frac{(1-\alpha)c^2 dm_{p0}}{\gamma e_0} + (1-\eta)\alpha c^2 dm_{p0} \quad (2)$$

where:

$$\gamma_0^2 = 1-(v_0/c)^2 \; and \; \gamma e_0^2 = 1-(ve_0/c)^2 \quad (2a)$$

Total energy is conserved in this process (and in all others) thus $E_{before} = E_{after}$. Combining Equations (1) and (2), reducing algebraically, and retaining only first order terms in derivatives, we have

$$-m_s \frac{d\gamma_0}{\gamma_0^2} = \left[1-(1-\eta)\alpha - \frac{(1-\alpha)}{\gamma_{e0}}\right] dm_{p0} \quad (3)$$

Now, for acceleration of the vehicle we require that dv_o be positive, thus that $d\gamma_o$ be negative. In order for this to be so the quantity $[1-(1-\eta)\alpha - (1-\alpha)/\gamma_{eo}]$ must be greater than zero (we choose a positive sign convention for dm_{po}) hence the exhaust stream must satisfy the inequality $\gamma_{eo} > (1-\alpha) / [1 - (1 - \eta)\alpha]$. Since $\gamma_{eo}^2 = 1 - \gamma_{eo}^2/c^2$ the inequality can be written for v_{eo}, as

$$\left[\frac{v_{e0}}{c}\right]^2 < 2\alpha\eta \left\{ \frac{1-\alpha\left(1-\frac{\eta}{2}\right)}{\left[1-\alpha(1-\eta)\right]^2} \right\} \quad (4)$$

For all α-values associated with nucleon rearrangement reactions this reduces to $(v_{eo}/c)^2 < 2\alpha\eta$ as the condition for acceleration of our ramjet ship. If $(v_{eo}/c)^2 > 2\alpha\eta$ our ship will decelerate since we will be converting some of the ship kinetic energy into directed motion (kinetic energy) of the interstellar gas used as a propellant and nuclear energy source. We note here that v_{eo} is not the propellant exhaust velocity relative to the ship, but is the burnt fuel velocity relative to the space-frame. We have assumed that its velocity was zero in the space-frame before burning. Since the maximum total energy released by nuclear reaction is $\Delta E_{burn} = \alpha c^2 dm_{po}$, for a final zero space-frame velocity of burnt products, we can define an energy-utilization efficiency as:

$$\varepsilon = \frac{Energy\ added\ to\ ship}{energy\ released\ by\ mass\ conversion}$$
$$= \frac{(energy\ released) - (energy\ to\ kinetic\ energy\ of\ burnt\ fuel) - (energy\ lost\ to\ non-propulsive\ uses)}{energy\ released} \quad (4a)$$

or

[1] By limiting our discussion to one-dimensional motion we need not use vector notation in the analysis, thus when we speak of "velocity" here and hereafter we mean "magnitude of the velocity vector," etc.

$$\varepsilon = 1 - \frac{(total\,energy\,of\,burnt\,fuel) - (rest\,mass\,energy\,of\,burnt\,fuel) + (energy\,lost)}{energy\,released}$$

(4b)

Using the previously defined symbols this becomes:

$$\varepsilon = 1 - \frac{\left(\frac{1-\alpha}{\gamma_{e0}}\right) - (1-\alpha) + \alpha(1-\eta)}{\alpha} \quad (5)$$
$$= \frac{1}{\gamma_{e0}} + \frac{1}{\alpha} - \frac{1}{\alpha\gamma_{e0}} - (1-\eta)$$

For $v_{eo} = 0$, γ_{eo} is unity and the energy utilization efficiency is just $\varepsilon = \eta$, as expected. However, for (v_{eo}/c) small but non-zero, equation 5 gives the approximate expression:

$$\varepsilon \simeq \eta - \left(\frac{1-\alpha}{2\alpha}\right)\left(\frac{v_{e0}}{c}\right)^2 \quad (5a)$$

For acceleration, ε must be greater than zero, which leads again to the inequality $(v_{eo}/c)^2 < 2\alpha\eta$ for net positive acceleration. Since α is only 0.0071 for the most energetic known fusion reaction (the helium-producing proton-proton fusion chain) we see that the numerical value of ε approaches zero rapidly with increasing (v_{eo}/c). This energy-utilization efficiency is not a parameter within the control of the vehicle designer, as is η, since it is seen to depend upon the burnt fuel space-frame velocity v_{eo}, which must be determined by the conservation laws of relativistic mechanics.

In addition to energy [equation 3], linear momentum must be conserved. This requirement gives us an equality between the axial momentum before burning:

$$p_{before} = \frac{m_s v_0}{\gamma_0} \quad (6)$$

and the approximate momentum after:[2]

$$p_{after} = m_s\left[\frac{v_0}{\gamma_0} + d\left(\frac{v_0}{\gamma_0}\right)\right] + \frac{dm_{p0}(1-\alpha)v_{e0}}{\gamma_{e0}} \quad (7)$$

which reduces to:

$$-m_s c \frac{d\gamma_0}{\gamma_0^2\sqrt{1-\gamma_0^2}} = (1-\alpha)\left(\frac{v_{e0}}{\gamma_{e0}}\right)dm_{p0} \quad (8)$$

by making use of the identity $\gamma_o^2 = 1 - v_o^2/c^2$.

We now have two independent relations [equations 3 and 8] between the parameters m_{po}, γ_o and v_{eo}. To find a differential equation describing the system motion we must eliminate exhaust velocity parameters from (3) and (8) and introduce an appropriate time variable for integration.

The fuel increment dm_{po} is swept up in a time dt_o measured in the space frame, by our propulsion plant intake of area A_o normal to the flight path. For a galactic fuel density ρ_o we have:

$$dm_{p0} = \rho_0 A_0 v_0 dt_0 \quad (9)$$

The time variable t_o is not particularly useful since the point of most interest is the duration of travel in ship-time, i.e. in time as measured by the ship clocks. We denote ship-time increments by dt_s; related to the space-frame time by the Lorentzian expression

$$dt_s = \lambda_0 dt_0 \quad (10)$$

With this, equation 9 becomes:

$$dm_{p0} = \rho_0 A_0 v_0 dt_s / \gamma_0 \quad (11)$$

and we have all the relations needed to determine the desired equation of motion. Substituting from (11) into (3) and (8), introducing the

[2] To be exact this equation should include a term of the form $(1 - \eta)\,\alpha v_o\, dm_{po}$ expressing the net axial momentum in the space-frame of the energy radiated without an axial momentum component in the ship-frame. This term has little effect on the system dynamics if the efficiency is high (i.e. $\eta > 0.5$) and is not included here or in the following work as it introduces considerable formal complications. If low efficiencies are of interest it should be included from equation 7.

symbol $\beta_o = (v_o/c)$, and combining the resultant expressions to eliminate v_{eo}, and γ_{eo} we obtain

$$\frac{d\beta_0}{dt_s} = -\left[\frac{c\rho_0 A_0}{m_s}\right][1-(1-\eta)\alpha]\left[\beta_0^2-\beta_0\right]\sqrt{1-\left(\frac{1-\alpha}{1-(1-\eta)\alpha}\right)^2(1-\beta_0^2)} \tag{12}$$

We note, in passing, that this expression is just γ_o^2/c times the apparent acceleration (d^2s_s/dt_s^2) in the ship-frame, and that acceleration is possible (i.e., $d\beta_o/dt_s$ is positive) for all $\beta_o > 0$. This is not readily integrable in closed form, however we can easily obtain solutions for several asymptotic conditions. The "effective" burnable fraction $\alpha\eta$, is always much less than unity since $\eta << 1$ and α is never greater than 0.0071, as previously mentioned. With this in mind we can expand the various terms of equation (12) retaining only terms of first order in smallness, and find the approximate but actually quite close equation for $\alpha\eta << 1$.

$$\frac{d\beta_0}{dt_s} = -\left[\frac{c\rho_0 A_0}{m_s}\right][1-(1-\eta)\alpha]\left[\beta_0^2-\beta_0\right]\sqrt{\beta_0^2(1-2\alpha\eta)+2\alpha\eta} \tag{13}$$

We distinguish two asymptotic cases of most interest: Those when $\beta_0^2 >> \alpha\eta$, and when $\beta_0^2 << \alpha\eta$. The first of these pertains to the region of flight when the vehicle is moving with an appreciable fraction of optic velocity and ramjet-type operation is firmly established, while the second is applicable for small vehicle velocity at the beginning of powered flight.

For high-speed flight, equation 13 reduces to

$$\frac{d\beta_0}{dt_s} \simeq \left[\frac{c\rho_0 A_0}{m_s}\right]\alpha\eta(1-\beta_0^2)\ (for\, B_0^2 >> \alpha\eta) \tag{14}$$

which has the solution:

$$[\tanh^{-1}\beta_0 - \tanh^{-1}\beta_0^0] = \left[\frac{c\rho_0 A_0 \alpha\eta}{m_s}\right]\Delta t_s \tag{15}$$

Equation (14) describing motion in terms of ship-frame time is identical with that which describes the hyperbolic motion of a mass acted upon by a constant force (in the space-frame), as described by Moller [17], Laue [27] for example. Here β_0^0 denotes the initial ratio of vehicle velocity to optic velocity and Δt_s is the ship-time interval $(t_s - t_s^0)$ required to reach any desired $\beta_o > \beta_0^0$. This equation holds well for β_0^0 values of about 0.2 and larger.

For low speed flight equation (13) becomes:

$$\frac{d\beta_0}{dt_s} \simeq \frac{c\rho_0 A_0}{m_s}\sqrt{2\alpha\eta}\,\beta_0\ (for\, B_0^2 << \alpha\eta) \tag{16}$$

which integrates directly to:

$$\ln\left[\frac{\beta_0}{\beta_0^0}\right] = \left[\frac{c\rho_0 A_0\sqrt{2\alpha\eta}}{m_s}\right]\Delta t_s \tag{17}$$

Note that for $\beta_0^2 = \alpha\eta/2$, equations 14 and 16 are equal and both agree with equation 13 within 11%.

The local fuel density may be written as $\rho_o = nm_p$ where m_p is the proton mass and n is the number density of protons in space. Since proton and neutron masses are nearly the same we can regard n as the local density of nucleons. Using this defined identity, the numerical values $c = 3 \times 10^{10}$ cm/sec and $m_p = 1.67 \times 10^{-24}$ gm/proton, and introducing the symbol $\sigma_s = (m_s/A_o)$ our two asymptotic equations can be written as:

$$\Delta t_s = \frac{2x10^{13}}{\alpha\eta}\left[\frac{\sigma_s}{n}\right][\tanh^{-1}\beta_0 - \tanh^{-1}\beta_0^0]\ (for\,\beta_0^2 >> \alpha\eta) \tag{15'}$$

and

$$\Delta t_s = \frac{1.41x10^{13}}{\sqrt{\alpha\eta}}\left[\frac{\sigma_s}{n}\right]\ln\left[\frac{\beta_0}{\beta_0^0}\right](for\,\beta_0^2 << \alpha\eta) \tag{17'}$$

We see that for a given initial velocity ratio β_0^0 the elapsed ship-time required to attain any desired β_o in either the low or high velocity case is directly proportional to the frontal area loading density σ_s and inversely to the galactic density (n) of nuclear fuel.

We are also interested in the distance Δs_o traversed by our interstellar ship as it accelerates continuously under the foregoing conditions. To find this we must integrate the instantaneous ship velocity v_o in the space frame over the appropriate time span. Since space-frame velocity is given as a function of ship-time by our earlier derived equations it is most convenient to perform the integration over dt_s.

$$\Delta s_0 = \int v_0(t_s)dt_0 = \int v_0(t_s)\left(\frac{dt_0}{dt_s}\right)dt_s$$
$$= \int \frac{v_0(t_s)dt_s}{\gamma_0(t_s)} = c\int \frac{\beta_0(t_s)dt_s}{\gamma_0(t_s)} \qquad (18)$$

by use of the time-contraction equation (10).

We consider only the asymptotic cases discussed previously and solve equations 15 and 17 for β_o as a function of t_s for $t_s^o = 0$. For large β_o:

$$\beta_0(t_s) = \tanh\left[\frac{\rho_0 A_0 c}{m_s}\alpha\eta t_s + \tanh^{-1}\beta_0^0\right](for\,\beta_0^2 >> \alpha\eta) \qquad (19)$$

while low β_o yields:

$$\beta_0(t_s) = \beta_0^0 \exp\left[\frac{c\rho_0 A_0}{m_s}\sqrt{2\alpha\eta}t_s\right](for\,\beta_0^2 << \alpha\eta) \qquad (20)$$

The first case is simplified by change of variable to $u = (1 - \beta_o^2)$ which gives the differential relation

$$\frac{du}{u^{3/2}} = -\frac{2\alpha\eta\rho_0 A_0}{m_s}ds_0 \qquad (20a)$$

when substituted into equation 18. This is immediately integrable and yields:

$$\Delta s_0 = \left[\frac{m_s}{\alpha\eta\rho_0 A_0}\right]\left[\frac{1}{\gamma_0} - \frac{1}{\gamma_0^0}\right] \qquad (21)$$

where $\gamma_o^2 = 1 - \beta_o^2$, with β_o given by equation 19 for $\beta_o^2 >> \alpha\eta$.

For low β_o, change of variable to $u = \beta_o$ yields the differential relation:

$$\frac{du}{\sqrt{1-u^2}} = \frac{\rho_0 A_0\sqrt{2\alpha\eta}}{m_s}ds_0 \qquad (21b)$$

which integrates to:

$$\Delta s_0 = \left[\frac{m_s}{\rho_0 A_0\sqrt{2\alpha\eta}}\right][\sin^{-1}\beta_0 - \sin^{-1}\beta_0^0] \qquad (22)$$

with β_o given by equation 20 for $\beta_o^2 << \alpha\eta$). Using $\rho_o = nm_p$ and evaluating constants as previously, we obtain the two asymptotic equations:

$$\Delta s_0 = \frac{6x10^{23}}{\alpha\eta}\left[\frac{\sigma_s}{n}\right]\left[\frac{1}{\sqrt{1-\beta_0^2}} - \frac{1}{\sqrt{1-(\beta_0^0)^2}}\right](for\,\beta_0^2 >> \alpha\eta) \qquad (21a)$$

and

$$\Delta s_0 = \frac{4.24x10^{23}}{\sqrt{\alpha\eta}}\left[\frac{\sigma_s}{n}\right][\sin^{-1}\beta_0 - \sin^{-1}\beta_0^0]\,(for\,\beta_0^0 << \alpha\eta) \qquad (22a)$$

Interstellar ramjet performance as described above is shown in Figure 2, which portrays elapsed ship-time as a function of distance traversed, by use of the parameters (Δt_s) ($n/\sigma s$) and (Δs_o) ($n/\sigma s$). The various curves are as labeled for different values of the starting velocity ratio, β_o^o, and lines of constant final velocity ratio, $\beta_o f$ are shown intersecting these. Equations 15' and 21' were used in calculation for all $\beta_o^{o\,2} > \alpha\eta/2$; equations 17' and 22' were employed for $\beta_o^{o\,2} < \alpha\eta/2$. Note that although Δt_s becomes infinite for $\beta_0^0 = 0$ [equation 17'] a very small initial "boost" velocity suffices to reduce ship travel times to values only slightly longer than those attainable with a large initial starting velocity.

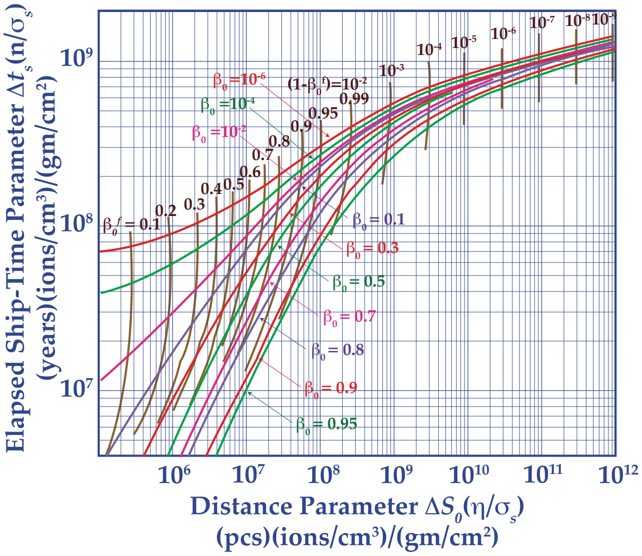

Figure 2 — Interstellar ramjet performance for αη = 0.005

In fact, we see that starting velocity-ratios of order β_0^0 ⌋ 10⁻⁵ well within reach of present rocket technology, will increase the ship-time required for interstellar journeys across large distances by only 10% or less from that for β_0^0 ⌋ 0.1, for example. The additional ship-time would be only about 6 months when starting from β_0^0 = 10⁻⁵ as compared with that for β_0^0 = 0.1, for a vehicle with maximum ship-frame acceleration capability of 1 g_o (see discussion following). For any flight at all we must accelerate our ramjet vehicle by rocket boosting to some finite initial velocity, however there appears little incentive to strive for starting velocities as high as those which might be attained by relativistic rockets, as discussed by Ackeret [1]. Boosting to velocities readily reached by present-day chemical rockets would be sufficient for any desired interstellar flight.

To see the necessity of rocket boosting to a non-zero value of β_0^0 we examine the vehicle acceleration as a function of β_0^0. As previously noted, apparent acceleration in the ship-frame is just:

$$a_s = \frac{c}{\gamma_0^2}\frac{d\beta_0}{dt_s} = \frac{d^2 s_s}{dt_s^2} \quad (23)$$

Using this with equations 14 and 16, we find that accelerations in the high and low β_o cases are:

$$a_s = \frac{c^2 \rho_0 A_0}{m_s}\alpha\eta \; (for\, \beta_0^2 >> \alpha\eta) \quad (24)$$

and

$$a_s = \frac{c^2 \rho_0 A_0}{m_s}\alpha\eta \; (for\, \beta_0^2 >> \alpha\eta) \quad (25)$$

These show that the apparent acceleration is zero for β_o zero (thus boosting is required), increases linearly with β_o for small β_o faster as β_o becomes larger, and approaches an asymptotic constant value given by equation 24 as β_o approaches unity. This asymptotic value is:

$$a_s^m = 1.5x10^{-3}(\alpha\eta)(n/\sigma_s) \quad (24a)$$

From this it is evident that attainment of maximum accelerations the order of earth-gravity (⌋10³ cm/sec²) requires ($\sigma s/n$) ratios the order of 10⁻⁸ [(gm/cm²)/(nucleon/cm³)] for use of the (*p, p*) fusion reaction chain at high efficiency. Clearly, interstellar ramjet ships must be large in size and relatively tenuous in construction unless regions of high fuel density (large n) can be found within the galaxy.

By combination of equations 15, 21, and 24 we can relate the ship-time for flight over any space-frame distance to the ship-frame acceleration. For the case of $\beta_o^{o2} >> \alpha\eta$ this is:

$$\Delta t_s = \frac{c}{a_s^m}\left\{\cosh^{-1}\left[\left(\frac{1}{\gamma_0^0}\right) + \Delta s_0\left(\frac{a_s^m}{c^2}\right)\right] - \tanh^{-1}\beta_0^0\right\} \quad (26)$$

a result already obtained in [6], [26] for rocket flight at constant acceleration starting from β_0^0 = 0, $\gamma_o{}^o$ = 1. In passing, we recall that we are only considering continuously accelerating rectilinear flight, thus equation 26 gives the ship-time required to arrive at Δs_o at maximum velocity. For the traditionally more practically interesting case of constant acceleration during the first half of the journey and constant (and equal magnitude) deceleration during the second half, equation 26 must be multiplied by 2, and modified by the replacement of Δs_o by $(\Delta s_o/2)$. If these changes are made the symbols Δt_s and Δs_o will still stand for total elapsed ship-time and total space-frame flight distance for the new flight program. Similar corrections must be applied to Figure 2 if it is to be used for the accelerate-decelerate flight program, rather than for the constant acceleration program as shown.

3. Galactic Fuel Sources

Astrophysical research in recent years by Van de Hulst, Oort, and co-workers at Leiden [18], Kerr at Sydney [19], and many others has shown that the interstellar void is, in reality, filled with matter. Aside from interstellar dust clouds known from the early days of observational astronomy, measurements of the intensity and source direction of 21 cm electromagnetic radiation from atomic hydrogen in space indicate that neutral hydrogen atoms are present throughout the galaxy, with an overall average density of about 1-2 atoms/cm^3. As discussed by Pawsey and Bracewell [20] it is believed that these constitute the major part (> 90%) of all interstellar matter. It is known that the distribution of these atoms is not at all uniform, but that they are congregated in a whole array of clouds and various filamentary structures. On the simplest picture the hydrogen is taken to be distributed in clouds the order of 10-40 parsecs across (1 parsec = 1 pc = 3.262 light years) with an atom density the order of 5-50 atoms/cm^3; the clouds themselves distributed with an average density the order of 10^{-4} clouds/(pc)^3 so that a line-of-sight will cut some 5-10 clouds per kiloparsec. On this model, regions between clouds may have densities of 10^{-1} atoms/cm^3 or less. This picture is much too simplified to account for the wealth of detail observed both by radio and observational astronomy and, as Oort has remarked,[21] actually has only slight resemblance to the reality of structure in the interstellar medium. We cite it here to indicate that variations in neutral H-atom density (HI regions) of 10^2 to 10^3 may be expected in the interstellar gas. In addition there are a great many regions of appreciable size in which essentially all of the hydrogen is ionized (HII regions). These are in the Stromgren spheres which surround type O and B stars, the hottest in the stellar temperature scale. Ionization of the H is by absorption of photons emitted from the stellar photosphere. These regions extend outward with almost complete ionization until a relatively sharp cut off is reached when the effective (randomized) photon energy has dropped significantly below the ionization energy. Typical Stromgren spheres are the order of tens of parsecs in radii. In HI regions the effective kinetic temperature is low, the order of 100°K; but in HII regions the kinetic temperature may be as high as 10^4°K. In addition to these clouds there are known vast regions of ionized H associated with clusters of O type stars. These cloud complexes are hundreds of parsecs across and occupy 5-10% of the space near galactic plane. An example of these is the Cygnus X radio source, described by Davies [22], which has a mean diameter of some 200 pc and an average ion density of about 5 ions/cm^3. Further examples of structures not fitted to the simple cloud model are planetary nebulae with ion densities of order 10^4 ions/cm^3, and small HII regions of high density such as NGC1976 in Orion with nearly 300 ions/cm^3 and a diameter of 2 pc [22]. An excellent detailed summary of the state of information to mid-1957 in this field is given by Van De Hulst and others in the Proceedings of the Third Symposium on Cosmical Gas Dynamics.[23]

Almost nothing is known about the interstellar density of another possible nuclear fuel; deuterium. Estimates of the H/D ratio have been derived from various assumed models of the evolution of the galaxy and vary from infinity (no D present) to the earthly ratio of about 8000/1 depending upon the galactic model considered, the assumed method of formation of the heavy elements, etc. It seems likely that the relative density of deuterium in interstellar space is considerably less than that on earth, but true knowledge of this awaits experimental measurement.

4. Some Consideration of Technological Problems

Information on this and for other elements is of importance when considering the problems involved in design of that section of the interstellar ramjet propulsion system which is to carry out the nuclear burning. The principal difficulty seen in exploitation of the often-cited (*p, p*) fusion reaction chain arises from the extremely low reaction cross-section of the first step in the chain:

$$p + p \rightarrow D + e^{+} + \nu \ (neutrino) \qquad (27)$$

This is shown in Figure 3 as a function of relative particle energy.

The beta-decay in equation 27 is the villain responsible for the low reaction cross-section since the reaction rate is limited by the necessity of beta-decay of a proton to a neutron plus positron while in the two-body He^2 configuration. It is for this reason that we may be quite interested in deuterium as an alternate fuel source since the reactions:

$$D + D \begin{cases} \nearrow He^{3} + n^{0} \ (\alpha \simeq 0.0009) \\ \searrow T + P \ (\alpha \simeq 0.0011) \end{cases} \qquad (28)$$

of roughly equal probability are not so limited. In the tens-of-kilovolts region, the (D, D) reaction cross-section is seen from Figure 3 to be 24 orders of magnitude greater than for (*p, p*). Also shown is the cross-section for the (*p*, D) reaction:

$$p + D \rightarrow He^{3} + \gamma \ (\alpha \simeq 0.0020) \qquad (29)$$

which is seen to be some 16 orders of magnitude greater than for (*p, p*). Since reaction rates in any fusion reactor (assuming one can be devised) are proportional to the product of the cross-section and the square of the fuel density, the (D, D) reaction can in principle be achieved with only 10^{-12} and the (*p*, D) with 10^{-8} of the nuclear density required for an equal power generation from the (*p, p*) reaction. Engineering difficulties in the fusion reactor design may be much less for the lower density systems.

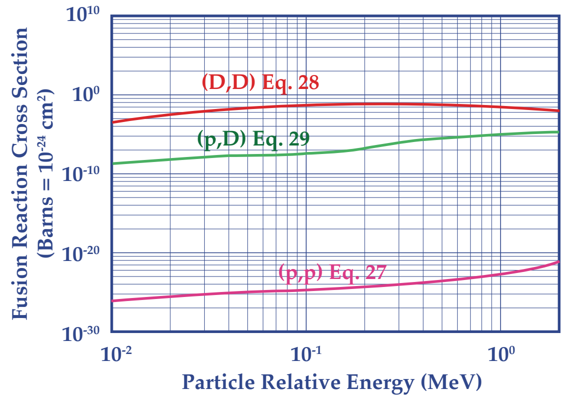

Figure 3 — Fusion reaction cross-sections of interest for interstellar gas. [Data from: Arnold, et al., Physical Review 93, 483 (1954); Fowler, et al., Physical Review 76, 1767 (1949); and Salpeter, Physical Review 88, 547 (1952).]

Unfortunately, if our vehicle is to be powered by (D, D) rather than (*p, p*) reactions we are faced with a more difficult engineering problem for the vehicle as a whole. This is a consequence of the fact that vehicle accelerations vary linearly with fuel density, as seen from equation 24. Thus, achievement of a given acceleration for use of (D, D) would require a vehicle structure more tenuous by the ratio of H to D densities than that needed for use of (*p, p*) reactions. In effect we have a choice between more difficult reactor design but less difficult problems of vehicle structure or vice versa by choice of (*p, p*) versus (D, D) reactions for use in propulsion.

For purposes of illustration we might sketch this hypothetical vehicle as in Figure 4. Here we show the vehicle moving to the right so that in the vehicle frame ions appear to approach. it from the right. As these cross the nominal frontal area plane A_o they are deflected by an electric or magnetic field which causes them to arrive at a focal point some distance L back of the A_o plane. At the focal point these ions are led into a fusion reactor of unspecified (indeed, unknown) type, made to react and generate power which is then fed back into the fusion products through a similarly unspecified conversion device, to the increase of their kinetic energy and momentum, with consequent reaction on and acceleration of the vehicle.

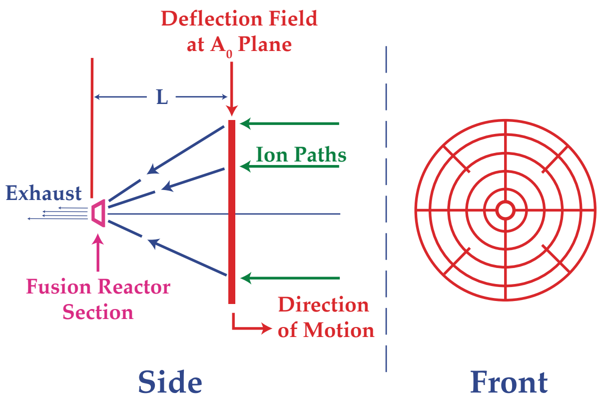

Figure 4 — Schematic outline of one concept of an interstellar ramjet vehicle

Since the random velocities of the interstellar gas atoms are believed small (order of 5-10 km/sec) compared to the kilovolt relative energies required for effective fusion reactions we must add the necessary relative energy after swallowing the interstellar gas. At large ship velocity this could be accomplished simply by the deflection process required for focusing as well. The focusing field, whether magnetic or electrostatic, accelerates the incoming ions radially, transversely to their initial direction relative to the ship. For magnetic field deflection, the source of energy for this is the kinetic energy of the ship, but separately generated electrical energy is required for the use of electric field deflection. The relative energy needed per particle is small compared to the energy release in the fusion reaction, thus the necessity of supplying this need will have little effect on the vehicle performance if the fusion energy can be utilized efficiently. We could include this effect as a slight reduction in the value of IX used in calculation. By choosing the appropriate beam focusing length (L in Figure 4) the ratio of axial to transverse energy of the deflected particle can be made as desired for the instantaneous flight conditions. For a deflection field of fixed strength, the focusing length required at high velocity will be very much greater then that for low velocity flight. However, if we can recover efficiently energy added to the particles during deflection then we can still use a small focusing length (comparable to or less than the intake area radius, for example) and achieve a focus by accelerating the incoming ions to radial energies comparable to their axial energy at crossing of the intake plane by variation of the deflection field strength with flight velocity.

Conversion of kinetic energy of fusion to directed motion of the fusion products is possible in principle in a number of ways. If electrical power is produced by the reactor, electrostatic acceleration through a multi-stage field could be used. Another method of acceleration could make use of electromagnetic waves to extract energy from incoming particles while adding energy to outgoing particles in a traveling wave type of transformer. Photon momentum could be used to provide high exhaust velocity (c) more directly for some fraction of the energy (i.e., mass) involved.

Requirements on exhaust velocity can be obtained by solution of equation 3 for β_{eo} combined with equation 12 for high or low β_o flight. The resulting expressions for β_{eo} correct to lowest order in the parameter of smallness pertinent to the regime of interest, are:

$$\frac{1}{\beta_{e_n}^2} = 1 + \left(\frac{1-\alpha}{\alpha\eta}\right)^2 \beta_0^2 \; (for\, \beta_0^2 >> \alpha\eta;\ \alpha\eta\, small) \tag{30}$$

and

$$\frac{1}{\beta_{e_n}^2} = 1 + \left[\frac{1-\alpha}{\sqrt{2\alpha\eta}\left[1-\frac{\alpha}{2}\left(1-\frac{\eta}{2}\right)\right] - \beta_0[1-(1-\eta)\alpha]}\right]^2$$

$$(for\, \beta_0^2 << \alpha\eta,\ \beta_0 small) \tag{31}$$

Recall that $v_{eo} = c\beta_{eo}$ is not the exhaust velocity relative to the vehicle frame but is the velocity of exhaust particles in the space frame. To obtain the exhaust velocity $v_e = c\beta_e$ in the shipframe we make use of the Lorentz velocity transformation:

$$\beta_e = \frac{\beta_{e0} + \beta_0}{1 + \beta_0 \beta_{e0}} \quad (32)$$

where we have chosen signs such that exhaust velocities are measured positive in a direction opposite to vehicle motion while vehicle velocities are positive along the flight path, as sketched in Figure 1.

Expanding equations 30 and 31 to first order in small quantities and using the velocity transformation above we obtain the approximate expressions:

$$\beta_e \simeq \beta_0 \left[1 + \alpha\eta \left(\frac{1 - \beta_0^2}{\beta_0^2} \right) \right] (for\, \beta_0^2 >> \alpha\eta) \quad (33)$$

and

$$\beta_e \simeq 2\beta_0 + \sqrt{2\alpha\eta} \; (for\, \beta_0^2 << \alpha\eta) \quad (34)$$

We see that the exhaust velocity relative to the ship must increase slowly from a value of $\beta_e \simeq 0.1$ at $\beta_0 = 0$ for $\alpha\eta = 0.005$, as before, to the velocity of light as β_0 approaches unity.

There is no thought that anything resembling the required reactor and propulsion section could be built today, however there is likewise no reason to assume such a device is forever impossible since known physical laws are sufficient to describe its desired behavior. For example, ion collection or trapping at the focal point could in principle be accomplished by magnetic mirror or mirror-cusp field geometries similar to those being studied [24] for earth-bound thermonuclear reactors. Principal losses of particle energy while trapped within the fields in our case would be due primarily to diffusion to the walls and to ion cyclotron radiation and bremsstrahlung from electrons trapped within the system. Ion cyclotron radiation decreases with increasing orbital radius and wall losses decrease with decreasing surface-to-volume ratio. Both effects favor large size for the reaction chamber. Bremsstrahlung losses depend strongly upon ion charge (z = 1 either for H or D) and electron-ion collision density. Since this latter is approximately proportional to the square of the ion density (assuming equal numbers of electrons and ions in the system to assure space-charge neutrality) as is the fusion reaction rate itself, the situation is much less favorable for (*p, p*) than for (*p,* D) or (D, D) reactions because of the lower density allowed for the latter reactions to be achieved under fixed pressure (i.e., field strength) conditions.

Whether or not such devices eventually can be constructed to operate successfully at high efficiency is a matter to be determined by engineering technology of the future.

As previously noted, a low frontal area loading density σ_s, must be achieved for the vehicle if acceleration is to be made large. For example, if (σ_s/n_e) is to be 10^{-8} (gm/cm³)/(nucleon/cm³) as required for earth-gravity flight, then our vehicle can carry only 10^{-5} gm/cm² for flight through an interstellar region of density n_e = 10^3 protons/cm³.

Though quite small in comparison with ordinary missiles, a vehicle with frontal area density of this order would be affected only insignificantly by radiation and field pressures in interstellar space. To see this we write acceleration crudely as $a \simeq P/\sigma_s$, where P denotes the pressure field acting on the vehicle. Reported values [25] for the radiation density and interstellar magnetic field density are of order 10^{-12} erg/cm³, giving comparable field pressures on reflecting media. Vehicle accelerations caused by such field pressure would be of order $10^{-12}/10^{-5} = 10^{-7}$ cm/sec². In contrast, pressure from solar radiation at the orbit of the earth would yield about 4 cm/sec² if totally reflected. Of course, unlike solar “sails,” our ramjet vehicle should not be designed as a radiation reflector, rather as an ion collector and focusing device plus reactor, crew quarters, etc.

For an arbitrarily chosen vehicle mass of m_s = 10^9 gm (about 2.2 million pounds) the intake area must be $A_0 = 10^4$ km², yielding an ion collector radius of nearly 60 km. This is very large by ordinary standards but then, on any account, interstellar travel is inherently a rather grand undertaking, certainly many magnitudes broader in scope and likewise more difficult than interplanetary travel in the solar system, for example. The engineering effort required for the achievement of successful short-time interstellar flight will likely be as much greater than that involved in interplanetary flight as the latter is more difficult than travel on the surface of the earth. However, the expansion of man's horizons will be proportionately greater; and nothing worthwhile is ever achieved easily.

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