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Panspermia Revisited, or Have We Already Contaminated Mars?

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> In respect to the future, we are now setting about the forlorn task of disseminating among the stars the seeds of a new humanity. For this purpose we shall make use of radiation from the sun . . .[1]

Svent Arrhenius is credited with giving scientific recognition to the ancient theory of Panspermia in 1908 in his remarkably farsighted book.[2] The concept states that very small microbial or sporelike organisms can spread through the universe disseminating life from the planets of one solar system to those of another.

This idea has been given serious consideration in recent years and conflicting opinions have been expressed concerning its feasibility.[3] In his consideration of the subject, Arrhenius postulated that the initial microbial escape velocity could be achieved by a combination of meteor impact and electro-static ejection, the microorganisms being subsequently propelled through space by solar radiation pressure. Haldane, in 1954,[4] similarly made the suggestion that life might have been disseminated by intelligent beings from other stellar systems; he coined the term "astroplankton" to describe possible living forms which would travel in space. Lederberg[5] has suggested that microorganisms for many reasons are best prospects on which to concentrate marginal capabilities for extraterrestrial life detection; however,

he has emphasized the two major difficulties associated with the Arrhenius Panspermia concept. The first is the lack of a clear-cut, plausible natural mechanism for impelling the spore-bearing particle out of the gravitational field of its planet. Secondly, if this problem is solved the particle is then presumably very vulnerable to destruction by the hazards of space. It has been generally believed that the solar radiation would kill any microorganisms which managed to survive the high vacuum and dangerous temperatures of outer space.

The main hazard that "naked microorganisms" would face consist of low temperature and ultra high vacuum conditions combined with the inactivating effects of the solar radiation and cosmic rays. While conflicting predictions have been made concerning the effects of high vacuum, the general concensus has held that organisms should be able to survive this. Low temperatures, which are more likely to be encountered than high ones, are likely to preserve rather than destroy. The main danger is the solar radiation. Most predictions on this account have been that the organisms would swiftly die. Sagan has stated[8], "If we assume .....the radiation sensitivity of the most resistant known microorganism, solar ultraviolet radiation at wave lengths short of 3,000 angstroms would kill the putative Panspermia at the moment of their departure--within a day of their ejection from earth into interplanetary space. In the extremely unlikely case that the ejected microorganism has an infinite tolerance to ultraviolet radiation, then X-rays and protons of solar origin would kill the bugs before the orbit of Neptune is reached." Thus it appears at first sight that microorganisms liberated into space in this manner are destined to die long before they

could reach some other planetary body. However a more careful analysis of the probable fate of the organisms reveals that this is not so true as it first appears. Almost all of the data on ultraviolet, X-ray, and other radiation exposures of microorganisms have been done in the wet state. Very little definitive information exists on dried organisms and that which is available has usually been done on relatively small numbers. In general, when dried organisms are used considerably greater survival is obtained than with the wet organisms, particularly with respect to heat inactivation and ultraviolet radiation. In the dry state, those organisms which lie beneath a protective coating of more superficial cells, are not free to diffuse into the superficial layers; they therefore remain highly protected throughout the exposure. It is possible that in the extreme vacuum of outer space where pressures of 10^{-16} to 10^{-20} are predicted, the extreme dessication produced may offer even greater stability. It is noteworthy that studies performed on the heat stability of microorganisms with respect to pressure have shown a linear relationship between logarithm of surviving fraction and pressure indicating a considerable increase in stability as pressure decreases from atmospheric. This appears to be at least partly related to the role of oxygen in causing microbial inactivation.

The final test of space stability of unprotected terrestrial microorganisms depends on survival studies in the space environment itself. Such studies have now been accomplished by my laboratory in collaboration with Dr. C. Hemenway of the Dudley Observatory, Albany,

and have furnished considerable preliminary data on the subject. The results[9, 10, 11, 16] have indicated that although marked inactivation of microorganisms rapidly occurs on exposure to the solar radiation in space, this high inactivation rate is not maintained at its initial level for more than a few minutes. Thereafter self screening of aggregates of microorganisms apparently provides considerable protection against the most lethal component of the radiation which appears to be short wave length ultraviolet light and possibly soft X-rays. Experiments have shown that metal filters of only 800 Å prepared by the evaporation of aluminum or gold on to formvar membranes supported above the microorganisms[10] offer greater than 1,000-fold protection. Experiments performed on the Gemini spacecraft[11] showed significant surviving fractions of microorganisms after 6 hours of exposure. The main results of the relevant experiments are shown in Table I.

It can be seen that in the Luster I experiment, [a] survival of the T 1 bacteriophage was very low (0.00004), whereas in similar rocket flights on a later occasion the survival was 0.3 and 0.8. However in the latter experiments, the specimens received little or no solar radiation owing to the time of launch. Since [this] is apparently the main cause of microbial death in space, this fact explains the high survival in these experiments. the sun

The figures given for the Agena experiment show the results obtained with specimens placed both inside and outside the box which remain closed throughout the 2-month space exposure period. The outside specimens were fully exposed to the air blast and heat of the launch which

may explain why no surviving organisms were found. It is evident that the organisms inside the box (screened by approximately 5 mm aluminum and 2 mm steel) were virtually unaffected though exposed to the vacuum which at 400 miles altitude is more complete than any terrestrial vacuum. The data shown in Table 1 are reduced in Table 2 to the main values for a comparison of the survival in space for different times. These figures are based on comparison of the exposed values with the inverted (screened but vacuum exposed) flight samples. This procedure gives a value for the effect of direct solar radiation and eliminates any other effects such as heat transmitted through the specimen exposure box and "non-specific" inactivity effects during storage and handling on the ground. The values shown for the Agena 8 are derived from the reciprocal of the number of infective units found in the laboratory controls at the termination of the experiment, and represent the threshold of sensitivity of the test. When the data of Table 2 is expressed as an inactivation curve, it represents the sum total of our present knowledge on microorganism survival in space; this is shown in Figure 1. On the basis of the available information, it can be seen that the initial rate of inactivation at least for T1 phage is not maintained, and that the inactivation curve appears to flatten out with respect to time. The final inactivation rate in space can only be determined by obtaining more results in the region of several hours--up to, hopefully, many days--utilizing well controlled experimental systems so that losses from radiation can be distinguished from other hazards during the space flight and return to

earth. Prolonged UV inactivation[9] of T1 phage in the laboratory, with phage preparations deposited on large pore-size (450 millimicrons) millipore filters (which presumably offered some protection from UV radiation) gave an inactivation curve which flattened off and was not significantly lower after 600 seconds than after 25. If space radiation effects are comparable, the inactivating factor would be approximately 4 log 10 units of loss during the first 2 hours and then relatively little loss during the ensuing days.

The significant fact then emerges that under these circumstances it is possible that the inactivation rate during the 3-4 weeks transit time between the terrestrial and Martian orbits might involve losses only slightly greater than this, e.g., a factor of 10^{-6}. It is also pertinent to consider the effects of minor amounts of shielding upon these figures. The results of the experiments previously mentioned[9, 10, 11] indicated that a few hundred angstroms of aluminum or gold could offer protective factors of approximately one thousand. On this basis it can be assumed that aggregates of crystalline and organic material debris, plus dust particles could be expected to offer very significant protection to a large proportion of the microorganisms released, so that the over-all inactivating factor may be significantly lower than 10^{-6}.

A consideration of the possibilities that high energy components of the solar radiation may similarly inactivate the microorganisms reveals that the [probability of] possibilities for this [are] considerably less than might at first be supposed. While [daily] doses of penetrating radiation may be in the neighborhood of

1-2 rad. per day, a 30 day period at this level would only amount to some 60 rad. total dose. The dosage necessary for a mere tenfold inactivation of Streptococcus faecalis runs into thousands of rads, and for some of the more stable radiation-resistent organisms can be ten to one hundred times greater. It is seen that the significant danger to microbial life is in the range of the lower energies considered above. Having examined the evidence for considering that there is a real probability for the survival of a significant proportion of microorganisms liberated in space, it is worth considering the possible sources of these resulting from the current period of space exploration.

Consideration of the present level of spacecraft technology reveals that feats of extravehicular activity have undoubtedly liberated significant quantities of bacterial contaminants into space. Although constructed and maintained in white room conditions of cleanliness, the typical space capsule is nevertheless heavily contaminated bacteriologically both before and after flight.[6] Upon an even larger scale, the excretory activities of astronauts must have already provided a large quantity of frozen-dried microbial meteoritic material, composed almost entirely of microbes of multiple types and conceivably including viruses. This material has been liberated at orbital heights and speeds. Fecal disposal in plastic bags can be expected to result in ultimate bursting of the bag by gas liberated during the decomposition which must occur while the material is warmed by sunlight resulting in dissemination of the material in a finely divided particulate form. Once free in space, these particles

would steadily dehydrate by evaporation and sublimation. In the case of the urinary disposal systems, dissemination is in minute aerosol-sized droplets (see Fig. 2) which would be subject to the same "freeze-drying" process. Conceivably some of the liberated microorganisms would be significantly accelerated by blasts of gas from the spacecraft altitude control jets.

Our next task is to attempt to determine the probability that some of the liberated particles may leave the terrestrial environment. The organisms are already moving at orbital velocity, so that if acceleration is given to them by solar radiation pressure in successive pulses as they revolved around the earth (see Fig. 3), a certain proportion would reach escape velocity and depart centrifugally away from the sun. Consideration of Fig. 3 indicates that the accelerative and decelerative effects of the solar radiation pressure on suitably sized particles would exert a pumping effect resulting in a variety of orbital characteristics departing from an ideal or circular form. While the net gain in velocity under perfectly circular orbital conditions would be zero, (since on each orbit the particles would spend equal time being accelerated and decelerated) as random collisions and variations in orbital paths occurred, the range of velocities and directions would become wider. The orbits of slower particles would decay while the faster ones entered wider and more varied orbits, until those with the greatest velocity were in increasingly eliptical orbits.

From the moment of liberation, microorganisms would be subject to the combined impulses from collisions with other particles at the time of release, plus additional acceleration from the impact with particles in the zodiacal cloud and ions plus the effects of electrostatic and magnetic forces, as well as solar radiation pressure. Belton has pointed out[12] that velocity studies of the zodiacal dust by Ring and his co-workers[13] indicate that most of the particles are in direct orbit (in the same sense as the Earth) at more than twice the velocity of particles in circular orbits. If these estimates are correct one could expect collision of microorganisms with these zodiacal particles to confer terrestrial escape velocity upon high proportions of the organisms (provided they survived the impact). The remarkable stereoscopic photographs obtained by Tousey[14] with a solar flare camera show particles traveling obliquely away from the Earth at velocities greater than that of the sounding rocket used. The path of microbial particles after they become members of the zodiacal cloud is presumably as complex as the behavior of a cometary dust tail, which Belton has pointed out[13] "appears to be, because of the electric charge carried by the particles, yet another example of a plasma in nature. The dynamics of these tails is thus removed from the pristine realm of celestial mechanics and becomes a rather difficult problem in plasma dynamics."

The end result of all these accelerations would be a scattering off or shedding of a proportion of the organisms from the spacecraft in orbit (as shown in Fig. 4). These would be expected to travel in the direction of the orbit of Mars. Once this has occurred, according to the calculations of

Arrhenius, the organisms would cross the orbit of Mars after about 20 days, Jupiter after 80 days, and Neptune after 14 months. Sagan[7] has checked these calculations and agrees that organisms leaving Earth would be propelled to Mars by solar radiation in a matter of weeks. Only those microorganisms with a diameter of approximately 0.2 to 0.6 microns would have a $\frac{P}{g}$ ratio of greater than one,[7, 12] where p = pressure of solar radiation and g = solar gravitational force acting on the microorganism. Since both of these obey the inverse square law, the ratio $\frac{P}{g}$ does not vary with distance from the sun, but the net force p-g acting on the microorganism varies inversely as distance to the sun. It may be noted in passing that the microorganisms falling outside this size range will have a $\frac{P}{g}$ ratio of less than one which will mean that they will, when free of the earth's gravitation, be drawn toward the sun rather than propelled away from it, so that they will tend to proceed toward the orbits of Venus and Mercury. It is of interest that Belton[12] emphasizes that calculations indicate that the particle size of 0.7 μ is of particular optical importance in the zodiacal cloud; this size is exactly right for particles in the small bacteria-large virus range. However, the density of microorganisms (wet or frozen) is about 1.3 whereas zodiacal particle densities are considered[12] to be about 5.0. After microorganisms have dried, their density will be only about 0.3 thereby increasing the size range of particles swept towards Mars.

Let us consider some of the factors governing the proportions of particles which would be expected to ultimately arrive at Mars. If we assume that this shedding occurs almost exclusively from the "down (solar)

wind" portion of the spacecraft orbit, the flow or organisms would proceed from a disc approximately equivalent to that of the Earth's diameter in a fashion analogous to the behavior of Type II cometary tails (see Fig. 4). There will be at least two factors which will increase the area of spread of the particles by the time they have been driven to the orbit of Mars by solar radiation. These are the random angle at which they leave Earth's orbit (shown as 2Θ on Fig. 4) and the angle of inclination (23°) between the planes of orbit of the particles and the plane of the ecliptic. This angle results in Mars only passing through the "spray" zone of particles scattered from Earth at the points of intersection of these planes. If we assume that a significant bulk of escaping particles (say about 30%) will escape in a direction almost parallel with the sun's rays, say within ±5° of this, the resulting spread at the orbit of Mars will be d to $2.\Theta$ where d = the distance between the orbits of Earth and Mars or 48.7×10^6 miles and $\Theta \mp 5°$. The chance of an organism hitting Mars is proportional to the diameter of Mars divided by the "spread" distance = $\frac{4220}{48.7 \times 10^6 \text{ Tan } 10°}$ or 4.9×10^{-4}. There will also be some spread of the "thickness" of the disc of spinning organisms, though this may be so small as to be negligible, or only reduce the chance of a hit by about an order of magnitude. This gives an overall hit probability due to the "spray effect" of 1.5×10^{-5}. If we consider the situation for the most ideal juxtaposition of Mars and Earth, in order for the former to receive the maximum concentration of liberated particles/at the appropriate time, some three weeks before, the probability of a particle impinging upon Mars is governed by the relative proportions of the target area of Mars compared

to the overall area over which the particles are dispersed. If we ignore the "spray" and other diverging effects considered above, but regard the particles as simply "blowing" off the surface of the earth, the situation is something like taking a shot at a football with a shotgun from fairly long range. Here the angle of spread of the "shot" is then governing by angle of spread of the solar radiation between the orbits of Earth and Mars. This "shotgun" probability can thus be calculated as:*

$$\text{Chance of organisms hitting Mars} = \frac{\text{Area of Mars}}{\text{Area of Dispersion}} = \frac{\pi\left(\frac{dm}{2}\right)^2}{\pi\left(\frac{de}{2} \times \frac{rm}{re}\right)^2} =$$

$$\frac{\pi\left(\frac{dm}{2}\right)^2}{\pi\left(\frac{de}{2} \times \frac{rm}{re}\right)^2} = \frac{\pi\left(\frac{4220}{2}\right)^2}{\pi\left(\frac{7927}{2} \times \frac{141.7}{93}\right)^2} = \frac{4450000}{26469521} = 0.1215$$

Since the chances are small that Earth and Mars will be ideally located at the time a significant number of microbial particles are liberated, it is necessary to consider the general case where the two planets may be anywhere on their respective orbits. Under these conditions the calculation becomes:*

$$\frac{\text{Area of Mars}}{\text{Area of Dispersion}} = \frac{\pi\left(\frac{dn}{2}\right)^2}{\pi\, 2.r_m \cdot d_e \times \frac{r_m}{r_e}} = \frac{\pi\left(\frac{4220}{2}\right)^2}{\pi . 2.141700000 \times 7927 \times \frac{141.7}{93}} =$$

$$\frac{4\ 452000}{2 \times 141700000 \times 7927 \times \frac{141.7}{93}} = \frac{445 \times 10^4}{3423 \times 10^{10}} = \frac{4450}{3423} \times 10^{-6} = \frac{445000 \times 10^{-6}}{3423} =$$

$$1.30 \times 10^{-6} \quad = 1.3 \times 10^{-6}$$

* where dm = diameter of mars, de = diameter of earth, rm = radius of orbit of mars, re = radius of orbit of earth.

Thus the general situation of Mars' location gives rise to a 100,000 times lower chance of a particle arriving on Mars than in the "optimal" case. It is now worth considering all of the above factors to arrive at an over-all figure for the probability of microorganisms in terrestrial orbit reaching Mars. The factors are summarized in Table 3 from which it appears that somewhere between 10^7 and 10^{16} viable organisms must be liberated in orbit for/of them to have a reasonable probability of landing alive on Mars. The major variable in this probability range is the relative positions of Earth and Mars.

The final factor to be considered in this approximate survey is the question of the number or "dose" of viable organisms which might conceivably be - or have been - liberated in space by man. Suppose we consider the situation of orbits lasting for a total of 30 days involving two men with complete fecal and urine disposal into space with 10 periods of EVA, and complete venting of the capsule's atmosphere on each occasion. It should be remembered that while some dumping of fecal material has definitely occurred in space, precise quantitative information of this type of space contamination is lacking. The over-all microbial contamination will involve the liberation of microorganisms from fecal, urinary and atmospheric sources within the capsule. The possible liberation of other spacecraft organisms will not be considered and it is assumed that the attitude control jets are sterile. Let us take each of these sources in turn.

The viable count of organisms in feces is given[15] as 10^8 - 10^{14} per person per day. For 2 men excreting feces in orbit for 30 days this would give a range of 6×10^9 to 6×10^{15} viable organisms liberated, of which about 1.4×10^8 to 1.4×10^{14} are likely to be spores. In the case of urine, the volume liberated will be approximately 40,000 ml; contaminating organisms which occur in the urinary system of the capsule can be assumed to have a viable count of approximately 10^5 organisms per ml, which would give a total of 4×10^9 organisms liberated. In the case of the spacecraft atmosphere, if we assume the volume of the spacecraft to be approximately 6×10^6 cubic centimeters and the count of airborne microorganisms to be 10^3 per ml, this would give a total of 6×10^{10} microorganisms liberated; it is assumed that about 1% of these are likely to be spores. The figures for these calculations are shown in Table 4. It is clear that the major source is the fecal material, and that the other sources are relatively insignificant.

A comparison of the final figures of Tables 3 and 4 reveals that the probability ranges overlap, i.e. the number of organisms liberated is within the range for there to be a realistic probability for some to land on Mars. For this to happen, somewhere between 10^7 - 10^{16} organisms need to be liberated, of which 10^7 to 10^{14} have already been distributed. Thus there is at least a 1:100 chance that Mars is already contaminated; moreover if the liberation had occurred during optimal positions of the two planets, the probability for contamination would become 1000 to 1. A closer estimate of the effect of the spacial relationship of the two planets

at the time of previous (and future) manned orbital space flights could readily be made. While the figures given here can only be considered as a first approximation, the subject appears to justify much closer attention. The question of escape of terrestrial particles is only now being actively explored, and the possibility of an exchange of particulate material through space between the solar planets and even more distant celestial bodies may prove to occur on a surprisingly large scale.

The implications of these possibilities has a profound bearing on our concept of life on the cosmic scale. If microbial exchange can occur, possibly without the assistance of man, several consequences are obvious. Life forms in a given planetary system can be expected to have much in common and to "overlap" and a goodly portion of our concern for the enforced sterilization of interplanetary vehicles may be unfounded. The task of proving that [only] microbial life forms discovered elsewhere are truely extraterrestrial will be immensely more difficult than if a completely alien structure were the rule. Perhaps it is no coincidence that the red color of Mars is similar to that of the heavily red-pigmented strains of the most highly radiation resistant terrestrial microorganisms. A spectroscopic comparison of these two colors should be made to see if the resemblance can be pushed to a significant degree.

While Arrhenius proposed the Panspermia concept to avoid what he considered to be the impossibility of spontaneous generation, it may be that both events occur and are relatively commonplace.

Table I

Surviving Fractions* of Microorganisms Exposed in Space

			Vehicle					
			Luster I Rocket	Luster 2 Rocket	Dudley Rocket	Gemini 9 Spacecraft	Agena 8 (Inside Box)	Agena 8 (Outside Box)
Exposure time**			11 AM	8 AM	7:30 AM	-	-	-
Exposure period			3 min.	3 min.	3 min.	6 hours	2 months	2 months
Altitude (miles)			31	31	31	150	400	400
ORGANISM	Penicillium	Exposed	-	0.6	-	0.00003	1.0	0
		Inverted	-	1.0	-	0.7	1.0	-
		Laboratory	-	0.7	-	1.0	1.0	1.0
	T1 phage broth medium	Exposed	0.00004	0.3	0.8	0.000002	-	0
		Inverted	1.0	1.0	1.0	0.006†	0.007††; 0.1	-
		Laboratory	-	0.04	0.6	1.0	1.0	1.0
	T1 phage synthetic medium	Exposed	-	0.00007	0.1	0	-	-
		Inverted	-	1.0	1.0	0.00002	0.006†† 0.02	-
		Laboratory	-	0.01	2.0	1.0	1.0	-
	B. subtilis	Exposed	-	0.4	-	-	0.3	-
		Inverted	-	1.0	-	-	1.0	-
		Laboratory	-	1.0	-	-	1.0	-
	TMV	Exposed	-	-	-	0.002	-	-
		Inverted	-	-	-	0.02	-	-
		Laboratory	-	-	-	1.0	-	-

*Ratio of number of organisms surviving after full exposure, to number in similar specimen which remained in the laboratory.

**Only Luster I rocket and the orbiting spacecraft were fully exposed to direct sunlight.

†This value was the same as in the "back up" samples which remained on the ground and therefore is due to some handling factor and not due to space exposure.

††This value is listed under "inverted" since it was "exposed" inside a closed box since the astronauts were unable to complete the manual opening procedure.

Table 2

Surviving Fraction of Organisms Exposed to Full Solar Radiation in Space, Relative to Controls Shielded by 2 mm. Aluminum

		Vehicle		
		Luster I Rocket	Gemini 9 Spacecraft	Agena 8 Spacecraft
ORGANISM	Exposure Period	3 min.	6 hours	2 months *
	Altitude (miles)	31	150	400
	Penicillium		0.00004	$<1 \times 10^{-4}$
	T1 Phage (Broth)	0.00004	0.0003	$<1 \times 10^{-9}$
	TMV		0.1	

*These specimens were also exposed throughout the launch, and inside the Gemini capsule after recovery of the box.

Table 3

The Influence of Various Factors on the Over-all Probability of an Orbiting Microorganism Contaminating Mars

Factor	Influence on Probability of Contaminating Mars
Lethal radiation	$4 \times 10^{-5} - 4 \times 10^{-7}$*
Slight shielding	10^{3} x - 10 x
"Spray" effect	1.5×10^{-5}
"Shotgun" effect	$1.2 \times 10^{-1} - 1.3 \times 10^{-6}$
Over-all range	$7.2 \times 10^{-8} - 7.8 \times 10^{-17}$

*Projection of 6-hour penicillium survival to three weeks.

Table 4

The Number of Microorganisms Liberated from a 2-Man Space Capsule during 30 Days in Terrestrial Orbit, with 10 Periods of EVA

Source	Total Organisms	Total Spores
Feces	$6 \times 10^{9} - 6 \times 10^{15}$	$1.4 \times 10^{8} - 1.4 \times 10^{14}$
Urine	4×10^{9}	
Air	6×10^{10}	6×10^{8}
Over-all range	$7 \times 10^{10} - 6 \times 10^{15}$	$7.4 \times 10^{8} - 1.4 \times 10^{14}$

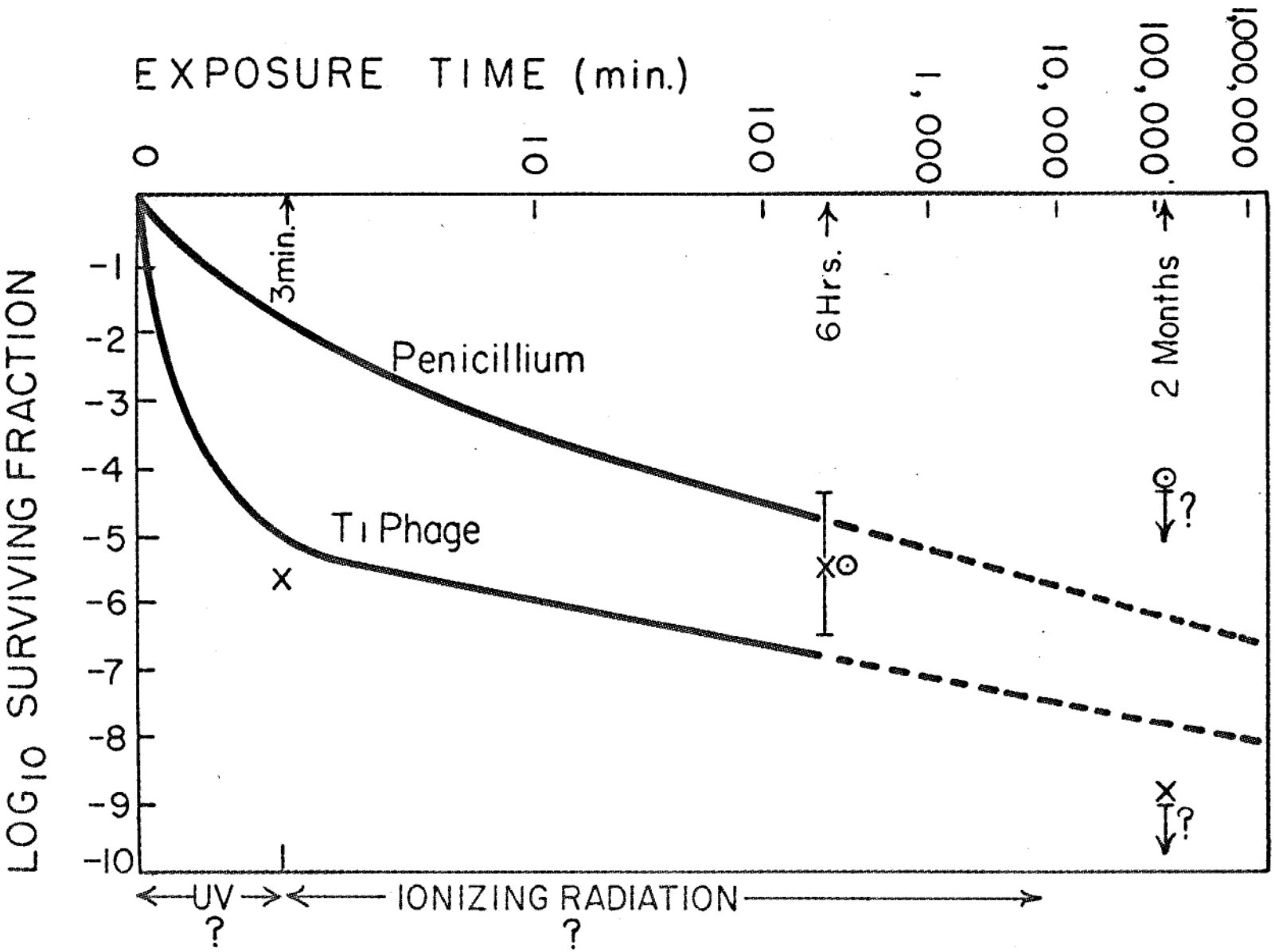
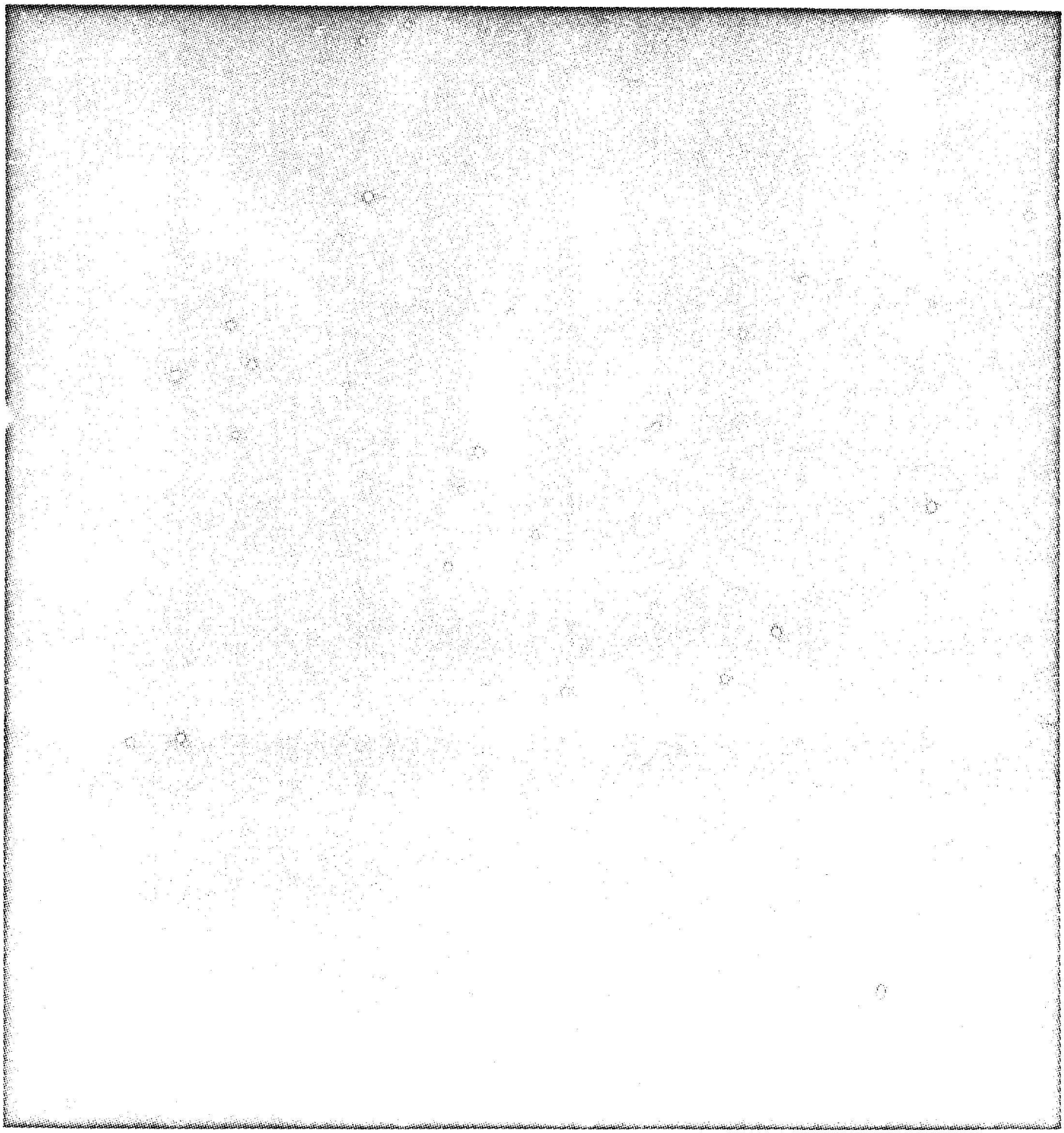


Fig 1

Inactivation of "Naked" Microorganisms Exposed to Solar Radiation on Metal Surface in Space (tentative)

Fig 2



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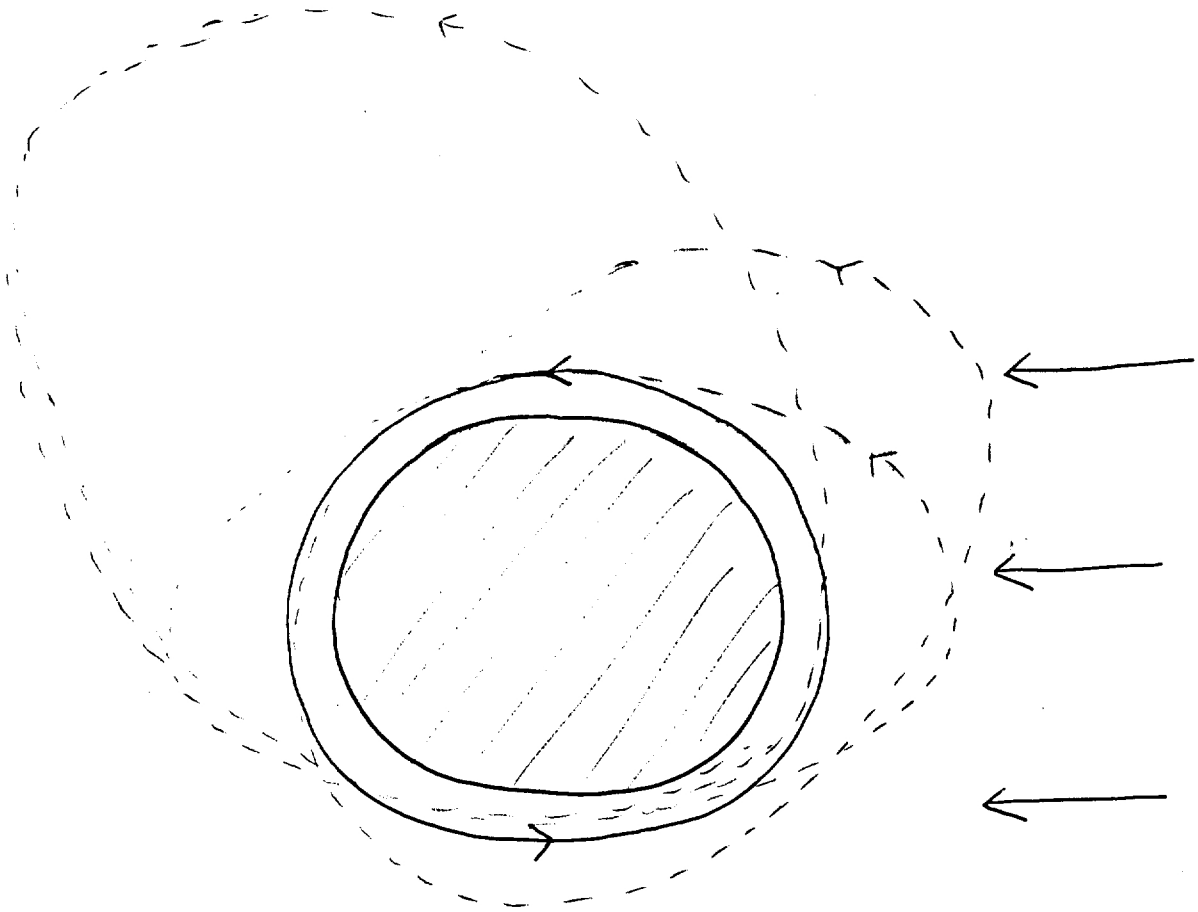
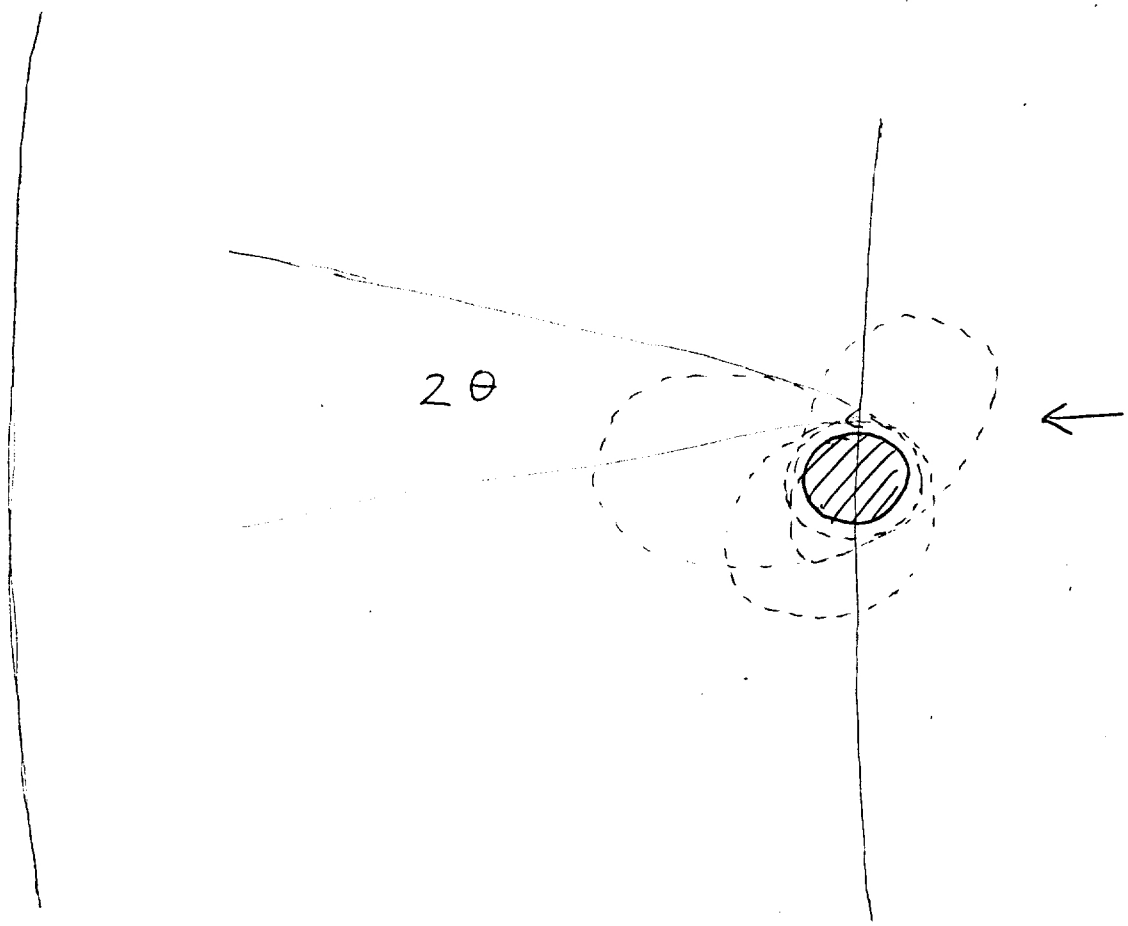


Fig. 3

Diagram showing accelerative and decelerative effects of solar radiation on particles in orbit around Earth.

Fig. 4

Diagram to show the expected direction of movement of particles escaping from Earth's orbit as a result of a solar-radiation pumping effect.



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