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Some New Ideas for Nuclear Explosive Spacecraft Propulsion

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SOME NEW IDEAS FOR NUCLEAR EXPLOSIVE SPACECRAFT PROPULSION

by

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ABSTRACT

Because of the deleterious effects of galactic cosmic radiation, solar flares, zero gravity, and psychological stress, there is a strong motivation to develop high-specific-impulse and high-thrust spacecraft for rapid transport of astronauts between the planets. I present a novel spacecraft design using a large lightweight sail (spinnaker) driven by the pressure pulses from a series of nuclear explosions. The spacecraft appears to be a singularly competent and economical vehicle for high-speed interplanetary travel. Remarkably, the mass of the spinnaker is theoretically independent of the size of its canopy or the number or length of its tethers. Consequently, the canopy can be made very large to minimize radiation damage from the nuclear explosions and the tethers can be made very long to mitigate radiation hazard to the crew. I calculate the specific impulse of the nuclear explosive propellant as a function of the mass and yield of the explosives and the thrust as a function of yield and repetition rate. I show that the weight of the sail can be greatly reduced by tethering the canopy in many places on its surface and that the canopy mass is directly proportional to the bomb yield and inversely proportional to the number of tethers. The pressure from the nuclear explosion imparts a large impulsive acceleration to the lightweight spinnaker, which must be translated to a small smooth acceleration of the space capsule by using either the elasticity of the tethers or a servo winch in the space capsule or a combination of the two. If elasticity alone is used the maximum acceleration suffered by the space capsule is inversely proportional to the tether length. I address the question of thermal damage to the tethers and canopy by cursory calculation for low-yield explosives. Finally, I derive the optimum canopy shape and show that it will generally intercept about 2π of the solid angle from the detonation point. Should the political questions connected with this unconventional use of nuclear explosives be favorably resolved, the invention will be a good candidate for propulsion in the Mars mission.

Introduction

The concept of rocket propulsion using a kind of disposable reactor or external nuclear motor* is nearly as old as the concept of a nuclear bomb. Nuclear explosive propulsion was considered in the late 50s and early 60s under the ORION[1] program at Los Alamos[2] and General Atomics Corporation[3]. ORION was a heavy-lift vehicle, launched from the

* The first recorded discussion of nuclear explosive propulsion was in a Los Alamos Memorandum by F. Reines and S. Ulam dated 1947.

earth or from high altitude. The nuclear explosives, which ranged in yield from a few tons to several kilotons, were detonated behind a pusher plate fitted with shock absorbers[4] to mitigate the impulsive acceleration. Nuclear explosive schemes using a pressure vessel and conventional rocket nozzle with liquid hydrogen or water as a coolant and propellant were also considered under the name of HELIOS[5] These were abandoned as being generally heavier and less effective than externally driven vehicles.

A baseline U.S. Air Force design had a launch mass more than 3,000 metric tons (mt) and a payload mass of about 900 mt. The craft was a behemoth, frequently referred to as a *space battleship*. The pulse rate was $\sim$ 0.1 to 1 s^{-1} and the springs and dashpots were designed so the crew would suffer accelerations of only $\sim 10^3$ $cm \cdot s^{-2}$. The mission of ORION faded as chemical boosters became more powerful and it was realized that nuclear warheads for ICBMs could be designed with rather modest weights.

At the dawn of the laser-fusion era, researchers believed that the use of microexplosions could greatly reduce the weight of ORION, certainly the shock absorbers could be made less massive or eliminated entirely. Under the unofficial title SIRIUS[6], the laser-fusion innovators designed a spacecraft with a launch mass of a mere 20 mt and a payload of nearly 10 mt. They assumed, however, that the laser necessary for driving the fusion capsules[7] would weigh only 500 kg. We now realize that much bigger lasers will be required. Undaunted by the enhanced mass requirements, imaginative scientists at Lawrence Livermore National Laboratory have recently designed a huge laser-fusion-powered spacecraft, which has been dubbed VISTA[8].

We are now entering an era where manned flight to the planets is being taken seriously as evidenced by White House pronouncements on the subject. ORION may have a mission, but not the ORION of the past.

MEDUSA

For interplanetary missions, the vehicle will be assembled in space — it need not launch from earth as ORION did. Because there will be great concern that no radioactive debris reaches the Earth, the spacecraft will probably be assembled and launched from one of the Lagrange points. That location will place it well out of the magnetosphere and no charged particles will be trapped into Earth-bound trajectories.

In addition to its ill-favored environmental impact, ORION suffered from several problems mainly owing to its mission: (1) the pusher plate intercepted only a small solid angle from the detonation point and, even though a great deal of effort was devoted to designing asymmetrical bombs, only a fraction of the bomb-debris momentum was collected for propulsion; (2) the pusher plate and attendant shock absorbers had to be enormously massive and had to be carried with the spacecraft as long as it was under power; and (3) radiation damage to the vehicle as well as dose to the crew was a continuing problem. In space we have a lot of room and no gravity to deal with, so we can replace the pusher plate with a large sail or *spinnaker* whose canopy can intercept as large a solid angle as we choose. The elasticity of the tethers or a programmable servo winch can be used to smooth out the impulsive acceleration of the canopy. The tethers can be tied in many places on the canopy's surface to reduce stress on the canopy material*. As will be shown, the mass of the canopy is independent of its size and the mass of the tethers is independent of their length. The canopy can be very large and thus its fabric will be relatively immune to radiation damage from the nuclear explosions. Similarly, the tethers can be made very long, reducing shielding requirements for the crew. The concept is sketched in fig.(1).

One can visualize the motion of this spacecraft by comparing it to a jellyfish. The repeated explosions will cause the canopy to pulsate, ripple, and throb. The tethers will be stretching and relaxing. The concept needed a name: its dynamics suggested *MEDUSA*.

Pressure Pulse from an Explosion in a Vacuum

To get an estimate of the thrust imparted to the canopy and the specific impulse of the nuclear explosive, we need to know the pressure impulse imparted by an atom bomb exploded in a vacuum. To make this estimate, we must find the density and velocity distribution of the sudden expansion of a sphere of gas. There is no exact analytic solution to this problem, but an approximate solution can be constructed on the basis of an analogous plane problem. It is given in a book by Stanyukovich[9] and is quoted by Zel'dovich[10],

$$\rho = \frac{C}{R^3}\left(1 - \frac{r^2}{R^2}\right)^{\alpha}; \qquad \alpha = \frac{3-\gamma}{2(\gamma-1)}; \qquad R = u_{max}t. \tag{1}$$

where

$$u_{max} = \frac{2}{\gamma - 1}c_0 = \sqrt{\frac{4\gamma}{\gamma-1}\frac{E}{m_b}}, \tag{2}$$

c_0 is the sound speed, and E and m_b are the energy and mass of the bomb respectively. The solution is valid only for integer values of α and the parameter C is determined from mass conservation. For our present purposes, we can choose $\gamma = 5/3$ and Eq.(1) becomes

$$\rho = \frac{15m_b}{8\pi R^3}\left(1 - \frac{r^2}{R^2}\right). \tag{3}$$

The equation of motion for the limits $t \to \infty$ and $R \to \infty$ takes the asymptotic form

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial r} = -\frac{1}{\rho}\frac{\partial p}{\partial r} \sim \frac{1}{R^{1+3(\gamma-1)}} \to 0, \tag{4}$$

so the velocities of the fluid particles approach constant values and $u \simeq r/t$.

Thrust

Say the spinnaker canopy is at a distance r from the bomb. The mass hitting the canopy per unit area per unit time is ρu. The momentum per unit area per unit time (*momentum flux*) is ρu^2. The debris stagnates against the canopy, which in the frame of the debris acts

* Apparently this is not an obvious approach. That stress can be reduced in this manner is not generally appreciated by sail or parachute makers.

like a piston moving at velocity u. The piston produces a shock in the colliding debris. The pressure behind this shock[11] is

$$\rho u^2 \left(\frac{\gamma - 1}{2}\right), \tag{5}$$

and because it is a shock, the density will increase a factor of

$$\frac{\gamma + 1}{\gamma - 1}. \tag{6}$$

Thus the impulsive pressure exerted on the canopy is

$$P = \frac{\gamma + 1}{2}\rho u^2 = \frac{4}{3}\rho u^2, \tag{7}$$

for $\gamma = 5/3$. There will be an additional thrust imparted to the canopy by the re-expansion of the debris away from the canopy after stagnation. The largest possible impulsive pressure including all effects would be $P = 2\rho u^2$, but because the debris will radiatively cool during stagnation, we will ignore the impulse from re-expansion.

Then the approximate pressure applied to the canopy is

$$\begin{aligned} P &= \frac{4}{3}\frac{15 m_b}{8\pi u_{max}^3 t^3}\left(1 - \frac{r^2}{u_{max}^2 t^2}\right)\left(\frac{r}{t}\right)^2 \\ &= \frac{1}{8\pi}\sqrt{\frac{2 m_b^5}{5E^3}}\frac{r^2}{t^5}\left(1 - \frac{m_b r^2}{10Et^2}\right). \end{aligned} \tag{8}$$

Of course, the thrust is zero until the first debris arrives at the canopy, which occurs at a time

$$t_0 = r\sqrt{\frac{m_b}{10E}}. \tag{9}$$

The average thrust is simply

$$F = \bar{P} A_p, \tag{10}$$

where A_p is the projected area of the canopy, and

$$\bar{P} = \frac{1}{\Delta t}\int_{t_0}^{\Delta t} P \, dt, \tag{11}$$

where Δt is the time between detonations.

Specific Impulse
From Eq.(8) we have the velocity imparted to the spacecraft with everything initially at rest as

$$\begin{aligned}\Delta V &= \frac{A_p}{M_i}\int_{t_0}^{\infty} P\,dt \\ &= \frac{25A_p}{24M_i\pi r^2}\sqrt{\frac{2m_bE}{5}},\end{aligned} \tag{12}$$

where M_i is the initial total mass of the spacecraft. Suppose we constructed the canopy as a hemispherical shell with the bomb at its center. Then $A_p = \pi r^2$ and we have

$$\Delta V = \frac{25}{24M_i}\sqrt{\frac{2m_bE}{5}}. \tag{13}$$

If we use n bombs, the final velocity of the spacecraft is

$$V_f = V_i + \frac{25}{24}\sqrt{\frac{2m_bE}{5}}\sum_{j=0}^{n}\left(\frac{1}{M_i - jm_b}\right), \tag{14}$$

where V_i is its initial velocity. In the limit of a very large number of bombs ($n \to \infty$), we can approximate

$$V_f \simeq V_i + \frac{25}{24}\sqrt{\frac{2E}{5m_b}}\ \ln\frac{M_i}{M_f}, \tag{15}$$

where $gM_f = g(M_i - nm_b)$ is the "dry weight" of the spacecraft. By analogy with the rocket equation, we have

$$I_{sp} = \frac{25}{24g}\sqrt{\frac{2E}{5m_b}}. \tag{16}$$

The specific impulse goes as the square root of the yield-to-weight ratio. A bomb weighing 25 kg with a yield of 25 tons $\simeq 10^{18}$ ergs would have a specific impulse $I_{sp} \simeq 4.25 \times 10^3$ s. The best chemical fuels have a typical specific impulse of 500 s. To get to 50 km $\cdot$ s^{-1}, the final mass M_f would be about 1/3 the initial mass M_i.

Canopy Stress
To find the time of maximum impulse pressure, we set

$$\frac{dP}{dt} = \frac{r^2(7m_br^2 - 50Et^2)}{32\pi t^8}\left(\frac{5}{2}\right)^{\frac{3}{2}}\left(\frac{m_b}{E}\right)^{\frac{5}{2}} = 0, \tag{17}$$

which gives

$$t_{max} = \frac{r}{5}\sqrt{\frac{7m_b}{2E}}, \tag{18}$$

which substituted into Eq.(8) gives

$$P_{max} = \frac{18750}{1029\pi\sqrt{5\cdot 7}}\frac{E}{r^3} \simeq 0.98\frac{E}{r^3}. \tag{19}$$

The spinnaker canopy can be tethered in many places, as shown in fig.(1). As a result of the pressure differential, the canopy will billow out in cup-like shapes between the tethers. For simplification, we take each of these cups to be spherical in shape. The stress in each cup will be related to the impulse pressure by

$$\pi \Re^2 P = 2\pi \Re \tau \sigma, \tag{20}$$

where $\Re$ is the spherical radius of the cups, σ is the stress in the canopy material, and τ is the thickness of the canopy material. Equation (20) can be rewritten as

$$\tau_{min} = \frac{P_{max}\Re}{2\sigma_{max}}, \tag{21}$$

where σ_{max} is the stress limit (tensile strength) of the canopy material and τ_{min} is the minimum canopy thickness. From Eqs.(19) and (21) we see that for a given canopy material, **the canopy mass is (1) independent of its radius, (2) directly proportional to the bomb yield, and (3) inversely proportional to the square root of the number of tethers.** The total mass of the tethers depends only on the force they must bear and is independent of their number.

If we fabricated the canopy in a quilt of equilateral triangles as shown in fig.(2), the total number of triangles would be

$$N = \frac{4A_c}{\beta^2\sqrt{3}} \tag{22}$$

where β is the edge length of the triangles and A_c is the spherical area of the canopy (not counting the dimples). The smallest radius that can be obtained is approximately the distance from the center to the corner of the triangle, so the optimum cup radius is

$$\Re \simeq \frac{\beta}{\sqrt{3}}. \tag{23}$$

The area of canopy material in a single cup is less than but approximately equal to $\beta^2\sqrt{3}/2$. The total mass of the canopy is

$$m_c \simeq \frac{N\eta\tau\beta^2\sqrt{3}}{2} = 2A_c\eta\tau, \tag{24}$$

where η is the density of the canopy material. On average, the dimples (cups) produced by the multiple tethers increase the mass of the canopy by a factor of two over what it would be if the canopy were smooth.

It should be emphasized that this treatment gives an <u>extreme</u> upper estimate of the canopy stress. It does not account for the inertia of the canopy material and assumes infinite resistance at the points where the tethers are tied. It is an extremely conservative estimate.

Spacecraft Dynamics

If we neglect the mass of the tethers, it is easy to show that if both canopy and capsule are initially at rest and the canopy is suddenly given a velocity ΔV, then the position of the canopy is given by

$$x_c = V_{cm}\left[t + \frac{m_s}{m_c}\sqrt{\frac{\mu}{k}}\sin\left(t\sqrt{\frac{k}{\mu}}\right)\right] + l \tag{25}$$

and the position of the space capsule is given by

$$x_s = V_{cm}\left[t - \sqrt{\frac{\mu}{k}}\sin\left(t\sqrt{\frac{k}{\mu}}\right)\right], \tag{26}$$

where the space capsule starts at the origin, l is the tether length, k is the spring constant for the tethers,

$$\mu = \frac{m_c m_s}{m_c + m_s} \tag{27}$$

is the reduced mass and

$$V_{cm} = \frac{m_c \Delta V}{m_c + m_s} = \frac{\mu \Delta V}{m_s} \tag{28}$$

is the center-of-mass velocity. The spring constant of the tethers is given by

$$k = \frac{Y A_t}{l}, \tag{29}$$

where A_t is the total cross sectional area of the tethers and Y is Young's modulus for the tether material. The elongation of the tethers is given by

$$\begin{aligned}\frac{\Delta l}{l} &= \frac{x_c - x_s - l}{l}\\ &= \frac{V_{cm}}{l}\left(\frac{m_s}{m_c} + 1\right)\sqrt{\frac{\mu}{k}}\sin\left(t\sqrt{\frac{k}{\mu}}\right),\end{aligned} \tag{30}$$

and from Eqs.(29) and (30), maximum elongation of the tethers is given by

$$\left(\frac{\Delta l}{l}\right)_{max} = \frac{\Delta V}{l}\sqrt{\frac{\mu}{k}} = \Delta V\sqrt{\frac{\mu}{Y A_t l}}. \tag{31}$$

The total mass of the tethers is $m_t = A_t l \eta$, so using the definition

$$\left(\frac{\Delta l}{l}\right)_{max} \equiv \frac{\sigma_{max}}{Y}. \tag{32}$$

in Eq.(31) we can obtain the total mass of the tethers

$$m_t = \frac{\Delta V^2 Y \mu \eta}{\sigma_{max}^2}. \tag{33}$$

The mass of the tethers is independent of their number and independent of their length. The acceleration of the space capsule is

$$\ddot{x}_s = V_{cm}\sqrt{\frac{k}{\mu}}\sin\left(t\sqrt{\frac{k}{\mu}}\right), \tag{34}$$

so

$$(\ddot{x}_s)_{max} = V_{cm}\sqrt{\frac{k}{\mu}}. \tag{35}$$

Using Eqs.(28), (29), and (35), we can write

$$(\ddot{x}_s)_{max} = \frac{\Delta V^2 Y \mu}{m_s \sigma_{max} l}. \tag{36}$$

It is reasonable to make the canopy in the shape of a spherical segment at radius r out to angle θ as shown in fig.(2). The canopy area is

$$A_c = 2\pi r^2(1-\cos\theta), \tag{37}$$

and the projected area is

$$A_p = \pi r^2 \sin^2\theta. \tag{38}$$

Following the same procedure that led to Eq.(12), we have the velocity imparted to the canopy with everything initially at rest as

$$\Delta V = \frac{25 A_p}{24 m_c \pi r^2}\sqrt{\frac{2 m_b E}{5}}, \tag{39}$$

which when combined with Eqs.(24), (37), and (38) gives

$$\Delta V = \frac{25\sin^2\theta}{96\pi r^2 \eta \tau (1-\cos\theta)}\sqrt{\frac{2 m_b E}{5}}. \tag{40}$$

I will show later how to optimize θ for maximum F/W, but smaller values of θ give smaller effective I_{sp}.

Application to the Mars Mission

The principal reason for high F/W and high I_{sp} is to reduce exposure to GCR and solar flare radiation. Considerable uncertainty still surrounds the effects of exposures to skin, eye, and blood-forming organs (BFO). NASA calculations show that a $22\text{g}\cdot\text{cm}^{-3}$ water shield[12] would reduce a large solar flare to 5 rem and the annual GCR to 24 rem. The minimum energy round trip to Mars is about 18 months giving 36 rem from GCR alone. Astronauts might accept these exposures on a one-time basis, but they are probably unacceptable when Earth-Mars travel becomes routine. Spacecraft volumes of 100 $m^3 \cdot \text{person}^{-1}$ are used in NASA planning for two-month missions. A spherical four-man spacecraft would have a surface area of about $2.3 \times 10^2 m^2$, and the shield weight would be about 50 mt, assuming the NASA figures are accurate. But secondary radiation introduces a strong nonlinearity in the shielding requirement. If the tolerance levels for BFO were overestimated by as little as 30%, the shielding requirements would be quadrupled, and more than 200 mt of water would be required. NASA estimates have run as high as 1000 mt.

If the trip time is reduced by a factor of 5 to 10, the nonlinearity works so favorably as to reduce the shielding requirements to practically nothing. Part of the shield could be fuel (bombs), and could be made asymmetrical to point toward the sun in case of a solar flare. A crawl space inside the fuel could be used for shelter during a solar storm. Protons move more slowly than light, so the astronauts could be given some warning. Furthermore, solar-flare forecasting is becoming more accurate.

Example

It is time for a numerical example. For now, I will take $\theta = \pi/2$ corresponding to a dimpled hemispherical shell. We can reduce the mass of the canopy indefinitely by increasing its radius and the number of tethers. The tethers and the canopy material become progressively thinner. Mylar can be fabricated to a thickness of about $\frac{1}{4}$ mil, but other practical considerations, such as cost, will come into play long before the fabrication limit is reached. I will be conservative and say that we can spin-deploy a canopy 500 m in radius with 10^4 tethers. For the bomb, we will again assume a yield of 25 tons $\simeq 10^{18}$ ergs in a mass of 25 kg.

The best material for the canopy is probably high-strength polyethylene (aligned polyethylene). While it is essentially a one-dimensional material, we can easily imagine weaving it into a two-dimensional form much as they do for bullet-proof vests. The best material that is commercially available at this time is *Allied Signal Spectra 1000*, which has a density $\eta = 0.97 \text{ g} \cdot \text{cm}^{-3}$, a Young's modulus $Y = 170$ GPa, and a tensile strength $\sigma_{max} = 3$ GPa. A material that has been synthesized but is not presently commercially available is *Solid-State Extruded Polyethylene*, which has a density $\eta = 0.99 \text{ g} \cdot \text{cm}^{-3}$, a Young's modulus $Y = 220$ GPa, and a tensile strength $\sigma_{max} = 5$ GPa. Certainly materials superior to these will be available by the time manned interplanetary flight becomes a reality.

Using $r = 5 \times 10^4$ cm, we have from Eq.(19)

$$P_{max} = \frac{18750}{1029\pi\sqrt{5 \cdot 7}} \frac{E}{r^3} = 7.84 \times 10^3 \text{dyn} \cdot \text{cm}^{-2} \tag{41}$$

and

$$A_c = 2\pi r^2 = 1.57 \times 10^{10} \text{cm}^2. \tag{42}$$

With $N = 10^4$ cups (the number of tethers is actually $N + 2$), Eq.(22) gives the triangle edge as

$$\beta = \sqrt{\frac{4A_c}{N\sqrt{3}}} = 1.9 \times 10^3 \text{cm}, \tag{43}$$

and the cup radius is

$$\Re \simeq \frac{\beta}{\sqrt{3}} = 1.1 \times 10^3 \text{cm}. \tag{44}$$

Assuming we use Solid-State Extruded Polyethylene, we find from Eq.(21), that the canopy thickness is

$$\tau = \frac{P_{max}\Re}{2\sigma_{max}} = 8.62 \times 10^{-5} \text{cm}, \tag{45}$$

and from Eq.(24)

$$m_c \simeq 2A_c\eta\tau = 2.68 \times 10^6 \text{g}. \tag{46}$$

To be conservative, I will multiply the canopy thickness by nearly a factor of four, making the canopy mass approximately 10 metric tons. From Eq.(39) this gives

$$\Delta V = \frac{25}{24m_c}\sqrt{\frac{2m_b E}{5}} = 1.04 \times 10^4 \text{cm} \cdot \text{s}^{-1}. \tag{47}$$

Taking 50 tons as a baseline space capsule weight, we obtain from Eq.(27)

$$\mu = 8.33 \times 10^6 \text{g}, \tag{48}$$

and from Eq.(28)

$$V_{cm} = 1.74 \times 10^3 \text{cm} \cdot \text{s}^{-1} \tag{49}$$

and from Eq.(33)

$$m_t = \frac{\Delta V^2 Y \mu\eta}{\sigma_{max}^2} = 7.95 \times 10^5 \text{g}. \tag{50}$$

The maximum acceleration of the capsule is

$$(\ddot{x}_s)_{max} = \frac{\Delta V^2 Y \mu}{m_s \sigma_{max} l} = \frac{7.33 \times 10^7 \text{cm} \cdot \text{s}^{-2}}{l}. \tag{51}$$

If we want the maximum to be an Earth gravitational acceleration (980 cm $\cdot$ s^{-2}), then the tether should be about 7.5 km in length. Each tether will be 1.16×10^{-2} cm in diameter. The time interval between detonations should be

$$\Delta t = \frac{\pi}{2}\sqrt{\frac{\mu}{k}} = 2.56 \text{ s}. \tag{52}$$

The Servo Winch

To make a nuclear explosive with mass 25 kg and yield 2.5 kT is not much more difficult or expensive than to make the 25-kg, 25 T device we have used in this example. Equation (16) shows that the higher yield device would have ten times the specific impulse. The bungee-jumping approach I have shown, however, would lead to impractically long tethers. A very attractive alternative is to use a winch. When the explosive is detonated, a motorgenerator powered winch will pay out line to the spinnaker at a rate programmed to provide a constant acceleration of the space capsule. The motorgenerator will provide electrical power during this phase of the cycle, which will be conveniently stored. After the space capsule has reached the same speed as the spinnaker, the motorgenerator will draw in the line, again at a rate programmed to provide a constant acceleration of the space capsule. The acceleration during the draw-in phase will be less than during the pay-out phase, which will give a net electrical energy gain. The gain will provide electrical power for ancillary equipment in the space capsule. I have not yet worked out the details of this approach. I will reserve it for a future paper.

Thermal Damage to Spinnaker

Tethers too close to the detonation point will melt. There is a natural stay-out region that will affect the overall design of the canopy. Because of the low yield, I suspect the debris temperature to be more important than radiation. We want the temperature of the debris to be less than the melting temperature of the tether material, although this limit might be exceeded if the debris density is small enough and the specific heat ratio is favorable. We can crudely approximate the temperature of the debris by

$$T = \left(\frac{\rho}{\rho_0}\right)^{\gamma-1} T_0, \tag{53}$$

where T_0 and ρ_0 are the temperature and density of the bomb at explosion time. Again choosing $\gamma = 5/3$ and combining Eqs.(3) and (53), we have

$$T = \frac{R_0^2 \bar{w}}{15 N_A k t^2} \left(\frac{5}{2}\right)^{\frac{2}{3}} \left(1 - \frac{m_b r^2}{10 E t^2}\right)^{\frac{2}{3}}, \tag{54}$$

where $\bar{w}$ is the average particle weight (atomic, molecular, or whatever the state prescribes), $N_A = 6.02 \times 10^{23}\text{mole}^{-1}$ is the Avogadro constant, and $k = 1.38 \times 10^{-16}\text{erg}\cdot{}^\circ\text{K}^{-1}$ is the Boltzmann constant. The maximum temperature is found by setting

$$\frac{dT}{dt} = \frac{R_0^2 \bar{w}(m_b r^2 - 6Et^2)}{45 N_A t^5 E k} \left(1 - \frac{m_b r^2}{10Et^2}\right)^{-\frac{1}{3}} \left(\frac{5}{2}\right)^{\frac{2}{3}} = 0, \tag{55}$$

which gives a time for maximum temperature

$$t = r\sqrt{\frac{m_b}{6E}}, \tag{56}$$

and when substituted in Eq.(54) gives a maximum temperature

$$T_{max} = \frac{2R_0^2 E\bar{w}}{5m_b N_A k r^2}. \tag{57}$$

If the canopy melts at a temperature T_{melt}, then we must have

$$r > R_0\sqrt{\frac{2E\bar{w}}{5m_b N_A k T_{melt}}}. \tag{58}$$

If we take $E = 10^{18}$erg, $m_b = 2.5 \times 10^4$g, $R_0 = 20$cm, $T_{melt} = 600°K$, and $\bar{w} = 25$, we obtain $r > 18$ m, which is not very restrictive. However, this crude approximation is also relatively sensitive to selection of γ.

Nuclear radiation damage is a long-term problem to be considered. If a hydride bomb is used, less radiation escapes and the neutrons that do emerge are less energetic.

Optimal Canopy Shape

As a final item, I turn to the question of the optimal canopy shape. There is an intrinsic trade-off between thrust-to-weight ratio and specific impulse, both of which are functions of canopy angle θ as given in fig.(2). The weight of the spacecraft is

$$W = (m_c + m_s)\,g,$$

where m_s is the mass of the space capsule plus the tethers, although the mass of the tethers will be a smaller component. The mass of the tethers may also be a function of θ if the capsule is not very far from the canopy. Using Eqs.(10), (37), and (38), we find the thrust-to-weight ratio is

$$\frac{F}{W} = \frac{\bar{P}A_p\nu}{(2A_c\eta\tau + m_s)g} = \frac{\pi r^2 \bar{P}\nu \sin^2\theta}{[4\pi r^2\eta\tau(1-\cos\theta) + m_s]g}, \tag{59}$$

where $\bar{P}$ is the time-averaged pressure on the canopy. Following the derivation of Eq.(16) it is easy to see that the specific impulse will be

$$I_{sp} = \frac{25\sin^2\theta}{24g}\sqrt{\frac{2E}{5m_b}}. \tag{60}$$

The spherical segment angle $\theta_{t/w}$ for which there is maximum F/W can be found by setting

$$\frac{dF/W}{d\theta} = \frac{2\pi r^2\bar{P}\nu\sin\theta}{g}\,\frac{2\pi r^2\eta\tau(1-\cos\theta)^2 - m_s\cos\theta}{4\pi r^2\eta\tau + m_s - 4\pi r^2\eta\tau\cos^2\theta} = 0, \tag{61}$$

which gives

$$\theta_{t/w} = \arccos\left[1 + \frac{m_s}{4\pi r^2\eta\tau} - \sqrt{\left(1 + \frac{m_s}{4\pi r^2\eta\tau}\right)^2 - 1}\right]. \tag{62}$$

In our numerical example, we chose $m_s/4\pi r^2\eta\tau \simeq 5$, for which Eq.(62) gives $\theta_{t/w} = 1.487$ rad $= 85.2°$. Our use of $\theta = \frac{\pi}{2}$ was pretty good.

Political Considerations

We are currently prohibited by treaty from: (1) deploying weapons of mass destruction in space and (2) testing nuclear weapons in space. MEDUSA violates neither the letter nor the spirit of either prohibition, but it does use nuclear explosives. The radioactive debris from MEDUSA's exhaust is so finely dispersed that it will be nearly undetectable. I assert that MEDUSA's net environmental impact is less than NERVA; you have to do something with the spent reactor. I see no reason why nuclear explosive propulsion for interplanetary missions cannot be made politically acceptable. Perhaps we can be more creative and consider an international mission in which the nuclear explosives were jointly supplied by the superpowers. What a wonderful approach to nuclear disarmament and the enhancement of science for the benefit of all humanity!

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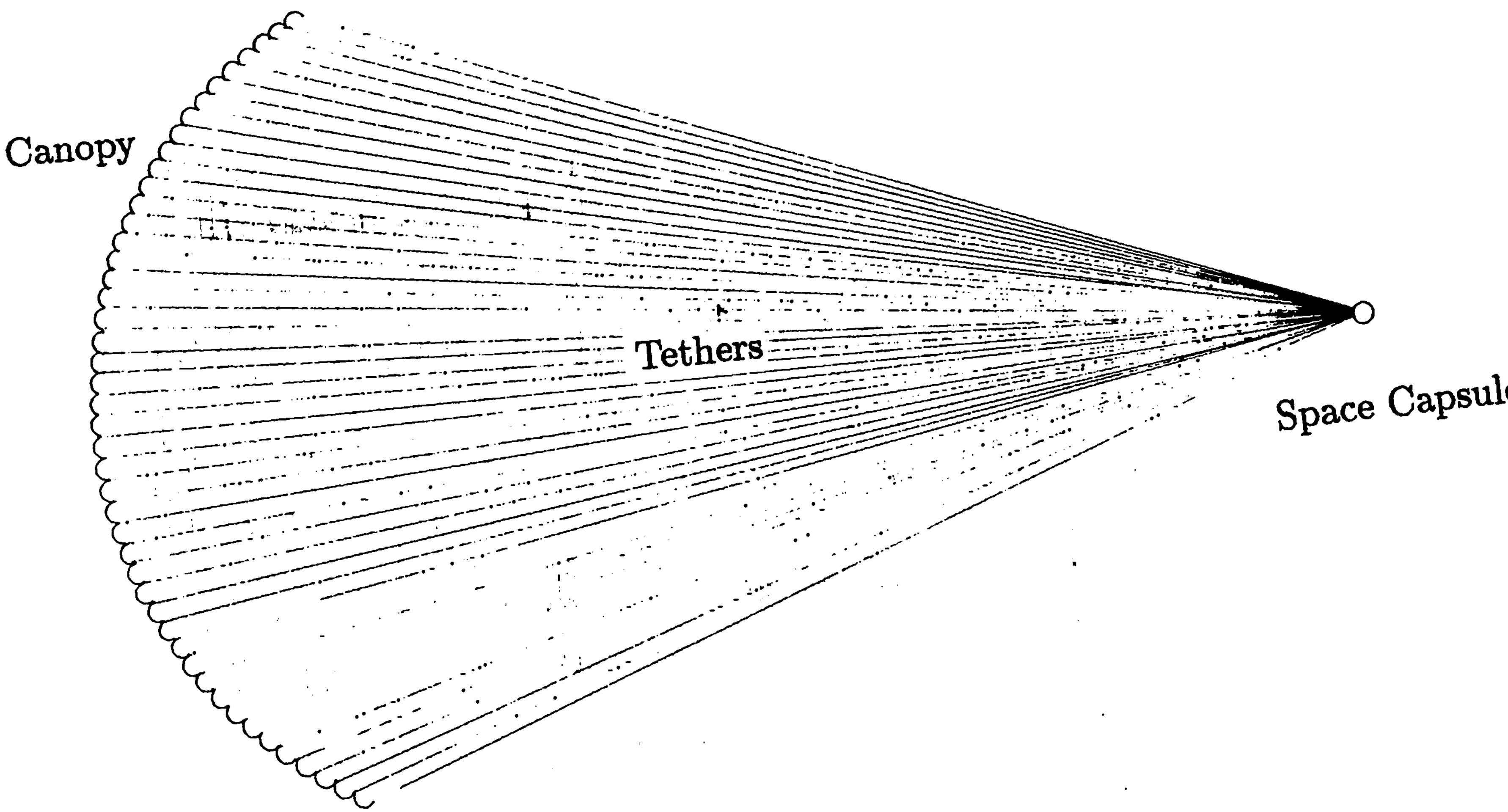
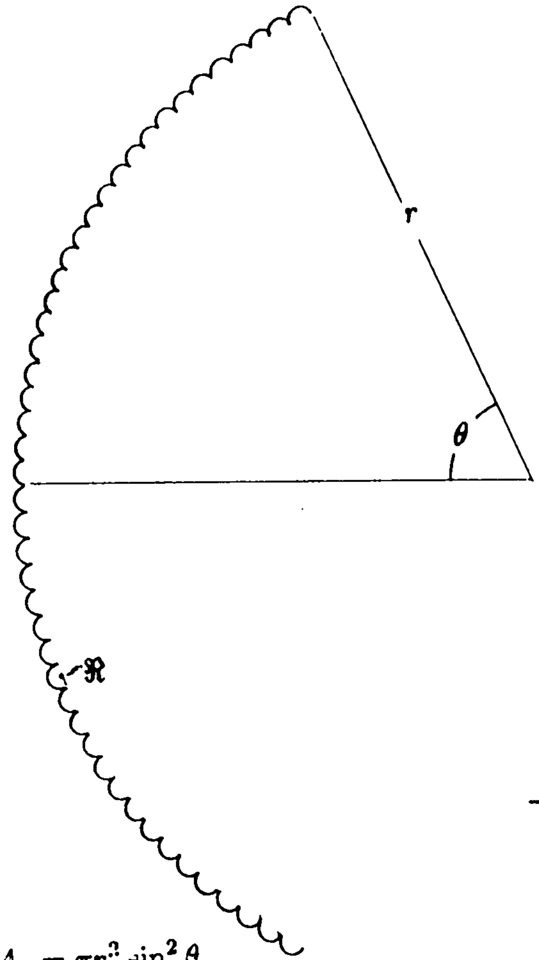


Figure 1. Schematic of spacecraft design.

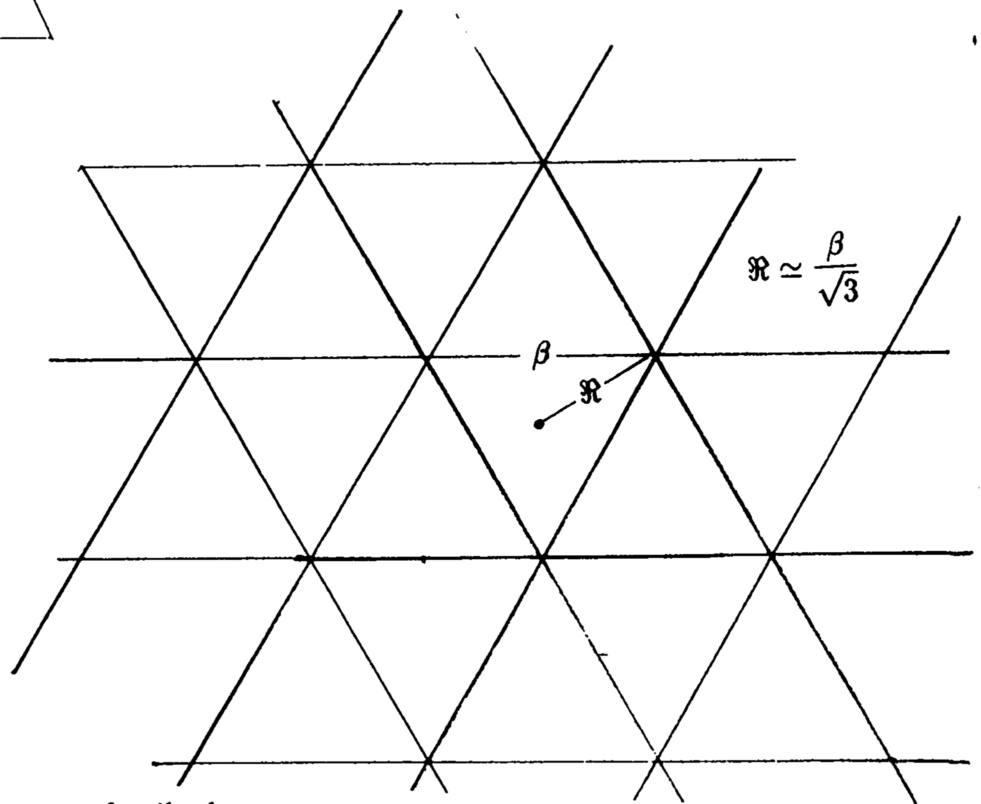


$$A_p = \pi r^2 \sin^2\theta$$

$$A_c = 2\pi r^2(1-\cos\theta)$$

$$N = \frac{4A_c}{\beta^2\sqrt{3}}$$

$$m_c \simeq \frac{N\eta\tau\beta^2\sqrt{3}}{2} = 2A_c\eta\tau$$



$$\Re \simeq \frac{\beta}{\sqrt{3}}$$

Figure 2. Geometry of quilted canopy.

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