A PHOTON ROCKET

by

G. G. Zel'kin (Moscow)

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From

PRIRODA (Nature), NO. 11, 1960

Translated by

Z. Jakubski

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The insatiable human mind, armed with precise mathematic calculations, paves the way to future travels into the stellar world. What powerful forces will carry the man to the stars? What kind of spaceship will be capable of flight even to the closest of stars, within one man's life-time?

In the April copy of our journal, professor S.M. Rytov drew the picture which will unroll before the astronaut of such a spaceship. He told about the tremendous difficulties which must be overcome in order that the relativistic ship may travel through interstellar space. The problems of designing such a ship would be no less difficult.

The Idea of a Photon Rocket

The primary rocket engine characteristics which must be considered are the exhaust velocity and the mass consumption of the matter producing the reaction force (working medium). The problem of interstellar flights requires the exploration of new methods for the highly efficient transformation of the mass of this medium into energy of motion, in order to make possible flight vehicles with a maximum velocity approaching the speed of light (speed of light $c \approx 299792$ km/sec).

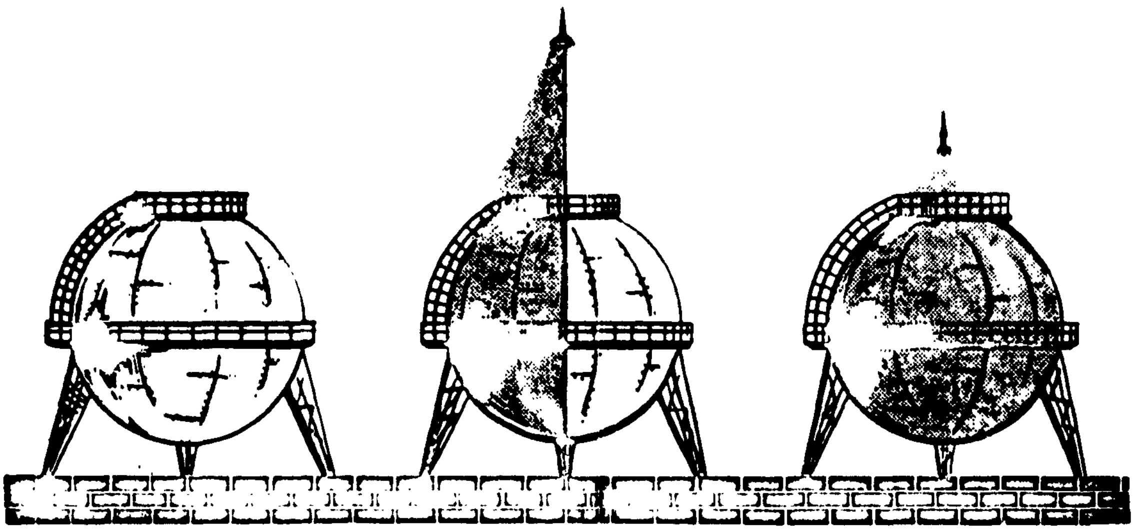
The higher the exhaust velocity, the greater the velocity of a rocket vehicle; since light has the highest velocity in nature, it was conceived that light quanta (photons) could possibly be utilized to attain velocities approaching the speed of light. P.N. Lebedev, the eminent Russian physicist, was the first to discover and measure, in 1899, the pressure of light.

As is known, every photon has a certain impulse, equal to its energy divided by the speed of light. On the other hand, the impulse is also equal to the product of the mass times the speed of light. Thus we introduce the concept of the most efficient mass for every quantum of light. Where electromagnetic radiation is concentrated in the form of a directed ray, the total impulse is then equal to the sum of all impulses of photons, and the reaction force, or thrust, is proportional to the rate of transformation of mass into radiant energy.

Classification of Rockets

In order to discuss the utilization of radiant energy to create reaction force in a rocket engine, it is necessary to find what part of the total mass of rocket fuel can be transformed into radiant energy. This is what we call the mass efficiency coefficient.

Let us examine three groups of rocket engines in relation to their mass efficiency coefficients. If in addition the nature of transformation of fuel mass into energy is considered, then such a classification will include all possible varieties of rocket engines (Figure 1).



a b c

Figure 1. The Diagram Shows the Degree of Transformation of Fuel Mass into Energy of Motion for Different Groups of Rocket Engines. The Reservoir Shows the Total Mass of Rocket Fuel, and the Nozzle the Rate of Transformation of the Fuel Mass into the Energy of Motion; the White Section of the Nozzle Shows the Transformation of Fuel Mass into Radiant Energy, and the Shaded Part the Transformation into Kinetic Energy of the Remaining Part of the Fuel Mass.

Group 1. The case of an ideal photon rocket (Figure 1a). The total fuel mass is transformed into radiation and the emission of light rays occurs with no losses.

Group 2. The case of a non-ideal photon rocket (Figure 1b). The part of the mass of the rocket fuel is spent on radiation. The remaining mass, in the form of combustion products, is ejected from the rocket without adding to its thrust. As in the case of the ideal rocket, thrust is produced by the ejection of photons.

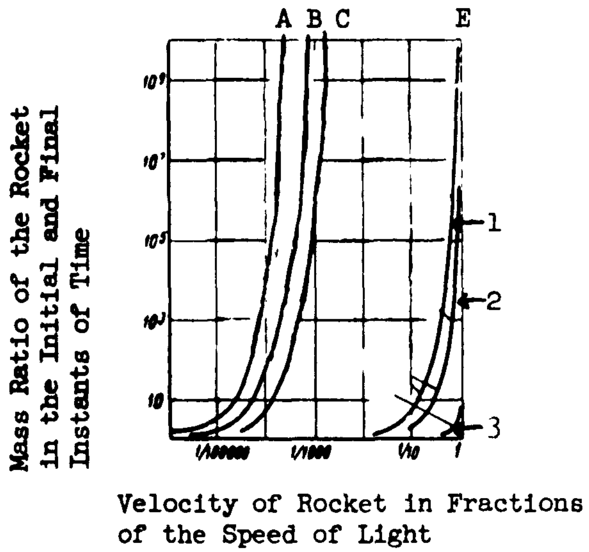
Group 3. The case of a nonphoton rocket (Figure 1c). Unlike the rockets of the second group, part of the mass of the rocket fuel is spent, not on radiation but on the production of kinetic energy in the remaining part of the fuel-mass. The exhaust velocity of the ejected particles is lower than c and depends essentially on the mass efficiency coefficient.

The following table indicates what part of the fuel mass is transformed into kinetic energy in various rocket engines;

The Type of Rocket Engine	The Mass Efficiency Coefficient (mass – energy)	Ratio of Exhaust Velocity of the Working Substance to the Speed of light: v/c
Chemical	$5 \cdot 10^{-11}$	$1.2 \cdot 10^{-5}$
Plasma	$5 \cdot 10^{-10}$	$3 \cdot 10^{-5}$
Ion	$5 \cdot 10^{-8}$	$1 \cdot 10^{-4}$
Nuclear		
Fission	$1 \cdot 10^{-3}$	0·04
Fusion	$4 \cdot 10^{-3}$	0·1
Photon (ideal)	1	1

The table also shows the ratio of the exhaust velocity of the working substance to the speed of light for each type of rocket engine. For an ideal photon rocket this ratio is unity.

The coefficients shown in the table are based on the assumption that the emitted energy is transmitted into kinetic energy without losses, and that the exhaust velocity represents the velocity under adiabatic zero-pressure conditions (ideal velocity).



A. Rocket with a Chemical Engine
B. Rocket with a Plasmatic Engine
C. Rocket with an Ionic Engine
D. An Ideal Photon Rocket
E. Rocket with a Nuclear Engine
   1. Fission
   2. Fusion

Figure 2. The Graph of the Dependence of the Mass Coefficient on the Velocity of the Rocket Shows that Each Type of Rocket has a Velocity Limit Beyond Which it Cannot Be Accelerated. The Nature of the Curves Shows that Any Attempt to Increase the Velocity of a Given Type of Rocket Above the Maximum Velocity Results in a Drastic Increase of the Initial Mass of the Rocket.

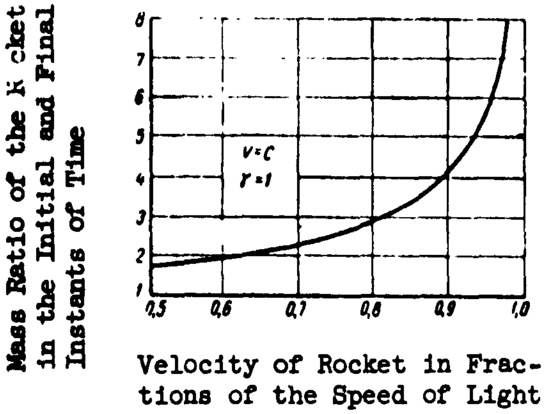


Figure 3. The Nature of Dependence of the Ideal Photon Rocket on its Final Velocity Shows That Requiring the Final Rocket Velocity to Approach the Speed of Light Leads to a Catastrophic Increase in the Initial Mass of the Rocket. Here γ is the Mass Efficiency Coefficient; V is the Exhaust Velocity of the Working Substance.

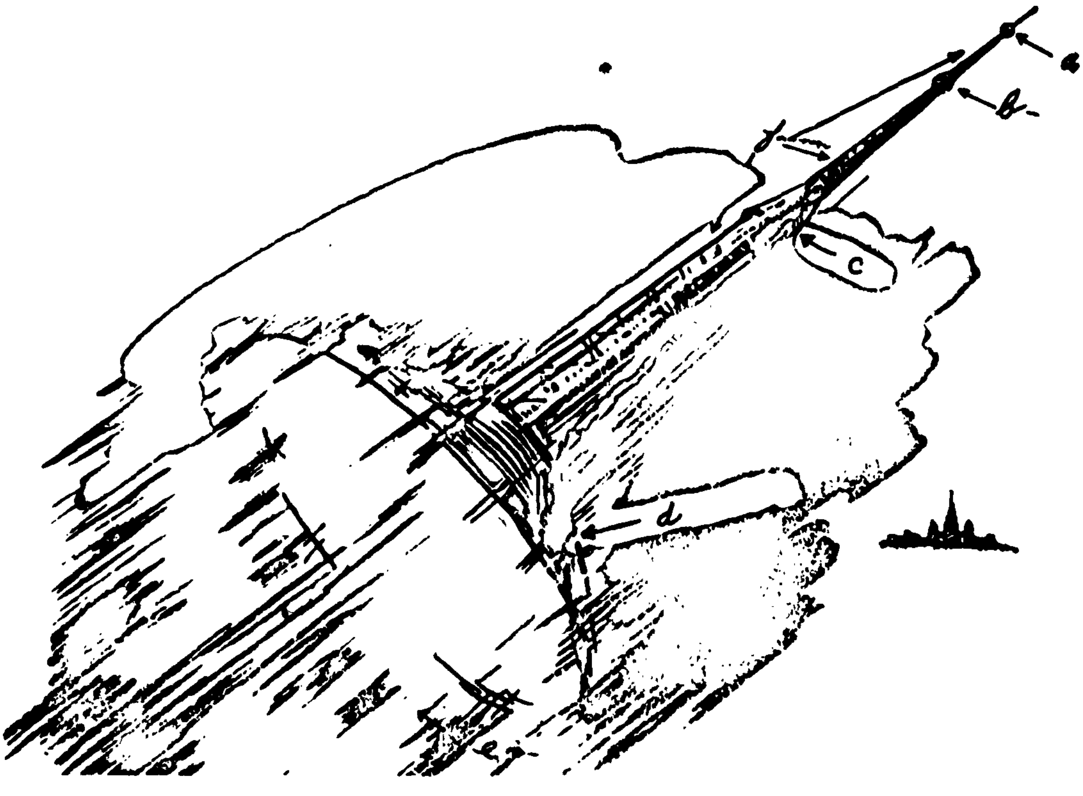


Figure 4. Schematic Drawing of an Assumed Photon Rocket: a - Crew Compartment, b - Instrument Capsule, c - Power Plant, d - Reflector, e - Directed Radiation, f - Protection From Radiation. In Order to Give an Idea of the Size of the Reflector, There are Shown to the Right of it, on the Same Scale, the Buildings of Moscow State University on Lenin Hills.

Necessary Fuel

It is extremely important to know what amount of fuel is required in order to accelerate the rocket from the initial velocity V_o to the specified final velocity V_1. The initial mass of the rocket will decrease by the amount of fuel consumed. Let us denote the mass of the rocket at the initial and final instants by M_o and M_1 respectively, and by μ, the mass coefficient, which is the ratio of M_o to M_1. For different types of rockets having various exhaust velocities of the working substance V, different amounts of fuel will be required.

The curve at the extreme left in Figure 2 pertains to a chemical rocket, and the curve on the extreme right pertains to an ideal photon rocket. The graph shows that each type of rocket has a velocity limit beyond which it can not be accelerated. An ideal photon rocket can reach a vinal velocity approaching the speed of light for quite realistic values of μ.

The Energy of Photon Rockets

In order to realize what energies will be involved in photon rockets, let us consider the following examples.

Let us assume that we have an ideal photon rocket by means of which we wish to perform a flight with a vehicle having a dry mass (without fuel) of 50 tons. Operating time of the engine is one year, the aircraft accelerates with a constant acceleration until it reaches the final velocity $V_1 = 0.886$ c (as in the paper of professor S.M. Rytov, the value of the final velocity has been selected for convenience of calculation). The graph in Figure 3 shows that for the value $V_1 = 0.886$, the initial total mass of the ideal photon rocket should be 200 metric tons. Transformation of 150 tons of fuel into photons during one year is accompanied by an emission of energy equal to $3.76 \cdot 10^{15}$ kwh. Let us recall, for purposes of comparison, that the amount of electric energy produced by the world in 1957 was $3 \cdot 10^{12}$ kwh.

From the graph in Figure 2 it follows that the requirement for a final velocity closer to the speed of light leads to a catastrophic increase in the initial mass of the rocket.

Figure 4 shows the imaginary photon rocket. In contrast to chemical rockets, the fuel mass of a photon rocket is commensurate with its total mass. Multistage construction is, therefore, not necessary in a photon rocket.

The general length of a photon rocket will be many km. In order to protect its crew from the lethal effects of radiation from the working photon engine, the crew compartment will be situated in the nose cone of the vehicle. The instruments should also be shielded from radiation.

Thus, the photon ship leaving for the limitless space of the universe will have a dry mass measured in thousands of tons.

One can imagine that the propulsion system of a photon rocket will be able to produce enormous energies. The jet stream of such a rocket, passing a planet, will be capable of "washing-off" whole continents. It is obvious that the launching of such a rocket will be possible only from a point fairly remote from the earth.

The magnitude of the problems to be solved in the designing of an engine able to utilize such energies is evident. The presence of even negligible heat losses, accompanying the process of transformation of the fuel mass into radiant energy, will lead to unsurmountable difficulties in the protection of vehicle equipment from heat transfer. The propulsion system of an ideal photon rocket should absorb no more than one ten-millionth of the total energy. Consequently, there is a necessity for a direct transformation of the total fuel mass into radiant energy, or for the so-called "annihilation process of particles and antiparticles."

Equipment for the Production of Directed Radiation

Assuming that the problem of storing and controlling the expenditure of antiparticles will be solved, there will still remain the problem of the directed radiation which produces the reaction force propelling the photon rocket. In order to create such directed radiation, it is necessary to have a guiding apparatus in the form of an enormous reflector which would collect the emitted radiant energy and in turn direct it opposite to the direction of the flight. Since the annihilation processes taking place in a photon rocket will involve energies measurable in millions of electron volts, the efficiency of the collimating apparatus should be not less than 0.9999999 or 1 minus 10^{-7}. Otherwise, the energy absorbed by the collimator will instantly turn the vehicle into vapor. To protect the vehicle, it is probably possible to use a gaseous mirror to reflect the radiant energy. Approximate calculations indicate that such a mirror would have a diameter measurable in kilometers.

Actual construction of a photon rocket requires the solution of a whole complex of scientific and engineering problems.

The first stage of the investigation program should be directed toward the study of photon rocket mechanics. The problems of flight mechanics include rocket acceleration, mass consumption, and others. They are chiefly theoretical investigations in relativistic mechanics (mechanics using the laws of relativity theory).

There will be other complex problems: the problem of the efficient transformation of the mass of the substance into radiation energy, the problem of the annihilation processes in the photon engine; the high intensity radiation in the photon rocket could, most probably, be obtained from an extremely hot plasma having a temperature of the order of 150,000°K or higher. It will be necessary, therefore, to have a installation assuring sufficient thermal isolation and an unusually high capacity for letting the radiation "pass through."

Magnetic fields will probably be used in the solution of these problems.

It will also be important to study the problem of directed radiation for the creation of the reaction force in the photon rocket. It will be necessary to design an apparatus to collect the emitted radiant energy and redirect it opposite to the direction of flight.

Extremely complex problems are those connected with the design of a control installation for the power plant, and a navigation system capable of insuring a safe flight of a rocket of relativistic velocity into interstellar space, and also the problem of reliable protection of the crew and the equipment of the rocket from radiation.

Thus, everything connected with the photon rocket and relativistic rocket mechanics presents an unusually wide field for numerous theoretical and experimental investigations. And one can say with certainty that the creation of a photon rocket would surpass all the previous achievements of man throughout all the many centuries of his history.

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