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Radiation Conditions in Relativistic Interstellar Flight

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Abstract. Radiation hazard on board of a relativistic rocket can be of internal and external origin. Due to its highest specific energy density, antimatter is commonly considered the preferred rocket fuel for acceleration of a multi-ton rocket up to relativistic speed. High-energy products of matter-antimatter annihilation (γ- and meson radiation) can create a severe radiation hazard for crew and electronics without a reliable radiation shield. Two physical factors can stand against our pursuit to the stars: 1) cooling of a multi-GW propulsion engine, which can be done in space by thermal radiation only, and 2) intense nucleonic radiation originated from the oncoming relativistic "headwind" of interstellar gas and cosmic rays. When a rocket accelerates to a relativistic speed, the rarefied interstellar gas of neutral and ionized molecules and atoms turns into an oncoming flux of high-energy nucleons irradiating the rocket and creating a severe radiation hazard on board. In addition, the oncoming flux of relativistic dust granules imposes a threat of mechanical damage to the rocket body. Possible protection measures are discussed.

1 Introduction

Technical and physical problems inherent in relativistic interstellar flight with an energy source and propellant on board of a starship are considered in details in [1]. Here we discuss one physical factor we will inevitably meet on our road to the stars, namely intense ionizing radiation either originated from a propulsion engine or from the oncoming relativistic "headwind" of electrons, nuclei, atoms, and molecules of interstellar gas and cosmic rays. It is well known that no chemical, magneto-hydrodynamic (MHD), and nuclear rocket engines are able to accelerate a multi-ton rocket to a relativistic speed above $0.1c$, where c is the speed of light, because of their relatively low energy capacity. In general, the higher the specific energy density of a fuel is, the lesser fuel reserve and therefore smaller launching mass of a rocket can be chosen, allowing higher acceleration and faster velocity gain with the same rate of fuel consumption. Alternatively, we can choose longer acceleration thus higher achievable speed with the same initial mass of fuel. The propulsion exhaust velocity v_j of the conventional rocket engines is relatively small thus a copious mass exhaust, and fast fuel and propellant consumption is needed to produce the same thrust according to the expression for the thrust $F = v_j(\mathrm{d}M/\mathrm{d}t)$, where $\mathrm{d}M/\mathrm{d}t$ is the mass flow rate ($F = \gamma_j\beta_j v_j(\mathrm{d}M/\mathrm{d}t)$, where $\beta_j = v_j/c$ and $\gamma_j = 1/(1-\beta_j^2)^{1/2}$, if v_j is relativistic). The achievable speed of chemical and MHD rockets is of several tens km/s and the speed of an ion rocket powered by a nuclear reactor [1, 2] can be optimally of several hundred km/s. To reduce the mass flow rate while getting the same thrust, we have to increase the propellant ex-

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haust velocity. One viable option to produce a necessary thrust for years of flight and to accelerate a multiton rocket to a relativistic speed is the propulsion by relativistic exhaust jet either produced or powered by annihilating antimatter; the ultimate fuel of the highest specific energy density, virtually all mass of which can be converted into energy [1, 2, 3, 4]. Matter-antimatter annihilation can be used for propulsion by annihilation products (direct annihilation propulsion) such as photon rocket propelled by γ-photons [3] and meson rocket propelled by π- or μ-mesons [4] as well as for generation of electrical power in an annihilation reactor to power the ion thrusters producing the exhaust beam of high-energy ions (relativistic ion propulsion) [1, 2]. The photon rocket is supposed to carry a sort of fuel containing positrons which annihilate with electrons at the focal spot of a photon-reflecting mirror to emit γ-photons. The meson rocket carries an antimatter fuel annihilating with ordinary matter in a magnetic nozzle to produce a flux of charged and neutral π-mesons. Virtually all the products of matter-antimatter annihilation, be it γ-photons, mesons, electrons, or other particles, can be hazardous for astronauts and electronics, if they leak from the annihilation zone and irradiate the rocket body. A possible exception is the flux of neutrinos from the annihilation zone of a propulsion engine of any kind because of their weak interaction with matter.

Ionizing radiation produced by the oncoming relativistic flux of interstellar gas and plasma is the most dangerous for crew and electronics and will require a robust frontal shield to absorb this flux of high-energy nucleons. Cosmic rays and γ-radiation add to the radiation hazard and may also require some protection measures. Interstellar dust grains become the relativistic micro-projectiles bombarding the frontal parts of a rocket and producing mechanical damage, when it accelerates to a relativistic velocity. Many technical problems must be solved before we risk flying with a relativistic speed beyond the solar system and among them the problem of shielding of a spacecraft from the ionizing radiation of internal and external origin as well as from damaging bombardment by the relativistic dust grains is one of the most challenging.

2 Radiation from a Propulsion Engine

Two concepts of direct rocket propulsion by the products of matter-antimatter annihilation have been proposed: 1) photon rocket propelled by a beam of γ-photons born in the process of electron-positron annihilation and reflected from a mirror [3] and 2) meson rocket propelled by a jet of charged π- and μ-mesons produced by protons and antiprotons annihilating in a magnetic nozzle [4].

2.1 Photon Rocket

Two or several electron and positron (antielectron) beams cross in the focal spot of a photon-reflecting parabolic dish (Figure 1). Each act of electron-positron annihilation releases two γ-photons with their energy of the order of 0.5 MeV in opposite directions, and one or both photons impact the parabolic dish mirror depending upon the axial extent of the dish so that each of reflected photons transfers to the mirror its mechanical momentum $hf/c = h/L$, where h is the Plank constant, f is the frequency of electromagnetic wave associated with the emitted photons and L is the wavelength of this electromagnetic wave. Assuming all electrons and positrons annihilate at the spot of beams crossing, the size of which is small in comparison to the focal distance and the overall size of the mirror, the emission spot can be treated as a point source of γ-photons creating an almost ideally parallel beam of photons after reflection from the mirror. To estimate the radiation hazard from the photonic propulsion engine, the emission rate and flux of γ-photons can be estimated from the photon rocket equation for a chosen rocket launching mass and engine power [1, pp. 16–17]. The flux of photons and the efflux beam power are shown in Figure 2 as functions of the rocket acceleration per one ton of the rocket mass. To produce acceleration of 1 m/s^2 (one tenth of free-fall acceleration on the Earth's surface), the propulsion power of a hundred-ton rocket must be of the order of 100 GW which corresponds to the photon emission rate of the order of 10^{27} (ten to the power of 27) photons per second. The total flow rate of electron and positron beams to annihilation spot must be the same.

Alas, the idealistic design of the photon rocket with a hundred percent mirror shown in Figure 1 is unrealizable in principle. The wavelength of electromagnetic wave corresponding to 0.5 MeV photons is below the inter-atomic distances in all known materials thus no material can respond to this high-frequency electromagnetic wave as a medium characterized by its refractive index and reflection coefficient due to collective reaction of atoms and molecules to electromagnetic waves. It means almost no reflection of 0.5 MeV photons from

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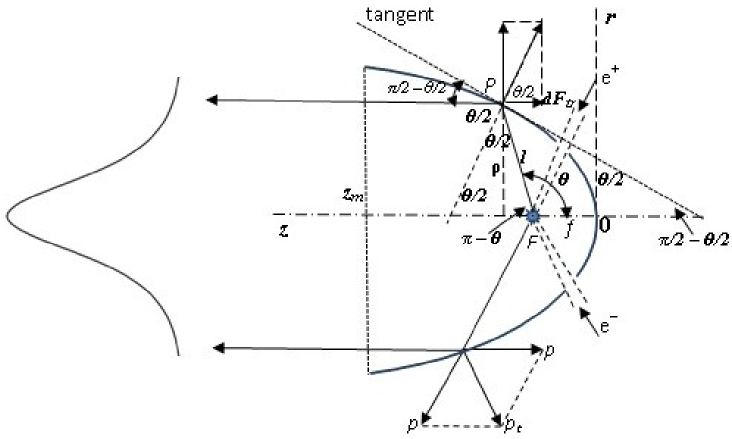

FIGURE 1. *Schematic cross-section of a photon-propulsion engine with a parabolic mirror (reproduced from the reference [1]). The focused electron and positron beams are inserted from the sides of a mirror to cross at its focal spot. After electron-positron annihilation at the crossing region, the emitted photons are reflected from the mirror surface and form an exhaust beam. The radial distribution of energy density in the photon efflux beam is shown to the left of the mirror. The details and discussion can be found in [1, pp. 14–15].*

the known materials. Photon-absorbing dishes [3] are also thinkable but it means the dish material should absorb, withhold, and dispose to space all the power of the photon flux otherwise either the rocket itself will be irradiated by an enormous flux of γ-radiation or a thick and heavy dish will be required together with a huge thermal radiator to dispose the heat to space (cooling in space vacuum can be done by thermal radiation only). It should be also noted that transportation and focusing of high-current electron (positron) beams in vacuum is not an easy task and their annihilation cross-section in realistic conditions is quite small to count on complete annihilation in a small focal spot. Either annihilation will be incomplete or the size of annihilation zone should be of hundreds of meters or more thus no parallel photon beam can be formed unless a mirror is of many kilometers in size [1, p. 55]. The hope for positronium (quasi-atom consisting of an electron and a positron) stored on board as a fuel seems to be futile because no stable material containing the positronium atoms which are normally short-lived has ever been suggested. The whole concept of photon rocket powered by electron-positron annihilation meets many unresolved problems and seems to be unrealizable.

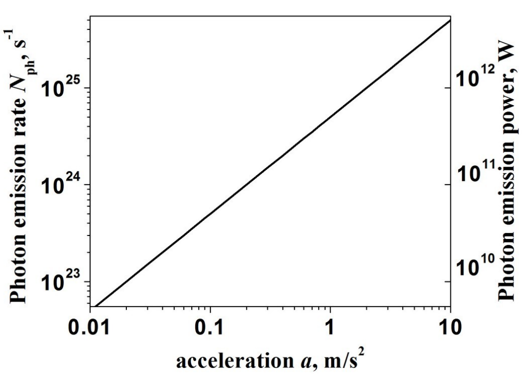

FIGURE 2. *Photon emission rate N per second and emission power (in W) per one ton of the rocket mass as a function of proper acceleration of the photon rocket with a hundred-percent mirror (reflection coefficient $R = 1$). The length of the mirror is taken equal to its focal distance. Reproduced from [1, p. 18].*

2.2 Meson Rocket

Radiation hazard may arise from annihilation products escaping the magnetic nozzle to the rocket body [1, pp. 23-32]. The idea of using a magnetic nozzle for propulsion stems from thermonuclear research on magnetic traps (magnetic bottles) in which the charged particles can be contained. The magnetic field of a mag-

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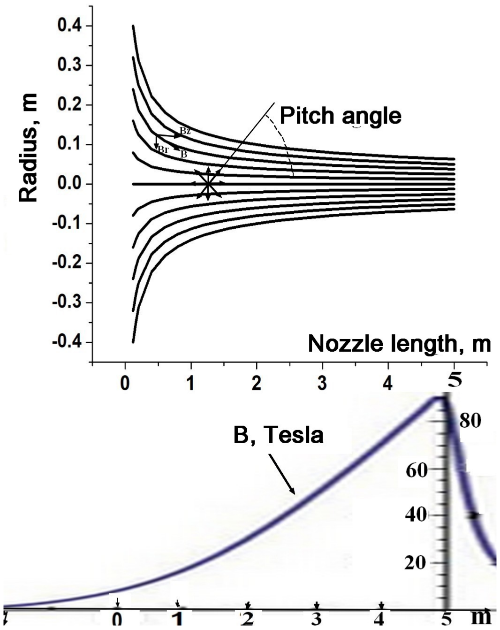

FIGURE 3. *Map of magnetic lines in the five-meter nozzle (see Figure 4 below) with a constant gradient of magnetic field* $\mathrm{d}B/\mathrm{d}z = 19.98\,T/m$ *along the z-axis assuming* $B_0 = 0.1\,T$ *at* $z = 0$ *(the exhaust end of the magnetic nozzle). An isotropic point-like source of* π*-mesons is positioned on the z-axis closer to the exhaust end (*$r = 0$*). The axes are labeled in meters. Shown below is the distribution of magnetic field inductance* B *along the z-axis of the nozzle. The z-axis is directed along the magnetic field gradient and the thrust vector. Adapted from the reference [1, figures 1.9 and 1.14]*

netic nozzle is configured to form a jet of charged products of matter-antimatter annihilation [4]. According to the concept, two or several beams of protons and antiprotons cross inside a chamber, where a gradient magnetic field is induced by a system of current-carrying coils to produce mainly longitudinal magnetic field with its intensity B diminishing to the exhaust end of the chamber. Each proton-antiproton pair annihilates on average into five π-mesons with three charged π-mesons and two neutral π-mesons. It can in principle decay also into three neutral π-mesons however the probability of decaying into purely neutral π-mesons is relatively small and their contribution to the energy balance is less than 4%. Each neutral π-meson virtually instantly decays into two γ-photons with their energy about 200 MeV. Charged π-mesons (pions) decay into correspondingly charged μ-mesons (muons) and neutrinos with the decay time of 70 ns and then every positively charged muon decays into positron and corresponding antineutrino while every negatively charged muon decays into electron and neutrino. Mechanical momentum of charged particles from this chain of annihilation products can be used to produce a thrust provided a magnetic field of appropriate configuration is induced which forces all charged particles to exhaust predominantly in one direction from the nozzle to form an efflux jet. The charged products of proton-antiproton annihilation gyrate in the magnetic field and drift along the magnetic lines. In the configuration of predominantly longitudinal magnetic lines with a gradient magnetic inductance (Figure 3), the longitudinal "force" acting on a gyrating particle is proportional to $\mathrm{d}B/\mathrm{d}z$. It slows down the particles drifting originally in the direction of stronger magnetic field (initially emitted at a pitch angle below 90 degrees, i.e. to the right in Figure 3), and accelerates their drift, when they move in the direction of the magnetic field slope. A possible configuration of current-carrying coils to form a gradient magnetic field with linear increase of magnetic inductance along z-axis and to produce a thrust by the π-mesons only is shown in Figure 4 [1]. Trajectories of π-mesons emitted from some point on z-axis of this magnetic nozzle for different initial pitch angles [1] are shown in Figure 5. The average time of flight of charged pions before decaying into μ-mesons is about 70 ns in the rocket coordinate frame (the time interval during which a half of pions will decay), thus the full travel s_π of pions along a spiral trajectory until their decay is about 20 m.

If we want to produce thrust by π-mesons predominantly, the length of the magnetic nozzle from the point of maximum magnetic field to the exhaust end should not exceed five meters to provide a sufficient time for π-mesons initially emitted at relatively small pitch angles to exit the nozzle before their decay. A better solution would be a much bigger nozzle allowing for the π-mesons to decay into μ-mesons with their essentially longer decay time thus saving virtually all produced π-mesons for thrust while getting an additional thrust produced by μ-mesons gyrating in the magnetic field [1, pp. 38–41]. In this case, the length of magnetic nozzle can be of tens and even hundreds of meters. Alas, the magnetic mirror has its own essential drawbacks. Firstly, injection of beams of hydrogen and antihydrogen ions from the sides of the magnetic nozzle is impossible because the charged particles cannot propagate across the magnetic lines. The only possibility is to inject the beams through the nozzle's bot-

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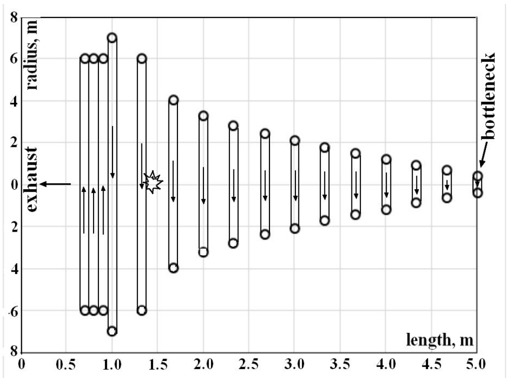

FIGURE 4. *Five-meter magnetic nozzle to produce thrust by π-mesons mostly. It consists of the current loops with their radii increasing to the exhaust end and with their separation $d = 0.33\,m$ between them to produce an almost linear slop of magnetic inductance B along the z-axis toward the exhaust end $z = 0$. Direction of current is indicated by arrows. To dump partially the tail of non-linear magnetic field near the exhaust end and to make it as short as possible, three additional loops carrying the opposite current with respect to all other loops of the nozzle are added at the exhaust end of the assembly. The value of current in all the loops $I = 2.5\times10^7\,A$ except the third one from the left, where the current is increased by the factor of 2.5. The position of the pion source for the calculations of the pion trajectories shown in Figure 5 below is marked by a star. The z-axis is directed along the magnetic field gradient and the thrust vector. Adapted from the reference [1, figure 1.14]*

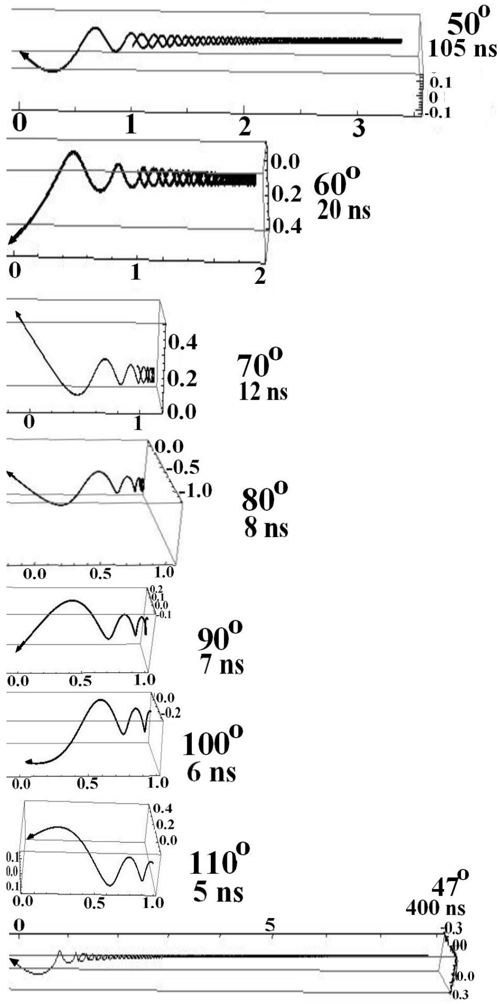

FIGURE 5. *Trajectories of the positively charged π-mesons in a five-meter magnetic nozzle with a linear gradient of magnetic field calculated for different initial pitch angles (angles of emission of π-mesons relative to z-axis). The z-axis is directed along the magnetic field gradient. Adapted from the reference [1, figure 1.12]*

tleneck (the nozzle edge with the maximum of magnetic field) along the z-axis, i.e. from the right in Figures 3 and 4. Both beams must follow the same way and be pretty thin (small diameter) otherwise they will be redirected by the strong radial component of the magnetic field near the entrance into the magnetic nozzle and will never cross to annihilate inside the magnetic nozzle [1, p. 41]. Secondly, the calculated π-meson trajectories [1] demonstrate practical impossibility to create a nearly parallel exhaust jet of π-mesons and analogously of μ-mesons with their velocity vectors closely aligned with the z-axis. It means a reduced thrust and the lower rocket acceleration in comparison with an ideally aligned exhaust jet. Another essential drawback of the magnetic mirror is a leak of the charged mesons through the bottleneck. Even if we manage to tightly focus the beams and produce an ambiplasma (mixture of both beams) in which all the protons and antiprotons annihilate inside the magnetic nozzle, the mesons with their original pitch angle $\sin\alpha < (B/B_m)^{1/2}$, where B is the magnetic inductance at the point of their emission and B_m is the maximum magnetic inductance at the bottleneck, will not be reflected to the exhaust end but continue to travel to the rocket body producing firstly some braking thrust and secondly creating a severe radiation hazard for crew and electronics in addition to γ-radiation from the decaying neutral π-mesons [1, p. 36]. Positioning the point of proton-antiproton annihilation closer to the exhaust end of the magnetic nozzle will

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reduce the thrust produced by the π-mesons emitted at the initial pitch angles > 90 degrees. Shifting it closer to the bottleneck will enlarge the loss-cone of π-mesons and μ-mesons escaping through the bottleneck and reduce the thrust, too.

The only possible protection option against the flux of γ-radiation is a shield of γ-absorbing material. To get an acceleration of a thousand-ton rocket of 1 m/s^2, the total annihilation power should be of the order of 2×10^8 MW and the kinetic power of the π-meson efflux jet of 5×10^7 MW [1, p. 56]. The emission rate of 200 MeV γ-photons will be of the order of 10^{24} photons per second which corresponds to the radiation power of 6×10^7 MW. To reduce the flux of photons to a relatively safety level, the rocket protecting shield of lead should be well above one meter in thickness and such a shield would take a lion's share of the rocket dry mass. Positioning the propulsion engine sufficiently far from the control bridge and crew quarters can help to reduce the shield mass due to geometric reduction factor but the rocket axial elongation to tens kilometers or more will be hardly acceptable. According to calculations performed in [1], the loss-cone of pions through the bottleneck of nozzles with the maximum magnetic field of 100 T is about or wider than 1 sr thus ten or more percents of π-mesons or μ-mesons will leak through the bottleneck to the rocket body creating a huge radiation hazard in addition to γ-radiation. To screen the rocket from the flux of charged mesons, a magnetic shield analogous to the shield against the oncoming nucleonic flux of interstellar gas (see Section 3) should be mounted between the nozzle and the rocket body to absorb or deflect the charged mesons. However, it cannot eliminate the shield of dense and heavy material against γ-radiation. Taking into account the problem of injection of proton and antiproton beams into the magnetic nozzle and a huge practical size of annihilation zone (tens or hundreds of meters) for achievable diameter of proton/antiproton high-power beams, the direct propulsion by the annihilation products seems to be not a promising solution for interstellar relativistic rockets.

2.3 Relativistic Ion Propulsion

Alternative antimatter-powered propulsion has been suggested in [1, 2]. According to the conception, an antimatter annihilation reactor is used for electrical energy production to power a high-energy ion thruster. Basically, any energy-generating reactor (nuclear, thermonuclear, or antimatter annihilation reactors) can be utilized for thrust production. Because of its highest energy release per unit mass of annihilating matter and antimatter (fuel), thus much lower rate of fuel consumption to generate the same power, the antimatter annihilation reactor is preferable for relativistic interstellar spacecrafts, provided the problem of antimatter storage on board of a rocket is solved [5]. Its function is to generate the electrical power and supply to one or several ion accelerators of conventional matter to produce the efflux beam of high-energy ions. These fully or partly ionized atoms have their kinetic energy E comparable with their mass-energy m_0c^2, where m_0 is the mass of rest, so a significant portion of the reactor power goes predominantly to the kinetic energy of an almost completely aligned relativistic jet of ions. To compensate the positive charge of the ion beams, the emitters of electrons are to be installed around the exhaust end of ion accelerators in analogy with the ion thrusters already in use at the interplanetary probes. From the rocket equation [1, 2], the achievable speed $v_{0.5}$ of a rocket at the moment, when a half of the rocket launching mass M_0 is used for propulsion, which includes propulsion exhaust and matter-antimatter mass loss in the reactor, is shown in Figure 6 as a function of exhaust ion velocity factor $\beta_i = v_i/c$ for several propulsion efficiency coefficients (efficiency of annihilation reactor with gas turbines for electrical energy production plus the efficiency of ion thrusters) [6]. Also shown are the graphs of the rocket speed at the moment, when three quarters of the rocket launching mass are exhausted. The graphs are valid for any launching mass and propulsion power, however it should be remembered that the rocket acceleration and the time of flight to the moments, when a half of rocket launching mass (or three quarters of rocket launching mass) is exhausted, are functions of the rocket launching mass and propulsion power. The graphs of the rocket speed and flight distance are given in [1, pp. 65–68] as functions of time of flight measured by the rocket clock for the launching masses of 1000 to 10000 tons and for propulsion power of one TW to hundred TW.

The advantage of relativistic ion propulsion powered by a reactor is that it gives much better freedom and flexibility in choosing the energy source and propellant. Also it opens a possibility of independent control of kinetic energy and mass flow to the exhaust jet. Any liquidized gas from hydrogen to xenon can be used for ion propulsion and these elements can be found almost everywhere in the universe. An increase of kinetic energy of ions in the exhaust jet by increasing

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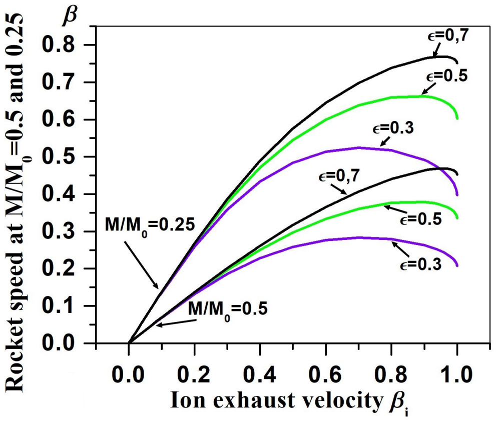

FIGURE 6. *Map-velocities $\beta_{0.5} = v_{0.5}/c$ and $\beta_{0.25} = v_{0.25}/c$ of a rocket at the moments when the residual mass of the rocket $M = 0.5M_0$ and $0.25M_0$ as functions of the proper velocity β_i of the efflux of protons. The graphs are shown for the values of propulsion efficiency $\epsilon = 0.3, 0.5,$ and 0.7. The graphs are valid for any efflux power and launching mass. Adapted from the reference [6, figure 2]*

their exhaust velocity will results in reduction of the propulsion mass flow rate to obtain the same rocket acceleration. It allows achieving higher cruising velocity due to longer thrust with the same propellant reserve and even saving some propellant for braking. The price we have to pay for the increased exhaust velocity is either a higher energy consumption to get the same thrust or a lesser rocket acceleration with the same propulsion power thus longer time for picking-up the desired speed. Nonetheless, the possibility of achieving a higher rocket velocity at the moment, when a predetermined portion of rocket launching mass is exhausted (say, a half of rocket launching mass as in Figure 6), is advantageous because the total time of flight to a remote destination including the stage of rocket cruising with the higher constant speed can eventually become shorter.

A significant portion of mass-energy of annihilating atoms and antiatoms in an annihilation reactor can be converted to electricity. The inevitable loss is neutrinos and antineutrinos escaping freely to space (14.56% of the total mass-energy of annihilating protons and antiprotons). Another possible loss (additional 26% of annihilation energy) is the γ-photons emitted by neutral π-mesons, which can produce a severe radiation hazard onboard unless either a thick blanket is mounted around the annihilation reactor for effective absorption of γ-radiation or at least a shield is installed between the reactor and the rocket's parts requiring their protection against γ-radiation. Possibly, a reactor, in which antiprotons irradiate a heavy-nuclei material (e.g. tungsten or uranium), will be advantageous because some γ-photons can be absorbed by the nuclei at which antiprotons annihilate [7] to add energy to the nuclei fragments (it is supposed that antiproton annihilates with a proton or a neutron mostly at the surface of a heavy nucleus so that the γ-photons entering the nucleus will be absorbed inside together with some charged π-mesons (pions) resulting in nucleus excitation and possible fragmentation). The charged pions emitted away from the nuclei and eventually from the heavy-nuclei material will create a radiation hazard on board of a rocket, if they are not absorbed in the reactor's blanket. A portion of γ-rays from the decaying neutral π-mesons not absorbed in the annihilating material also add to the radiation hazard. Thus, either the reactor blanket should be thick enough to absorb both the mesons and γ quanta or a protecting shield should be installed to protect the rocket body. In principle, an annihilation reactor module can be imagined containing a thick chunk made of a heavy-nuclei material with its high melting point (e.g. tungsten), which is irradiated by antiprotons or antihydrogen molecules (atoms) annihilating at its surface and depositing the energy of pions and gammas into the material to heat the chunk together with the primary reactor cooler. If this prime heater is irradiated by antiprotons (antihydrogen) beams from its side opposite to the rocket's parts sensitive to radiation, it can serve a shield against γ- and meson radiation. Higher kinetic energy of irradiating antiprotons would be preferable because of the effect of relativistic beaming of the annihilation products which could increase the portion of mesons and gammas entering the nuclei and absorbed by them. Neutrons generated in the process of nuclei fragmentation can also add to the radiation hazard [7]. Annihilation of protons with heavy-nuclei gases and solids gives birth to many other physical effects not properly studied so far [8]. We must also provide for a means to replenish the annihilated material on the chunk surface for example covering its working surface by a layer of liquid heavy-nuclei material with which antiprotons actually annihilate with. A material such as melted metal or salt would seep through the pores in the chunk to replenish the annihilating liquid layer in analogy with sweating surfaces of the walls of a thermonuclear reactor suggested many years ago.

3 Hard Ionizing Radiation of External Origin

3.1 Interstellar Gas

Outer space beyond Earth's atmosphere is not just an empty void. Interplanetary space and interstellar space contain rarefied gas and dust. Interstellar gas is a necessary component of every galaxy: it is constantly replenished by stellar wind (flux of gas and plasma emanated from the star surface analogous to the solar wind) and in catastrophic star explosions such as novas and supernovas. The clouds of interstellar gas give birth to new generation of stars with their planetary systems, which, after living through their life cycle, replenish the interstellar gas to give birth to the next generation of stars (stellar recycling) [9]. Every galaxy is an evolving system of interdependent stellar and gaseous components. Cosmic gas fills our galaxy unevenly: there are relatively low-density regions and denser clouds (our Sun was formed in a dense gaseous cloud more than four billions of years ago). Luckily, our Sun is located currently in a low-density local cavity about 400 light-years in size in the Orion spur [10]. Concentration of neutral and ionized atoms and molecules (mostly hydrogen and helium) in the local cavity $n \sim 3{\times}10^5$ m^{-3}. Interstellar gas contains about 89% of hydrogen with 10% admixture of helium. Also, it contains about 1% of heavier elements like carbon, oxygen, silicon, iron, etc. mostly accreted in dust granules[1] [10, 11, 12].

When a rocket accelerates to a relativistic velocity v, all gaseous components and dust grains form a frontal flow incident on the rocket with the relativistic velocity and this effect is irrelevant to the method of starship propulsion, its size, or its mass. The headwind of otherwise innocuous interstellar gas turns into an ongoing stream of high-energy ions and atoms while the dust granules become relativistic micro-projectiles bombarding the rocket hull. Kinetic energy of every particle relative to the rocket is $mc^2(\gamma{-}1)$, where m is its mass of rest (either a gas atom or a dust grain), $\gamma = (1{-}\beta^2)^{-1/2}$, and $\beta = v/c$. Kinetic energy of ionized and neutral atoms of hydrogen, which is the main component of interstellar gas, exceeds 100 MeV at $v > 0.5c$ and this is actually a high-energy nucleonic radiation analogous to that of high-energy ion beams produced at the high-power accelerators. Despite a deep vacuum in interstellar space, the flux of relativistic ions,

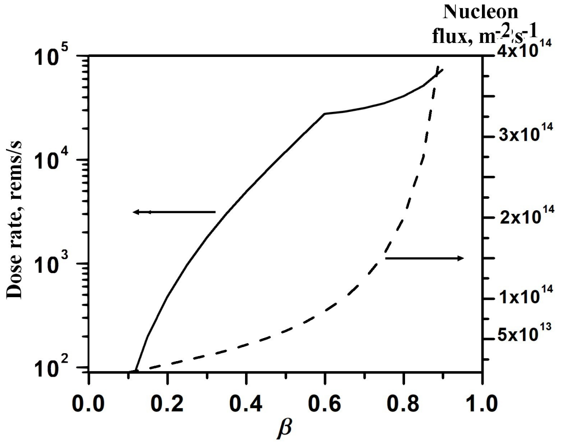

FIGURE 7. *Flux of interstellar atoms and ions per square meter per second (dashed) incident on a rocket and the radiation dose rate (rems per second) obtained by an unprotected astronaut as functions of rocket map-velocity $\beta = v/c$. A brake on the graph of the dose rate near $\beta = 0.6$ corresponds to the velocity at which the penetration depth of the nucleons (protons mostly) in the tissue is equal to the average thickness of a human torso (∼30 cm). Adapted from the reference [6, figure 3]*

atoms, and molecules in the local cavity $P = \gamma n v$ (in the rocket coordinate frame) exceeds 10^9 per square centimeter per second (10^{13} per square meter per second) for the rocket velocity above $0.3c$. The rate of radiation dose absorbed in the tissue of an unprotected astronaut will exceed 10^4 rems per second [1, 13]. Relativistic factor γ in the expression for P is due to the effect of relativistic time contraction. The flux of atomic particles and the dose rate for an astronaut without a radiation protection are plotted in Figure 7 as functions of rocket velocity factor $\beta = v/c$.

The safe radiation dose is equal to 5 rems according to the NIST safety regulations. The dose of hundred rems is considered dangerous due to high probability to develop cancer, and the dose of thousand rems or more is almost hundred percents lethal. According to Figure 7, the lethal dose can be accumulated in the astronaut body in a fraction of a second, if $v \geq 0.3c$. To reduce the dose rate, a robust radiation-absorbing shield has to be mounted in front of the rocket. Material protective shield would require tens centimeters of iron or several meters of water or ice [1, p. 101], which means many tons of additional mass to the rocket dry mass. A magnetic shield alone will not work because of a significant percentage of the neutral component in inter-

[1] see also https://en.wikipedia.org/wiki/Local_Interstellar_Cloud

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stellar gas. A relatively light-weight shield comprising a magnetic system and a thin electron stripper [1, 13] can protect the rocket from the relativistic flux of ionized and neutral components of interstellar gas. The shield consists of two parts: a relatively thin solid disk (umbrella) at some distance in front of the rocket and a solenoid behind it which induces a magnetic field perpendicular to the rocket velocity vector by a winding of superconductive wires [1, p. 112]. The superconducting coils can be made of high-temperature superconducting ceramics wound around a tank filled with a cryogenic liquid to form either a toroidal solenoid producing the azimuthal magnetic field or a flat solenoid to generate a field with the strait magnetic lines. High-temperature superconducting ceramics are known to conduct currents of more than 1 MA/cm^2 and to generate magnetic fields up to 30 T [5]. Combination of both geometries can also be implemented to cover all the cross section of the rocket body [1, pp. 110–112]. A relatively thin solid umbrella in front of the solenoid can be virtually transparent to the oncoming nucleons and atoms. Its purpose is stripping the neutral atoms from their electrons in order to produce a flux of completely charged particles behind. This flux of charged nucleons submerges into a tank with liquid hydrogen or helium through the relatively thin superconducting winding around the tank. The charged nucleons gyrate across the magnetic lines inside the tank and lose their kinetic energy in collisions with the atomic electrons and nuclei of liquid hydrogen. For a rocket speed below $0.8c$ and a magnetic field inductance of 10 T, the radius of gyration of incoming H and He nucleons in the tank will be below one meter. A magnetic shield of two meters in thickness, which is significantly smaller than the full penetration depth of these nucleons along their trajectories in liquid hydrogen (about 10 m), will be sufficient for the rocket protection. Possible accumulation of positive charge on the tank and on the rocket body will be compensated by negatively charged electrons accumulating on the electron stripper provided the magnetic shield and the stripper are electrically connected. An additional advantage is that the secondary μ-mesons and γ-radiation generated in the tank by gyrating nucleons in their collisions with the nuclei of a liquid that fills the tank will not be directed exclusively to the rocket body but distributed over 2π angle reducing their portion directed to the rocket. The sketch of conceptual relativistic ion-propulsion rocket containing the most important elements and powered by an annihilation reactor is shown in Figure 8.

3.2 Cosmic Rays and γ-Rays

Cosmic rays consist mostly of high-energy protons (90%) and α-particles (9%) bombarding an unmoving target uniformly from all directions [14]. Their energy maximum lies between 300 MeV and 1 GeV. Actually, radiation hazard caused by cosmic rays is tangible both for non-relativistic and relativistic space flights. Strictly speaking, a complete shielding against cosmic rays would require something analogous to Earth's atmosphere for example a shell of water of 5 m in thickness around the rocket [15]. This will not be a welcomed solution both for interplanetary and interstellar flights because of a significant increase of rocket dry mass. Even a water shell of 1 m in thickness, satisfying the radiation safety standard, could be excessively heavy. In addition, a layer of dense material will be needed to absorb the highly penetrating secondary γ- and muonic radiation due to cosmic rays collisions with the nuclei of the shield inevitably enlarging the rocket mass. If the NASA's limit of 400 rems per individual during his duty (meaning the doubled probability to develop cancer) will be accepted for interstellar flights, a thinner material shield therefore its lower mass can be accepted for short-term missions (1 to 5 years). Lifelong interstellar travels will definitely require almost complete shielding of the crew quarters.

In analogy with the phenomenon of aberration of light relative a spacecraft moving with a relativistic speed, which is determined by the equation for transformation of incident angles from the map-frame to the comoving coordinate frame [16, 17], an equation for transformation of the angles of incidence of relativistic massive particles moving in space isotropically in all directions can be obtained [1, 13]. A frontal shield installed to protect crew and electronics from the relativistic headwind of interstellar gas can also absorb some portion of cosmic rays because of their increasing beaming with the rocket speed closer to the speed of light. However, the beaming effect is not as significant at the achievable rocket speed up to $0.7c$ (Figure 6) to expect a significant reduction in cosmic rays intensity from the sides. Accepting the average radiation quality factor $Q = 6.5$ for cosmic rays ($Q = 5$ for protons and $Q = 20$ for α-particles according to European Nuclear Society[2]), the estimated annual equivalent radiation dose accumulated in an astronaut body

[2]Radiation weighing factors, ENS publication, `https://www.euronuclear.org/info/encyclopedia/r/radiation-weight-factor.htm`

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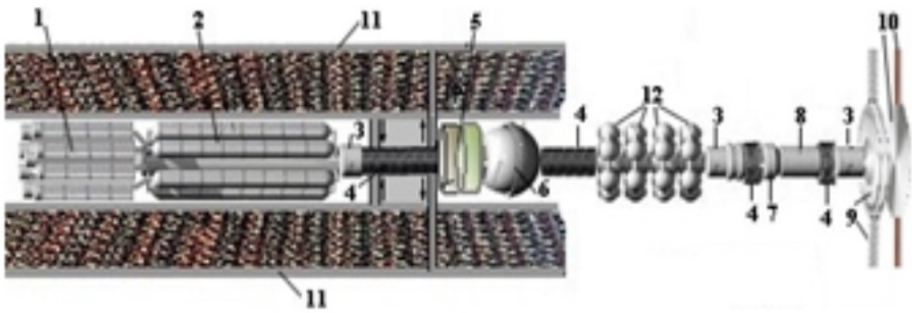

FIGURE 8. *Conceptual relativistic interstellar rocket: 1 – ion thruster (an assembly of ion accelerators producing the beams of relativistic ions); 2 – propellant tanks; 3 – low-temperature refrigerators; 4 – thermal insulation system; 5 – gas turbines system to generate electrical power; 6 – annihilation reactor; 7 – control bridge; 8 – crew quarters (if any) or auxiliary equipment room; 9 – magnetic shields to protect the rocket body and thermal radiators from the headwind of charged nucleons; 10 – electron stripper of oncoming neutral atoms and absorber of oncoming free electrons from interstellar gas; 11 – thermal radiators for power unit cooling; 12 – antihydrogen tanks. Reproduced from the reference [1, figure 3.7]*

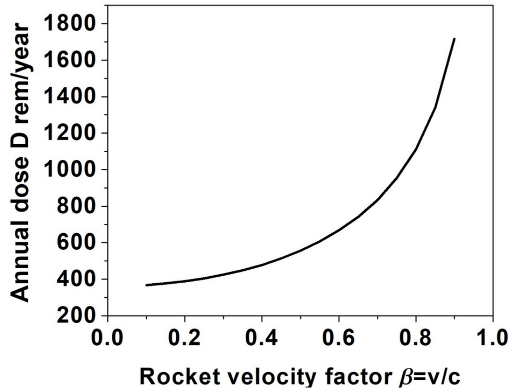

FIGURE 9. *Annual dose accumulated in an unprotected astronaut body from cosmic rays as a function of the rocket velocity factor$\beta = v/c$.*

from unshielded cosmic rays $D \sim 30N$ rem per year is plotted in Figure 9 as a function of the rocket velocity factor $\beta = v/c$, where N is the flux of cosmic rays per square centimeter per second integrated over the angles of incidence [13], [1, p. 106].

Cosmic γ-rays are emitted mostly from the galactic plane and imaged across the sky as a strip along the Milky Way with their maximum intensity in the direction to the center of our galaxy [18]. Some local bright sources such as Crab nebula can add to the γ-rays intensity. Intensity of galactic γ-rays exponentially decreases in the energy range between 10 to 1000 MeV. The spectrally integrating flux of γ-rays is about 10 $m^{-2}s^{-1}sr^{-1}$ photons. Most γ-rays are absorbed by the Earth's atmosphere except may be for the most energetic quanta. For the rocket velocity below $0.7c$, the flux of γ-rays will not differ significantly from the flux incident on Earth atmosphere and the radiation danger from galactic γ-rays seems to be not a big concern in comparison with cosmic rays due to their much lower intensity unless a starship gets close to a local source of intense γ-radiation.

3.3 Radiation Impact on Electronic Components

Every high-energy nucleon passing through an electronic component inevitably produces free electrons, i.e. it deposits some electric charge in the semiconductor material producing parasitic signals and causing bits to flip, latch up, or burn out in computer memory. This deposition of charge can "upset" the memory circuits, and the upset rate of a particular part of electronic equipment caused by cosmic radiation in the vicinity of Earth can vary from 10 per day for commercial RAMs to 1 every 2800 years for radiation-hardened RAMs (radiation-hardened component is a device specially designed to resist nucleonic radiation). Two other effects can cause degradation of electronics: a) Total Dose Effect which is the change of electrical properties of components upon their prolonged exposure to radiation and b) Displacement Damage which occurs when the nucleons slow down and nearly come to rest at the

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end of their penetration depth, where they knock semiconductor atoms out of their proper locations in crystal lattice creating defects in a crystal structure capable of trapping the conduction electrons. The laboratory tests of the electronic components irradiated by protons and heavy ions were performed by LaBel et al. [19, 20]. SEEs (single event effects) and other effects were detected virtually in all devices bombarded by heavy ions and some showed SEEs under proton irradiation. The cumulative effects such as degradation of current transfer ratio, reference voltage degradation, functional failure, and displacement damage were commonly observed under proton fluence above 10^{11}cm^{-2} protons. The headwind of hydrogen atoms at a rocket speed above $0.3c$ in the local low-density cavity exceeds 3×10^9 cm^{-2}s^{-1} therefore the unshielded electronic components will degrade to an inoperable condition in minutes of exposure. Hence, a frontal shield against the nucleonic radiation of oncoming relativistic headwind is equally necessary for unmanned (robotic) and manned relativistic spacecrafts. Any relativistic spacecraft, no matter how small or gigantic it is, must be shielded from the oncoming high-energy nucleons. Cosmic rays seem to be not of great concern for radiation-hardened electronics regarding SEEs with their malfunction rate of 10^{-9} – 10^{-10} errors/bit per day during relatively short missions of years of flight but the effect of cumulative degradation of electronic components can be a significant damaging factor in the long-range flights of tens of years or more without proper protection.

3.4 Interstellar Dust

The concentration of interstellar dust grains with their sizes from 10^{-5} to 10^{-6} m (1 to 10 μm) and their masses from 10^{-17} to 10^{-20} kg is about 10^{-8} m^{-3} in the local low-density cavity [11, 12]. Dust concentration can be thousands times higher in the dense clouds of the galactic arms. The oncoming dust will bombard the frontal parts of the rocket with a rate from 1 to 10 m^{-2}s^{-1}, if $\beta > 0.3$. Despite their smallness, the grains can pierce through the frontal protective shield damaging the magnetic coils, walls, and frontal parts of the rocket making micro-holes in the worst scenario or sputtering the shield and rocket hull. Impact of relativistic multi-atomic grains on the materials has never been studied because we do not possess a means for accelerating the multi-atomic granules to relativistic velocities.

To what type of hazard we can relate the oncoming flux of relativistic dust granules by their influence on the materials, electronics, and tissue is not clear. Should we consider them as solid projectiles depositing their kinetic energy into materials and producing a mechanical damage like riffle bullets? Or maybe treat them better as lumps of densely packaged nuclei and electrons causing ionization and displacement of atoms and molecules in a target as nucleonic radiation? Relating to our experience with common kinetic projectiles such as small-shots, bullets, cannon shells, etc. we are inclined to consider relativistic granules as producing some mechanical damage to materials and tissues. At a relativistic speed however, the kinetic energy of each atom in the grain significantly exceeds the potential energy of interatomic ties in the lattices of all known materials thus even the atomic ties of electrons with nuclei in both the dust grain and the rocket hull can be disrupted by their collision. Apparently, such a relativistic dust grain with its kinetic energy of tens to hundreds MeV per atom can be better treated as a micro-drop of plasma consisting of nuclei and electrons incident on another dense plasma also consisting of nuclei and electrons. In this case, a portion of atomic electrons will be stripped away from the dust granule by the frontal material shield (electron stripper), so each granule becomes an electrically charged micro-drop of plasma and we can hope on its deflection away of the rocket body by the magnetic field of the frontal magnetic shield. May be, the nuclei of a grain will scatter on the nuclei of the shield in agreement with the relativistic Coulomb scattering effect. There is no theory of relativistic grain collision with material targets and it is not clear if we can effectively protect a relativistic rocket against the oncoming flow of relativistic dust without a thick and massive bulge of solid material in front of the rocket. Possibly, a relatively thin shell of constantly renewable material such as a layer of freezing ice permanently grown on a mesh of thin tubes with refrigerating liquid can compensate the loss of material due to sputtering by the dust granules while serving an electron stripper for neutral atoms in the oncoming relativistic gas. Obviously, the frontal shield will be the most vulnerable part of a relativistic spacecraft.

In addition to gas and dust, interstellar space contains multi-atomic molecules such as polycyclic aromatic hydrocarbons and even fullerens [21] that fill the gap between atomic/molecular gas and dust. Every galaxy including our Milky Way is a dusty place filled with gas and dust which is the necessary component of every galaxy directly participating in the processes of star formation and evolution of galaxies (stellar recycling).

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Regardless of the means of thrust production and mass of interstellar module, no relativistic flight can be undertaken without a proper protection of crew (if any), electronics, and construction elements against the oncoming relativistic flow of all the components of interstellar medium.

4 Radiation Hazard in Braking Stage

We have to mention here a circumstance related to the radiation hazard on board of a relativistic spacecraft somehow omitted earlier, namely the issue of rocket protection from the oncoming relativistic headwind of interstellar gas and dust during the braking stage. Obviously, the frontal shield can perform its protective duty from ongoing nucleonic radiation and dust during acceleration and following cruising with a constant relativistic speed, i.e. when the rocket's nose together with the protective shield is directed strictly forward. Inevitably, the moment will come to start braking in order to cancel the rocket speed upon arrival to a destination. In order to start braking, the rocket must be either turned around as a whole by 180 degrees or have its parts rearranged to bring the propulsion thruster in front while rotating it around to redirect the efflux jet ahead. Since the protective shield cannot be placed in front of the rocket and obscure the exhaust jet, we have two options: either we risk to turn the whole rocket by 180 degrees exposing it to the full fury of the relativistic flux of interstellar gas and dust without the protective shade of the frontal shield or we transform the rocket keeping all vulnerable parts (crew quarters, control rooms, radiators, etc.) in the shade of the frontal shield while redirecting the propulsion ion beams mostly forward. The first maneuver would leave the propulsion engine and other parts of the rocket without any protection against the relativistic headwind of gas and dust unless the forward efflux jet could be capable of sweeping away the gas atoms (ions) and dust granules in front of the rocket. At a relativistic velocity, no gas dynamics is applicable to estimate the ion jet sweeping ability. To evaluate the action of the jet ions on interstellar gas molecules, atoms, and ionized atoms, we must consider the processes of atomic ionization and Coulomb scattering [1, pp. 113–116]. Hence the efflux jet of high-energy ions emitted from accelerators is supposed to be neutralized by electrons to avoid charge accumulation on the rocket body, the jet is actually a relativistic jet of plasma piercing through interstellar gas with the map-velocity $\beta_{jet} = (\beta + \beta_i)/(1 + \beta\beta_i)$ according to the relativistic addition formula, where β is the rocket map-velocity relativistic factor and β_i is the proper velocity factor of the efflux jet of ions and electrons in the rocket coordinate frame. The estimations performed in [1, pp. 114–115] for 1 TW and 100 TW ion propulsion showed inability of the ion efflux beam to completely ionize the neutral component of interstellar gas and to sweep the ionized interstellar atoms out of the way at the rocket speed above $0.2c$. The only possibility to keep all parts of the rocket together with the ion thruster behind the protective shield during the braking stage is to make a transformable ion thruster consisting of several ion accelerator units installed symmetrically around the rocket aft, so that each is able to turn around and to redirect the efflux jet almost ahead of the rocket at a small angle with respect to the rocket velocity vector while avoiding a possible damage of the rocket construction elements including the protective shield [6]. This way, the thrust engine together with the rocket body can remain in the shade of the protective frontal shield and operate in normal regime. Such a transformation widens slightly the angle of propulsion jet and may result in some reduction of thrust but it can be acceptable accounting for the reduced total mass of the rocket by this moment.

It should be mentioned that every shielding system designed for the protection of relativistic rocket or any other relativistic spacecraft in the local low-density cavity can be insufficient in the high density galactic clouds. If we find a way to send the interstellar ships or modules beyond the local cavity, the navigation charts and maps of interstellar clouds will be needed for laying out a safe course through the low-density tunnels in the galactic arms.

5 Conclusion

Among the factors that can potentially limit our pursuit for unrestrained expansion into the universe, ionizing radiation originated from the propulsion engine as well as arising from the very fact of rocket movement with a relativistic speed through space filled with rarefied gas will be the ones of our highest concerns. Despite the extremely low concentration of gas and plasma in interstellar space, three nucleonic components are hazardous for crew and electronics on board of a relativistic rocket: neutral and ionized components of interstellar gas, cosmic rays and galactic gamma-radiation. Inter-

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TABLE 1. *Most relevant factors of radiation hazard in the relativistic flight. For the products of proton-antiproton annihilation, the energies of γ-photons and kinetic energies of massive particles near the maxima of their energy distributions are adapted from the reference [4]. Kinetic energy of the oncoming nucleons $E_k = mc^2(\gamma-1)$ is a function of the rocket velocity v through the γ-factor: $\gamma = 1/(1-v^2/c^2)^{1/2}$.*

Radiation origin	Radiated particles	Particle energy (MeV)
Rocket engine:		
Photon rocket	γ-photons	0.511
Meson rocket	γ-photons	∼200
	π-mesons	∼250
	μ-mesons	∼190
Annihilation reactor	γ-photons	∼200
	π-mesons	∼250
	μ-mesons	∼190
Relativistic headwind of gas at $v > 0.3c$	electrons	>0.025
	H ions (protons)	>50
	He ions (α)	>200
Cosmic rays	mostly protons	100 – 1000
Galactic γ-rays	γ-photons	10 – 1000

stellar gas turns into an extremely intense flow of nucleonic radiation incident on the rocket frontal parts. Even at a moderate relativistic speed, the radiation hazard originated from the oncoming headwind of nucleons contained in interstellar gas can be huge (hundreds to thousands rems per second), so that a proper windward shielding becomes a necessity. Unshielded electronic components will also degrade in minutes of flight at a relativistic velocity thus even an unmanned rocket or a relativistic module of any kind will require protection against the nucleonic radiation of oncoming relativistic “headwind”. A thick and heavy material shield in front is hardly acceptable because of a significant increase in dry mass. The presence of a neutral component in interstellar gas excludes the use of a magnetic shield alone. A combination of an electron stripper and a magnetic shield can be a solution.

Isotropic cosmic rays can be subjected to frontal relativistic beaming in the rocket’s coordinate frame, if the rocket moves with a relativistic speed close to the speed of light, so that the frontal magnetic shield can absorb or deflect cosmic ray nucleons away from the rocket body. However at a moderate speed below $0.7c$, the relativistic beaming is not sufficient to significantly reduce the intensity of cosmic rays from the sides and from the aft of the rocket. A robust shielding of crew quarters from isotropic cosmic rays will be also needed for the long-term interstellar flights. The variety of hazardous ionizing radiation and potential radiation sources are listed in Table 1.

In addition to nucleonic radiation, interstellar dust can cause a mechanical damage of the frontal parts of a rocket or a relativistic module of any kind. A shield against nucleonic radiation of interstellar gas headwind will be the most vulnerable to dust bombardment. At a relativistic speed, the dust granules can be rather considered as dense lumps of plasma of high-energy nucleons and electrons, which collide with the nuclei of a shield or rocket hull materials knocking atoms from their position in the lattice and producing some secondary mesonic radiation. Radiation hazard for crew and electronics from the oncoming relativistic headwind and sputtering of the rocket elements by the relativistic interstellar dust granules are one of the most serious problems to be solved before attempting a relativistic flight to other stars.

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