INTERSTELLAR TRANSPORT

Two space-ship designs show that nuclear-bomb detonations could take over from chemical propulsion as an energy source for long-range space travel. If our economic growth continues at its present rate, interstellar voyages with ships like these could begin in about 200 years' time.

FREEMAN J. DYSON

THE ORION PROJECT, with which I was involved about 10 years ago, aimed to build space ships powered by nuclear explosions. We began work on Orion after the Russian Sputnik went up and before the US was committed to a big space program with chemical propulsion. We felt then that there was a reasonable chance that the US could jump directly into nuclear propulsion and avoid building enormous chemical rockets like Saturn V. Our plan was to send ships to Mars and Venus by 1968, at a cost that would have been only a fraction of what is now spent on the Apollo program. We never got the green light; so nobody can be sure if our schemes were sound. I am not against the Apollo program; I much prefer it to no program at all. Still, I believe that fundamentally a Saturn V bears the same relation to an Orion ship as the majestic airships of the 1930's bore to the Boeing 707. The airships were huge, flimsy, with a payload absurdly small in comparison to their size, just like the Apollo ships.

Chemical and nuclear propulsion

Chemically propelled ships are inefficient for journeys to the moon, and are practically incapable of making round trips to the planets, because of their staging problem. A chemical propulsion system has an exhaust velocity of about 3 km/sec, which means that about n stages are needed in a ship designed for velocity increments of $3n$ km/sec. Each stage represents a factor of about 4 in the total weight. So the mass ratio

$$R = \frac{\text{take-off weight}}{\text{final weight}}$$

is given approximately by

$$R = 4^n = 4^{V/3}$$

for a chemically propelled ship, where V is the total velocity change required in km/sec. Roughly we have

for low earth orbit
$$n = 2, R = 16$$

for high earth orbit
$$n = 3, R = 64$$

for soft landing on moon
$$n = 4, R = 256$$

for landing on moon and return
$$n = 5, R = 1024$$

These numbers show that chemical propulsion is not bad for pottering around near the earth, but it is very uneconomic for anything beyond that.

The basic virtue of an Orion ship[1] is that it has only one stage, with a mass ratio well under 10 for long trips around the solar system. It can be built small and rugged, and it is comparatively cheap. It avoids big mass ratios because the effective exhaust velocity of the debris from a nuclear explosion is hundreds or thou-

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sands of kilometers per second instead of the 3 km/sec debris velocity of a chemical rocket.

In 1960 Edward Purcell[2] poured concentrated scorn on the notion of interstellar space travel. He said: "All this stuff about traveling around the universe in space suits—except for local exploration, which I have not discussed—belongs back where it came from, on the cereal box." What Purcell in fact demonstrated quite correctly is that round trips to other stars within times of about ten years are impossible. Thus it is absurd to imagine an individual like you or me taking a business trip to Alpha Centauri as we can now go to Europe and as we may one day be able to go to Ganymede. Let us explore what kind of trips to Alpha Centauri are possible with present-day technology, how long they would take and how much they would cost.

EFFICIENCY AND VELOCITY

Suppose we want to achieve the maximal mission velocity V (the total velocity change in all acceleration or deceleration maneuvers) with given total energy E and given initial and final masses RM and M. Let m be the mass as a function of time, beginning at $m = RM$ and ending at $m = M$. Let u be the exhaust velocity as a function of m. The equation of motion is

$$\text{acceleration } a = \frac{u}{m}\frac{dm}{dt}$$

Hence

$$V = \int a\,dt = \int_M^{RM} \frac{u}{m}\,dm$$

The total expenditure of energy is

$$E = \int \tfrac{1}{2} u^2\,dm$$

and the final kinetic energy of the ship is

$$K = \tfrac{1}{2}\,MV^2$$

Hence the energy efficiency, or the fraction of propulsion energy actually imparted to the ship, is

$$\epsilon = \frac{MV^2}{2E} = \frac{M\left[\int_M^{RM} um^{-1}\,dm\right]^2}{\int_M^{RM} u^2\,dm}$$

By Cauchy's inequality the mission velocity is a maximum when u is inversely proportional to m

$$u = Am^{-1} \text{ with } A \text{ constant.}$$

Then

$$V = A\int_M^{RM} \frac{1}{m^2}\,dm = \frac{A}{M}\left(1 - \frac{1}{R}\right)$$

$$u = V\left(\frac{R}{R-1}\right)\frac{M}{m}$$

$$E = \tfrac{1}{2}A^2\int \frac{1}{m^2}\,dm$$

$$= \tfrac{1}{2}AV = \tfrac{1}{2}MV^2\left(\frac{R}{R-1}\right)$$

$$\epsilon = 1 - \frac{1}{R}$$

$$V = [2\epsilon E/M]^{1/2}$$

The maximal exhaust velocity required is

$$U = u_{\max} = u_{M=m}$$

$$= V\frac{R}{R-1} = \frac{V}{\epsilon}$$

Efficiency and costs

The numerical details of the abandoned Orion project are still secret, but the general principles of nuclear propulsion can show us what can be achieved in the long run.

Hydrogen bombs are the only way we know to burn the cheapest fuel we have, deuterium. If controlled-fusion reactors turn out to be equally cheap, which I consider unlikely, we may be able to use them instead of bombs. Deuterium costs \$100 per pound, as it is one fifth by weight of heavy water and heavy water is about \$20 per pound. Burning a pound of deuterium to helium at 50% efficiency gives

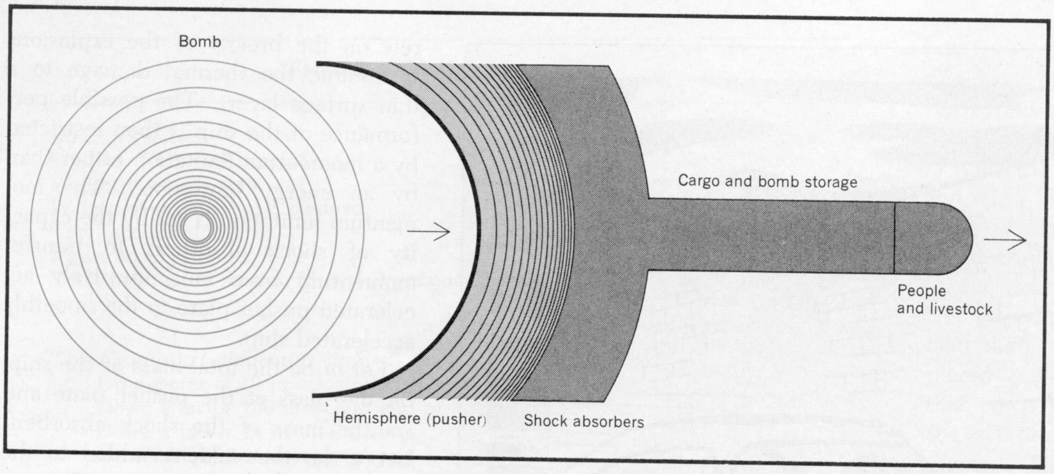
$$1/2 \times 0.006 \times Mc^2 = 3 \times 10^7 \text{ kilowatt hours}$$

So the ideal fuel cost for deuterium burning is about 0.0003 cent per kilowatt hour. This cost is almost 1000 times cheaper than oil-fueled or uranium-fueled power. The factor 1000 is precisely what makes hydrogen bombs so uniquely efficient as weapons of mass murder. My motivation in pushing for nuclear propulsion in space is to put this factor of 1000 to a more constructive use.

Let us see what can be done in space by a propulsion system limited to a fixed amount of available energy. The box on this page shows the relation of exhaust velocity U, the mission velocity V and the efficiency ε for a single-stage ship with fixed M (mass of empty ship and payload) and RM (mass of ship, fuel and payload).

We have the important result that good energy efficiency ($\varepsilon > 1/2$) is obtainable with a single-stage ship and a reasonably small mass ratio ($R < 4$) provided that the mission velocity V is significantly less than the maximal exhaust velocity U (say $V < 3U/4$). This condition fails dismally for chemical propulsion ($U = 3$) on solar-system missions ($V \approx 20$).

What is the appropriate value for U? I do not know exactly how efficient hydrogen bombs are, and if I did know I would not tell you. So I will put upper and lower limits on the numbers that we are not supposed to know exactly. We find a theoretical upper limit to the debris velocity of a thermonuclear explosion by as-



BOMB-PROPELLED SPACE SHIP. Debris from the exploding bombs transfers momentum to the shock absorbers and hence to the payload section of the ship. Mission velocities for this primitive design would be 500–10 000 km/sec; the upper limit is similar to supernova-debris velocities.

suming the thing to be made of pure deuterium burning completely to helium, with all its energy going into kinetic energy of the debris. This gives as the upper limit for the debris velocity

$$U' < \sqrt{2 \times 0.006}\, c = 3 \times 10^4 \text{ km/sec}$$

On the other hand we find a lower limit for U' from the well known fact that at least some hydrogen bombs weigh less than a ton per megaton of yield (for example, the Soviet 57-megaton bomb was carried in an airplane and presumably weighed less than 57 tons). One megaton per ton is 4×10^{16} ergs per gram, so

$$U' > 3 \times 10^3 \text{ km/sec}$$

The upper limit to debris velocity therefore lies somewhere in the range 3000–30 000 km/sec, that is, between 1% and 10% of the velocity of light.

Ideal exhaust velocity

The relation of debris velocity to exhaust velocity depends on the design of the ship. The most primitive design for a bomb-propelled ship is a big hemisphere with bombs exploding with spherical symmetry at its center and with a layer of shock absorbers connecting it to the main structure of the ship (see figure on this page). In this idealized design the momentum contained in the backward-moving debris is $mU'/4$, where m is the total mass of debris and U' the debris velocity. Hence the effective exhaust velocity is $U = U'/4$. If one were able to aim the debris so that it all moved exactly forward and backward, one would have $U = U'/2$. So the upper and lower limits for the maximal available exhaust velocity are

$$U'/4 < U < U'/2$$

or

$$750 \text{ km/sec} < U < 15\,000 \text{ km/sec}$$

The economic mission velocities V are of the same order, say

$$500 \text{ km/sec} < V < 10\,000 \text{ km/sec}$$

Incidentally, the velocity of 10 000 km/sec is just about what one could reach by "surf riding" on the expanding shell of debris from a supernova remnant like Cassiopea A. This equality may not be entirely coincidental.

We have seen that the energy density of thermonuclear fuel makes mission velocities in the range 10^3–10^4 km/sec reasonable. Our next problem is to understand how we can use an energy source that delivers energy only in bursts of about 1 megaton or 4×10^{22} ergs each. In other words, we have to design an engine to run on hydrogen bombs.

The design of a bomb-propelled ship is subject to two limitations in principle; one is in energy and the other in momentum. The energy limitation sets a lower limit, a most pessimistic performance that can certainly be bettered; the momentum limitation sets an upper limit, a most optimistic performance that can probably not be bettered within our presently known technology.

Heat-sink space ship

The energy limitation states that a ship can certainly survive a hydrogen-bomb explosion if the exposed surface has a sufficiently large heat capacity to absorb the entire incident energy without melting. If we are planning to absorb the energy we should make the exposed surface out of a good heat conductor such as copper. Copper can take about 100 calories per gram, (specific heat 0.1 cal gm^{-1} K^{-1}, melting point 1080°C).

Thus we need 10^{13} grams or 10^7 tons to absorb a megaton of energy. Since, at most, half of the megaton is coming forward at the ship, we can say that we need at most 5 million tons (5×10^{12} grams) of exposed surface to take care of a megaton. This figure gives an idea of the general scale of a ship using the conservative heat-sink design.

If we make our 5×10^{12} grams of copper into a hemisphere with 10-km radius, the thickness is 1 gram/cm^2 or 1 millimeter. The heat conductivity of copper (1 cal K^{-1} cm^{-1} sec^{-1}) is sufficiently large to spread the heat through this thickness in 0.01 second, which is about equal to the duration of the pulse of hot debris arriving at a distance of 10 km from the explosion. After the copper is heated it will radiate into space about 1 cal cm^{-2} sec^{-1}, and we must wait about 100 seconds between bursts. The momentum given to the hemisphere by each burst is very small. The pressure pulse on the surface is equivalent to only about 0.1 atmosphere sustained for 0.01 second. The mean pressure averaged over the 100-second cycle is about 10^{-6} atmosphere. The accelerations are so gentle that the structural strength of the copper shell and of the framework connecting it to the rest of the ship do not present any problems.

The dimensions and performance of the conservatively designed heat-sink type of ship are summarized in the table on the following page.

We assume the conservative energy

UNSAFE AT ANY SPEED?

The problem of shock-absorber design for these space ships is closely connected with the problem of automobile safety. Instead of a hydrogen bomb applying an impulse, think of a brick wall bringing a car to an abrupt stop. Suppose you consider the problem of designing a personal shock absorber to satisfy two conditions: Its mass must be comparable to your mass, and it must preserve you intact when you crash into an immoveable object with velocity w. The argument I have given (see text) shows that such a shock absorber can be built for w up to 30 meters/sec but not for greater velocities. Since 30 meters/sec is 70 miles/hour, this conclusion agrees quite well with the intuitive feeling of traffic authorities that driving up to 70 miles/hour could in principle be made safe, but speeds above that could not.

yield of 1 megaton per ton. These numbers represent the absolute lower limit of what could be done with our present resources and technology if we were forced by some astronomical catastrophe to send a Noah's ark out of the wreckage of the solar system. With about 1 Gross National Product we could send a payload of a few million tons (for example a small town like Princeton with about 20 000 people) on a trip at about 1000 km/sec or 1 parasec per 1000 years. As a voyage of colonization a trip as slow as this does not make much sense on a human time scale. A nonhuman species, longer lived or accustomed to thinking in terms of millenia rather than years, might find the conditions acceptable.

Ablation space ship

To define a ship of optimal performance we no longer require the entire energy of each explosion to be absorbed in solid material. We assume that instead of a heat sink the exposed surface of the ship is covered with some ideal ablating substance that protects the underlying structure, a negligible mass of ablating material being vaporized by each burst. We rely on the brevity of the explosions to confine the thermal damage to a thin surface layer. The possible performance of the ship is then restricted by a momentum limitation rather than by an energy limitation. The momentum limitation is set by the capacity of shock absorbers to transfer momentum from an impulsively accelerated pusher plate to the smoothly accelerated ship.

Let m be the total mass of the ship, fm the mass of the pusher plate and sm the mass of the shock absorbers. Let w be the velocity added to the ship by a single explosion. The impulsive velocity given to the pusher by each explosion is then w/f, and the internal energy of the relative motion of the pusher and the ship is $[mw^2/2][(1-f)/f]$. This internal energy has to be converted into elastic energy of the shock absorbers. Now the quantity of elastic energy per gram that any mechanism, whether piston and cylinder, gas bag or fly wheel, can support is limited by the strength of available materials. In fact the elastic energy per gram is limited by $Y/2\rho$ where Y is the tensile strength and ρ the density of the shock-absorber structure. The values of Y/ρ for a variety of good structural materials such as nylon or high-grade steel are around 10^9 cm²/sec². So the capacity of the shock absorbers to transfer momentum from the pusher to the ship imposes the inequality

$$[mw^2/2][(1-f)/f] < 0.5 \times 10^9\ sm$$

If we take for f and s some reasonable fractions such as

$$f = 1/3, \quad s = 1/50$$

the momentum limitation becomes simply

$$w < 30 \text{ meters/sec}$$

A choice for s of a value much greater

Table 1. Conservatively Designed Space Ship

Weight of copper hemisphere	5×10^6 tons
Weight of remainder of structure and payload	5×10^6 tons
Weight of empty ship	10×10^6 tons
Weight of 3×10^7 bombs	30×10^6 tons
Weight of fully loaded ship	40×10^6 tons
Mass ratio R	4
Energy efficiency	0.75
Mission velocity	1000 km/sec
Total acceleration time	3×10^9 sec = 100 years
Mean acceleration	$3 \times 10^{-5}\ g$
Total fuel cost of mission (3×10^9 pounds deuterium)	$\$6 \times 10^{11}$
	= one Gross National Product

Table 2. Ablation Space Ship

Mission velocity	10 000 km/sec
Weight of 3×10^5 bombs	3×10^5 tons
Weight of empty ship	10^5 tons
Weight of structure and payload	5×10^4 tons
Total acceleration time	10^6 sec = 10 days
Mean acceleration	1 g
Total fuel cost of mission (3×10^8 pounds deuterium)	6×10^{10} = 0.1 GNP

This optimistic (momentum-limited) design is:
Up a factor of 10 in velocity
Down a factor 100 in weight and payload
Down a factor 10 in total cost
Up a factor 10 in cost per pound
compared with the conservative (energy-limited) design of Table 1.

than 1/50 is unrealistic, because the design of a practical shock absorber appears always to require a supporting structure weighing considerably more than the part that carries the maximum load. Thus we can make the following general statement: The properties of available materials limit the velocity transferred by a single explosion to any fragile extended structure to about 30 meters/sec, independent of the nature and size of the explosion.

If we assume that the ship is to be uniformly accelerated at a rate of 1 g, with a velocity transfer of 30 meters/sec per explosion, the interval between explosions will be 3 seconds, and the stroke length of the shock absorbers will have the reasonable value

$$L = (w^2/4gf) = 75 \text{ meters}$$

Specifications for the most optimistically designed ablative type of ship are shown in the table on this page.

The cost per pound of payload will be about \$300 for the conservative design and \$3000 for the optimistic design. These costs are comparable to those of the present day for payload in low earth orbit and high earth orbit respectively. The difficulty with space ships in the 1000-km/sec class is not the high cost per pound but the large size of the smallest feasible ship.

The main qualitative difference between the conservative and optimistic designs is that the conservative design is a huge spidery affair 20 km in diameter, whereas the optimistic design is compact and rugged. The conservative design is mainly interesting for proving feasibility in principle. If ever bomb-propelled space ships are built I am sure they will be of a compact design with whatever compromises in performance are necessary to keep the effects of surface ablation tolerable.

The problems of radiation damage and shielding for machinery and people decrease exponentially with the mass available for shielding. When the mass is large enough the problems become trivial, and in the size range from 10^5 to 10^7 tons they are reasonably easy to handle.

When could all this happen?

What will be the consequences if the building of ships close to what I have called the "optimistic design" proves to be feasible? We are then talking about missions in the 10 000 km/sec class, costing about 10^{11} dollars for a payload of 10^4 tons. Because 10 000 km/sec is 1 parsec per century these missions could reach many nearby stars in the course of a few centuries. Nobody in his right mind would consider building such ships at a time when our Gross National Product is only a few times the cost of one of them. But if we are thinking on a time scale of centuries, our GNP is far from being a fixed quantity. Presumably the human race will either destroy itself or continue its economic growth at something like its present rate of 4% per year. If we destroy ourselves, space ships are not going to be of interest to the survivors for quite a long time. If we continue our 4% growth rate we will have a GNP a thousand times its present size in about 200 years. When the GNP is multiplied by 1000, the building of a ship for $\$10^{11}$ will seem like building a ship for $\$10^8$ today. We are now building a fleet of Saturn V which cost about $\$10^8$ each. It may be foolish but we are doing it anyhow. On this basis, I predict that about 200 years from now, barring a catastrophe, the first interstellar voyages will begin.

Who will go out on such voyages, and why? I cannot answer such questions. I am only concerned with the engineering aspects of the enterprise. By the time the first interstellar colonists go out they will know a great deal that we do not know about the places to which they are going, about their own biological makeup, about the art of living in strange environments. They will certainly achieve two things at the end of their century-long voyages. One is assurance of the survival of the human species, assurance against even the worst imaginable of natural or manmade catastrophes that may overwhelm mankind within the solar system. The other is total independence from any possible interference by the home government. In my opinion these objectives would make such an enterprise worthwhile, and I am confident that it will appear even more worthwhile to the inhabitants of our overcrowded and vulnerable planet in the 22nd century.

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I am grateful also to the US Air Force and to General Atomic (now Gulf General Atomic) of San Diego for their support of the Orion project in which these ideas originated. The Orion project was not directed towards interstellar travel, and this article has not been submitted to the Air Force for approval.

My gratitude is also extended to Theodore Taylor, originator of the Orion project, and to Stanislaus Ulam, inventor of the bomb-propelled space ship, for many conversations in which the outer limits of nuclear-propulsion credibility were delineated.

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