The General Limits of Space Travel

We may never visit our neighbors in space, but we should start listening and talking to them.

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The goal of this discussion is to find out whether interstellar space travel (travel from star to star) might become possible for us in the far future, and might therefore already be possible for other, more advanced beings. Is there any hope of making direct interstellar visits, or will all communication between civilizations be confined to electromagnetic signals? Certainly, from present estimates we cannot give a direct and conclusive answer of the yes-no type, but we can point out the significant basic facts and get as close to an answer as is possible at our present state of knowledge, leaving the final conclusion to the reader.

I shall begin by summarizing the present limitations and problems of space flight, trying to pin down the few basic points, and trying to separate the general difficulties from the merely temporary ones. From this starting point we may then proceed to estimate the possibilities of future space flight.

The prime postulate in these estimates is a technology much more highly advanced than our present one. Thus, we completely neglect all technical problems, however serious they actually might be. Only such fundamental properties as time, acceleration, power, mass, and energy are considered.

The results are given in terms of the minimum travel times deriving from various assumptions. Furthermore, we calculate some basic requirements for reaching these travel times.

Chemical binding energy. The only propelling mechanism actually used at present is acceleration of exhaust material by combustion, where the relatively low binding energy between atoms sets a limit in two ways: in the energy content of fuels, and in the heat resistance of combustion-chamber and nozzle materials.

In order to remove 1 kilogram of matter from the earth against gravity, we need an energy of 17.4 kilowatt-hours. But the best fuel, burning hydrogen with oxygen, yields only 3.2 kilowatt-hours per kilogram of fuel (explosives yield still less—for example, TNT yields 1.1 kw-hr kg). Thus we need 5.4 kilograms of fuel to remove 1 kilogram of matter, but the supply of fuel has to be accelerated too, and this again requires much more fuel, and so on. Despite this difficulty of low fuel energy content, small payloads can still be removed, but with an extremely low efficiency.

The availability of more energetic fuels would not be of too much help. No nozzle material can stand temperatures above about 4000°C at the utmost limit. If a combustion gas of that temperature escapes through a nozzle, it will do so with an exhaust velocity of 4.0 kilometers per second if it is water vapor, and of less than that if substances other than hydrogen are burnt. But the rocket itself needs a velocity of 11.2 kilometers per second to leave the gravitational field of the earth, and far greater velocities if interstellar distances are to be covered within a reasonable time.

The velocity of a rocket after burnout of all its fuel, V, the exhaust velocity generated by the propellant, S, and the so-called mass ratio, $\mathcal{M} = M_i/M_0$, are connected by the well-known rocket formula

$$\frac{V}{S} = \ln \mathcal{M} \qquad (1)$$

where M_i is the total initial mass of the rocket (including fuel) and M_0 is the mass after burnout—that is, M_i minus the mass of fuel. Now, the logarithm is a function which increases very slowly with its argument; even if fuel constitutes 90 percent of the initial mass, the rocket velocity will be only 2.3 times the exhaust velocity. And if a one-stage rocket with fuel constituting 99.9 percent of its initial mass could be built, even then we would achieve a velocity of only $V = 6.9\ S$. We cannot at present build such a rocket, but we do imitate it through multistage rockets. With these the difficulty remains the same, because the mass ratios of all stages accumulate in a multiplicative way (a tiny payload in the last stage, as compared to a huge fuel mass in the first stage), but the stage velocities accumulate only additively. Thus, with combustion-powered rockets, even of many stages, we are just able to leave the earth, but we cannot reach very high velocities.

In order to see this more precisely, we define the efficiency of a rocket, Q, as the useful energy (the energy contained in the final velocity of the empty rocket) divided by the energy content of all fuel burnt. We then have

$$Q = \frac{(V/S)^2}{e^{V/S} - 1} \qquad (2)$$

This efficiency has its maximum value, $Q = 0.647$, at $V/S = 1.59$, but it drops off very fast and is only 1 percent at $V/S = 9$. And in the case of many stages the efficiency gets still smaller by a large factor. The efficiency of an ideal multistage rocket is only 0.1 percent for $V/S = 6$.

These difficulties connected with low binding energy are only temporary ones, because they are confined to combustion processes. In increasing the energy content of fuels we can make a huge step if we use atomic energy; the fission of uranium, for example, yields 20 million kilowatt-hours per kilogram. And nozzles as well as high temperatures can be avoided completely when we learn to use ion thrust as a propelling mechanism (charged particles—ions—are accelerated by electrical fields to a high velocity, with which they leave the rocket). A 5000-volt acceleration, for example, could give S of the order of 100 kilometers per second. With this mechanism, S increases with the square root of the acceleration voltage.

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In dealing with these difficulties we have discovered one fundamental principle:

> In order to avoid unreasonably low efficiencies, the exhaust velocity S should be about as large as the required final velocity of the rocket, V, or at least of the same order of magnitude. (3)

Power-mass ratio. As soon as these two difficulties have been overcome, by obtaining a high energy content in fuel and a high exhaust velocity, one will immediately encounter the next fundamental difficulty. The acceleration of a rocket, b, is of course given by

$$b = \frac{\text{Thrust of engine}}{\text{Total mass of rocket}} \quad (4)$$

Now, the thrust equals the exhaust mass-flow (mass/sec) times the exhaust velocity S; and the needed power of the engine equals the mass-flow times one-half the square of the exhaust velocity. We thus can write (instead of Eq. 4):

$$b = 2\,P/S \quad (5)$$

where P is the ratio of power of engine to total mass of rocket.

This means that, if we are working with a high exhaust velocity S, we need a high power-mass ratio P, as otherwise we would get only a small acceleration b.

But nuclear reactors and all the equipment needed to give a strong ion thrust are so complicated and massive, as compared with the relatively simple combustion equipment, that there is no hope at present of reaching, with reactors, the value of P already attained with combustion rockets. The acceleration thus will be extremely small until we can find a way to increase the power-mass ratio of a reactor by many orders of magnitude.

Distances for Interstellar Space Travel

The only goal which may be important enough to justify the immense effort needed for interstellar space travel appears to be the search for other intelligent beings. In a recent article (*1*) I tried to estimate the distances between neighboring technical civilizations in order to guide preparations and stimulate a search for possible electromagnetic signals. The points of interest for our present purpose may be summarized as follows:

1) It would be megalomania to think that we are the one intelligent civilization in the universe. On the contrary, we should assume from our present knowledge that life and intelligence will have developed, with about the same speed as on earth, wherever the proper surroundings and the needed time have been provided. From our present limited data, we judge that this might have been the case on planets of about 6 percent of all stars. The nearest ten such stars are at an average distance from us of about 5.6 parsec (1 parsec = 3.09×10^{13} km = 3.26 light-years).

2) It would be equally presumptuous to think that our present state of mind is the final goal of all evolution. On the contrary, we should assume that science and technology are just one link in a long chain and will be surpassed one day by completely new and unpredictable interests and activities (just as gods and demons unpredictably have been surpassed by science in offering explanations of many important phenomena). We should assume a finite longevity L of the technical state of mind; if we call T the age of the oldest stars and D the average distance to the nearest ten technical civilizations, we get

$$D = 5.6 \text{ parsec} \left(\frac{T}{L}\right)^{1/3} \quad (6)$$

We may take about 10 billion years for T, but it is extremely difficult to estimate the value of L. It is my personal opinion that we should take some ten thousands of years for L, but since many scientists regard this as being too pessimistic, we will take 100,000 years for our present purpose—a value which gives about 250 parsec for D. Fortunately, the uncertainty of L enters the value of D only with the power 1/3, and if we change L even by a factor of 8, D will change by only a factor of 2.

With respect to interstellar space travel we must clearly separate two questions: (i) We may want to know what the possibilities are for *our* future interstellar travel. In this case we are interested in locating *any* kind of intelligent life, and the distance we are required to reach is

$$5.6 \text{ parsec } (= 18.6 \text{ light-years}) \quad (7)$$

(ii) We may examine the possibility of other beings visiting us. In this case the other civilization must be a *technical* one, and for the calculations that follow we will use, for the above-mentioned distance to be covered by these other beings

$$250 \text{ parsec } (= 820 \text{ light-years}) \quad (8)$$

In order to help visualize these astronomical distances, I will describe them with a model of scale 1:180 billion. The earth, then, is a tiny grain of desert sand, just visible to the naked eye, orbiting around its sun, which now is a cherrystone a little less than 3 feet away. Within approximately the same distance, some few feet, lies the goal of our present space travel: the other planets of our solar system, such as Mars and Venus. But the nearest star, Proxima Centauri, is another cherrystone 140 miles away; and the next stars with habitable planets, where we might look for intelligent life, are to be expected at a distance of 610 miles. The next technical civilizations, however, will be at a distance as great as the circumference of the earth. Just for fun one may add the distance to the Andromeda nebula, the next stellar system comparable to our own galaxy: in our model it is as far away as, in reality, the sun is from the earth. The most distant galaxies seen by astronomers with their best telescopes are 2000 times as far away, and here even our model fails to help.

Relativistic Treatment

One thing is now clear: in order to cover interstellar distances within reasonable times we ought to fly as close as possible to the velocity of light, the utmost limit of any velocity, according to the theory of relativity (and in accordance with all experiments with high-energy particles). But as we approach the velocity of light, the formulas of normal physics must be replaced by those of relativity theory.

This might be of some help, because one of the most striking statements of relativity theory is that time itself is not an absolute property but is shortened for systems approaching the velocity of light. If, for example, we are to move out and back a distance of 800 light-years, then people remaining on earth will have to wait at least 1600 years for the return of the rocket. But if the speed of the rocket closely approaches the velocity of light, then the flow of time for this rocket and its crew becomes different from that on earth, and one may expect that the crew members will have to spend only a few years, perhaps, of their own lifetimes between start and return.

The equations that follow are derived under the assumption that the formulas of the special theory of relativity still hold under conditions of permanent acceleration and deceleration—a view which is generally assumed but not yet accepted. I will keep this part of the discussion as short as possible, and any reader who abominates formulas, relativistic or not, may skip to the next section.

We use the following definitions: τ is rocket time and t is earth time (both equal zero at the start of the rocket flight); v is the velocity of the rocket (as seen from the earth); c is the velocity of light; b is the acceleration of the rocket (as measured *within* the rocket by the pressure of a unit mass against a spring), assumed to be constant; and x is the distance between the rocket and the earth.

The differentials of τ and t are connected by

$$d\tau = \mathrm{d}t\,(1-[v/c]^2)^{1/2} \tag{9}$$

and the differential equation for v reads

$$\frac{\mathrm{d}}{\mathrm{d}t}\left\{\frac{v}{(1-[v/c]^2)^{1/2}}\right\} = b \tag{10}$$

which is easily integrated. Solving for v we get

$$v(t) = \frac{bt}{(1+[bt/c]^2)^{1/2}} \tag{11}$$

With the help of Eq. 11 we can integrate Eq. 9:

$$\tau(t) = \int_0^t (1-[v/c]^2)^{1/2}\,\mathrm{d}t = \frac{c}{b}\operatorname{arc\,sinh}\frac{bt}{c} \tag{12}$$

while the distance is integrated according to

$$x(t) = \int_0^t v\,\mathrm{d}t = \frac{c^2}{b}\left\{(1+[bt/c]^2)^{1/2} - 1\right\} \tag{13}$$

We realize that, in order to get an equivalent to our rocket formula (Eq. 1), thrust and acceleration, if both are measured within the rocket, should be connected as usual:

$$-\frac{\mathrm{d}M}{\mathrm{d}\tau}\,S = Mb \tag{14}$$

where M is the total mass of the rocket at any time and $-\,\mathrm{d}M/\mathrm{d}\tau$ is the exhaust mass-flow. But in order to reach $v \approx c$, we need also $S \approx c$ according to relationship 3, and S in Eq. 14 should be replaced by $S(1 - S^2/c^2)^{-1/2}$. Furthermore, $S \approx c$ demands so much energy that in integrating Eq. 14 the mass loss due to mass defect should be considered, too. In the calculations that follow, however, we shall find that, even with atomic energy, both S and v still are much less than c, so that no relativistic treatment is needed, and Eq. 1 may be used.

Table 1. Energy per mass of fuel for nuclear reactions.

Fuel	Final product	Energy/mass (10^{18} ergs/g)
	Annihilation	
Matter plus antimatter	Radiation	900
	Fusion	
Hydrogen	Helium	6.3
Hydrogen	Iron	8.3
	Fission	
Uranium	Mixture, as produced in reactors	0.65
Uranium	Iron	1.1

The only means of reaching $v \approx c$ turns out to be complete annihilation of matter. In this case one will use photon thrust, and Eq. 14 should be written as

$$-\frac{\mathrm{d}M}{\mathrm{d}\tau}\,c = M\,b \tag{15}$$

We derive the following formulas for annihilation of matter as the energy source and photon thrust as the propelling mechanism (ignoring all doubts about the practical realization of either). We integrate Eq. 15 from start ($M = M_i$) to burnout of all fuel ($M = M_0$). The durations of this period of acceleration for the crew, τ_0, and (from Eq. 12) for people on earth, t_0, then are

$$\tau_0 = \frac{c}{b}\ln \mathcal{M} \tag{16a}$$

and

$$t_0 = \frac{2c}{b}(\mathcal{M} - \mathcal{M}^{-1}) \tag{16b}$$

where, again, $\mathcal{M} = M_i/M_0$, and the distance traveled between start and burnout, x_0, is

$$x_0 = \frac{c^2}{2b}(\mathcal{M} + \mathcal{M}^{-1} - 2) \tag{17}$$

After burnout, the final velocity of the rocket, V, is given by

$$V = c\,\frac{1-\mathcal{M}^{-2}}{1+\mathcal{M}^{-2}} \tag{18}$$

—a velocity which causes a time dilatation, on the further (unaccelerated) portion of the journey, of

$$\left(\frac{\mathrm{d}t}{\mathrm{d}\tau}\right)_0 = \frac{\mathcal{M}+\mathcal{M}^{-1}}{2} \tag{19}$$

We notice that the final velocity and time dilatation do not depend on b or t_0; it does not matter how quickly we burn our fuel.

The mass ratio should be, of course, as large as possible, and for $\mathcal{M} >> 1$ the equations just given reduce to

$$t_0 \approx 2\frac{c}{b}\mathcal{M} \tag{20a}$$

$$x_0 \approx \frac{c^2}{2b}(\mathcal{M} - 2) \tag{20b}$$

$$V \approx c(1 - 2/\mathcal{M}^2) \tag{20c}$$

and

$$\left(\frac{\mathrm{d}t}{\mathrm{d}\tau}\right)_0 \approx \frac{1}{2}\mathcal{M} \tag{20d}$$

(see *2*). Finally, Eq. 5 needs a slight modification, too; for photon thrust it reads simply:

$$b = P/c \tag{21}$$

Energy Content of Nuclear Fuels

Having seen, earlier in this article, that the energy per mass of fuel is one of the important considerations in space travel, we now ask for the most energetic fuels. The utmost possible limit is set by one of the fundamental laws of relativity:

$$E = m\,c^2 \tag{22}$$

which gives the energy E obtained by complete annihilation of matter of mass m. Or we might say it another way: energy E has an inertial mass (its resistance against acceleration) of $m = E/c^2$. If we call ε the specific energy content (energy/mass), we have for complete annihilation, $\varepsilon = c^2 = 9 \times 10^{20}$ ergs per gram.

Complete annihilation takes place only if matter and antimatter are brought together: when a proton combines with an antiproton, electron combines with positron, and so on. But the world we live in consists of matter only, and to store a large amount of antimatter with equipment consisting of matter seems quite impossible, from all we know. We thus have to look for some other source of energy.

If antimatter is omitted, then according to another fundamental rule of nuclear physics the combined number of heavy elementary particles (protons plus neutrons) must stay constant, and the only thing left is to unite several light nuclei into a heavy one (fusion) or to split up a heavy nucleus into several light ones (fission), leaving the sum of protons and neutrons constant. In doing this we may gain or lose energy, according to the different amounts of nuclear binding energy of the various elements. The total energy content per nucleon (proton or neutron), in case of annihilation, would be 931.13 million electron volts for hydrogen; it drops quickly to 924.88 for helium, and then slowly to a flat minimum of 922.55 for iron. From then on it increases again, but very slowly, to 922.65 for uranium. The differences in these figures represent the energy available for nuclear reactions, and the most energy is gained if we start at either end and stop at the lowest point, at about iron. Since hydrogen has a higher value than uranium, we can gain more energy by fusion than by fission; and furthermore, since the minimum is an extremely flat one, it is not important to stop exactly at iron.

At present we use fission in reactors; the fission products are a mixture of elements of all masses, and the gain in energy is about half that which would result if all fission products were iron. Fusion of hydrogen into helium is the source of energy of our sun and of most other stars; it is used in hydrogen bombs only. Scientists in many countries have worked hard to produce controlled fusion, but without success so far.

The only fuel used at present for space travel releases energy by chemical reactions, where the burning of hydrogen to water yields only an energy-mass ratio of 1.15×10^{11} ergs per gram. If we learn to use uranium reactors instead, the energy-mass ratio will be increased by a factor of 5.6 million. If it ever became possible to use the fusion of hydrogen into helium as a power source for space travel, one would gain another factor of 10; and if complete annihilation were practicable, a further factor of 140 would be gained. Table 1 summarizes these facts.

Acceleration and Time

Thus equipped with an understanding of nuclear fuel, if not with the real thing, and with relativistic formulas, we proceed with estimating the general limits of future space travel.

As a first step we neglect even the requirements of energy and power. The only limitation then remaining will be the maximum amount of acceleration which a crew can stand. It has been estimated (*3*) that a terrestrial crew can stand, for a period of *years*, approximately $b = 1g$. It seems likely that, over a long trip, any crew will stand only about as much acceleration as its members are used to experiencing on their home planet. This might differ from our case by a factor of, say, 2 or 3 in either direction, but probably by less if the conditions for the development of life are carefully regarded. In the following discussion we will use a limit of $1g$.

If the acceleration is limited to this fixed value, the shortest travel time for a given distance will result if we accelerate with $1g$ half of the way and then decelerate with $1g$ over the second half of the trip, returning in the same way. On the basis of this assumption and of Eqs. 11 to 13, Table 2 has been calculated.

We see that the relativistic time dilatation yields an effective gain for the crew only if the crew members spend more than about 10 years of their lives on the voyage. The further increase, however, is a very steep one (exponential); if the crew members spent 30 years of their lives on the voyage they would be able to fly to the Orion nebula and back, and 3000 years would have elapsed on earth between their departure and their return. For our goals of travel to distances of 5.6 and 250 parsec, we obtain the values in Table 3.

With these results, many readers may already have lost hope of future interstellar space travel; others still may be optimistic. But so far we have neglected the requirements of energy and power.

Energy and Time

Acceleration and deceleration require a lot of energy, which has to come from somewhere. One might perhaps think of providing the rocket with a large funnel in order to sweep up the interstellar matter for fuel. But the interstellar matter has only a very low density (about 10^{-24} g/cm^3), and in order to collect 1000 tons of matter (10 times the fuel of one Atlas rocket) on a trip to a goal 5.6 parsec away, one would need a funnel 100 kilometers in diameter; we will rule out this possibility. We cannot refuel under way in this manner, or in any other way while traveling at high speed, and thus the rocket must be provided initially with all the energy it needs to reach its goal. But we might allow for refueling at the destination point, when the rocket will be at rest. For our estimate we will consider a three-stage rocket: stages 1 and 2 are used for the trip to the destination, there stage 2 is refueled, and stages 2 and 3 are used for returning. There is thus one stage for each period of acceleration or deceleration.

The next thing to be fixed is the mass ratio $\mathcal{M}$ of a single stage. Our present values for $\mathcal{M}$ are around 10, but the values would become very low if any energy source other than combustion were to be used. Keeping in mind the extremely massive and complicated equipment needed for nuclear reactions, and for propelling mechanisms such as ion thrust, we think that a value of $\mathcal{M} = 10$ could be used as an extreme upper limit, even for a much more advanced technology.

The only source of nuclear energy now in sight is the fission of heavy nuclei such as uranium, where 1 gram yields 6.5×10^{17} ergs. The highest efficiency is achieved if the fission products themselves can be expelled for propulsion with their fission energy (although at present we have no idea how this can be accomplished). In this

Table 2. Total duration and distance reached, with constant acceleration and deceleration at $1g$.

Duration (out and back) (yr): For crew on board rocket	Duration (out and back) (yr): For people on earth	Distance reached (parsec)
1	1.0	0.018
2	2.1	0.075
5	6.5	0.52
10	24	3.0
15	80	11.4
20	270	42
25	910	140
30	3,100	480
40	36,000	5,400
50	420,000	64,000
60	5,000,000	760,000

Table 3. Total durations, for rocket-crew members and for people on earth, of round-trip voyages to distances of 5.6 and 250 parsec, with constant acceleration and deceleration at $1g$.

Distance reached (parsec)	Duration (yr): For crew	Duration (yr): On earth
5.6	12.3	42
250	27.3	1550

case, we will get an exhaust velocity of $S = 13{,}000$ km/sec $= c/23$—a value so small as compared to the velocity of light that Eq. 1 still may be used. With a mass ratio of 10 as a limit, the final velocity after burnout then is $V = 30{,}000$ km/sec $= c/10$. Relativistic effects, such as time dilatation, will not play a role of any importance. In order to reach greater distances we have to fly most of the time without acceleration (after burnout of the first stage) and decelerate shortly before reaching the goal with our second stage. The full travel time, out and back, is 380 years for 5.6 parsec and 17,000 years for 250 parsec. This certainly does not look very promising.

If one is optimistic enough to think that the fusion of hydrogen into helium might become usable for rocket propulsion, with a mass ratio of 10, even then only $V = c/5$ can be achieved, and time dilatation again will be unimportant. The full travel time is 180 years for 5.6 parsec and 8000 years for 250 parsec—not much better than before.

The utmost limit, which cannot be surpassed, is set by the mass equivalent of the needed energy itself (its resistance against acceleration), no matter how this energy is stored. Personally, I do not think that complete annihilation of matter, or some other means of storing "pure energy," ever will become practical for any purpose, let alone in rockets with a mass ratio of 10. But imagine that it does: then 98 percent of the velocity of light can be achieved, according to Eq. 20*c*, and as a result of the time dilatation, the time for the crew will get shorter than the time on earth (after burnout) by a factor of 5.0. For 5.6 parsec, the full travel time will be 14 years for the crew and 42 years on earth, and for a distance of 250 parsec we get 300 years for the crew and 1500 years on earth. We still must spend 14 years within a rocket in order to search for intelligent beings, and only after 300 years in a rocket will the inhabitants of some alien planet have a fair chance of meeting other beings, like ourselves, who are in just the same state of science and technology as they are.

I should mention again that the final velocity after burnout does not depend on the amount of acceleration b, either in the classical treatment (Eq. 1) or in the relativistic one (Eq. 18). Only the energy content of the fuel and the mass of the rocket are important, not the rate at which fuel is consumed. The latter rate will influence the duration of the acceleration period, of course, but not the final velocity. This means that if we should prepare the crew to resist very high acceleration (by freezing them in a solid block of ice, or the like), we could shorten the acceleration periods but not the duration of the unaccelerated flight in between.

In the case of fission or fusion, almost all of the travel time is spent in unaccelerated flight after burnout, and high acceleration will not help at all. In the case of annihilation, however, 9.5 years of the crew's time is spent in accelerated or decelerated flight, and this period could be shortened through greater acceleration, but we are still neglecting the power requirements. For a distance of 5.6 parsec, 4.2 years of the crew's time is spent in unaccelerated flight, and this period cannot be shortened in any way; again, for a distance of 250 parsec, almost all of the time is spent in unaccelerated flight.

Power-Mass Ratio and Acceleration

For the interstellar distances discussed earlier we need a travel velocity close to the velocity of light, and according to principle 3 we must have $V \approx S$ for reasonable efficiency. These criteria taken together then demand that $S \approx c$. Furthermore, we have seen that complete annihilation of matter is the only hope as a power source in interstellar space travel, and since we must not waste any matter by using it for propulsion, only photon thrust is left us. In that case Eq. 21 applies, and $b = P/c$.

From Eq. 16 we see that the acceleration must be as large as possible in order to hold τ_0 small, but we have argued that b must be limited to about $1g$. The two considerations then demand that $b \approx 1g$.

Now, if Eq. 21 holds and $b \approx 1g$, then the power-mass ratio must have the extremely high value of

$$P = 3 \times 10^{13}\ \text{cm}^2/\text{sec}^3 \qquad (23)$$

or, in the power units of watt or horsepower,

$$P = 3 \times 10^6\ \text{watt/g} = 4 \times 10^3\ \text{hp/g} \qquad (24)$$

In order to understand the full meaning of Eq. 24 we might consider our present fission reactors—those with the highest power-mass ratios. Reactors for ship propulsion, with power output of 15 megawatts and weight of 800 tons give $P = 0.02$ watt per gram—a value too low by a factor of 1.5×10^8 to fulfill Eq. 24. If no shielding and no safety measures were needed, then the highest value theoretically possible would be $P = 100$ watt per gram, still too low, by a factor of 30,000. In fact, according to Eq. 24, the whole power plant of 15-megawatt output (enough for a small town) should weigh not more than 5 grams (the weight of 10 paper clips). Or to express it another way, to fulfill Eq. 24, the engine of a good car, producing 200 horsepower, could not weigh more than 50 milligrams—one-tenth the weight of a paper clip.

But that is not all. Not only do we need power, we have to get rid of it, too. Photons might be emitted in the optical or the radio range, and propulsion will result if all emission is in one direction. A large transmitting station of 100-kilowatt power output can then give the tiny thrust of 30 milligrams, and so can an aggregate of searchlights with combined power of 100 kilowatts. And all this should weigh not more than 1/15 the weight of a paper clip. The power source and transmitter requirements must be combined, and the mass entering Eq. 24 must contain reactor as well as emitting stations.

So far we have neglected payloads and fuel, and the mass of these must be included in Eq. 24, too. As an example we start with a "small" space ship of 10-ton payload, and we add another 10 tons for power plant plus emitters. If we want to reach a velocity within 2 percent of that of light (with a dilatation factor of 5), we need a mass ratio $\mathcal{M} = 10$, according to Eq. 20*d*, and the total mass of the rocket will be 200 tons. We find, from Eq. 24, that in order to get an acceleration of $b = 1g$, we would need a power output of 600 million megawatts. Thus,

> We would need 40 million annihilation power plants of 15 megawatts each, plus 6 billion transmitting stations of 100 kilowatts each, altogether having no more mass than 10 tons, in order to approach the velocity of light to within 2 percent within 2.3 years of the crew's time. (25)

If requirement 25 is not fulfilled, we get equations for the periods of acceleration and deceleration as follows. From Eq. 16*a* we have

$$\tau_0 = \frac{c^2}{P} \ln \mathcal{M} \qquad (26)$$

and from Eqs. 20*a* and 20*b* we get

$$t_0 = 2\frac{c^2}{P}\mathcal{M} \qquad (27a)$$

and

$$x_0 = \frac{c^3}{2P}(\mathcal{M} - 2) \qquad (27b)$$

If, for example, we fail to fulfill requirement 25 by a factor of 10^6 (if we have 40 power plants plus 6000 transmitters, weighing, in all, 10 tons—still a fantastic value), then $b = 10^{-6}g$, and it would take 2.3 millions of years for the crew to approach the velocity of light to within 2 percent.

Or, to put it the other way round, if one wants to get an acceleration of, say, $b = 100g$, in order to take full advantage of having a deep-frozen crew, then 100 times the weight of the equipment mentioned in requirement 25 must not total more than 10 tons; this means that power plants plus transmitters should have an output of 6000 megawatts per gram. Purcell (*4*) has arrived at similar conclusions from a study of the requirements of relativistic rockets. There is no way of avoiding these demands, and definitely no hope of fulfilling them.

Conclusion

The various questions dealt with in this article have not led to the definitive answer that interstellar space travel is absolutely impossible. We have found simply the minimum travel times given by different assumptions, and we have found the requirements needed for reaching these limits. This is, at present, all we can do, and the final conclusion as to the feasibility of such ventures is up to the reader. The requirements, however, have turned out to be such extreme ones that I, personally, draw this conclusion: space travel, even in the most distant future, will be confined completely to our own planetary system, and a similar conclusion will hold for any other civilization, no matter how advanced it may be. The only means of communication between different civilizations thus seems to be electromagnetic signals (*5*).

References and Notes

1. S. von Hoerner, *Science* **134**, 1839 (1961).
2. A different derivation of Eq. 20, connecting *V* and *M*, has been given by J. R. Pierce [*Proc. I.R.E.* (*Inst. Radio Engrs.*) **47**, 1053 (1959)] together with a good explanation of the so-called clock paradox. Pierce also investigates interstellar matter as fuel, with the same negative result as that given in this article.
3. *Space Handbook: Astronautics and its Applications* (U.S. Government Printing Office, Washington, D.C., 1959), p. 113.
4. E. M. Purcell, *Brookhaven National Laboratory Lectures, No. 1.*
5. I wish to thank F. D. Drake for reading the manuscript.

News and Comment

Military in Space: Air Force Seems To Have Won Argument For Expanded Program

The Administration has denied that it is planning a major role for the military in space, but at the same time it has explained that it is taking out "necessary insurance against military surprise in space."

The dilemma that faces it on the military's role in space is an enormously complex one, with no simple answers ready at hand. In many respects the dilemma is similar to the one faced by the Truman Administration when it wrestled with the pros and cons of developing the hydrogen bomb. The decision in that case was that the United States could not afford the risk of denying itself destructive capacity of a new order unless there were an assurance that the Soviets would also forego development of the weapon. There was, of course, no such assurance, and U.S. efforts were spurred on by uncertainty about what the Soviets were up to, while the Soviets also went ahead, presumably figuring that it was too dangerous for them to stay out of the race.

It would have been astonishing if the H-bomb question had been decided otherwise, for the sad fact is that technological developments with military applications have inevitably ended up in military hardware. As far as a military space role is concerned, the principal impediment is that the role is not yet clearly visible, at least, not from this country's vantage point. In other words, there is not yet any certainty about what you can do in space to hurt an enemy or prevent him from hurting you that could not be done just as well—and more cheaply—from the earth.

This uncertainty need not remain indefinitely, for it is a fair assumption that, with the investment of enough money and talent, military functions can be developed for space. Among those that seem most feasible are surveillance and rendezvous techniques aimed at destroying hostile space vehicles; a more remote possibility, but getting some thought, is orbiting bombs.

Against this background the Administration has been trying to maneuver in the very limited area between accelerating the arms race and coming out second to the Soviets in military space technology. At the outset, the dominant view in the Administration seemed to be that the Soviets were not forging ahead with military space work, and that therefore the United States would only touch off a new line of arms competition if it undertook a major military space program. This was the view held by the civilian managers of the Department of Defense, and it seemed to be shared by Kennedy. Strongly opposed was the Air Force, which argued that the Soviet Union had never demonstrated any interest in refraining from weapon development. Furthermore, the Air Force argued, the great lead times required to develop space equipment should rule out any wait-and-see policy.

The effect of these arguments, possibly reinforced by intelligence findings that have not been made public, has been to move the Administration in the direction of the Air Force's