Evaluation of the level of assurance that no unsterilized Martian material naturally transferred to Phobos (and Deimos) is accessible to a Phobos (and Deimos) sample return mission

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CHANGE RECORDS

ISSUE	DATE	§ CHANGE RECORDS	AUTHOR
Draft	23/10/17	Draft Issue to ESA	DJS
1	30/10/17	First Issue to ESA	DJS
	30/10/17	Updated D.Rad going underground, dropped exponent	DJS
2 Draft	21/8/19	Issue for review Updated to Include Discrete ejections RIDS incorporated Executive Summary added	DJS
2	28/8/19	Issue released to ESA	DJS
2.1	6/9/16	No change to text, version that can be released openly.	DJS
2.2	8/10/18	Added section on uncertainties §14.	DJS

1. EXECUTIVE SUMMARY

This document presents the results of running the sterilization model developed on the Sterlim project. This models transfer of material between Mars and its Moons, and investigates how the hyper velocity collision with the moon, and the radiation environment on the moon, sterilize any life transferred.

The work has been performed in two phases, the first looking at the average rate of transfer, and the second extending this to cover discrete transfer originating from Martian craters modelled to the isochrones curves.

Key to the results is how much life can material ejected from Mars contain in the first place; taking Earth analogue such as the Atacama Desert, loading of life still varies by 5 orders of magnitude. This is greatest uncertainty in the process.

The original phase looking at average rates of transfer showed over a 10 million year period, that the typical transfer of mass, makes it marginal that a sample taken on a sample return mission has probability below 10^{-6} of containing life from Mars.

The Hypervelocity collision with the moon only gives minor sterilization; or more accurately has great variation. Specifically the leading edge of any impactor undergoes a large rise in temperature and pressure, likely to give sterilization. However the internals and back of the impactor experience far less heating – and it is here that life can be transferred.

The radiation environment on the moon can always kill life, but it takes time, the time being dependent on depth material is buried at. This gives times scales that range from a century on the surface, to 100,000 years at depth.

The second phase looking at discrete ejections, demonstrated that the important transfer of mass comes from the largest craters. These happen at low probability, but with higher than the 10^{-6} planetary protection requirement. For Phobos in particular this means that unless large craters can be shown to be in the distant past (at probabilities over 99.9999%), that Phobos cannot be said to be free from Martain life. For Deimos if the Mars ejecta contains low levels of life, the chance of life on Deimos can be lowered to below 10^{-6}.

A typical mass ejection from Mars is caused by an impact from the asteroid belt, this means the impact with Mars is over 6km/s. This in turn means that the ejecta have a range of velocities that drop off exponentially with some over the escape velocity. The range in velocities mean that Martian mass ejecta will cover most of the sky, and have a high probability of impacting Phobos and Deimos.

What is key with the most mass coming from the larger Martian craters, is the age of the crater. For material to remain viable on the surface of the moon, it must have been transferred within a few time constants for the radiation environment to sterilize. Hence it is key the age of the crater on Mars, is this within the few radiation time constants? Where a Martian crater can be aged to have happened in the distant past, then any mass transferred will be sterilized. However if a Martian crater cannot be said to have been in the distance past to a very high degree of probability, then the slim possibility that it may have been in the recent past is what will lead to the moon being above the planetary protection threshold for the possibility to detect life of 1 part in 10^6.

With the current age limits on recent large craters (such as Zunil and Mojave, etc) there is a probability above 1 part in 10^6 that the craters were created recently. Any one of these craters in the recent past would transfer enough life to the Moons, that it is almost certain that a sample return mission would return with Martian life. However if the large craters can be aged to be greater than a minimal age, consistent with the radiation time constant on the moon – then the moon would be below the level of life needed for planetary protection.

Much of the science of the transfer of life between Mars and its moons has uncertainties, not least of which are:

- How much life the martian ejected material has before ejection.
- The size distribution of the ejected material, with contradictory evidence that it is both fragmented to small scale, and that there is a not insignificant rate of spallation.
- The precise time of the ejection from the largest Martian craters, whilst Martian geological times, and crater evolution, give timescales of millions of years – but only a few craters can be more accurately placed in time. This is critical when the timescale for sterilization on the moon is far shorter than the million years.
- Accurate models of radiation sterilization, in particular tests have greater variation than can be easily understood. Some results such as the D Rad tests are unclear.

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2. INTRODUCTION

2.1. SCOPE AND PURPOSE

Produce a synthesis of the tests and modelling, and the material transfer analysis from Mars to Phobos (and Deimos).

Using these results, evaluate with sterilisation statistical models the probability that an unsterilized Martian material naturally transferred to Phobos is accessible to a Phobos sample return mission.

Results shall also be extrapolated to a possible Deimos sample return mission.

This work has been performed under ESA Contract number: 4000112742/14/NL/HB.

Under a CCN the work has been extended to include the effect of discrete ejections from Mars driven by the isochrones crater rate.

2.2. APPLICABLE DOCUMENTS

Acronym	Reference	Issue	Title
AD1	ESA-SRE-F-ESTEC-SOW-2015-00	1	Sterilisation limits for sample return planetary protection measures – Statement of Work
AD2	NNX10AU88G		Material Transfer from the Surface of Mars to Phobos and Deimos, Final Report:
AD5	Planetary and Space Science 87(2013)115–129		Mars impact ejecta in the regolith of Phobos:Bulk concentration and distribution.
AD3	SterLim-Ph2-TAS-TN19	3	Description of the sterilisation statistical model
AD4	SterLim-Ph1-TAS-TN-08	2r2	Statistical Analysis

2.3. REFERENCE DOCUMENTS

Acronym	Reference	Issue	Title
RD1	TN2.1		Identification of Representative Biological Models and Characterisation Approach of Sample Preparation and Conditioning for Tests
RD2	TN18		Hypervelocity Impact Modelling
RD3	TN15	1	Test report on the irradiation inactivation tests results
RD4	TN16	0.C	Radiation Simulation Analysis Results
RD5	Science 07 Nov 2003: Vol. 302, Issue 5647, pp. 1018-1021		Mars-Like Soils in the Atacama Desert, Chile, and the Dry Limit of Microbial Life
RD6	Meteoritics & Planetary Science 1–18 (2016)		Martian cratering 11. Utilizing decameter scale crater populations to study Martian history
RD7	Icarus 176 (2005) 351–381		The rayed crater Zunil and interpretations of small impact craters on Mars
RD8			“Global Surface Modification Of Asteroid 4 Vesta Following The Rheasilvia Impact” Timothy J Bowling, PhD Thesis, Purdue University
RD9	Icarus 207 (2010) 744–757		Dynamical erosion of the asteroid belt and implications for large impacts in the inner Solar System
RD10	Icarus 208 (2010) 621–635		Do young martian ray craters have ages consistent with the crater count system?

2.4. DEFINITIONS AND ACRONYMS

ACDP Advisory Committee on Dangerous Pathogens

Cfu Colony forming unit

ESA European Space Agency

GCR galactic cosmic radiation

LET Linear Energy Transfer

SEP Solar Energetic Particle

SoW Statement of Work

3. SENSITIVITY ANALYSIS – PARAMETERS THAT ARE VARIED

3.1. INTRODUCTION

The development of the model used to produce the results in this documenting is described in [AD3]. During development there were some parameters of the model, where only ranges could be set – there was no preferred value identified. For these parameters the suggested approach was to perform a sensitivity analysis, e.g. in this document it is considered the effect that varying these parameters has on the result.

Now varying of parameters, needs to be done with care. In particular each parameter affects a particular area (e.g. the ejection cone angle on Mars, affects the available angular momentum of the transfer to the Martian Moon – and so affects the arrival on the Martian Moon). Hence rather than probing all parameters in all distributions, instead the parameters are only varied where they will have most effect. This enables probing how sensitive the model is to the parameter and its allowed value.

This section documents which parameters can be varied – and the range chosen for those parameters.

3.2. BIOLOGICAL MODEL

This sensitivity area is mandated by the SoW. It is unknown what form martian life is present in, if at all. Therefore in this study the five terrestrial organisms have been used as biological models for martian life [RD1].

- *Deinococcus radiodurans* – Radiation resistant bacterium
- *Clostridium difficile* – Capnophilic spore forming bacteria. Whilst identified in Phase 1 of this project, in Phase 2 in was not possible to test with this organism due to its classification as an ACDP level 2 organism. Hence this is not studied here.
- *Bacillus atrophaeus* – Endospore forming bacterium
- *Brevundimonas diminuta* – Simple organism
- *MS2* coliphage – small resistant bacteriophage

As the characterisation, both for radiation, flash heating, and hypervelocity impact has been performed for all four remaining organisms, these four organisms are taken through the full model.

In addition a fifth organism is defined:

- *Super Bug* – the parameters of this organism are selected to be the hardiest of the other four organisms tested. This corresponds to:

- Beta, the cooling coefficient of *D. radiodurans*
- The thermal sterilization parameters (k0 and b) of *B. atrophaeus*
- The radiation resistance parameter (lambda) of *MS2*

3.3. MARS EJECTION CONE ANGLE

Ejections from Mars are expected to be the result of a collision with Mars. This is expected to produce an ejection cone, however the angle of the cone is not actually known. Hence the values used are:

- 1: fixed cone angle - 30°
- 2: fixed cone angle - 45°
- 3: fixed cone angle - 60°
- 4: Cone centred on 45° with a normal distribution in angle with standard deviation of 15°
- 5: Cone centred on 60° with a normal distribution in angle with standard deviation of 15°

The angle of the ejection cone is important as it affects the angular momentum the ejector has about Mars. This in turn has an effect on the first hyper velocity collision with Phobos (Deimos). Hence this first collision, will have a sensitivity analysis of the ejection cone angle.

3.4. MARS EJECTION MASS DISTRIBUTION

The mass of ejectors from Mars is poorly known, whilst it is expected to be a steeply falling distribution, with most particles towards the smallest size, what this smallest size will be is unclear. Here the values used are:

- 1e-6 kg
- 1e-5 kg
- 1e-4 kg
- 1e-3 kg

This ejector mass, will be the mass of the first collision with a Martian Moon. So where the sterilization is dependent on this mass – this needs to be modelled. Hence the first collision with the moon will be analysed for sensitivity.

3.5. MARTIAN MOON EJECTION MASS DISTRIBUTION

As with the Mars ejection, the size of objects ejected as a result of hyper velocity impacts with the moons in not clear. This only affects:

- Change that material is ejected from the Martian system when in the cloud

- Depth at which the material is deposited in subsequent collisions with the moon

With this knowledge two extremes for the mass distribution are taken:

- M=0; corresponding to the material fragmenting to very small objects. This will mean that the material will be ejected from the Mars system in the cloud, and lost.
- M=%age change of ejection times the impactor mass. This corresponds to the ejected %age being ejected as a single object. This will lead to the object eventually setting on the moon, and deposited at greatest depth where radiation will be minimized.

3.6. DEPTH DEPOSITED

The most likely resting place of the impactor material after a collision is on the surface of the moon. This depends on the assumption that the mechanical properties of the regolith on the moon, are such that the surface will bounce back, after the impact – returning the impact material to the surface.

Hence as there is no certainty in the properties of the moon regolith, the depth of deposition will be varied. Now the depth the impactor reaches before the bounce back, is a few times the impactor radii. Hence the depth deposited is varied between:

- 0 impactor radii, the material is on the surface
- 1
- 2
- 3

3.7. LOADING OF LIFE ON THE MARS EJECTA

The ejecta from Mars have the potential to carry life. The level of life that they carry is important for Req-10:

Req-10 : The probability that a single unsterilized particle from Mars ≥ 10 nm in diameter is in a sample returned from Phobos shall be ≤ 1×10^{-6}.

Sterilization is defined by life, life is characterised as unsterilized if it can be grown under suitable conditions into a colony. E.g. the count of colony forming units, or cfu is critical in defining sterilization.

This then gives the dependence, on what the loading of life is possible for Mars Ejecta. Req-10 though is not defined in terms of life on mars, but on the concept of an unsterilized particle. Particles however cannot be grown into cfu, and so a method is needed to characterise the cfu that Mars ejecta can contain. There is no rigorous method.

Here we look at terrestrial analogues, the landscapes on Earth considered as analogues are the arid areas, two in particular are used:

- The Atacama desert in Chile

- The Antarctic McMurdo dry valleys

Of these the Atacama desert is the best studied, and most often used. The level of life measured in the Atacama desert is quite variable, e.g consider [RD5], shown in Figure 3-1.

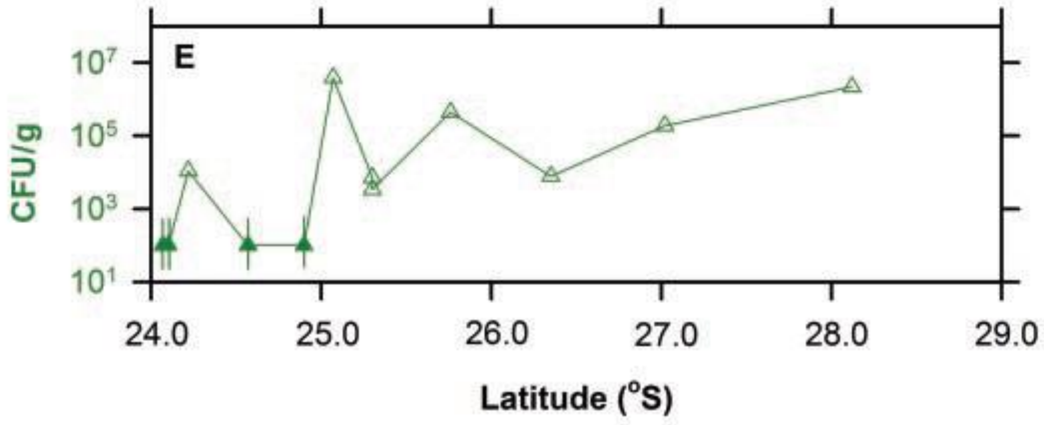

Figure 3-1. An extract from Fig.2 of [RD5], showing the life loading rate at various sites in the Atacama desert. The filled triangles are where no life was observed, and so an upper limit on life has been set.

At various sites life can be seen to vary between 1e2 cfu/g to 1e7 cfu/g, where the lower measurements come from the area close to Yungay.

In the case of Yungay, many of the measurements did not detect any life, and are shown as filled in triangles. In these cases an upper limit on life has been set at 1e2 cfu/g.

However even in the case of Yungay, the measurements are not consistent. E.g. an area close by has measured life at the level of 1e4 cfu/g.

In this study, we should cover a likely range of life. Taking the example from the Atacama suggests using the range:

- Low: 1e2 cfu/g = 1e5 cfu/kg for samples with no measured life
- Medium: 1e4 cfu/g = 1e7 cfu/kg for samples with measured life, but at the lower range of measurements
- High: 1e7 cfu/g = 1e10 cfu/kg for samples with the highest counts in the Atacama

Clearly though this is driven by the sensitivity with which life is detected in the regolith, with more precise measurements it is consistent with possible levels of loading well below 1e2 cfu/g.

Finally should be mentioned that two other areas are considered as possible arid zones as analogues for Martian regolith:

- María Elena South in the Atacama, possibly even drier than Yungay
- Antarctic McMurdo dry valleys, exceptionally dry and cold

These have not been considered here.

4. ASSUMPTIONS

4.1. GARDENING (DUE TO METEOR IMPACT)

The regolith on the Martian moons is slowly turned over due to continual impact of meteors. Over long time periods this produces extensive mixing, and this process is known as "Gardening". In Phase 1 of this project [AD4], analysis of the literature concerning gardening, suggested that on the Earth's moon , over a 10MY time period, that a turnover of one or more times happens down to a depth of ~2cm at 50% confidence (and ~1cm at 99% confidence). Turnover on Martian moons is expected to be lower, as the solar system impactor flux is 50% lower at Mars than Earth.

Hence in the analysis performed here gardening is ignored. Once material has settled on a moon, its position is assumed to not change over the 10MY period.

4.2. AVERAGE ORBIT PROPAGATION

Of the mass ejections from Mars, the vast majority do not impact Martian moons. This means a general simulation of mass ejections would be very inefficient in placing material on the moon. Now efficiency of coding is key to accurate estimates in the Monte Carlo.

Considering a mass ejection from Mars, integrating the mass ejection over all possible points on Mars, and over all possible rotational angles, and the resulting ejections will uniformly cross 4π steradians of space. The area of a moon can be calculated in steradians, and that the ejection solid angle is uniform, means that the probability of impact with the moon can be calculated exactly. This probability is then taken to be probability for all possible points of ejection, and rotational angles. On average, this gives exactly the transferred mass required, and scales between Phobos and Deimos (which have differing angular sizes, and distances). The assumption of uniformity is not held on a case by case basis (e.g. ejection from Mars equator is more likely to impact a moon, than for ejection from a Martian pole), just on average – but the huge efficiency it brings to the Monte Carlo makes its use justified. It means that all ejections can be assumed to hit the moon, with just the overall probability scaled, but scaled so the correct answer is achieved.

Note that Melosh [AD1] uses a different assumption to increase the probability of impact, the size of the moon is scaled to a larger value, which scales the probability of impact. This does not exactly flatten the probabilities distribution (e.g. most ejections still miss the moon, which for a Monte Carlo decreases the efficiency), however better estimates the geographical distribution of ejecta which impact with a moon. This difference has produced no observable difference between this work and that of Melosh.

Under the discrete ejections this approach is varied somewhat, the phasing of the moons position with respect to the point of ejection on Mars is still taken as uniform; however the effect of the ejection curtain is calculated analytically – and this is used to give a quick analytical solution to how much mass is transferred from each ejection. The uniform distribution of ejections on Mars is justified from the crater distribution.

4.3. BIOLOGICAL MODEL ASSUMPTIONS

Four biological models have been used to be representative of Martian life:

- *D. radiodurans*
- *B. atrophaeus*
- *B. diminuta*
- *MS2*

These organisms were selected in Phase 1 of the study, as the most suitable models of:

- Radiation resistant organism
- Bacterial spores
- A simple organism
- Small resistant virus

This gives reasonable coverage of microbiological organisms that are resilient to hostile environments, they are Earth based organisms – and have evolved to survive in Earth's environment.

Now Martian organisms will have evolved to survive in a Martian environment – the question is does this give potential for greater resilience than the Earth models. Specifically this work has looked at two types of sterilization:

- Heat sterilization (typically through the hyper velocity collision)
- Radiation resistance

Now with respect to each of these:

- The thermal environment during hyper velocity collision raises the temperature significantly above ambient. This will be equally true for a Martian environment as for an Earth environment. Hence it is not unreasonable to expect Martian organisms to behave similar to the terrestrial models.

- The radiation environment on Mars is dependent on the magnetic field of Mars. This was lost about four billion years ago, and similarly any significant Martian atmosphere was lost. Hence any Martian organism that has remained viable over that 10MY period, will have evolved mechanisms for surviving the radiation environment. This potentially gives greater resilience over terrestrial models.

Now with regards to the radiation tolerance, by selecting *D. radiodurans* the study has used the organism known to show increased resistance to radiation in a terrestrial environment, the radiation resistance of which is well beyond needed to survive Earth's radiation. Hence the study has maximized the resistance of the chosen organism.

However well justified, this still leaves the question of the suitability of terrestrial model organisms as representative of potential Martian organisms.

The Test Results of the radiation testing also show greater variably than is expected. The D Rad result in particular differs markedly from previous studies of the organism.

4.4. Hyper Velocity Assumptions

Testing during Phase 2 was necessarily limited:

- Impactor was a 2mm cylinder, and did not vary during testing

- The organism was always mounted in the same place, in a hole in the back

Hence the hyper velocity is very dependent on the quality of the HV model.

Specifically the modelling identified that once a sufficient velocity is reached, the impactor fragments to close to the grain size. This means that evolution of the hyper velocity collision becomes quite chaotic, which gives great variation in the temperature.

This brings in the first assumption, that sterilization is caused primarily via thermal heating in the collision.

Now the modelling of the sterilization seen in testing primarily uses the thermal sterilization model built up. Hence only one parameter (per organism) is fitted to the hyper velocity sterilization model – the rate of cooling of the organism. Hence the ability of the fit of the single parameter, over a range of velocities gives limited ability to fit the data.

This means the hyper velocity tests and sterilization modelling mainly becomes a validation of a sterilization model developed independent of the testing.

This validation gives confidence in the modelling, and hence gives confidence that the modelling when applied to Phobos/Deimos will give a good description.

4.5. Cloud Assumptions

Material that enters the cloud takes some time before it re-impacts a Martian moon. [AD2] gives this as months, years or centuries; it is clearly a far shorter period than the time on the moon (up to 10MY). Hence most material spends far longer on the Martian moon, than in the cloud.

So the model assumes that there is no sterilisation of material whilst it is in the cloud.

Where the time constant for sterilization becomes comparable to the maximal period in the cloud (centuries) then the cloud has the ability affect the result. This though will only be a second order effect, as most Martian material on the moons is expect to be transferred via direct transfer – and not spend any time in the cloud.

4.6. Radiation Assumptions

The radiation environment on the moons is assumed to be an infinite flat plane. Near the surface, it is expected that surface features (craters etc) will affect the radiation environment.

4.7. Isotropic Distributions

In building the Monte Carlo simulation, an important step in simplifying the calculation is isotropic distributions where this does not significantly affect the result:

- Isotropic distribution of impact events on Mars
- Isotropic probability for Mars ejectors to impact Phobos/Deimos dependent on orientation
- Isotropic distribution of impactors on the surface of Phobos/Deimos.

These assumptions are expected to have minimal effect on the results – and were used as they mean that the modelling was implemented in an efficient manner.

4.8. Sterilisation model assumption

For both the hyper velocity sterilisation model, and the radiation sterilisation model, when fitting the models to the sterilisation measurements, the measurements have no determination of error. Hence error can only be calculated in the fit of the model to the data. As error is a fitted parameter, there is no measure of goodness of fit of the model. This means there is an underlying assumption, that the model is correct, e.g. its form is not tested.

Now the model does receive some validation through examination of the fitted error, does it look consistent with the measurements (e.g. does it correlate to the spread in inactivation measurements).

4.9. VELOCITY OF IMPACT ON MARS

The isochrone distribution gives the size of craters on Mars, this is mainly driven by the size of the impactor. However the velocity of the impactor is also important, this has a minor effect on the size of crater produced, and a more marked effect on the mass of material ejected. Hence for a more complete description of the mass ejection needs both the crater size, and the impactor velocity.

Crater sizes are taken from the isochrones graph.

For the velocity of impact, the impactors are taken to arise predominantly from the asteroid belt. This is taken from Minton and Malhotra [RD9].

4.10. TIME OF EJECTION FROM MARS

The isochrones distribution gives the typical time period for craters of a certain size, observation of craters gives information on their age:

- Young craters have rays, where the material ejected leaves a mark on the surface of Mars
- As craters age, material slowly accumulates in the base of the crater, this means over time craters become less deep

This gives basic information on the time of ejection, but typically not on the scale of sterilization by radiation on the moon.

This means in in modelling only the average rate of emissions can be used, and the estimated variation this causes.

5. FOLLOWING LIFE, FOLLOWING IMPACT MATERIAL, TRANSFER FROM MARS TO THE MOON

5.1. INTRODUCTION

Phobos and Deimos are not expected to have any indigenous life. Hence any life that is present on Phobos and Deimos must have come from elsewhere. Considered here is the possibility for transfer of life from Mars to Phobos and Deimos.

Now Phobos and Deimos are airless, and that means all free water has sublimed – and so there is no free water. All known forms of life need free water to grow and multiply. Hence any Martian life transferred to Phobos and Deimos, must be desiccated when on the moon. This means that the organism is not growing (however it can still be viable if in a spore or dormant form). Because the organism cannot grow on Phobos, and there is no water in which it can be transported, it stays where it lies. The only process which can move the life is gardening, due to meteoroid impact on the surface, and during the 10MYear period considered under this study, the Phase 1 of this project identified that gardening will only give minor turnover of material [AD4].

Hence life ends up where the transfer from Mars deposited it. This means that transferred life follows the material on which it is transported. So by following the material transferred, one learns about the resting place of any life transferred.

Now if a Mars ejection has a possibility of impact with Phobos/Deimos, just minor differences in phasing will distribute material over half the surface area of the moon. Because of this, material is distributed over a wide area. Now if the material is re-ejected, it travels to the far side of the moon – again distributed over half the hemisphere. So after two collisions, material will cover the moon. The crux is the route to two collisions. In particular if the first collision dominates, what does this imply for distributed material, this is the question studied in this section.

5.2. PHOBOS

Considering first an ejection cone angle of 45°, and collision with Phobos.

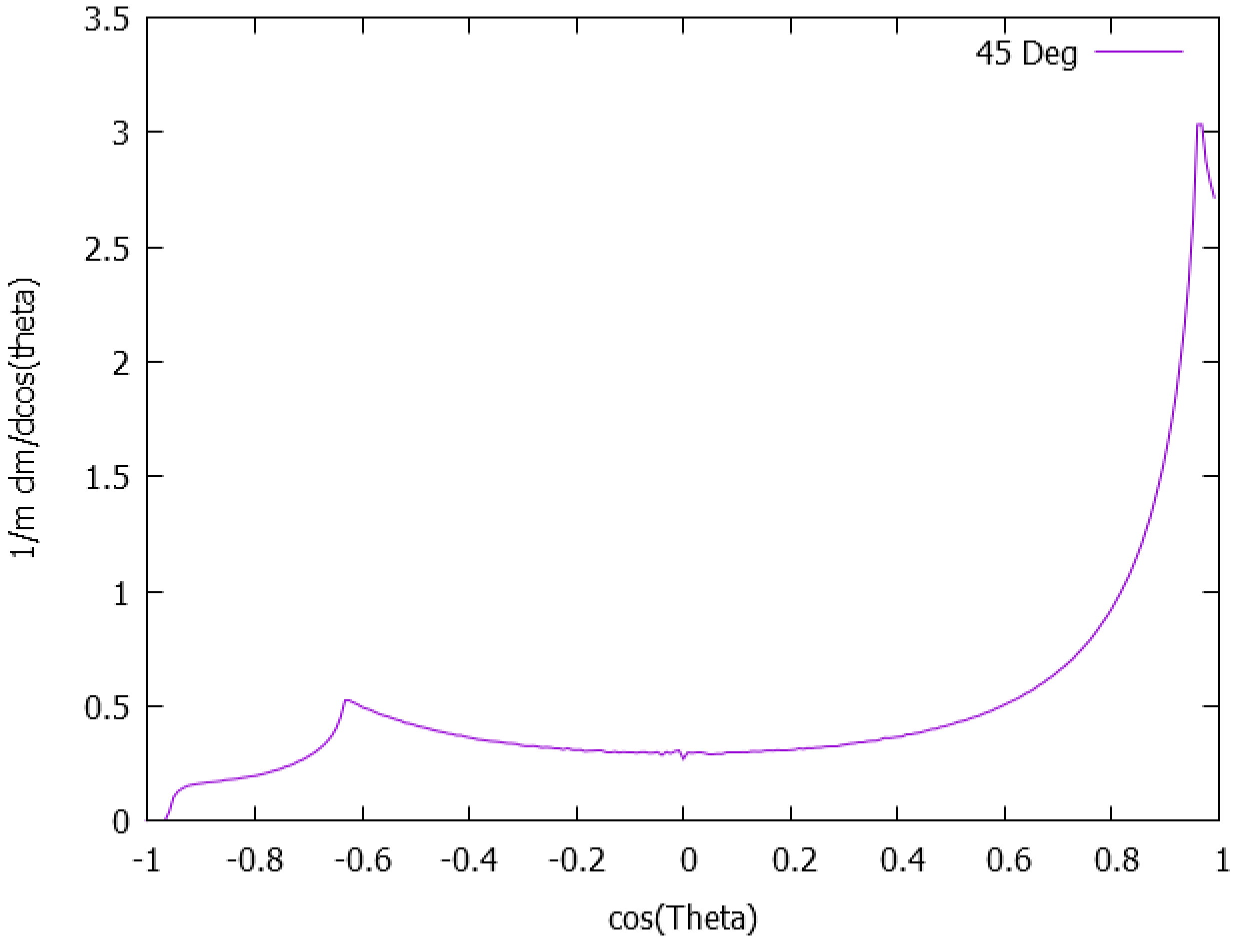

Figure 5-1. Normalised distribution for cosine of angle from facing Mars, most mass hits the face of Phobos towards Mars (cos=1), some material hits Mars on the way back on an elliptical orbit. There is no material that arrives from the direct anti mars direction, as possible material here has velocity over the escape velocity so does not return.

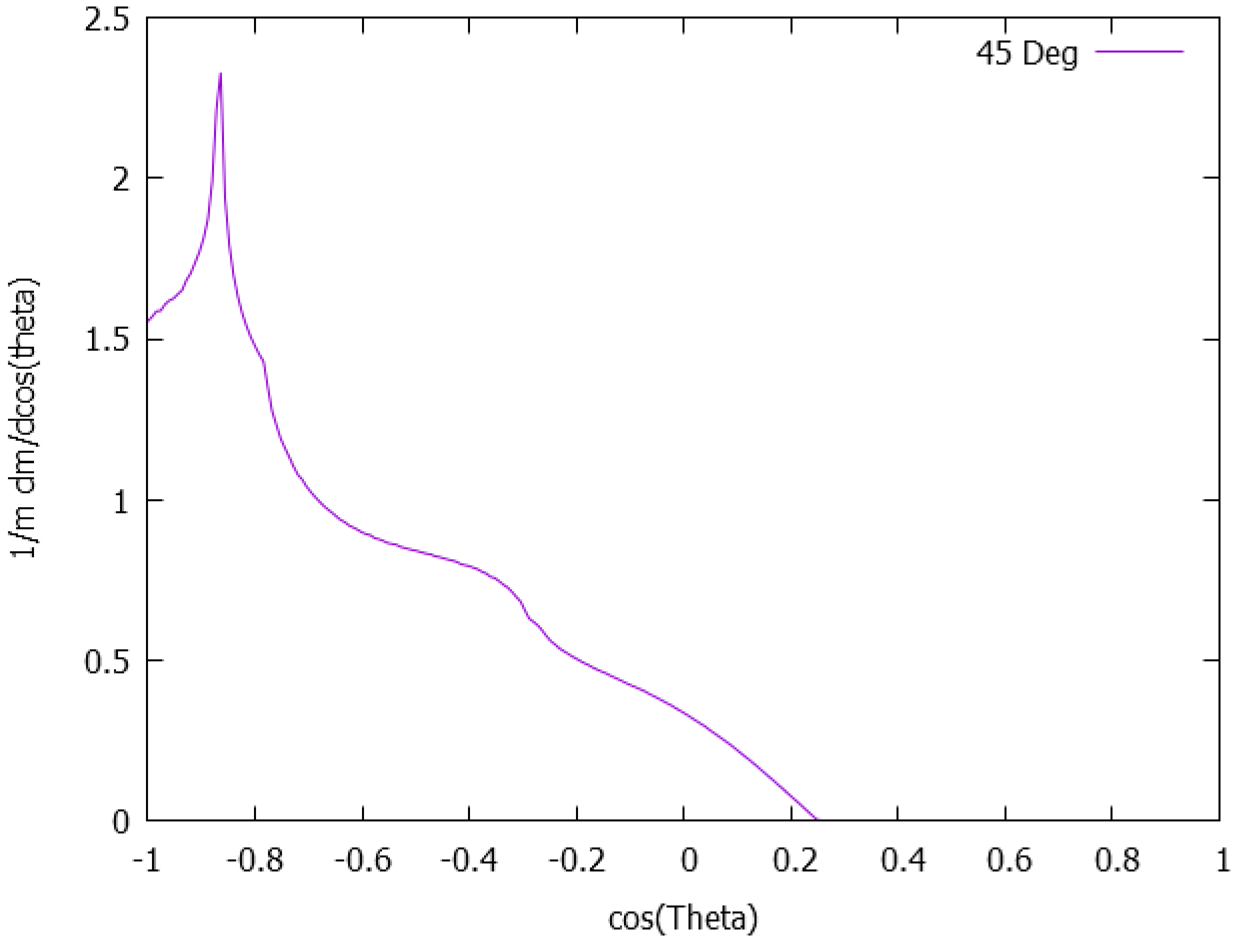

Figure 5-2. The normalised distribution for the cosine of the angle with respect to the direction of motion of the moon. As the moon moves at 2km/s most material hits the front face (cos=-1), with small amounts of material hitting the rear face.

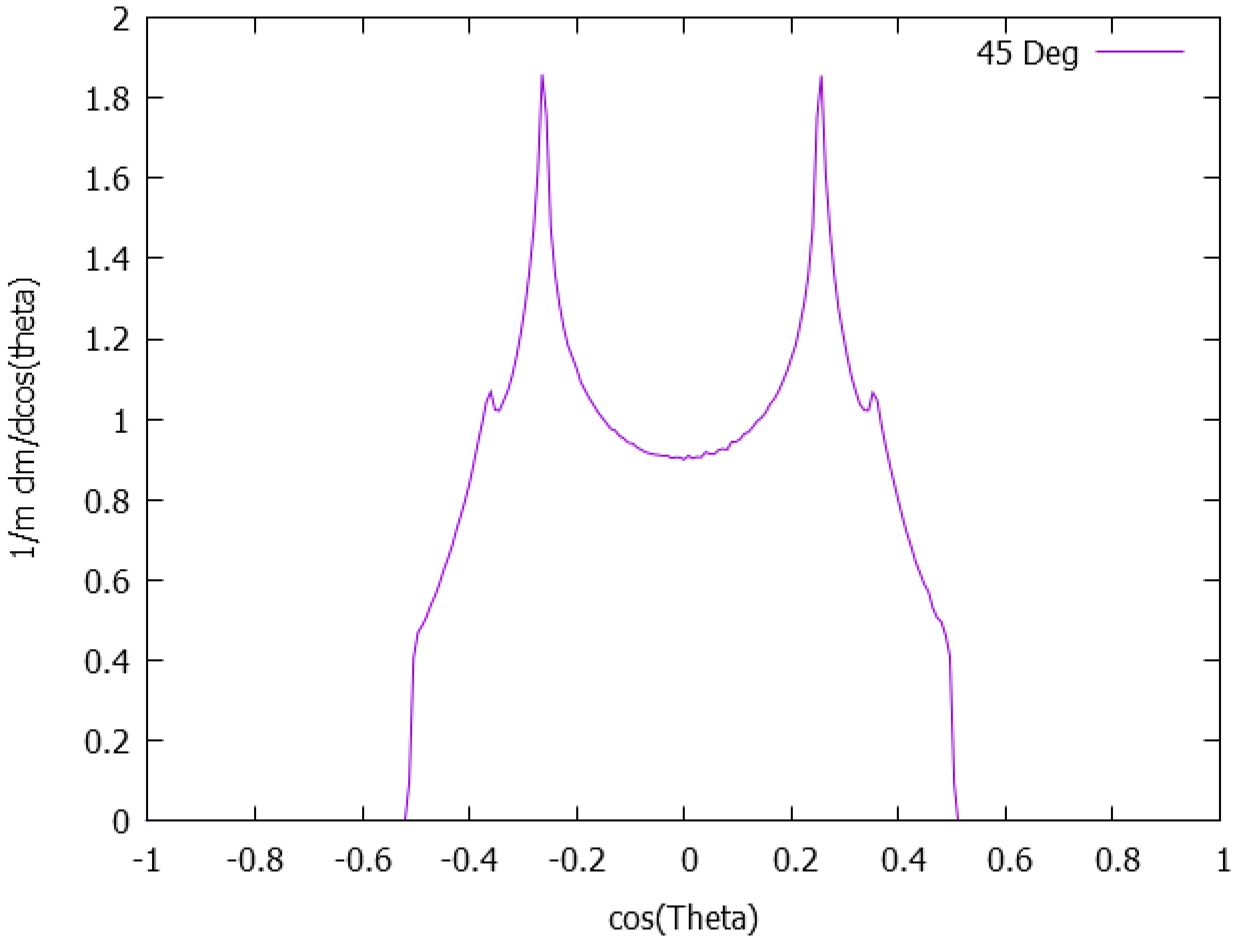

Figure 5-3. At 90 degrees to Phobos motion, no impacts directly from either side. With moons orbital velocity, this always gives velocity in this direction, so limiting the distribution.

These graphs show that the dynamic that dominates is the orbital velocity of Phobos. This means that the impact is preferably on the front face of Phobos. This limits the angular range of approach is limited in some cases. Now as each velocity vector will distribute material on half the area of Phobos, the range of the velocity vector mean much of the area of Phobos is covered. This justifies the approach of taking a uniform distribution of material deposited on Phobos.

There is a small area of exception, this is best seen by looking at the angle of approach around the orthogonal direction (so Mars is at theta=0, and Phobos travels in the theta=π/2 direction). This is shown in Figure 5-4. This will give a small area towards the tail of Phobos, where little material is deposited on the first collision.

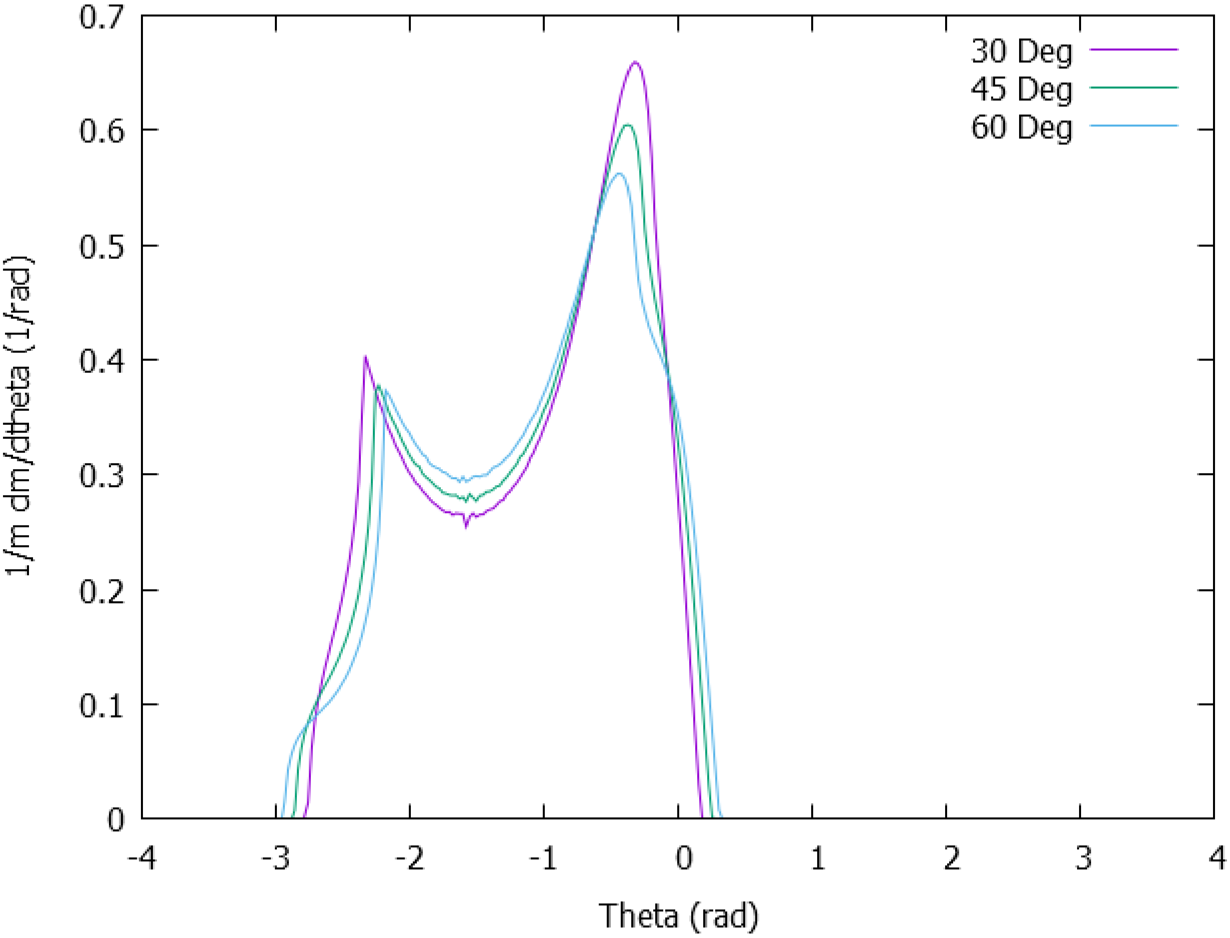

Figure 5-4. The normalised mass distribution for the angle about the orthogonal, for the velocity of first impact. Mars is in the theta=0 direction, Phobos velocity in the π/2 direction. This almost gives a full 180° where there is no material transferred. When mapped onto the Phobos surface this will give a small area in the tail of Phobos (against its velocity) where little material is deposited. The effect of the ejection cone angle (on Mars) is shown, as the cone gets wider more angular momentum is transferred, and this widens the area accessed.

5.3. DEIMOS

Taking these concepts to Deimos, the significant question is does there remain a small area where material is not deposited on the first transfer from Mars.

This is shown in the single graph considering the angle about the orthogonal direction to Deimos direction, with just a single ejection cone of 45°. The area of primary impacts is more restricted than for Phobos (presumably as most material can only hit Deimos on way out, and little on the return). Hence Deimos will have a larger area that does not have primary impacts.

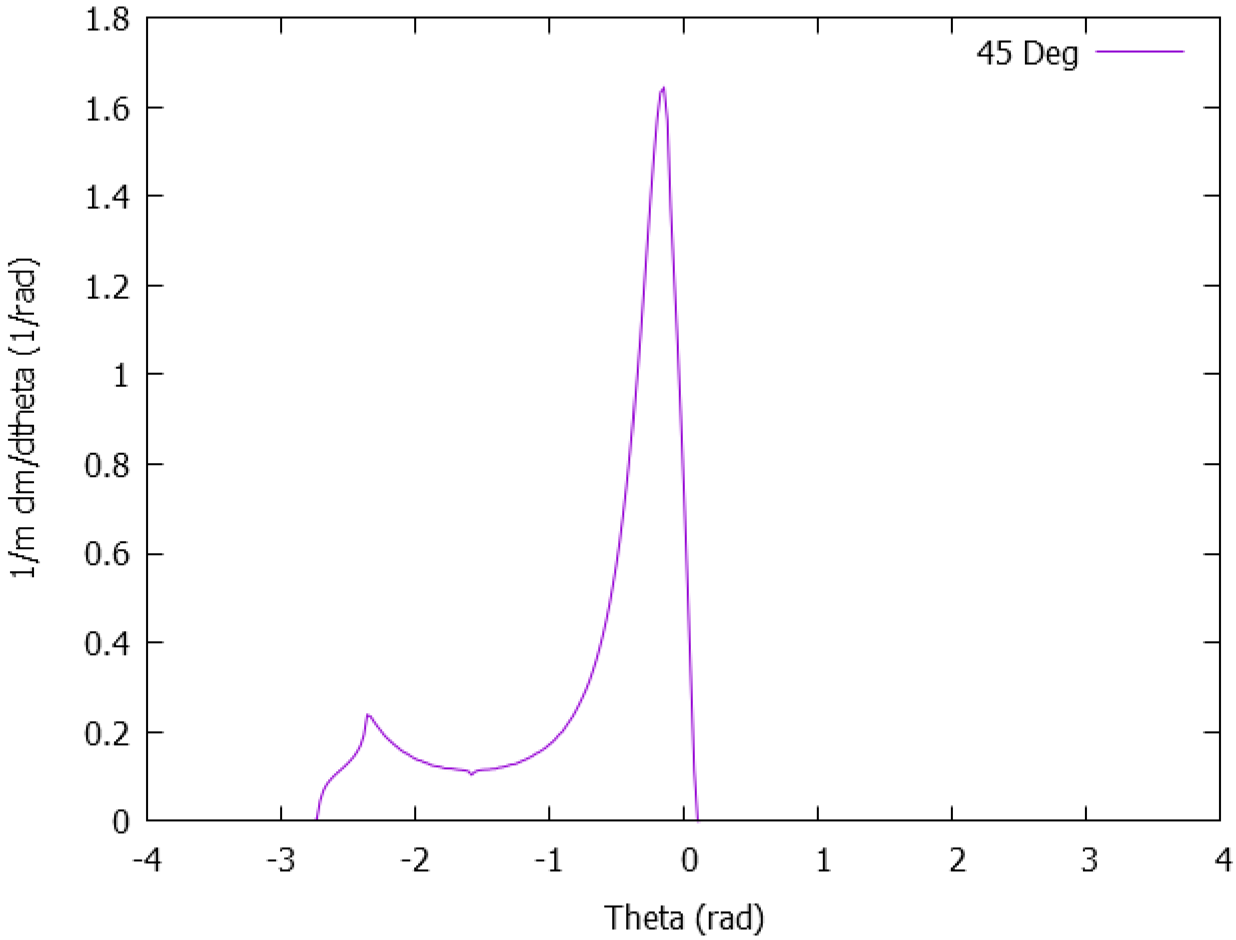

Figure 5-5. As for Figure 5-4, but plotted for Deimos and only for a 45degree ejection cone. The angular range is more restricted (most material hits Deimos on the way out, with little on the way back). This means Deimos will have a larger area where there are no direct impacts for material from Mars.

6. MASS TRANSFERRED – AND POTENTIAL LIFE CONTAINED

6.1. INTRODUCTION

The mass transferred has been normalised to Melosh [AD1] as detailed in [AD5]. As Melosh measured mass just up to ejection velocity of 5.5km/s; whilst the model used here generates all ejection velocities – this means we predict greater mass transfer. Melosh's value was for an ejection cone angle of 45°, here is tested the sensitivity to the ejection angle.

Finally the maximal loading of life in a sample is needed, this is taken as proportional to mass transferred [AD4](hence following mass in the Monte Carlo, follows life), the three values from the sensitivity analysis are considered:

- Low: 1e5 cfu/kg

- Medium: 1e7 cfu/kg
- High: 1e10 cfu/kg

6.2. PHOBOS

The level of life potentially transferred to Phobos is shown in Table 6-1.

Ejection Cone	Total Mass Transferred in 10MY	Potential Life Transferred		Life per area on Phobos (average)
30°	1.64e6 ± 4e2 kg	Low	1.64e11 cfu	1.06e2 cfu/m2
		Medium	1.64e13 cfu	1.06e5 cfu/m2
		High	1.64e16 cfu	1.06e7 cfu/m2
45°	1.63e6 ± 5e2 kg	Low	1.63e11 cfu	1.05e2 cfu/m2
		Medium	1.63e13 cfu	1.05e5 cfu/m2
		High	1.63e16 cfu	1.05e7 cfu/m2
60°	1.61e6 ± 5e2 kg	Low	1.61e11 cfu	1.03e2 cfu/m2
		Medium	1.61e13 cfu	1.03e5 cfu/m2
		High	1.61e16 cfu	1.03e7 cfu/m2

Table 6-1. Mass and life transferred for various ejection cone angles, and for various cfu loading rates for Mars Ejecta

The total mass transferred is higher than Melosh reported, as commented above this is due to this simulation covering mars ejection velocities over 5.5km/s. The graphs of the mass distribution with ejection velocity agree well.

The total mass transferred to Phobos isn't very sensitive to the ejection cone angle. The initial life transferred, with a maximal loading level of life on the transfer, is at a high level – however this is before any sterilization is considered.

The variation in life transferred to Phobos on loading of life on the Mars Ejecta is shown in Figure 6-1.

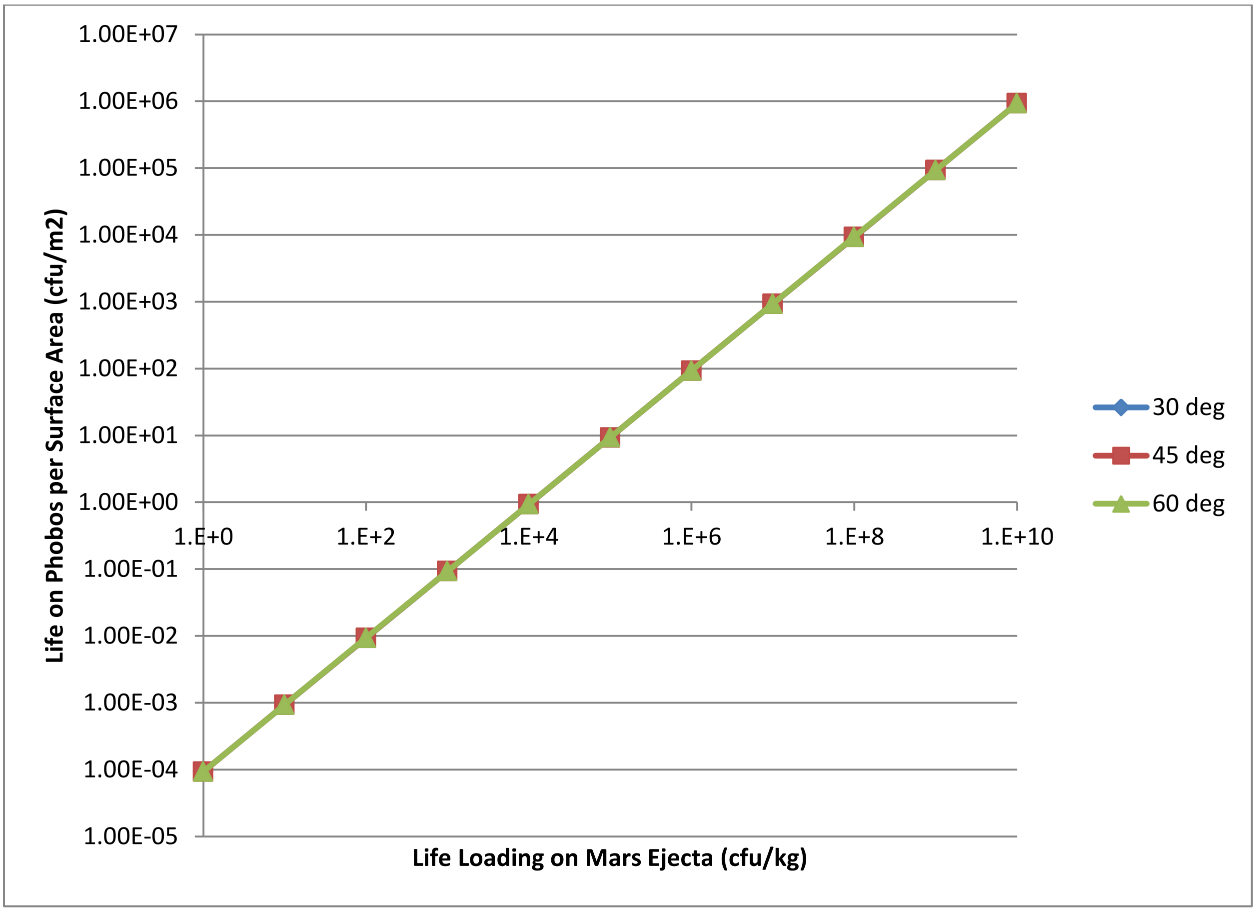

Figure 6-1. How life transferred to Phobos depends on life loaded on the Mars Ejecta

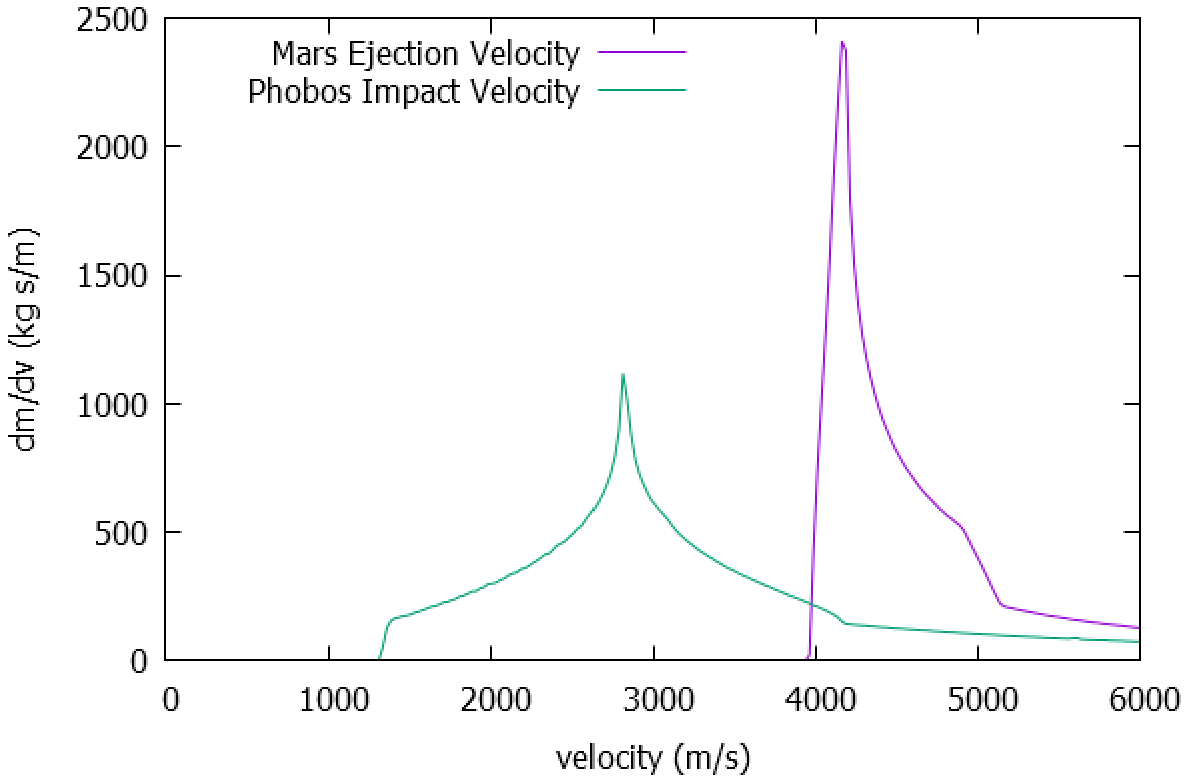

Figure 6-2. The mass distribution against velocity for Mars Ejecta, and Phobos Impactor, for impact with Phobos and a 30° ejection cone

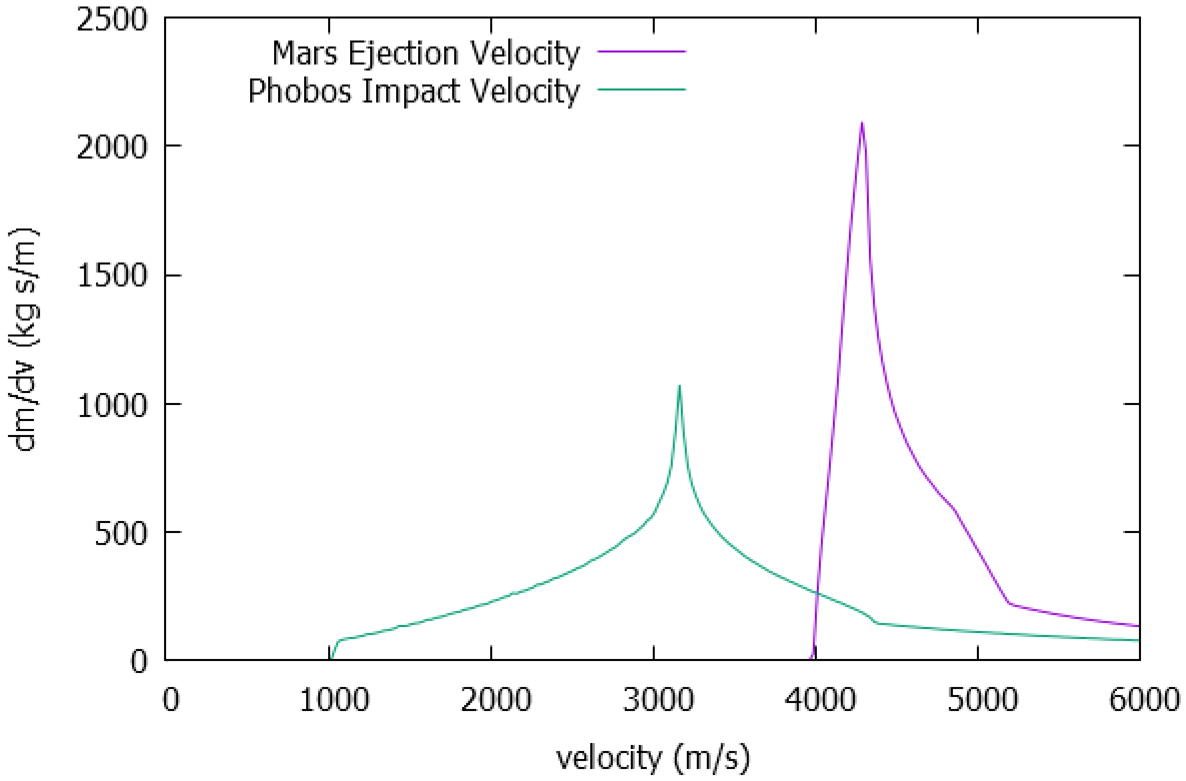

Figure 6-3. The mass distribution against velocity for Mars Ejecta, and Phobos Impactor, for impact with Phobos and a 45° ejection cone

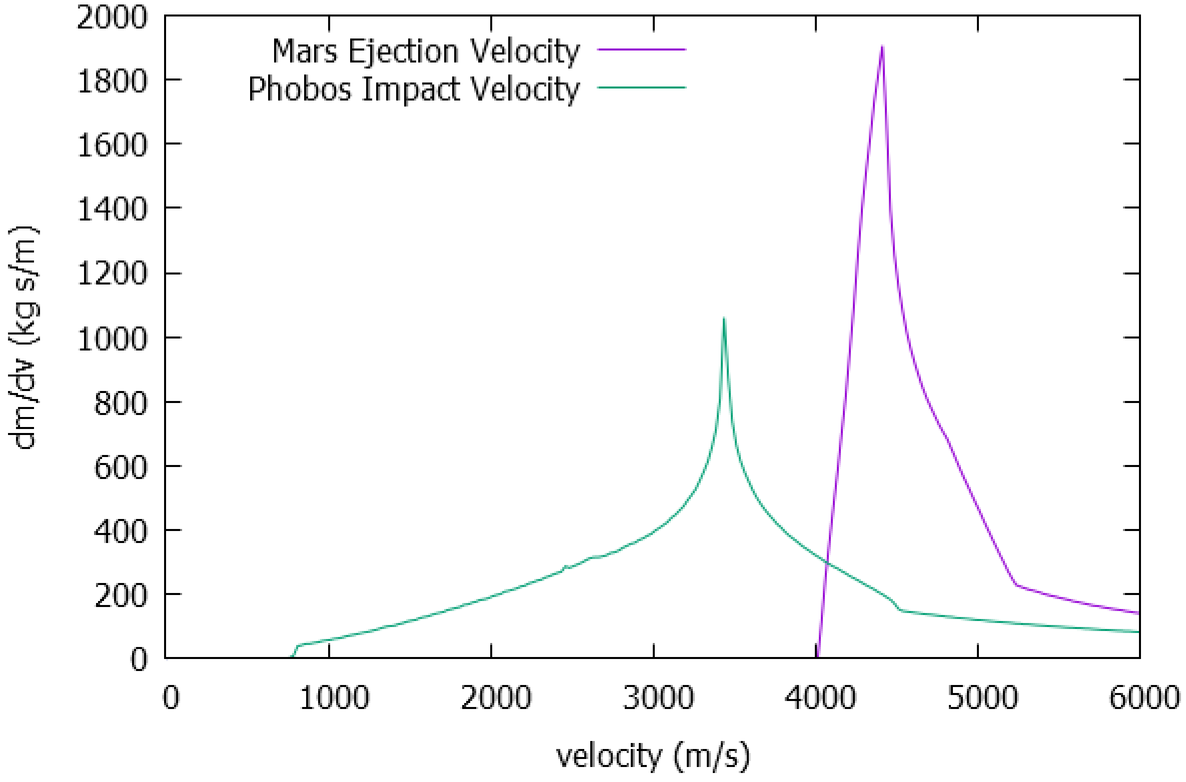

Figure 6-4. The mass distribution against velocity for Mars Ejecta, and Phobos Impactor, for impact with Phobos and a 60° ejection cone

Looking at the mass distributions against velocity, the Mars ejection velocity has minor dependence on the ejection cone, primarily the ejection cone angle affects the amount of angular momentum that ejector has – which has a minor effect on the orbital dynamics.

This differing angular momentum has a more marked effect on the impact velocity on Phobos, whilst wider cones generally increase the impact velocity, more important is that the distribution widens – and in particular goes to lower velocity. These lower velocities have the potential for less sterilization.

6.3. DEIMOS

For Deimos, the mass normalisation is still based on the Phobos value. However as Deimos is higher, it takes a larger velocity to reach, which decreases the mass transferred.

Ejection Cone	Total Mass Transferred in 10MY	Potential Life Transferred		Life per area on Deimos (average)
30°	4.61e4 ± 10 kg	Low	4.61e9 cfu	9.31 cfu/m2
		Medium	4.61e11 cfu	9.31e2 cfu/m2
		High	4.61e14 cfu	9.31e5 cfu/m2
45°	4.61e4 ± 9 kg	Low	4.61e9 cfu	9.31 cfu/m2
		Medium	4.61e11 cfu	9.31e2 cfu/m2
		High	4.61e14 cfu	9.31e5 cfu/m2
60°	4.62e4 ± 9 kg	Low	4.62e9 cfu	9.33 cfu/m2
		Medium	4.62e11 cfu	9.33e2 cfu/m2
		High	4.62e14 cfu	9.33e5 cfu/m2

Table 6-2. Mass and life transferred for various ejection cone angles.

The decreased mass means less life is transferred to Deimos, even with the maximal loading of life.

The dependence of life transferred to Deimos on the life loading rate on the Mars Ejecta is shown in Figure 6-5.

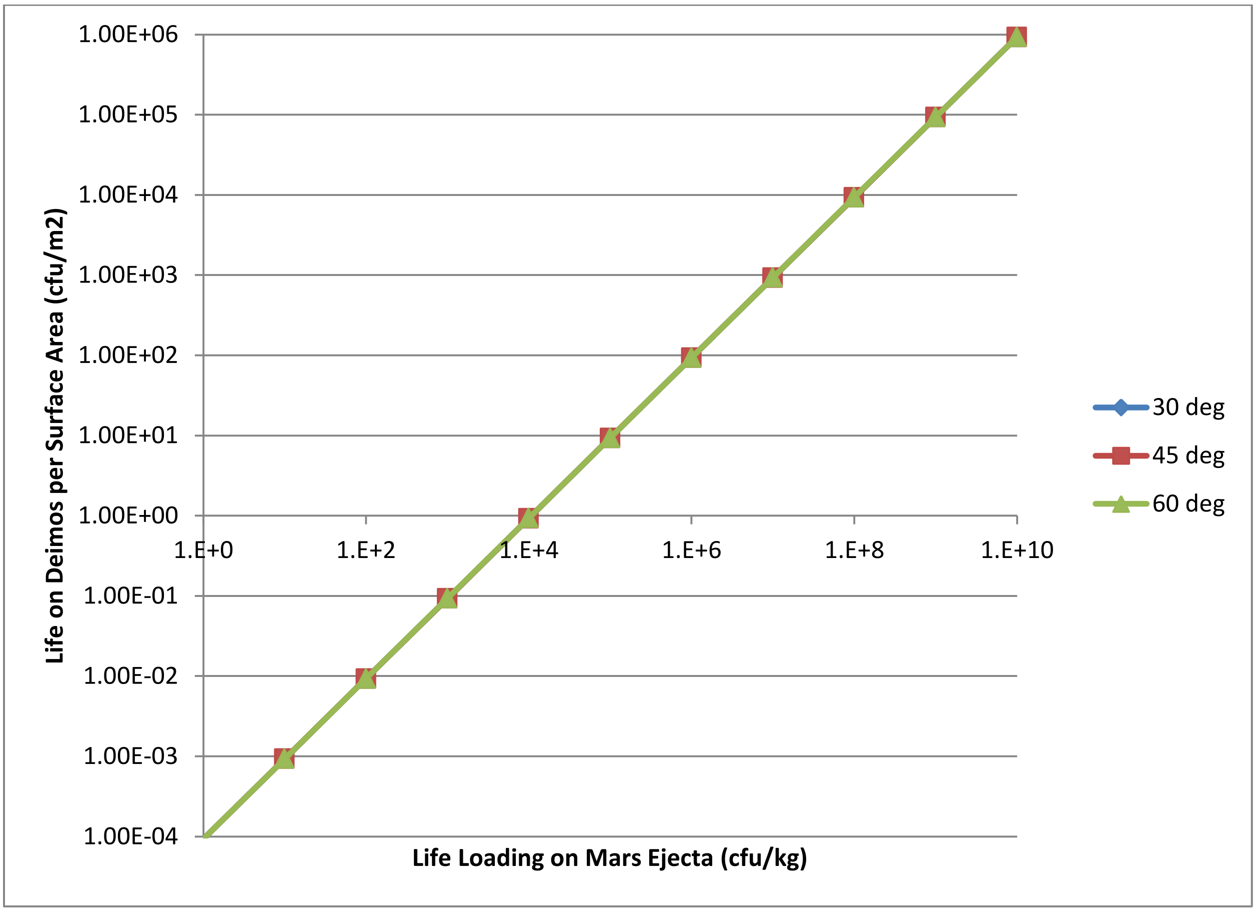

Figure 6-5. The dependence of life on Deimos on the loading of life on the Mars Ejecta.

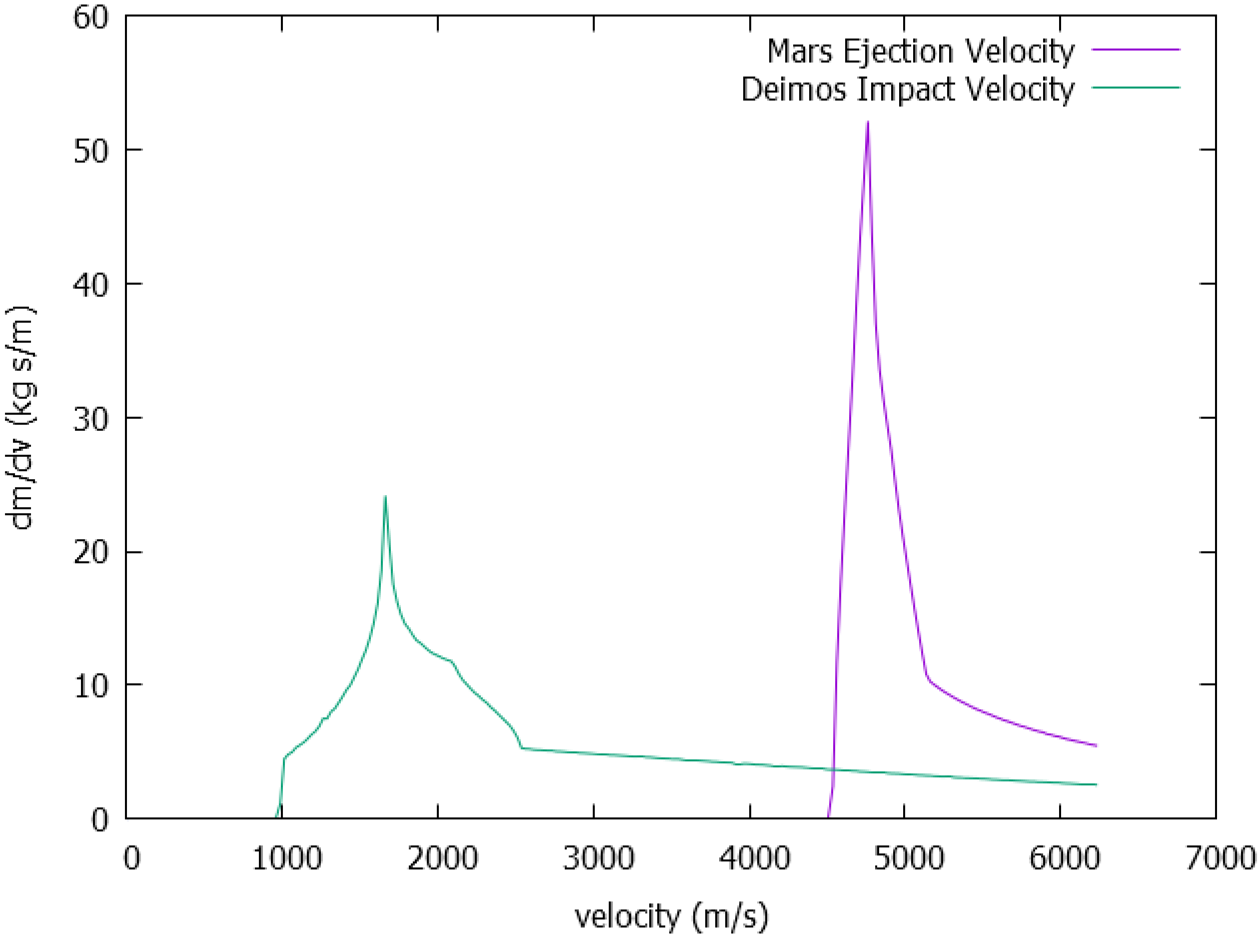

Figure 6-6. The mass distribution against velocity for Mars Ejecta, and Deimos Impactor, for impact with Deimos and a 30° ejection cone.

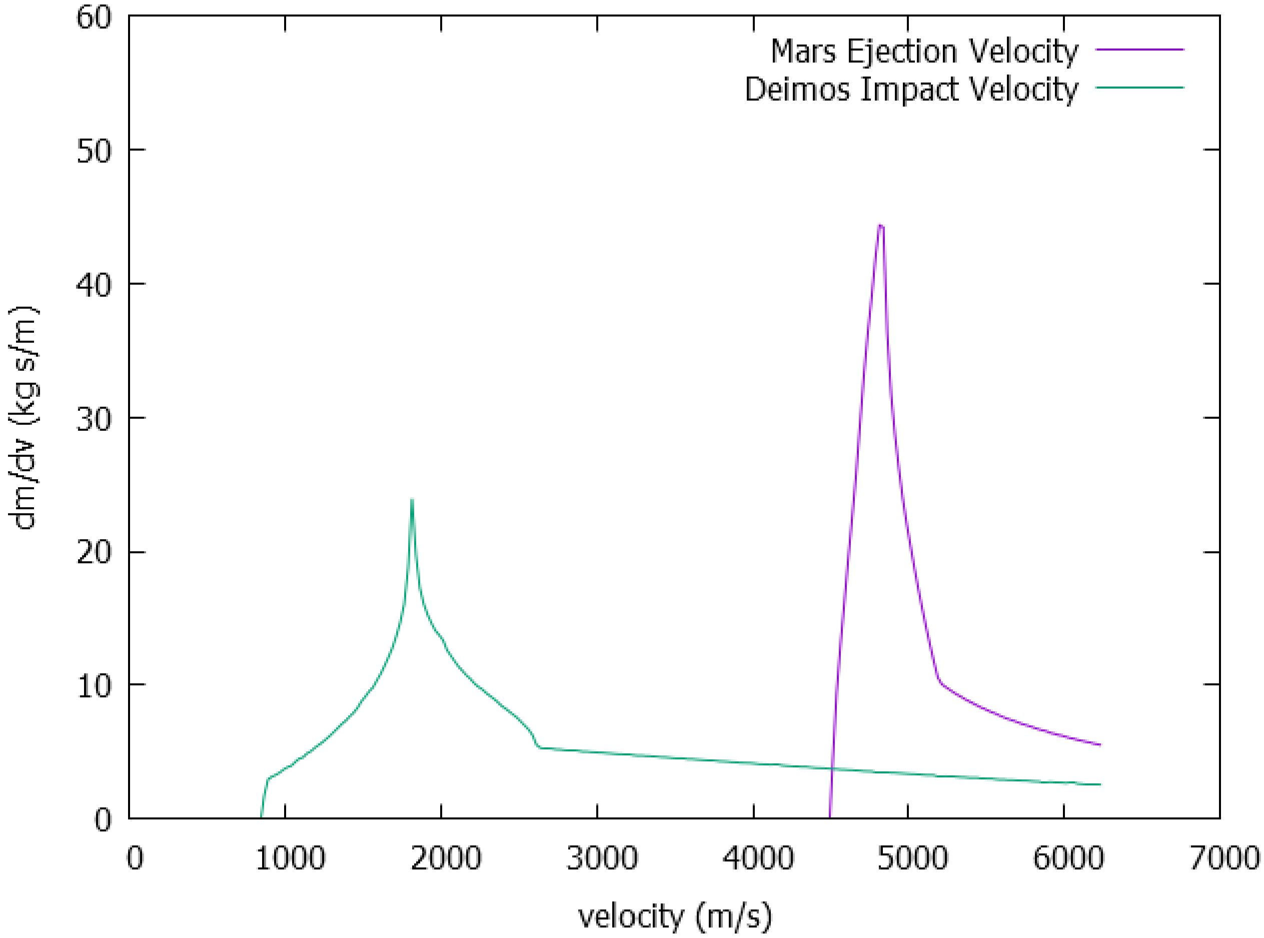

Figure 6-7. The mass distribution against velocity for Mars Ejecta, and Deimos Impactor, for impact with Deimos and a 45° ejection cone.

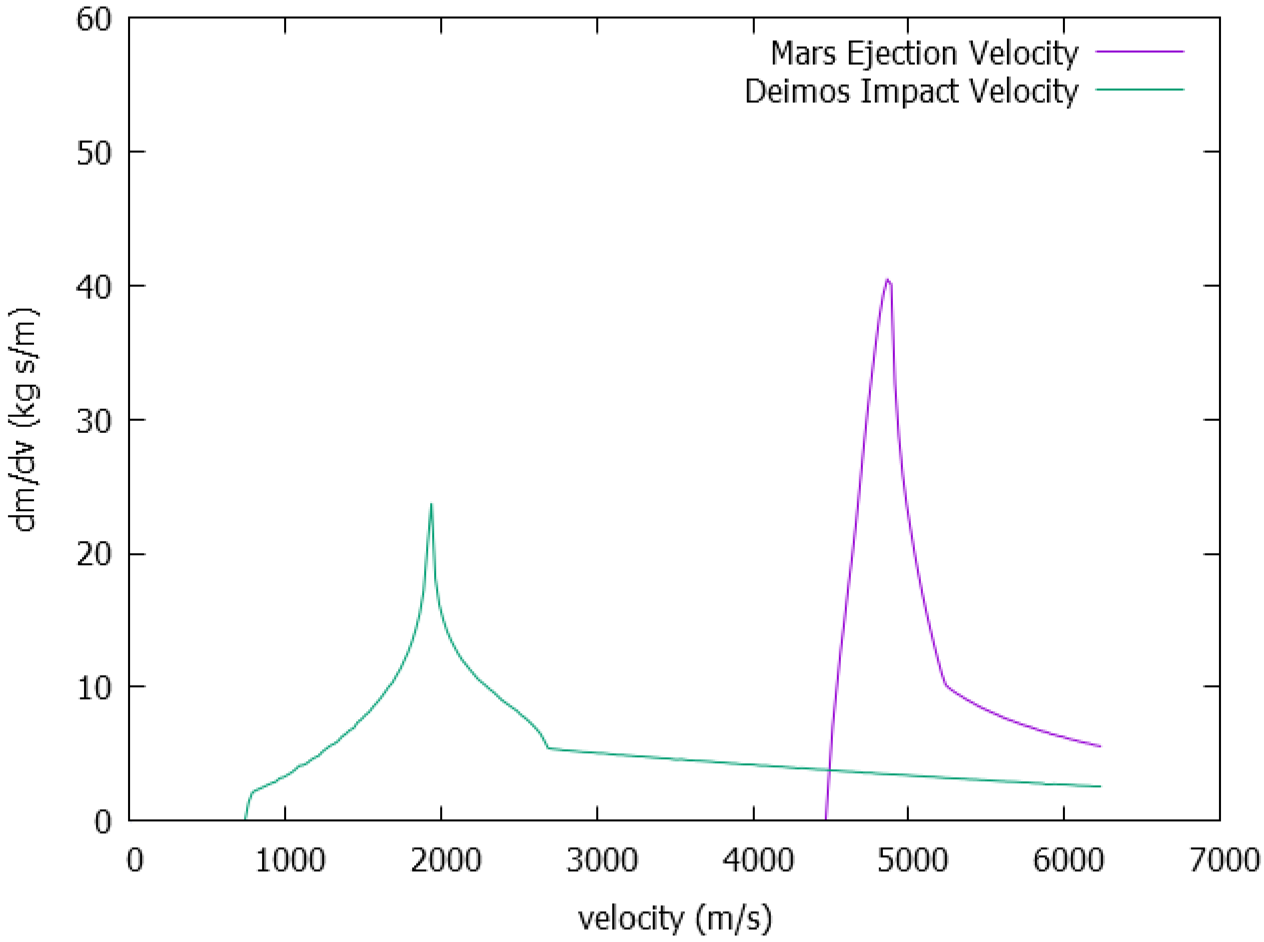

Figure 6-8. The mass distribution against velocity for Mars Ejecta, and Deimos Impactor, for impact with Deimos and a 60° ejection cone.

The minimum Mars ejection velocity to reach Deimos is increased, due to the larger orbit for Deimos. The impact velocity on Deimos if anything is decreased relative to Phobos, orbital speeds at Deimos altitudes are reduced, and this gives rise to slower impacts.

7. THE FIRST HYPERVELOCITY COLLISION WITH THE MOON

7.1. INTRODUCTION

The impact of the Mars ejector on Phobos/Deimos has multiple effects that affect life:

- The energy of impact gives rise to flash heating, which inactivates any organism. The level of organism inactivation, or sterilization, is a key process by which life is sterilized – and so a key result of the project.

- Ejection probability; material can be either deposited, or ejected, as a result of the impact. This affects the history of the material, does it get transferred to a cloud about Mars, and subsequent collision with Phobos/Deimos.

- If deposited on the moon, what depth is the material deposited at. Whilst this does not immediately sterilize material, it affects the long term radiation environment – which is the secondary sterilizing effect considered in the next section.

- If ejected, what is the velocity and mass of the ejected material. The velocity affects subsequent impacts with the moon, and so future sterilization. The mass, affects both subsequent impacts, and also if the material is small enough it is ejected from Mars orbit due to perturbations.

7.2. PHOBOS

7.2.1. Introduction

This section considers the mass that impacts Phobos, of that how much settles in the first impact, and of that how much of that mass is unsterilized.

The sterilization depends on the organism, and so all are tried in turn.

For these numbers one cone mode has been chosen, and this is documented.

7.2.2. Sterilisation

Organism	Mass deposited in first impact (kg)	Unsterilized mass in first impact (kg)	Potential Life Transferred		Life per area on Phobos (average)
B. atrophaeus	1.33e6 +/- 3.71e2	2.83e5 +/- 2.24e2	Low	2.83e10 cfu	1.83e1 cfu/m2
			Medium	2.83e12 cfu	1.83e3 cfu/m2
			High	2.83e15 cfu	1.83e6 cfu/m2
B. diminuta	1.33e6 +/- 3.71e2	2.87e5 +/- 2.32e2	Low	2.87e10 cfu	1.85e1 cfu/m2
			Medium	2.87e12 cfu	1.85e3 cfu/m2
			High	2.87e15 cfu	1.85e6 cfu/m2
D. radiodurans	1.33e6 +/-	3.50e5 +/-	Low	3.50e10 cfu	2.26e1 cfu/m2
			Medium	3.50e12 cfu	2.26e3 cfu/m2

	3.71e2	2.53e2	High	3.50e15 cfu	2.26e6 cfu/m2
MS2 coliphage	1.33e6 +/- 3.71e2	2.85e5 +/- 2.27e2	Low	2.85e10 cfu	1.84e1 cfu/m2
			Medium	2.85e12 cfu	1.84e3 cfu/m2
			High	2.85e15 cfu	1.84e6 cfu/m2
Super Bug	1.33e6 +/- 3.71e2	4.06e5 +/- 2.66e2	Low	4.06e10 cfu	2.62e1 cfu/m2
			Medium	4.06e12 cfu	2.62e3 cfu/m2
			High	4.06e15 cfu	2.62e6 cfu/m2

Table 7-1. Sterilisation caused by Hyper Velocity Impact, for three levels of life loading on the Mars Ejecta

The above table was calculated for a Cone Angle of 45°. This corresponds to 1.63e6 kg that impacts Phobos, of this 1.33e6 kg settles on first impact. The surface area of Phobos is taken as 1548.3km^2.

The sterilization achieved is less than 1 order of magnitude for all organisms considered. This has been traced back to the chaotic nature of the impact, where some areas are significantly heated – but a significant fraction has almost no heating. It is the mass that has no heating that transfers life – and clearly in this first collision much potential life is deposited on Phobos.

The dependence on the life loading rate on the Mars Ejecta is shown in Figure 7-1.

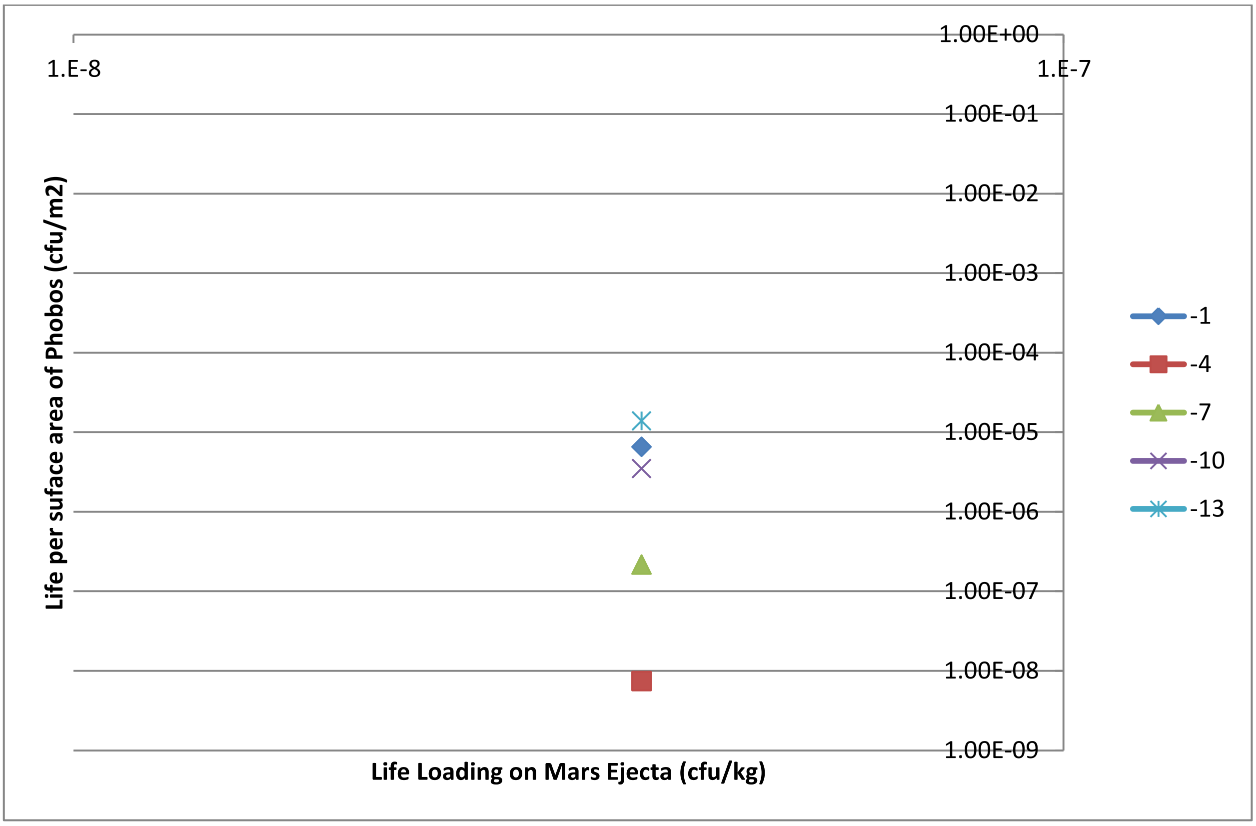

Figure 7-1. The dependence of the density of life on Phobos, on the loading of life on the Mars Ejecta.

7.2.3. Mass Deposited/Ejected

Cone Angle	Mass Deposited on first collision (kg)	Mass Ejected on First Collision (kg)	%age ejected
30°	1.34e6+/-3.38e2	2.98e5+/-1.70e2	22%
45°	1.33e6+/-3.74e2	2.96e5+/-1.67e2	22%
60°	1.32e6+/-3.82e2	2.93e5+/-1.79e2	22%

Table 7-2. Dependence of mass deposited on the Mars ejection cone angle

The previous section showed that that most mass is deposited on the first collision. How this depends on the cone angle is shown above. Clearly there is almost no dependence. This is not a surprise, the probability of ejection depends only on the impact angle, and the impact angle is down to the phasing of the Mars ejector, to Phobos phase – as such it is almost totally dependent on the shape of Phobos.

The 22% that is ejected, does this end on Phobos? This can only affect the life transferred to Phobos by ~22%, and so is not a major effect. Hence it can be seen that the dominant process is where mass is deposited on the Moon in the first collision.

7.2.4. Deposited Depth

The depth the deposited material is left at, depends critically on the properties of the Phobos regolith. With the most likely scenario, where the regolith bounces back to its original shape after the impact, almost all the impact material will be left on the surface.

Hence the primary question is if the regolith does not have the "bounce" effect. Then the depth of the deposited material is dependent on the size of the impactor. This in turn depends on the size of Mars ejecta, which is also poorly constrained. Typically the possible depth deposited is a multiple of the impactor radii.

So considering the minimum mass of Mars ejecta of 1g, a fairly large value. The depth deposited set to 1 radii. The resulting depth distribution is shown in Figure 7-2 for the total mass transferred to Phobos.

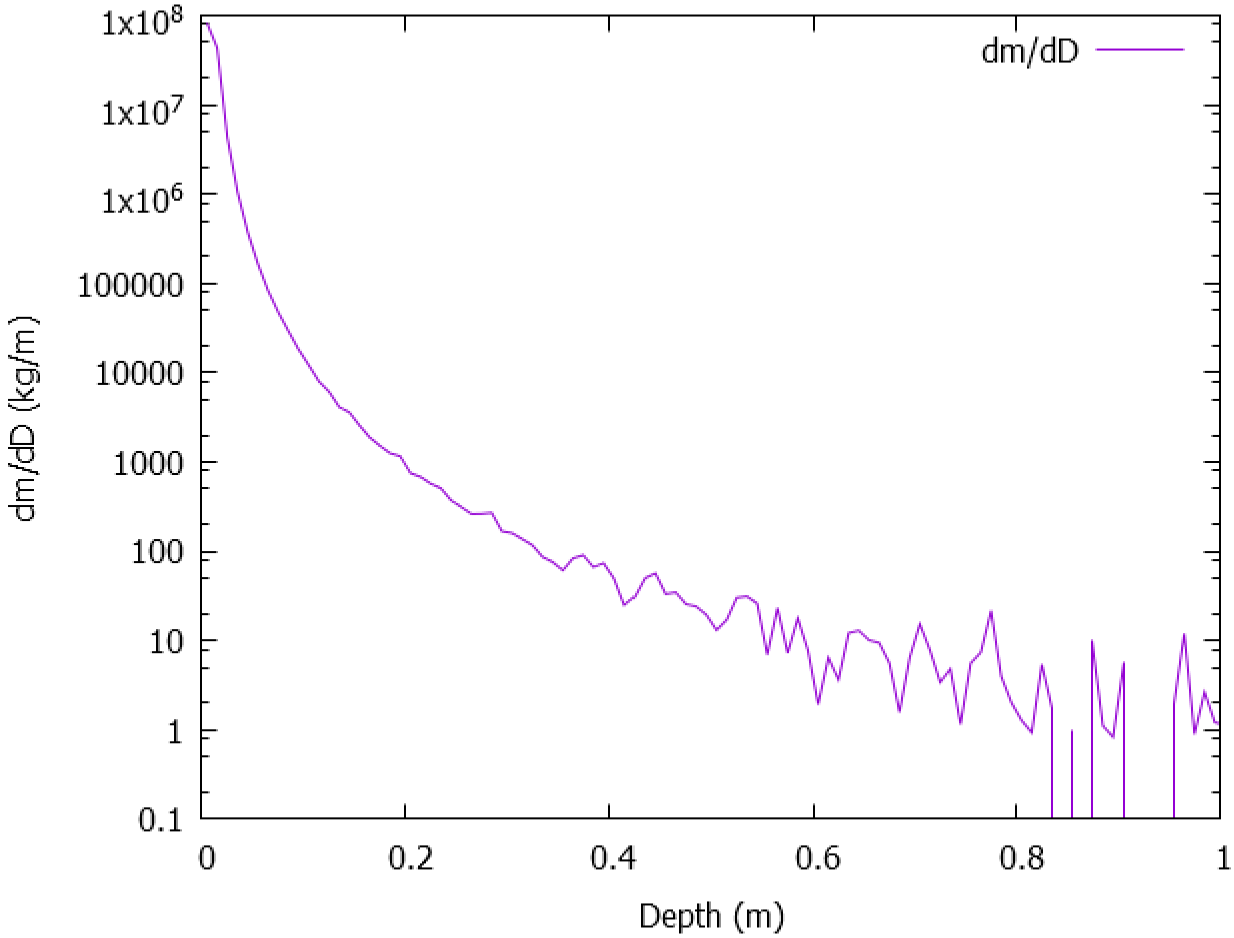

Figure 7-2. The depth distribution when impactors are deposited at 1radii.

What is clear, is that where depth deposited is dependent on the impactor size, the steeply falling mass distribution of Mars ejecta gives a steeply falling depth distribution – with most material deposited at the surface of Phobos. For a 1g lower mass of ejecta, the mass distribution of impactors is shown in Figure 7-3.

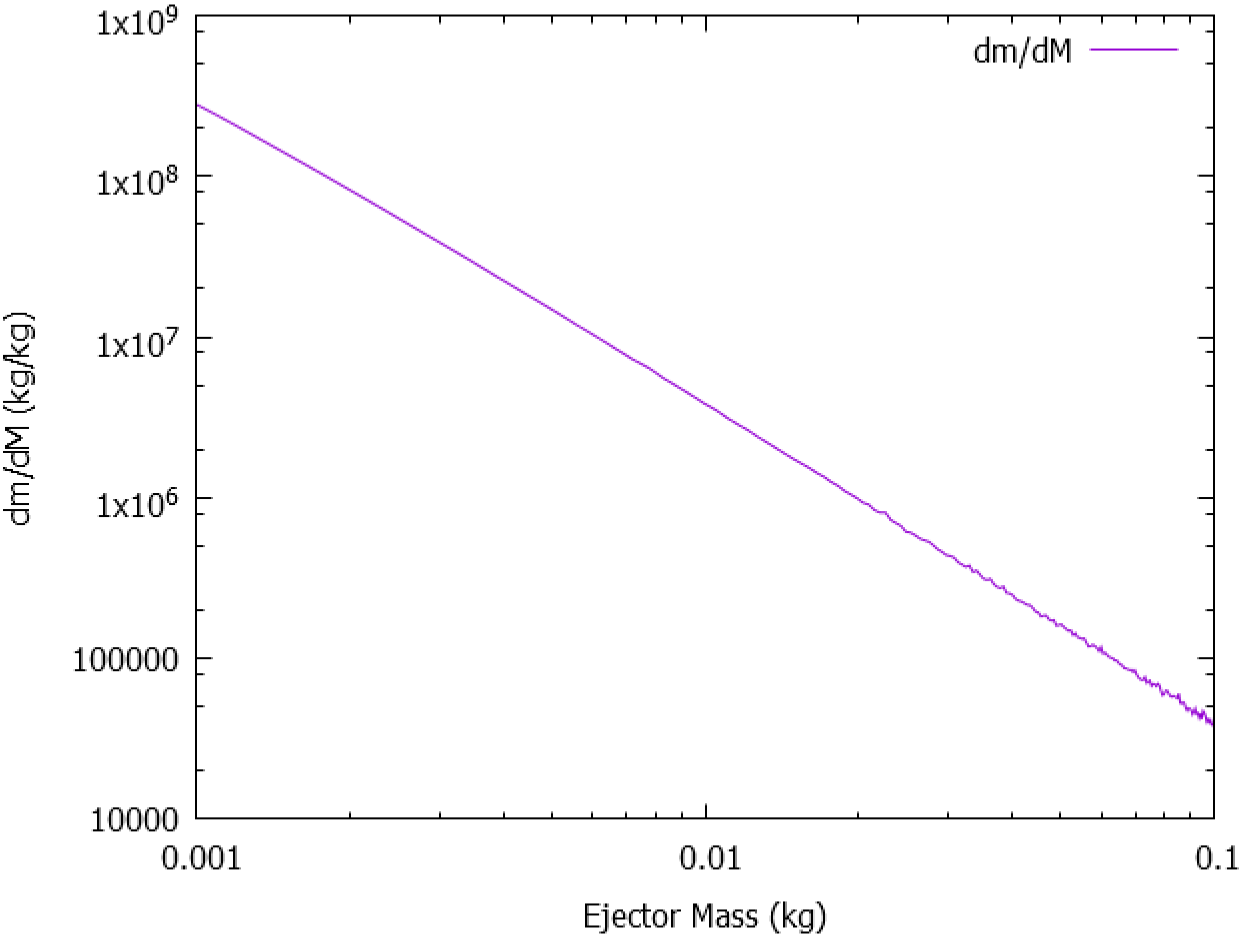

Figure 7-3. The mass distribution of the mars ejecta, where the minimum mass is 1g.

Where the steeply falling distribution means by far most mass is at the lower boundary.

Hence where the depth deposited depends on impactor radii, impactor radii depends on Mars ejecta mass, and the ejecta mass is poorly known other than it is a steeply falling distribution. So this would imply the depth that material is deposited is similarly poorly known.

Hence two elements point that material will be deposited on the surface of Phobos:

- The regolith is expected to bounce back after the compression of the collision, and return impactor material to the surface [RD2]
- The steeply falling mass distribution for Mars ejecta, means the impactors have very little potential for excavating into the surface of Phobos. [AD2]

So material will be very close to the surface.

7.2.5. Ejected Velocity and Mass

The ejected material has velocity distribution shown in Figure 7-4 this is to be compared to Figure 6-3 the impact velocity on Phobos when a 45° ejection cone is used.

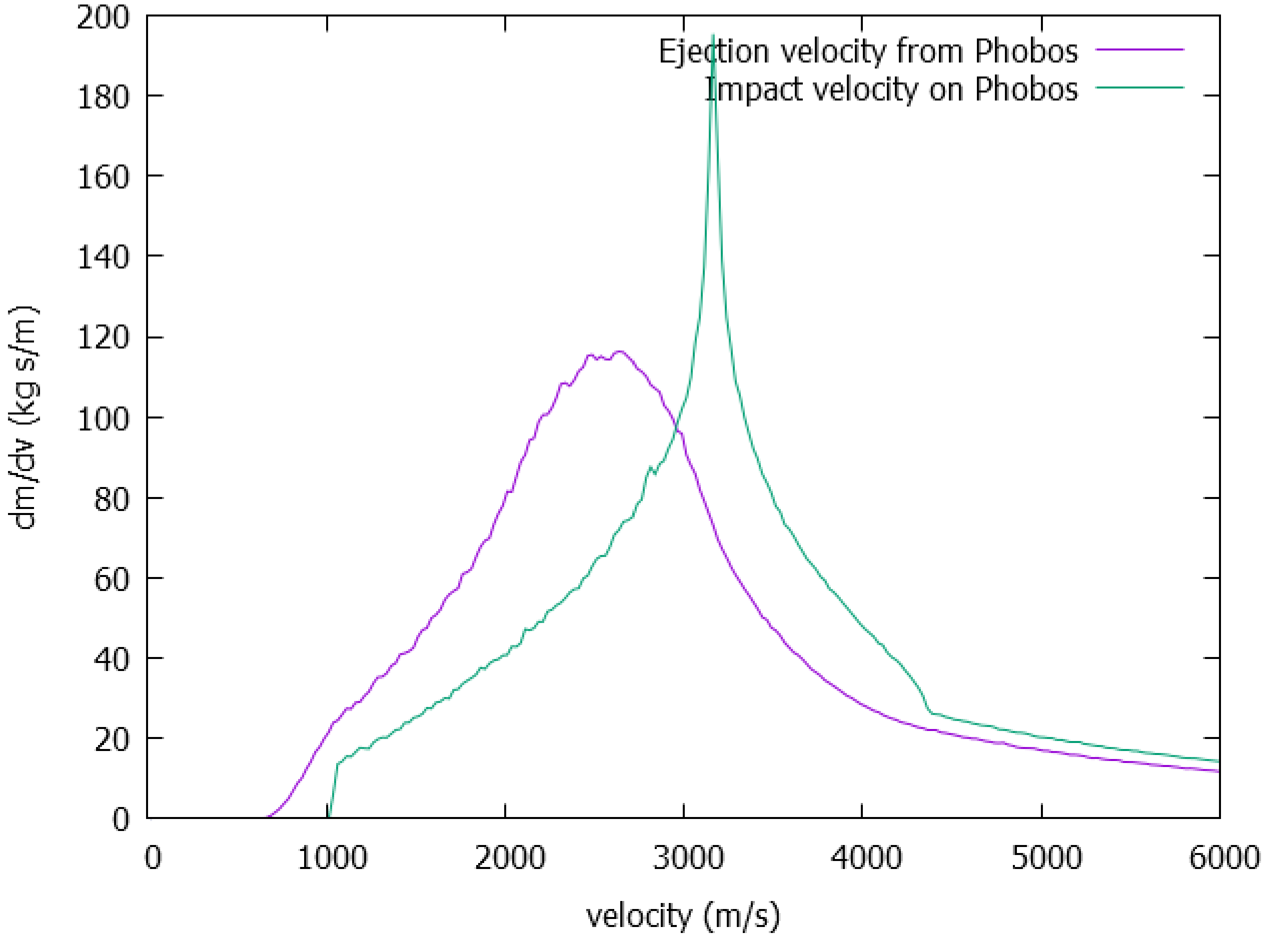

Figure 7-4. Velocity distribution, of the material ejected before and after first collision with Phobos in the Phobos frame.

The velocity is decreased during the impact, and the distribution has been smoothed. However the decrease in velocity is minor. This will mean that many of these ejecta will escape from the Mars orbit.

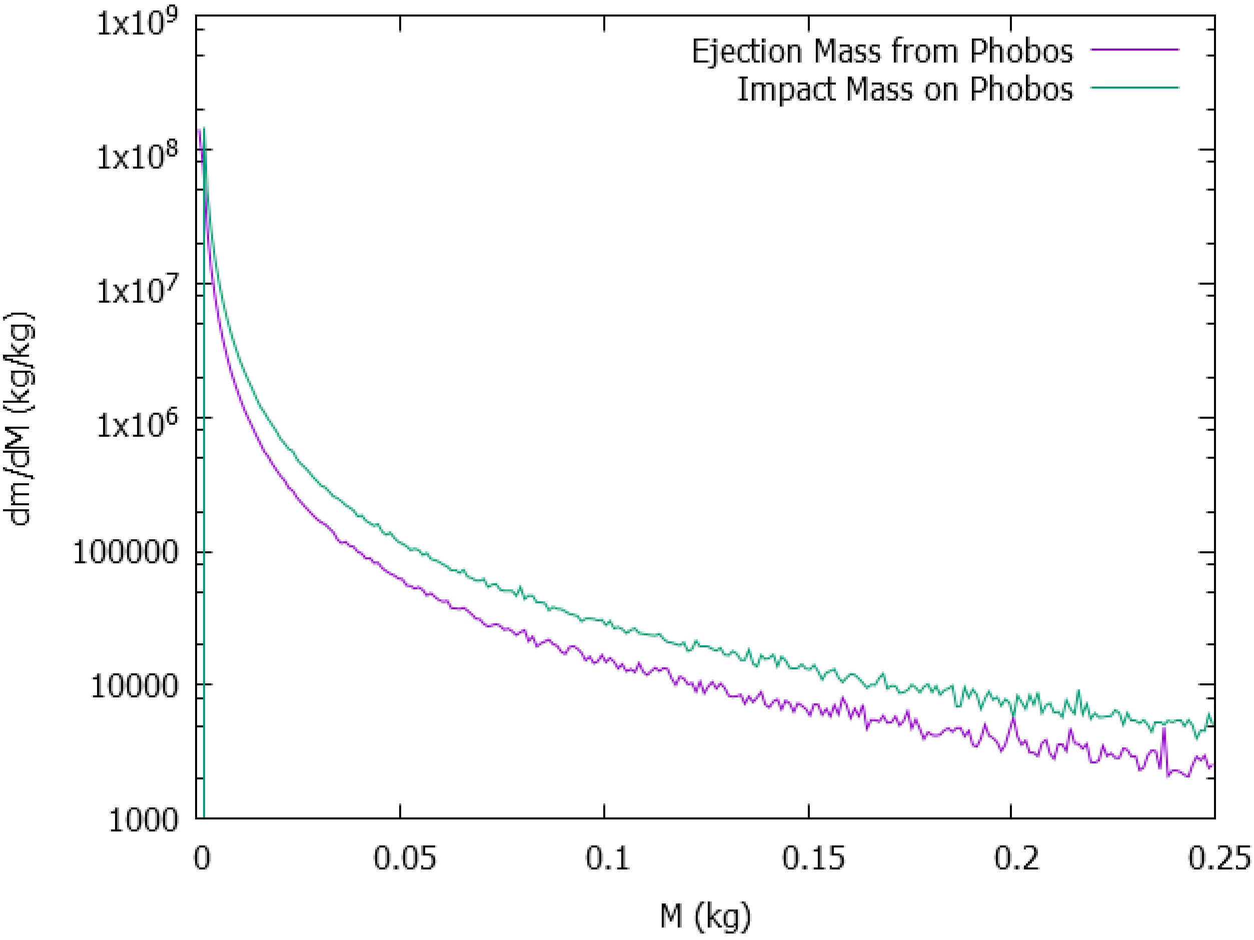

Figure 7-5. Comparison of the mass of material ejected (from the first Phobos collision) against the mass

Shown in Figure 7-5 is the mass distribution of ejected material, and also the same material when it impacted Phobos. This is plotted for the assumption that the ejected material stays as a single object, and is not fragmented. Clearly the mass of the object is decreased (as some material is typically deposited) however the decrease is minimal. Note that the impact mass is steeply falling distribution – as this is the expected distribution from Mars ejecta.

7.3. DEIMOS

7.3.1. Sterilization

Organism	Mass deposited in first impact (kg)	Unsterilized mass in first impact (kg)	Potential Life Transferred		Life per area on Deimos (average)
Bacillus atrophaeus	3.78e4 +/- 9.39	1.12e4 +/- 8.77	Low	1.12e9 cfu	2.26 cfu/m2
			Medium	1.12e11 cfu	2.26e2 cfu/m2
			High	1.12e14 cfu	2.26e5 cfu/m2
Brevundimonas diminuta	3.78e4 +/- 9.39	1.14e4 +/- 8.88	Low	1.14e9 cfu	2.30 cfu/m2
			Medium	1.14e11 cfu	2.30e2 cfu/m2
			High	1.14e14 cfu	2.30e5 cfu/m2
Deinococcus radiodurans	3.78e4 +/- 9.39	1.26e4 +/- 9.04	Low	1.26e9 cfu	2.54 cfu/m2
			Medium	1.26e11 cfu	2.54e2 cfu/m2
			High	1.26e14 cfu	2.54e5 cfu/m2
MS2 coliphage	3.78e4 +/- 9.39	1.13e4 +/- 8.81	Low	1.13e9 cfu	2.28 cfu/m2
			Medium	1.13e11 cfu	2.28e2 cfu/m2
			High	1.13e14 cfu	2.28e5 cfu/m2
Super Bug	3.78e4 +/- 9.39	1.35e4 +/- 9.05	Low	1.35e9 cfu	2.73 cfu/m2
			Medium	1.35e11 cfu	2.73e2 cfu/m2
			High	1.35e14 cfu	2.73e5 cfu/m2

Table 7-3. Sterilisation caused by Hyper Velocity Impact, with three levels of life loading on the Mars Ejecta

The above table was calculated for a Cone Angle of 45°. This corresponds to 4.61e4 kg that impacts Deimos, of this 3.78e4 kg settles on first impact. The area of Deimos is taken as 495.1548km^2.

The sterilization achieved is less than 1 order of magnitude for all organisms considered. This has been traced back to the chaotic nature of the impact, where some areas are significantly heated – but a significant fraction has almost no heating. It is the mass that has no heating that transfers life – and clearly in this first collision much potential life is deposited on Deimos.

The dependence on the life loading rate on the Mars Ejecta is shown in Figure 7-6.

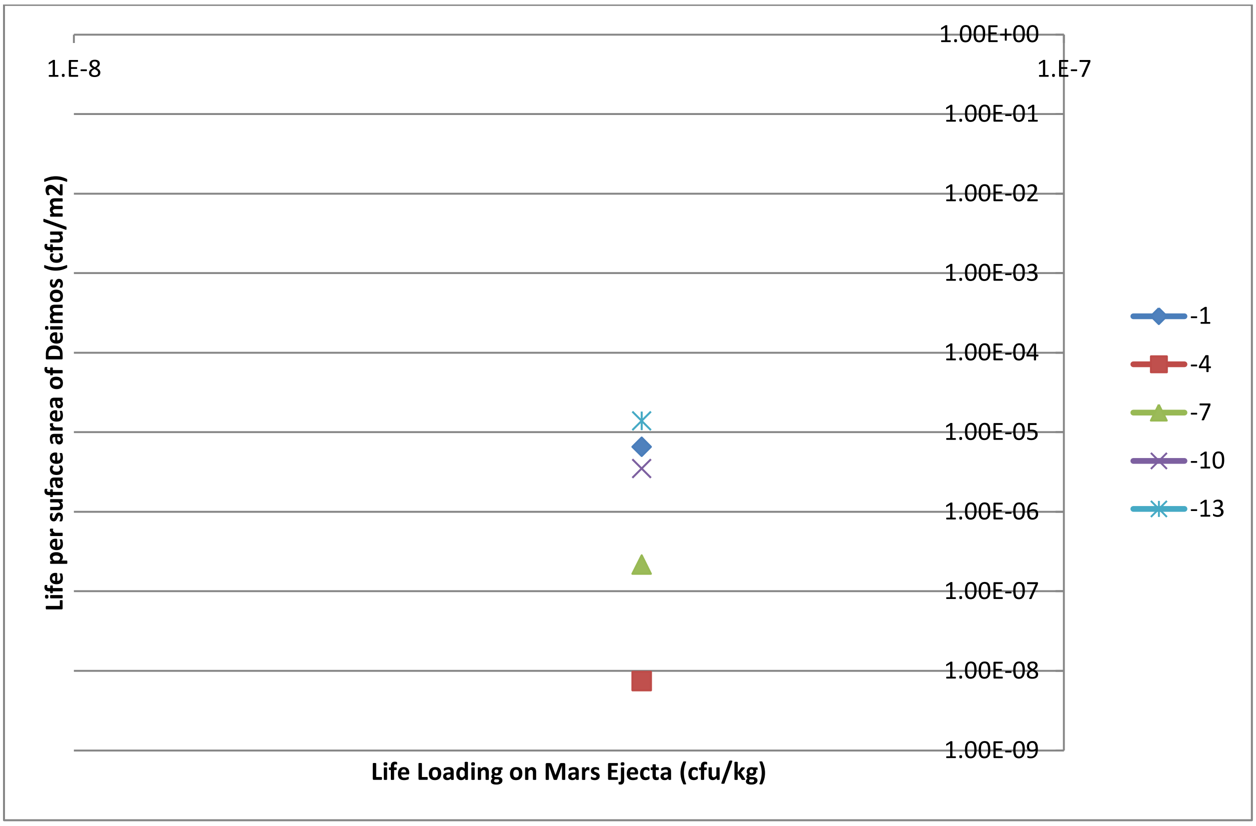

Figure 7-6. The dependence of the density of life on Deimos as a function of the life loading rate on the Mars Ejecta, after the first hypervelocity collision with Deimos.

7.3.2. Mass Deposited/Ejected

From the 45° case above, approximately 18% of the impact material is ejected. As with the Phobos case this is expected to be fairly insensitive to other parameters.

8. EJECTION AND LIFE IN THE CLOUD

8.1. INTRODUCTION

Ejected material can have several fates:

- If ejected at above the Mars escape velocity, the material is lost

- If the material is slow enough, it will collide with Mars, and is lost.
- If mass is below a certain cut off, orbital perturbations will drive the material from the Martian system, before collision with the moon is likely
- Other material will remain in orbit about Mars, crossing the moon orbit, until it eventually collides with the moon.

[AD3] and [AD4] identified that the period of time that material spends in the cloud, is far less than the 10MY period considered. Hence it has been assumed that material in the cloud is not sterilized. Also this was not an area of study of the project [AD1]. However note this is questioned in §11.3.3.

8.2. PHOBOS

8.2.1. Where does material in the cloud go?

So tracing where the mass that enters the cloud ends up:

Total Mass Enters the cloud	**2.96e5 kg**
Ejected from the cloud due to small size	0 kg
Ejected from cloud as over Mars escape velocity	2.06e5 kg
Ejected from cloud as hits Mars	4.66e4 kg
Eventually settles on the moon	4.33e4 kg

Table 8-1. Where material in the cloud ends up.

For the simulation here, the material ejected in the hyper velocity collision with the moon, is assumed to leave in one lumped object. This means that the material decreases in size only slowly, and so does not get down to the size where orbital perturbations eject the material. Clearly if the material is fragmented to very small size in collision with the moon, then significantly more material will be ejected.

Significant material ejected has escape velocity from Mars. This correlates well will the amount of material ejected from Mars with speed over the escape velocity. In the hyper velocity modelling of ejection of material, and the ejected material is correlated with the impact direction. However in the simulation this direction is randomized. Whilst this at first order has no effect (as escape velocity does not depend on direction) there is a minor effect, in how the orbital velocity of Phobos enters. In particular with a random ejection angle, and some material will be reflected back in the direction from which it comes. Such material will get a velocity boost of in the range of 4km/s which is sufficient to eject the material. Hence there is some uncertainty that quite so much material is ejected from Mars orbit.

Of the remaining material, about 50% is deposited on Mars, and 50% deposited on the moon. Specifically as the original Mars ejecta, has orbit the crosses the moon; the original orbit crosses both the moon and Mars. Now the perturbation of the orbit in the collision with the moon, has the potential to change the orbit such that Mars is missed, but if Mars can be hit, this will happen before a second collision with moon. Hence it is not surprising that material is split between the moon and Mars.

Hence this iterates that it is the primary collision between the ejecta and the moon that is the most important for transfer of material to the moon.

8.2.2. Velocity of final collision

When material is ejected in a hyper velocity collision, there is not much heat, and so not much sterilization. Some velocity though is lost, so how does the final velocity of collision compare to the first. If significantly reduced there is the possibility of material arriving on the moon with reduced sterilization. The velocity distribution is shown in Figure 8-1.

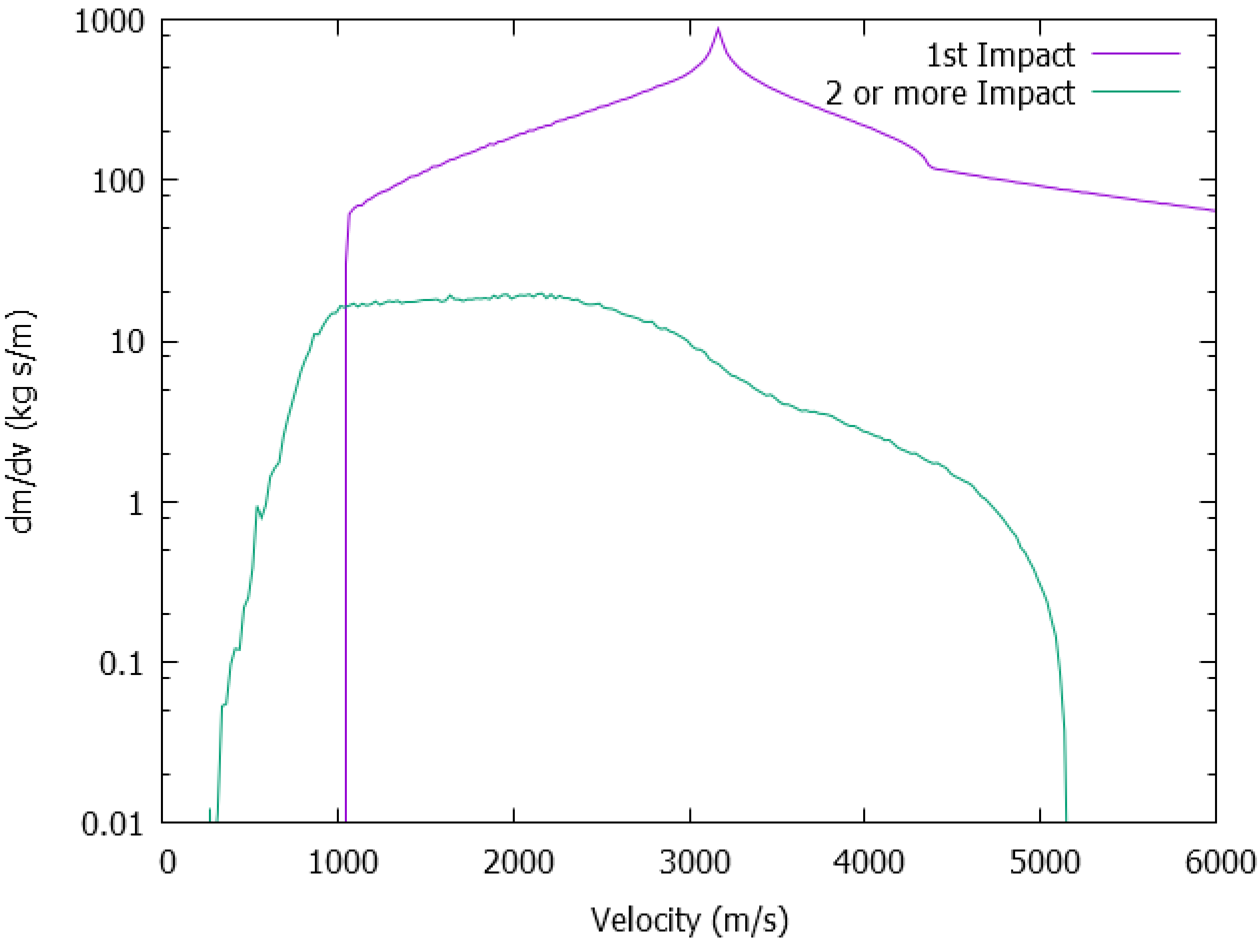

Figure 8-1. Velocity distribution of material that transfers direct from Mars, against material that spends sometime in the cloud.

There are some clear differences between velocity distribution for Martian material that is transferred directly to the moon, vs material that spends sometime in the cloud:

- Ejecta from Mars have a significant tail at high velocity. All this material passes Phobos at least once, and so has the possibility to impact the moon.
- Material in the cloud must have velocity below the escape velocity for Mars – this has two effects:
    - The distribution just above 5km/s has a strong cut off, above this velocity all material leaves the cloud
    - The shape of the distribution is softened at higher velocities, at velocities below 5km/s the stability of material in the cloud depends on angle between the velocity vector of Phobos, and that of material in the cloud.
- Material which is ejected during a hyper velocity impact with Phobos, has its velocity decreased, by a variable amount. This:
    - Smooths the distribution
    - Produces impacts with speeds well below 1km/s

Many of these will tend to decrease the sterilization, so the effect needs to be studied

8.2.3. Sterilisation

Comparing the mass transferred and unsterilized mass transferred, for material which is transferred direct from Mars, and that which goes via the cloud, give:

	Total Mass Transferred	Unsterilized Mass Transferred	Percentage unsterilized to total
Direct from Mars	1.33e6 kg	4.06e5 kg	31%
Via the cloud	4.33e4 kg	3.11e4 kg	72%

Table 8-2. How sterilisation differs between the primary impact, and secondary impacts from the cloud.

So it can be seen, that indeed – material which travels via the cloud, as its speed is decreased in each collision with Phobos, but it only has significant heating in the final collision, does have far less sterilization. This is where sterilization is considered against the Super Bug which has least sterilization.

This means that although 3% of material travels via the cloud, that it gives rise to 7% of the unsterilized material.

8.3. DEIMOS

8.3.1. Where does material in the cloud go?

Total Mass Enters the cloud	**8.38e3 kg**
Ejected from the cloud due to small size	0 kg
Ejected from cloud as over Mars escape velocity	6.96e3 kg
Ejected from cloud as hits Mars	3.94e2 kg
Eventually settles on the moon	1.03e3 kg

Table 8-3. Where material from the Deimos cloud ends up.

For material transferred from Mars, which impacts Deimos, and is then ejected – the story is similar to Phobos.

With the Mars Ejecta parameters chosen, all objects are over the size limit where they will be ejected from the cloud due to orbital perturbations. As with Phobos, this depends critically on the distribution of sizes of ejecta (both from Mars, and from HV collisions on Deimos), and this is not an area well understood.

As the minimum Mars Ejecta velocity to reach Deimos is increased relative to Phobos, and the velocity where material is on an escape velocity from Mars is the same, a greater percentage of Deimos ejecta leave with velocity over the Martian escape velocity. Hence a greater fraction of material is lost from the Martian system, and does not enter the cloud.

With Deimos higher orbit than Phobos, a corresponding smaller proportion of Deimos ejecta collide with Mars.

8.3.2. Velocity of final collision

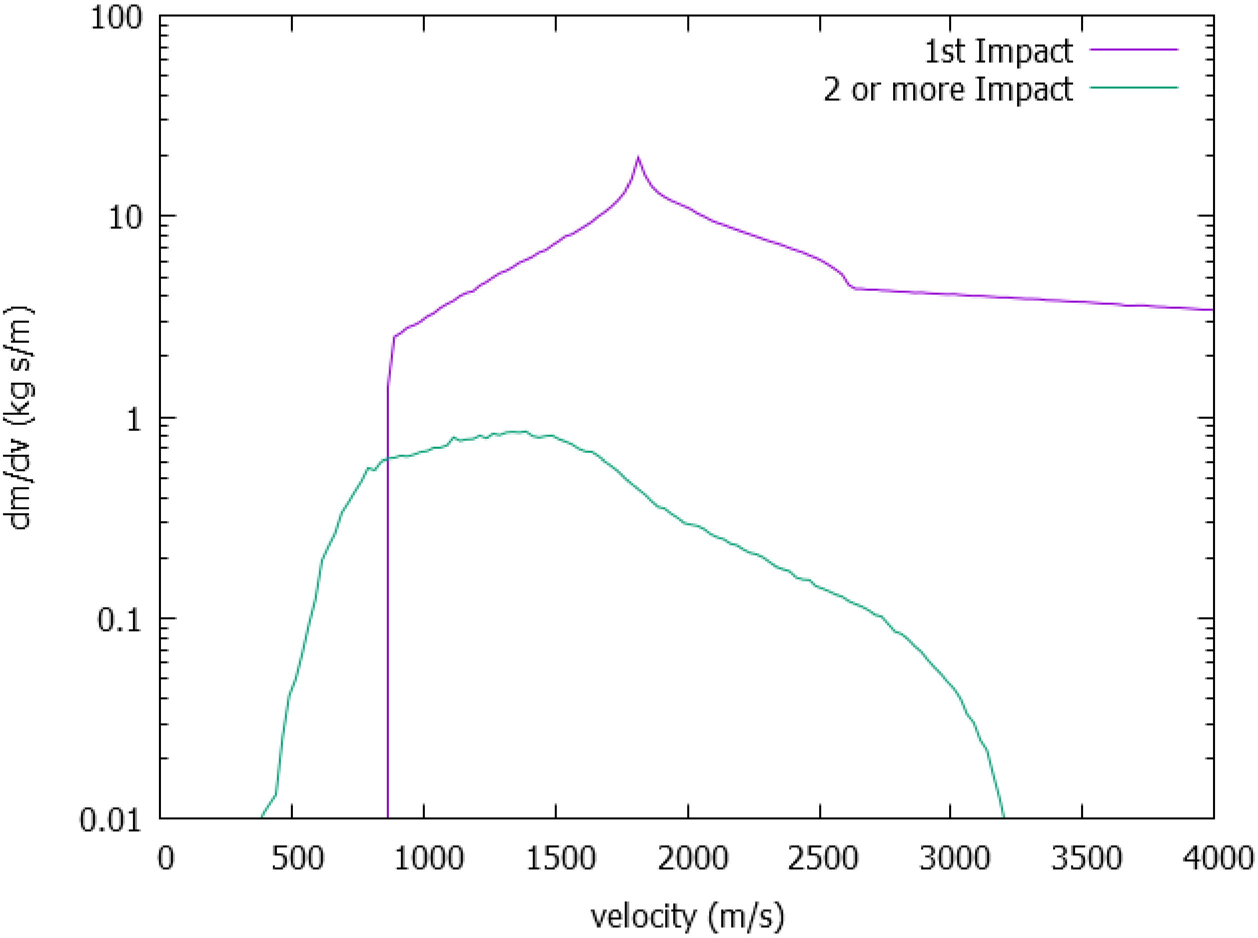

Figure 8-2. Velocity of collision with Deimos. Both for material transferred direct from Mars, and for material which goes via the cloud.

The velocities of collision with Deimos are lowered relative to Phobos, and this is for both primary impacts from Mars ejecta, and secondary impacts via the cloud around Mars. That the Mars escape velocity is lower at a Deimos orbit (compared to Phobos) means that the upper cut off on cloud speeds is lowered to just over 3km/s. The lower impacts speeds from the cloud are similar between Deimos and Phobos.

8.3.3. Sterilization

	Total Mass Transferred	Unsterilized Mass Transferred	Percentage of unsterilized to total
Direct from Mars	3.78e4 kg	1.35e4 kg	36%
Via the cloud	1.03e3 kg	9.23e2 kg	90%

Table 8-4. How sterilisation differs between the primary impact, and secondary impacts from the cloud.

The sterilization archived for the Super Bug is shown above. With the reduced speeds relative to Phobos, a greater percentage of life survives. 6% of unsterilized material is transferred via the cloud.

9. SETTLING ON THE MOON

9.1. INTRODUCTION

The Mars ejecta material that is of interest of this study is that which will eventually settle on a Martian moon. For most this will be due to a direct transfer from Mars, some though will have travelled via cloud of material orbiting Mars.

When material settles on a Martian Moon, the one parameter that affects sterilization, is the depth at which the material is deposited. The depth dictates the exposure to radiation, which is the last area of this study which focuses on sterilization (e.g. the study assumes that exposure to the dry vacuum on the Martian moons causes no sterilization in itself).

Hence this section focuses on the depth of deposition of all material transferred from Mars.

As noted before in §7.2.4, the depth of deposition under the primary assumption of the hyper velocity collision [RD2], is that the properties of the moon regolith are that all impact material will end up on the surface of the moon. However if the properties differ from the expected, it is possible that material will be deposited at a few times the impactor radii.

Now as radiation decreases with depth, a conservative approach is to look at material deposited at depth – and so this is where this section focuses. It should be noted though that this is not expected to be the real case, but is the conservative case. As “a few” is not defined, this section will plot depth at one radii of the impactor.

Thus as in §7.2.4, turn attention to the impactor size. In the simulation this is modelled through the impactor mass, converted into a size via the modelled density (2000kg/m^3 used). The mass of the Martian Ejectors, as discussed in §7.2.4, is known to be steeply falling – hence is not well modelled; most ejecta being close to the lower cut off for the ejecta mass. This lower cut off is a hard cut off in the modelling, in the real case on Mars, other processes will influence the minimal size:

- The smaller the size, the greater the drag in the thin Martian atmosphere. Eventually this drag will be sufficient such that particles do not make it out of the atmosphere. This has not been modelled.

- The physical process producing the Mars Ejecta (primarily hypervelocity collisions with Mars) will give some spectrum to the size, in particular the grain size of the Martian rock is a natural size to which rock will fragment, and fragmentation to smaller sizes with take significant additional force. This also has not been modelled.

Hence the model used here is driven by that minimal cut off, so as a conservative value is looked at, this has been set to the maximal value of cut off, which corresponds to 1g. Converting this to a size gives 5mm.

9.2. PHOBOS

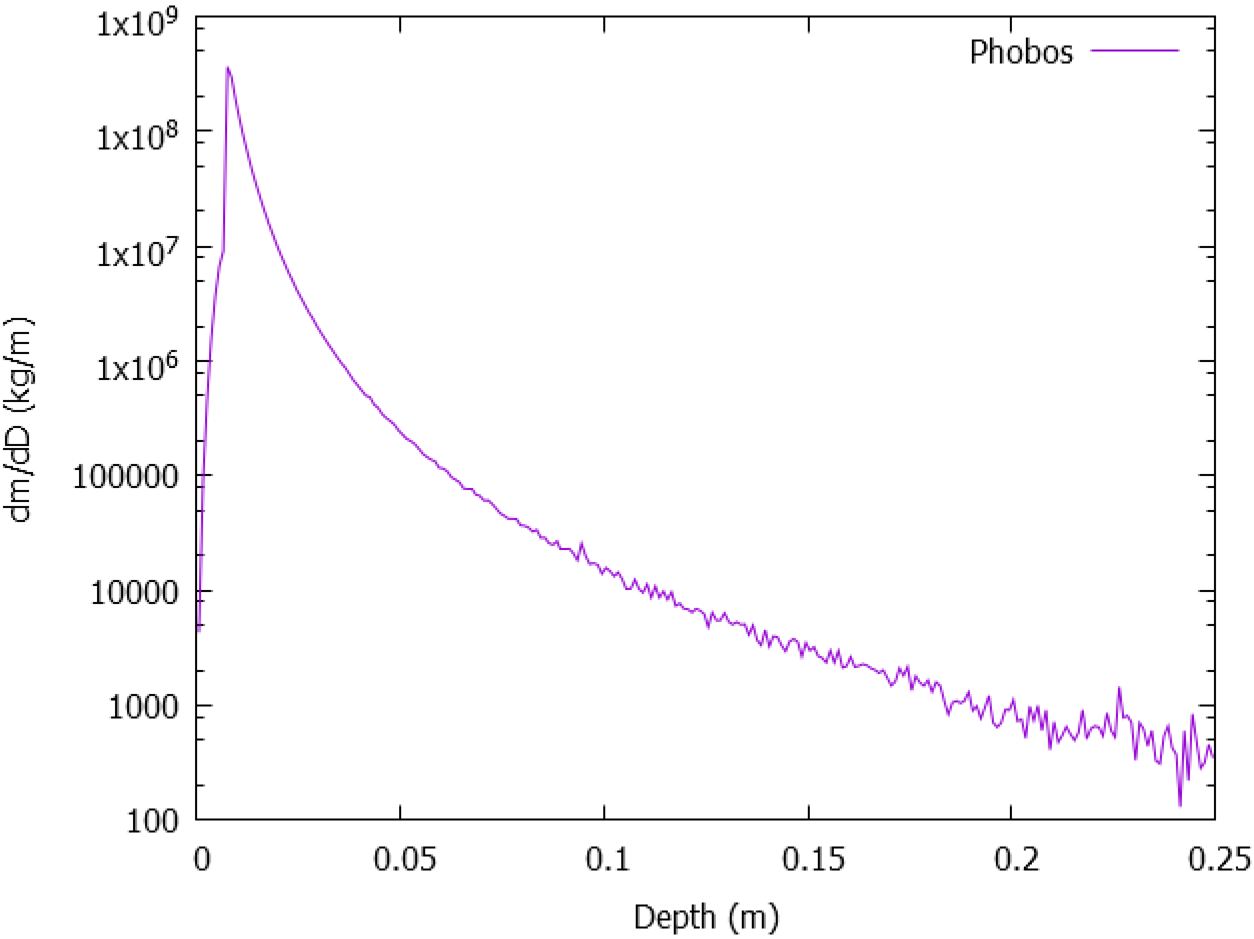

Figure 9-1. Depth Distribution for all material transferred from Mars to Phobos when it is buried at 1 radii

The Depth distribution is shown in Figure 9-1. A sharp peek can be seen at ~5mm, which corresponds to the minimum size, given by the lower mass cut off. The material from the cloud can get below this cut off, as on each impact with Phobos material is lost.

The large tail at greater depths is caused by larger impactors, this is driven by the power law on the mass distribution from Mars, taken from [AD2].

Compare this to the rate of Phobos gardening (turnover of Phobos regolith due to all impacts) – in 10MY this will turn over the regolith to ~1cm [AD4]. Hence it can be seen that the peak of the distribution is similar depth of gardening. So as expected in [AD4] the primary cause of the depth that material is deposited at, is due to the hyper velocity collision.

9.3. DEIMOS

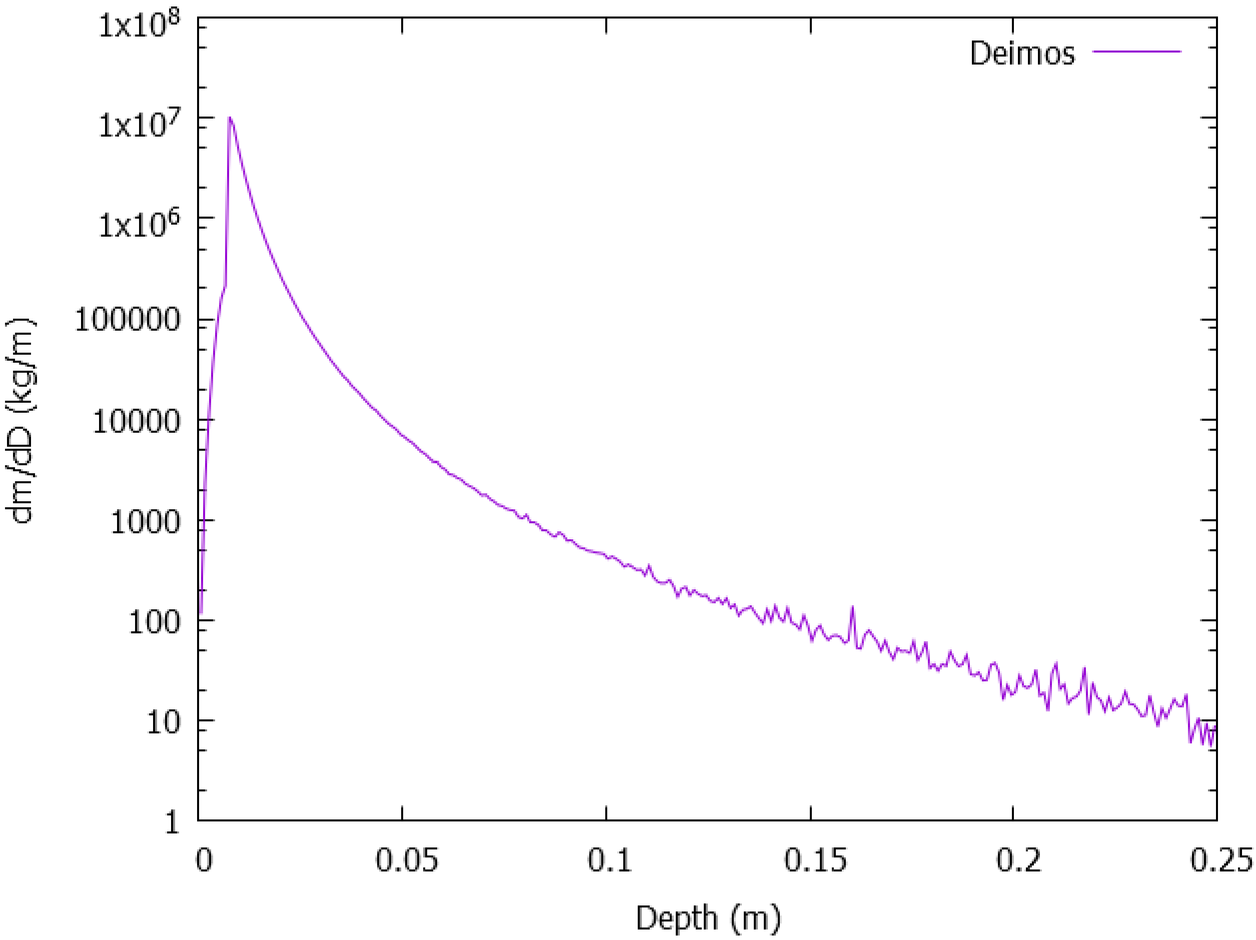

Figure 9-2. Depth Distribution for all material transferred from Mars to Deimos when it is buried at 1 radii

The depth distribution of impactors on Deimos is shown in Figure 9-2. The features are the same as for the Phobos case.

10. RADIATION ON THE MARTIAN MOON

10.1. INTRODUCTION

After material settles on a moon, it is exposed to the radiation environment. This happens for an extended period, until the present day. Now as the study looks at a period of 10MY, this has been used give the total mass transferred, which is how life is traced. Now the time in that 10MY when the material is ejected from Mars is unknown, hence is assumed to be uniform – e.g. material is ejected from Mars at an approximate constant rate.

So what is key, is the radiation environment as a function of depth, and how organisms survive in this environment. This was studied in [RD3] & [RD4], in the next section (§10.2) is presented results from these documents.

Finally this is folded with the mass transferred, to get an estimate of life at depth on Phobos and Deimos.

10.2. RADIATION ENVIRONMENT

[RD4] modelled the radiation environment on Phobos and Deimos. This was independent of location on the moon, and independent of which moon. The results are shown below in Figure 10-1.

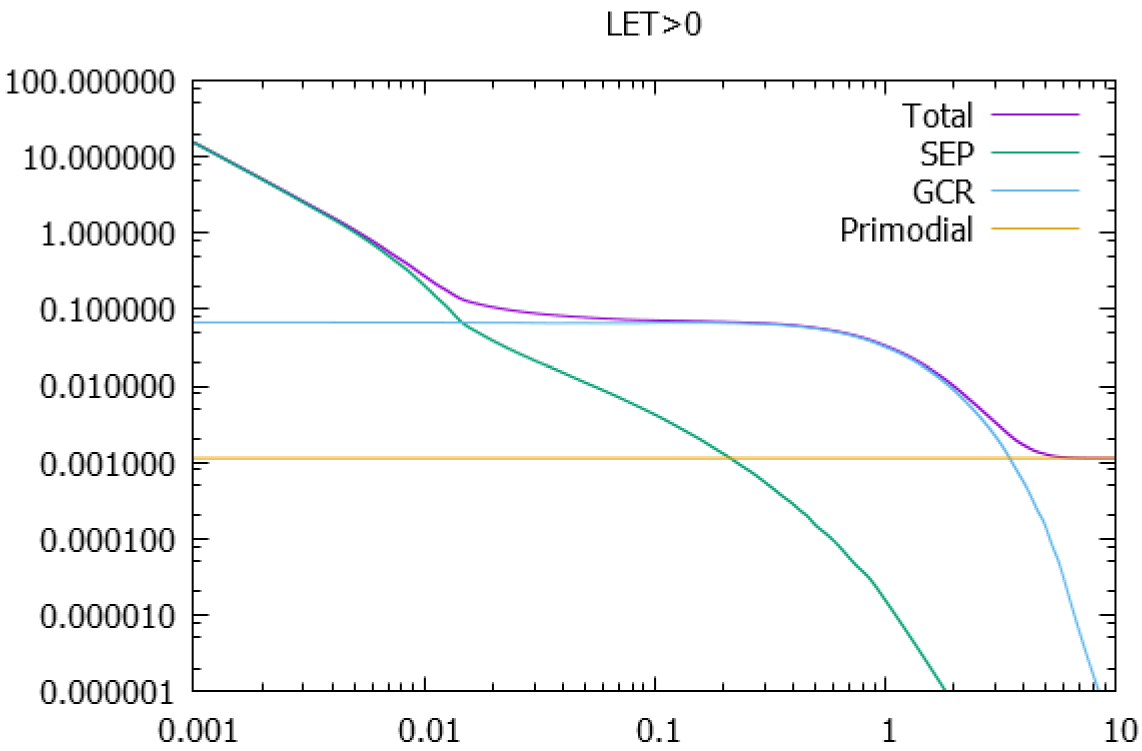

Figure 10-1. Radiation environment on Phobos (and Deimos) as a function of depth. Taken from §5.6.5 of [AD3]. Plotted is Dose (Gy/y) against Depth (m).

Now this radiation environment can be folded with the radiation needed to sterilize organisms:

$$\ln\left(\frac{N}{N_0}\right) = \lambda \frac{dD}{dt} t$$

$$\frac{N}{N_0} = \frac{1}{e} \quad \Longrightarrow t = \frac{-1}{\lambda \frac{dD}{dt}}$$

To give the time period needed to sterilize an organism by 1/e as a function of depth and organism, this is shown in Figure 10-2, where the sterilization model has been taken from [RD3].

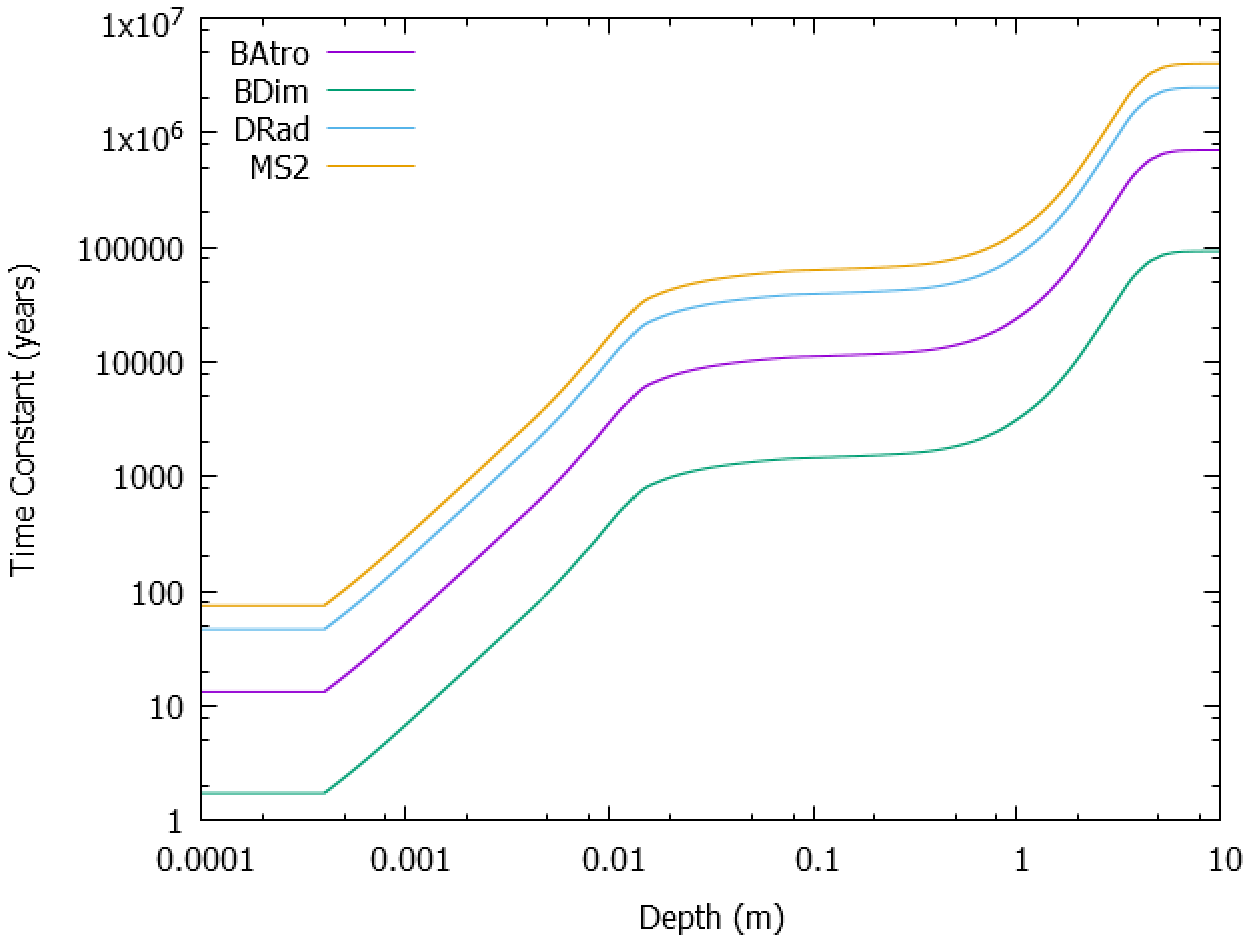

Figure 10-2. The time taken to decrease an organisms population by 1/e as a function of depth.

What can be seen is that between 1cm and 1m (where GCR dominates), the time to sterilize 1/e organisms is approximately constant, and varies between 1000 years (for *B.diminuta*) an 100kY (for *D.Radiodurans* and *MS2*).

10.3. LIFE ON THE SURFACE

10.3.1. Introduction

The hypervelocity modelling suggest with the expected properties of the moon regolith, that after a hyper velocity collision, the regolith will bounce back, leaving the impactor on the surface [RD2].

This section looks at this scenario – when material is left on the surface of the moon, what does the future bring, and what is the fate of the material.

As can be seen from Figure 10-2, this is where the radiation environment is most extreme, with a one log (base e) reduction between 1 and 100 years (dependent on organism), so it is expected that sterilisation will be rapid.

10.3.2. Phobos

The table below shows the total life left unsterilized.

Organism	Total Mass	Unsterilized mass	Cfu		Cfu/m^2
B. atrophaeus	1.37e6 ± 3.78e2kg	4.11e-1 ± 3.11e-4kg	Low	4.11e4 cfu	2.65e-5 cfu/m2
			Medium	4.11e6 cfu	2.65e-3 cfu/m2
			High	4.11e9 cfu	2.65 cfu/m2
B. diminuta	1.37e6 ± 3.78e2kg	5.47e-2 ± 4.21e-5kg	Low	5.47e3 cfu	0.353e-5 cfu/m2
			Medium	5.47e5 cfu	0.353e-3 cfu/m2
			High	5.47e8 cfu	0.353 cfu/m2
D. radiodurans	1.37e6 ± 3.78e2kg	1.77 ± 1.23e-3kg	Low	1.77e5 cfu	11.4e-5 cfu/m2
			Medium	1.77e7 cfu	11.4e-3 cfu/m2
			High	1.77e10 cfu	11.4 cfu/m2
MS2 coliphage	1.37e6 ± 3.78e2kg	2.35 ± 1.78e-3kg	Low	2.35e5 cfu	15.2e-5 cfu/m2
			Medium	2.35e7 cfu	15.2e-3 cfu/m2
			High	2.35e10 cfu	15.2 cfu/m2
Super Bug	1.37e6 ± 3.78e2kg	3.29 ± 2.08e-3kg	Low	3.29e5 cfu	21.2e-5 cfu/m2
			Medium	3.29e7 cfu	21.2e-3 cfu/m2
			High	3.29e10 cfu	21.2 cfu/m2

Table 10-1. Sterilisation caused by both hyper velocity collision and exposure to radiation, for three level of life loading on the Mars Ejecta

Clearly the amount of life that settles on the moon is very dependent on the loading rate of life on the Mars Ejecta. With the high loading rate of 1e10 cfu/kg life as high as 21.2 cfu/m2, a PhSR mission would need to sample an area smaller than 0.04mm^2 for the probability of life to be below 1e-6, with the *Super Bug*, with a limit of 0.07mm^2 for MS2 being not far behind.

On the other hand, the least resilient organism, *B.diminuta* would only allow an area of 2.8mm^2 to get the 10^{-6} probability – which although conceivable, would still be a challenge.

Looking at the available surface area that can be probed, and keep the probability of life below 1e-6 is shown in Table 10-2.

Organism	Cfu		Cfu/m^2	Square mm for a 1e-6 probability
B. atrophaeus	Low	4.11e4 cfu	2.65E-05	3.77E+04
	Medium	4.11e6 cfu	2.65E-03	3.77E+02
	High	4.11e9 cfu	2.65	3.77E-01
B. diminuta	Low	5.47e3 cfu	3.53E-06	2.83E+05
	Medium	5.47e5 cfu	3.53E-04	2.83E+03
	High	5.47e8 cfu	0.353	2.83E+00
D. radiodurans	Low	1.77e5 cfu	1.14E-04	8.77E+03
	Medium	1.77e7 cfu	1.14E-02	8.77E+01
	High	1.77e10 cfu	11.4	8.77E-02
MS2 coliphage	Low	2.35e5 cfu	1.52E-04	6.58E+03
	Medium	2.35e7 cfu	1.52E-02	6.58E+01
	High	2.35e10 cfu	15.2	6.58E-02
Super Bug	Low	3.29e5 cfu	2.12E-04	4.72E+03
	Medium	3.29e7 cfu	2.12E-02	4.72E+01
	High	3.29e10 cfu	21.2	4.72E-02

Table 10-2. The number of mm2 of surface area that can be sampled, for the various organisms, and various loading rate of life on Mars Ejecta

Considering the *Super Bug*, and we can see the dependence on the loading rate. With a low loading rate, a sample 6.8×6.8 cm^2 and the probability will be below 1e-6 as required by Req-10. On the other hand, the high loading rate and a 0.2×0.2mm^2 sample is allowed. The low loading rate would allow a mission to be viable and meet Req-10, whilst the high loading rate would not. This story is consistent across all organisms.

Finally considering the dependence on the life loading rate on the Mars Ejecta, this is shown in Figure 10-3.

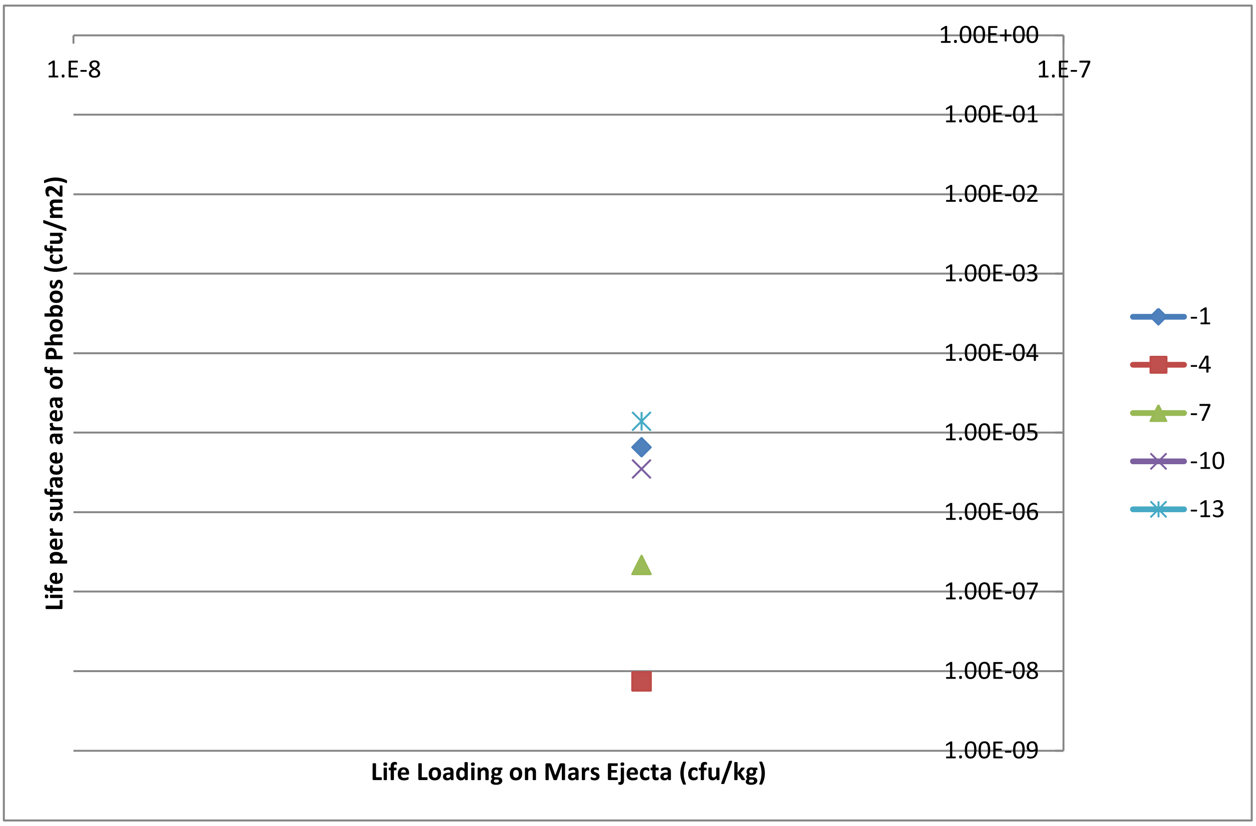

Figure 10-3. The dependence of the density of life on Phobos as a function of the life loading rate of the Mars Ejecta, after exposure to the radiation.

10.3.3. Age of organisms

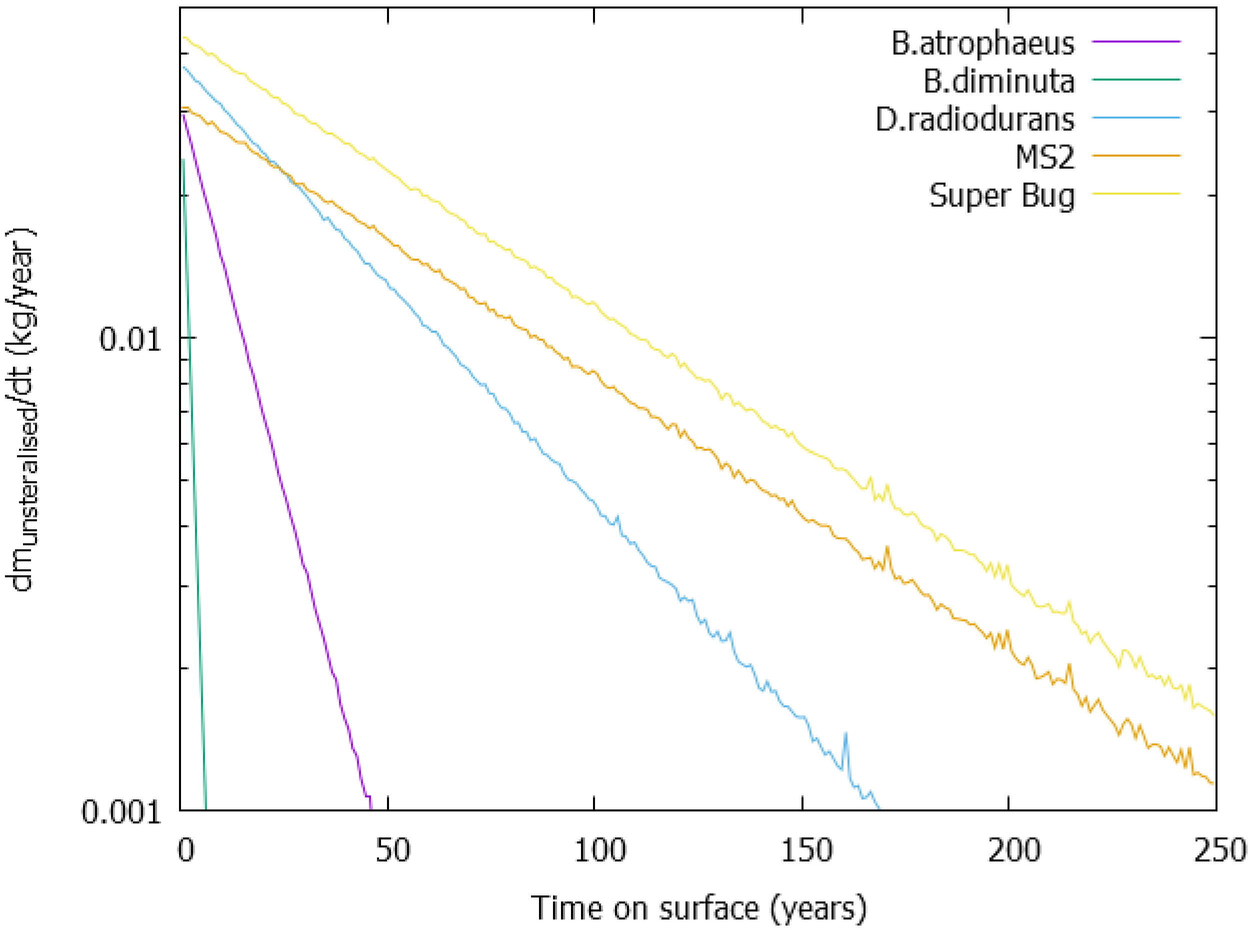

Figure 10-4. Time period that material spends on the surface of Phobos before being sterilised. For *B.diminuta* almost all unsterilized material arrives in the past 10 years. For the *Super Bug* (and similarly for *MS2*, and *D.radiodurans*) 90% of material arrived in the last 100-200 years. This is shown of a Life Loading rate on the Mars Ejecta of 1e10 cfu/kg.

The time that the material arrives has a direct effect on how sterilised the material is, the longer spent on the surface the greater exposure to the radiation – and this rapidly sterilises the material. Hence even for the most resistant organisms, only a small amount of viable material arrives after 200 years in the past, almost nothing arrives prior to 1000 years.

This is a critical result – although this study looks at the last 10Myears, for material deposited on the surface only the last 1000 years at most is relevant.

10.3.4. Deimos

Organism	Total Masskg	Unsterilized masskg	Cfu		Cfu/m^2
B. atrophaeus	3.88e+4 ± 9.71	1.60e-2 ± 1.21e-5	Low	1.60e3 cfu	0.323e-5 cfu/m2
			Medium	1.60e5 cfu	0.323e-3 cfu/m2
			High	1.60e8 cfu	0.323 cfu/m2
B. diminuta	3.88e+4 ± 9.71	2.13e-3 ± 1.60e-6	Low	2.13e2 cfu	0.0430e-5 cfu/m2
			Medium	2.13e4 cfu	0.0430e-3 cfu/m2
			High	2.13e7 cfu	0.0430 cfu/m2
D. radiodurans	3.88e+4 ± 9.71	6.32e-2 ± 4.37e-5	Low	6.32e3 cfu	1.28e-5 cfu/m2
			Medium	6.32e5 cfu	1.28e-3 cfu/m2
			High	6.32e8 cfu	1.28 cfu/m2
MS2 coliphage	3.88e+4 ± 9.71	9.14e-2 ± 6.89e-5	Low	9.14e3 cfu	1.85e-5 cfu/m2
			Medium	9.14e5 cfu	1.85e-3 cfu/m2
			High	9.14e8 cfu	1.85 cfu/m2
Super Bug	3.88e+4 ± 9.71	1.09e-1 ± 7.07e-5	Low	1.09e4 cfu	2.20e-5 cfu/m2
			Medium	1.09e6 cfu	2.20e-3 cfu/m2
			High	1.09e9 cfu	2.20 cfu/m2

Table 10-3. Sterilisation caused by both hyper velocity collision and exposure to radiation, shown for three levels of life loading on the Mars Ejecta

As before, converting the cfu per m^2 to the maximal area that can be sampled consistent with the 1e-6 probability required by Req-10. This is shown in Table 10-4.

Organism	Cfu		Cfu/m^2	Square mm for a 1e-6 probability
B. atrophaeus	Low	1.60e3 cfu	3.23E-06	3.10E+05

	Medium	1.60e5 cfu	3.23E-04	3.10E+03
	High	1.60e8 cfu	0.323	3.10E+00
B. diminuta	Low	2.13e2 cfu	4.30E-07	2.33E+06
	Medium	2.13e4 cfu	4.30E-05	2.33E+04
	High	2.13e7 cfu	0.043	2.33E+01
D. radiodurans	Low	6.32e3 cfu	1.28E-05	7.81E+04
	Medium	6.32e5 cfu	1.28E-03	7.81E+02
	High	6.32e8 cfu	1.28	7.81E-01
MS2 coliphage	Low	9.14e3 cfu	1.85E-05	5.41E+04
	Medium	9.14e5 cfu	1.85E-03	5.41E+02
	High	9.14e8 cfu	1.85	5.41E-01
Super Bug	Low	1.09e4 cfu	2.20E-05	4.55E+04
	Medium	1.09e6 cfu	2.20E-03	4.55E+02
	High	1.09e9 cfu	2.2	4.55E-01

Table 10-4. The square mm of Deimos surface that can be collected consistent with Req-10.

The story is similar to Phobos, in that meeting Req-10 is dependent on the loading of life on the Mars Ejecta, with low loading of 1e5 cfu/kg large samples can be taken, with a high loading rate of 1e10 cfu/kg and for many organisms that area is under one mm^2.

The dependence on the life loading rate of the Mars Ejecta is shown in Figure 10-5.

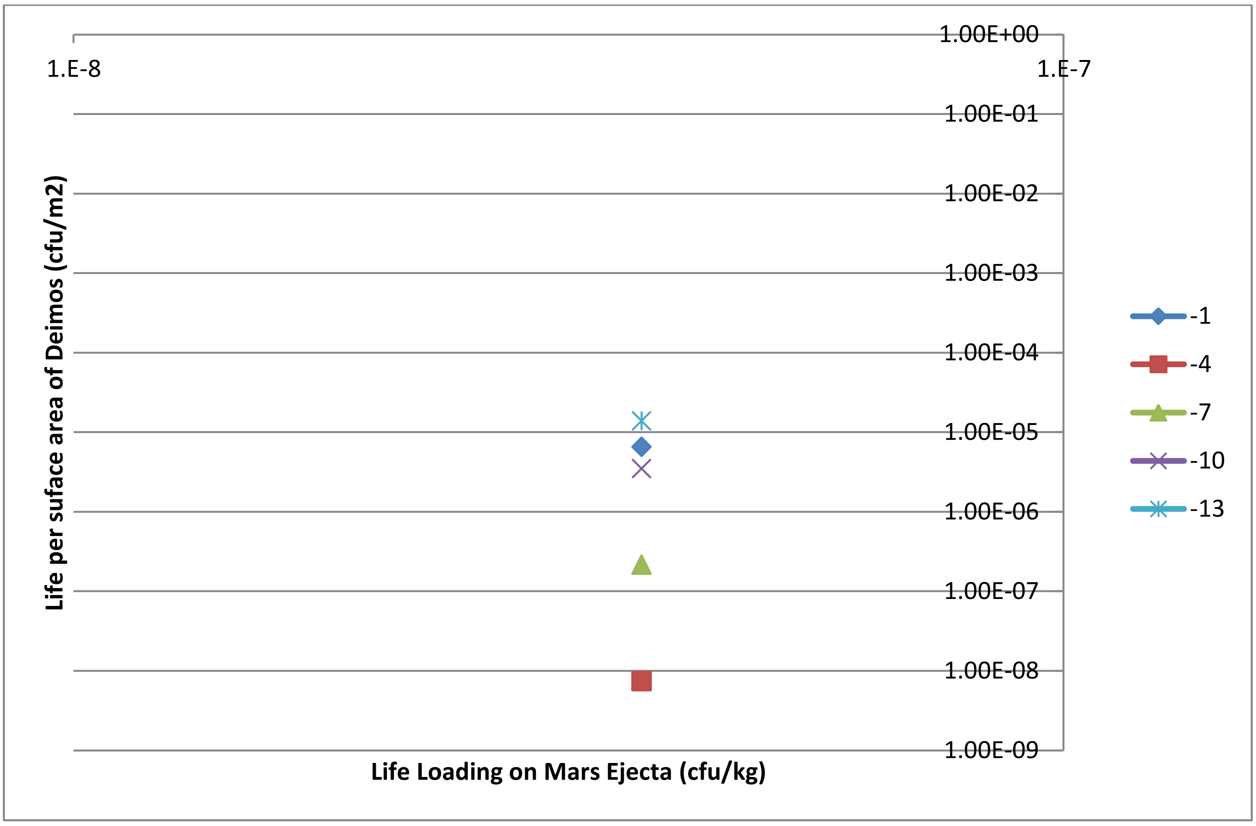

Figure 10-5. The density of life on Deimos as a function of the life loading rate of the Mars Ejecta.

10.4. Going underground

10.4.1. Introduction

The hypervelocity modelling [RD2] expects that during the post impact phase, that the impactor will rebound to the surface. However this depends critically on the moon regolith properties, with subtle changes it is possible the impact will dig a crater, then over time the collapse of the walls will bury material deposited at the base.

Where this happens, the critical process is how deep a crater does the impactor create, before there is any bounce back? This is poorly understood [RD2], however estimated in [RD2] to be "*several projectile radii*".

This section looks at this possibility, the deeper material is deposited the greater the shielding from the radiation environment by the regolith, does this mean more life?

Now the size of the impactor, is primarily driven by the size of the Mars ejecta – and this is one of the least well constrained parameters. As the Mars ejecta is the result of a hyper velocity collision on Mars, the general properties of Hyper Velocity Collision apply. In particular as the material will need to be ejected by almost 4km/s to reach Phobos, the impact will necessarily be at very high velocity and energy density. Hence during impact, the expectation has to be that the Martian regolith is predominantly fragmented to the grain size of the material. This gives the origin of the steeply falling m^{-2} law, which also follows the properties of the ejecta fan [AD2]. As a result most material is at the lower cut off, a parameter which is also unknown.

So to give a conservative estimate in this section, we simultaneously consider maximum radii (which for this model means depositing at 4 impactor radii), and with the highest cut off mass for the ejector (1e-3 kg).

10.4.2. Phobos

10.4.2.1. MASS DISTRIBUTION

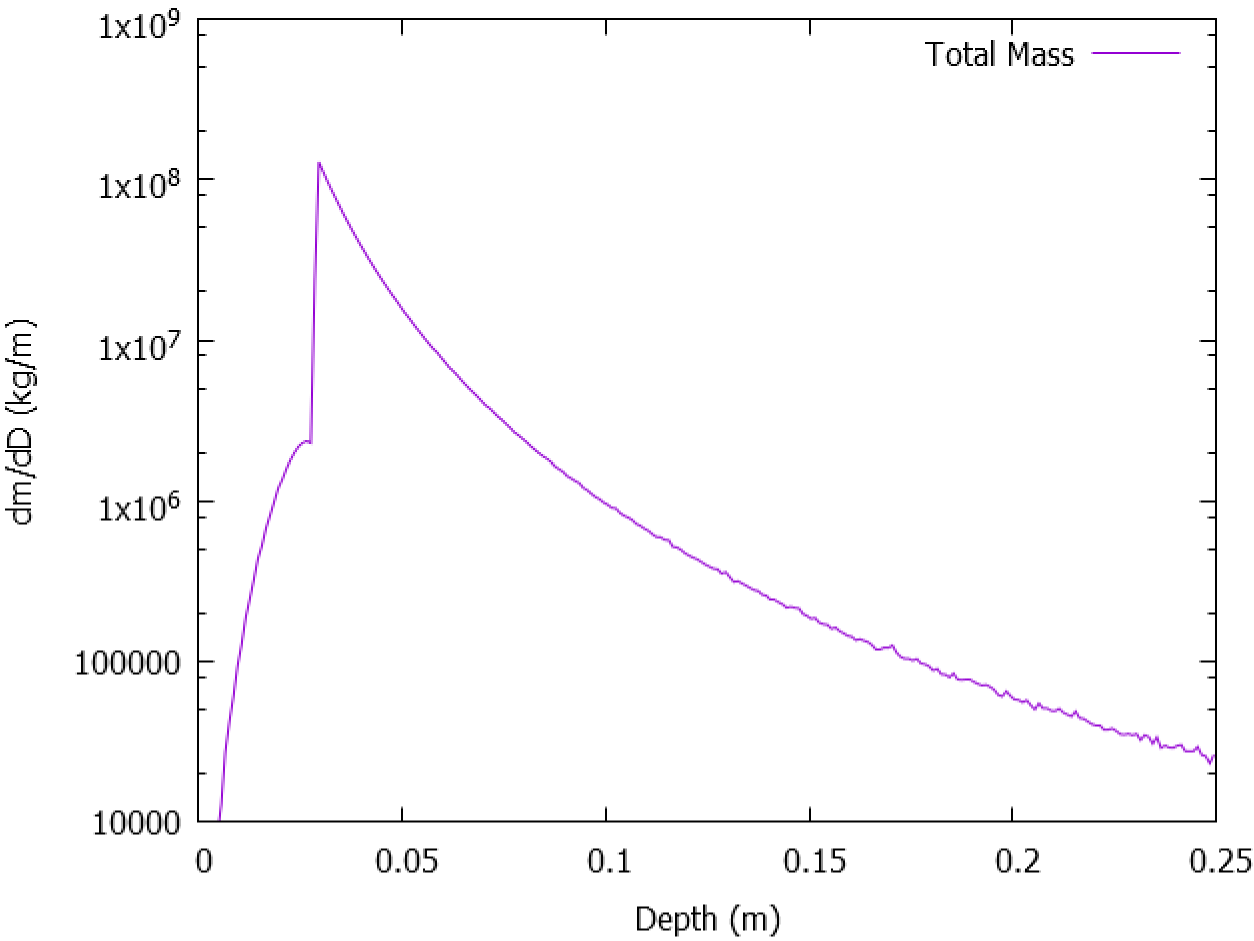

Figure 10-6. The depth distribution of all mass transferred.

Shown in Figure 10-6 is the depth distribution for all mass transferred. The minimal mass of 1g gives rise to the peak at 3cm, so with this mode of the simulation the sharp cut off in impactor mass, gives a sharp cut off in the depth distribution. In practice this will be rounded off by physics beyond this study (e.g. the actual minimum impactor size, and a more realistic depth of deposition), however it shows that the depth of deposition can exceed the 1cm threshold identified in Figure 10-2 where galactic cosmic radiation takes over – this gives an approximate constant radiation environment down to 1m. Now the depth of deposition is a strongly falling distribution (which follows from the strong power law on impactor sizes). This gives rise to a 3 order drop off in rate by 25cm depth, hence little if any material will be deposited below the 1m depth where GCR drops off, this is shown in Figure 10-7 where the distribution has fallen off by 10^5 at 1m depth which suggests that in 10MY only 1kg of martian material will be deposited at over 1m depth across the whole of Phobos.

Hence the importance of the GCR can be seen, even if the material is deposited above 4 times the impactor radii, this typically will not change the importance of GCR – e.g. with a 1 radii deposition depth the 3cm peak depth will move down to 7.5mm which is close to where GCR starts to dominate.

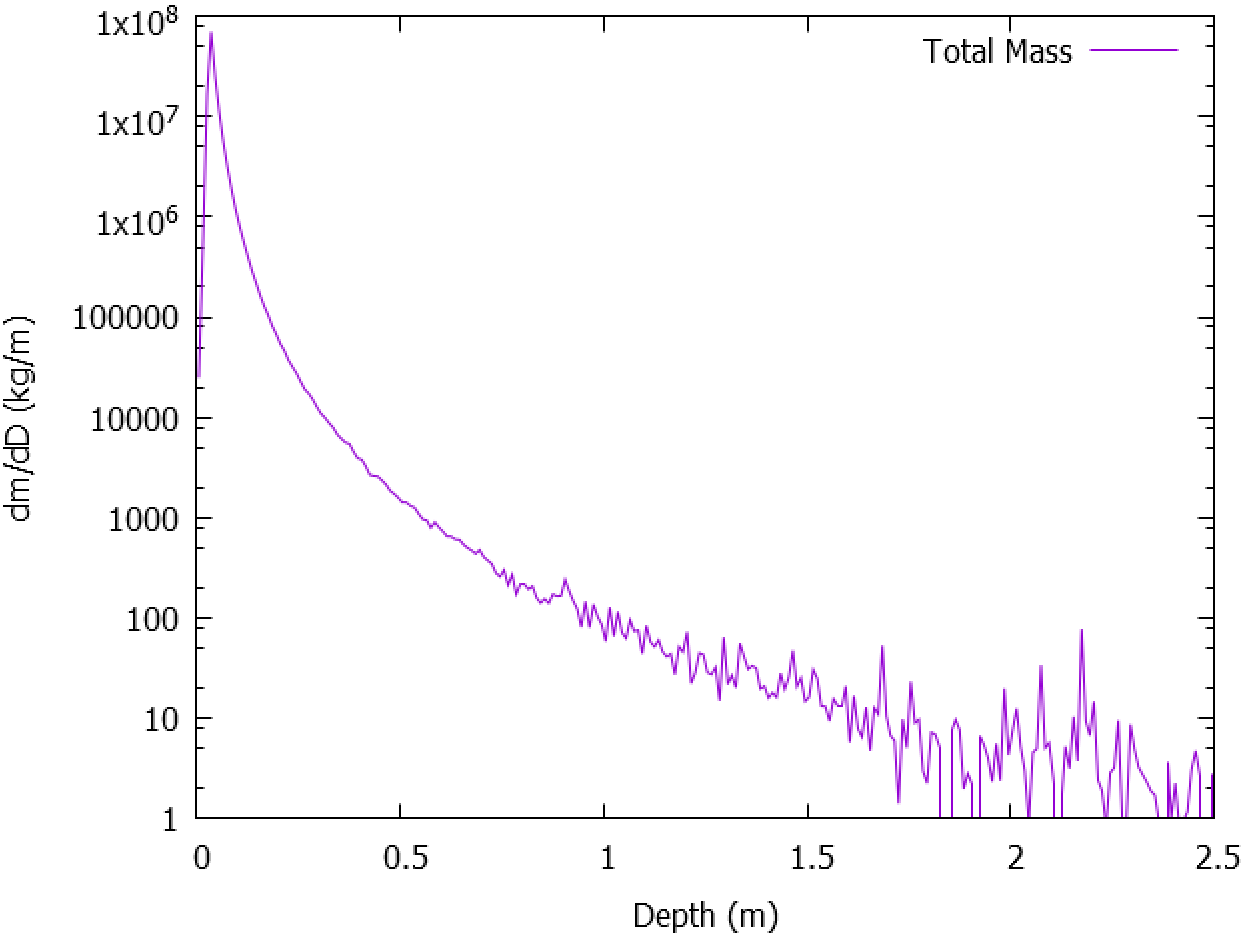

Figure 10-7. The depth distribution of all mass transferred to Phobos in 10MY, with the depth extended to 2.5m.

10.4.2.2. AND TOTAL LIFE

Organism	Total Mass	Unsterilized mass	Cfu		Cfu/m^2
B. atrophaeus	1.37e6 ± 3.78e2kg	297 ± 0.226 kg	Low	2.97E+7 cfu	1.92E-2 cfu/m2
			Medium	2.97E+9 cfu	1.92 cfu/m2
			High	2.97E+12 cfu	1.92E+3 cfu/m2
B. diminuta	1.37e6 ± 3.78e2kg	39.0 ± 1.18 kg	Low	3.90E+6 cfu	2.52E-3 cfu/m2
			Medium	3.90E+8 cfu	2.52E-1 cfu/m2
			High	3.90E+11 cfu	2.52E+02 cfu/m2
D. radiodurans	1.37e6 ± 3.78e2kg	1281.4 ± 0.893 kg	Low	1.28E+8 cfu	8.28E-2 cfu/m2
			Medium	1.28E+10 cfu	8.28 cfu/m2
			High	1.28E+13 cfu	8.28E3 cfu/m2
MS2 coliphage	1.37e6 ± 3.78e2kg	1700 ± 1.30 kg	Low	1.70E+8 cfu	1.10E-1 cfu/m2
			Medium	1.70E+10 cfu	1.10E1 cfu/m2
			High	1.70E+13 cfu	1.10E+04 cfu/m2
Super Bug	1.37e6 ± 3.78e2kg	2384 ± 1.51 kg	Low	2.38E+8 cfu	1.54E-1 cfu/m2
			Medium	2.38E+10 cfu	1.54E+1 cfu/m2
			High	2.38E+13 cfu	1.54E+04 cfu/m2

Table 10-5. Sterilisation caused by both hyper velocity collision and exposure to radiation, when the material is buried during impact, for three level of load loading on the Mars Ejecta

Converting to the maximal area of Phobos that can be sampled, this is shown in Table 10-6.

Organism	Cfu		Cfu/m^2	Square mm for a 1e-6 probability
B. atrophaeus	Low	2.97E+7 cfu	1.92E-02	52.0833
	Medium	2.97E+9 cfu	1.92	0.52083
	High	2.97E+12 cfu	1.92E+03	0.00052
B. diminuta	Low	3.90E+6 cfu	2.52E-03	396.825
	Medium	3.90E+8 cfu	2.52E-01	3.96825
	High	3.90E+11 cfu	2.52E+02	0.00397
D. radiodurans	Low	1.28E+8 cfu	8.28E-02	12.077
	Medium	1.28 cfu	8.28	0.121
	High	1.28E+13 cfu	8.28E+03	1.21e-04
MS2 coliphage	Low	1.70E+8 cfu	1.10E-01	9.09091
	Medium	1.70E+10 cfu	1.10E+01	0.09091
	High	1.70E+13 cfu	1.10E+04	9.1E-05
Super Bug	Low	2.38E+8 cfu	1.54E-01	6.49351
	Medium	2.38E+10 cfu	1.54E+01	0.06494
	High	2.38E+13 cfu	1.54E+04	6.5E-05

Table 10-6. The maximal surface area that can be sampled and be consistent with Req-10.

When material is buried, the lower radiation does means that more of the organism survives. This makes it more questionable if Req-10 can be met, for the Super Bug, even with a low loading of life on the Mars Ejecta, and still only 6mm^2 can be sampled. It should be membered that the expectation is for material to be left on the surface.

The dependence on the life loading rate of the Mars Ejecta is shown in Figure 10-8. Note this is still shown per unit surface area of the moon, this is justified as most deposited material is close to the surface.

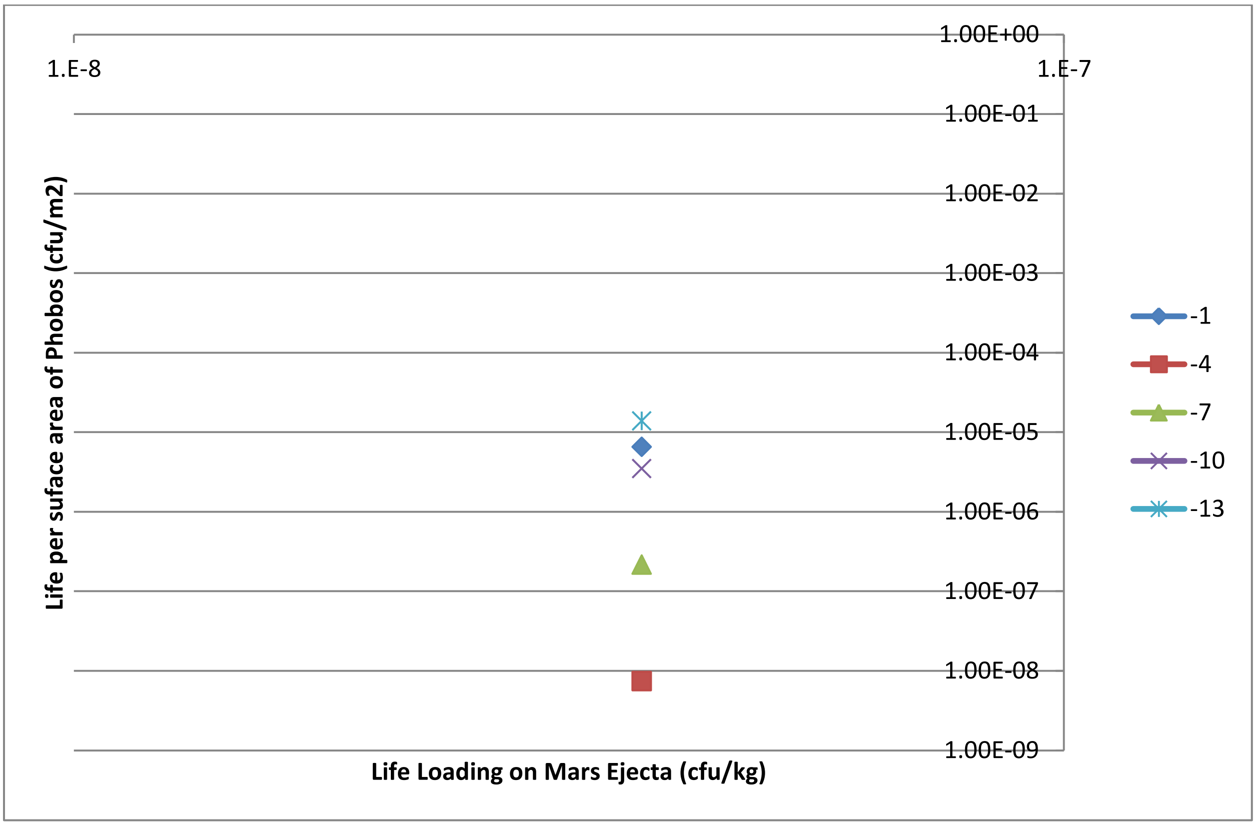

Figure 10-8. The density of Life on Phobos as a function of the loading of life on the Mars Ejecta.

10.4.2.3. AND DEPTH DISTRIBUTION

Now the total life is distributed over some depth, so does sampling over a limited depth reduce the life collected?

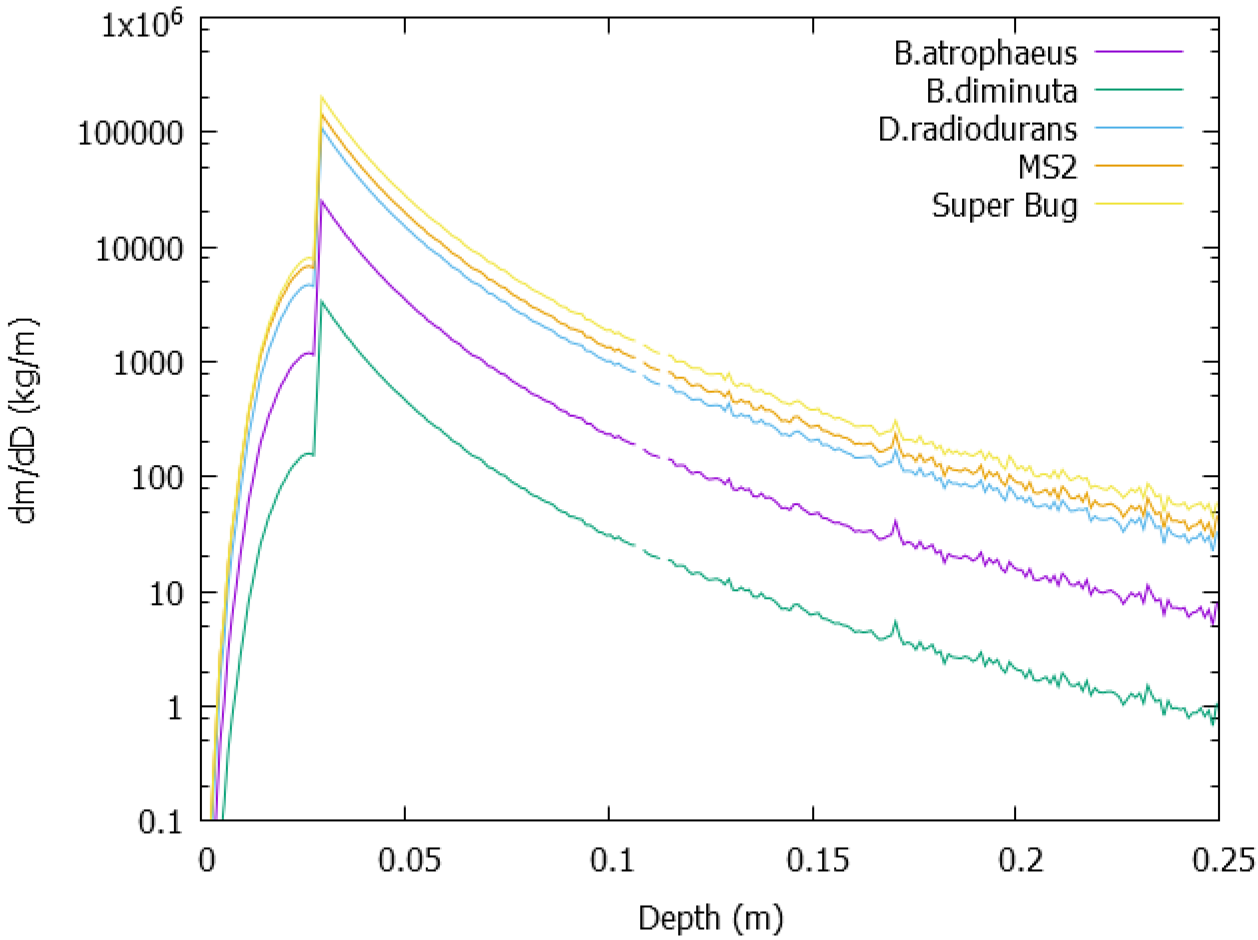

Figure 10-9. The depth distribution of unsterilized material, it follows the mass distribution.

Unsterilized material depth distribution is shown in Figure 10-9, as expected it follows the mass distribution, except for very close to the surface where the Solar Energetic Particles increase the sterilization.

What the graph illustrates, is that if the peak distribution of the transferred Martian material is drilled through, material then going deeper reduces the life. This is shown in Figure 10-10.

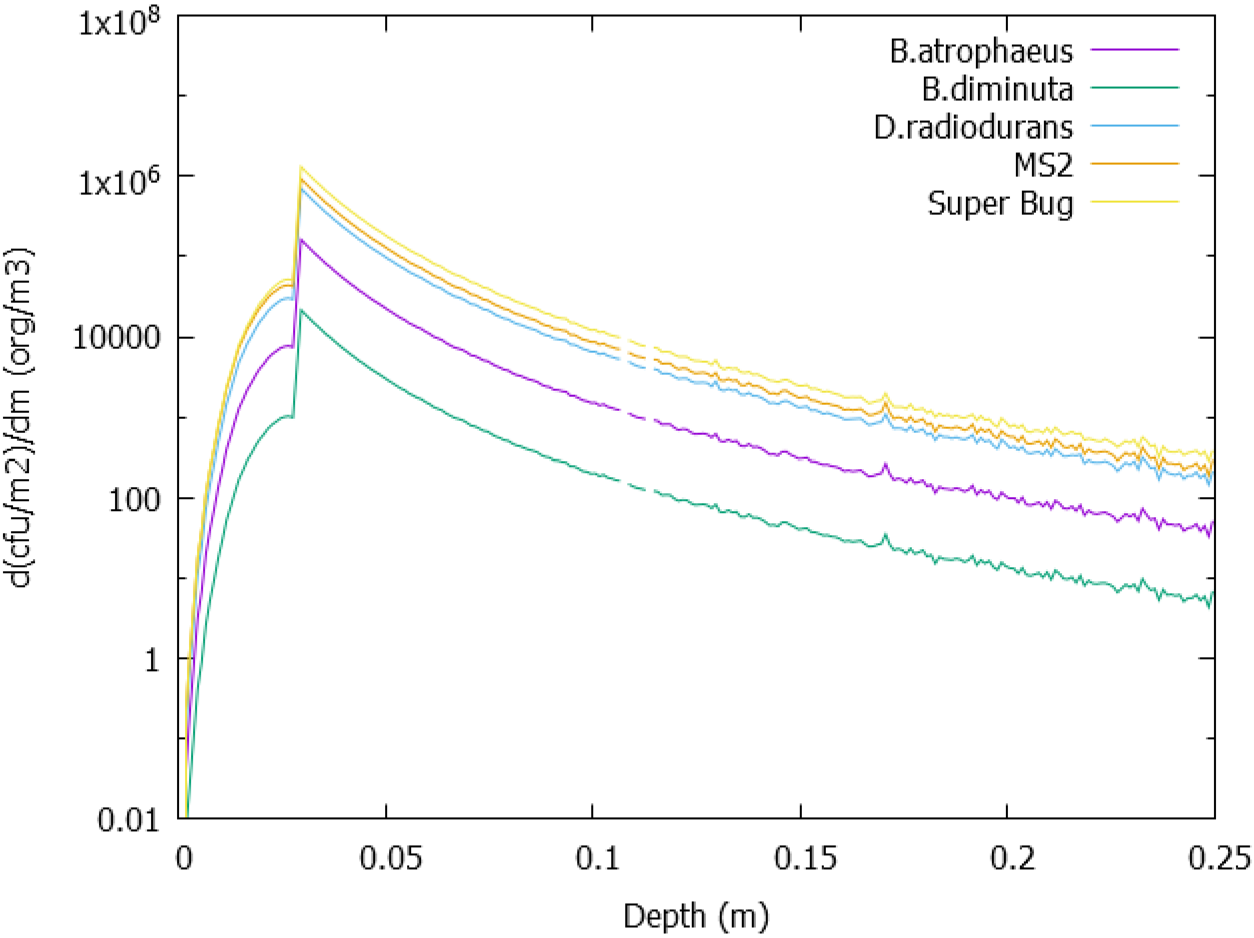

Figure 10-10. The amount of life per square meter of Phobos, as a function of depth. This is shown for a loading rate of 1e10 cfu/kg on the Mars Ejecta.

This shows that with a high life loading even at 25cm depth there is still enough life, that a 1mm×1mm×1cm(depth) sample would be close to requirement 10 limits. However care would be needed not to collect any material from where most Martian material is deposited. As the area where Martian material is deposited cannot be said with certainty (it depends on many variables, but will be close to the surface), the only viable conclusion is if material collected at depth, collects almost no material from the other areas passed through. This clearly is not viable.

10.4.2.4. TIME DURATION

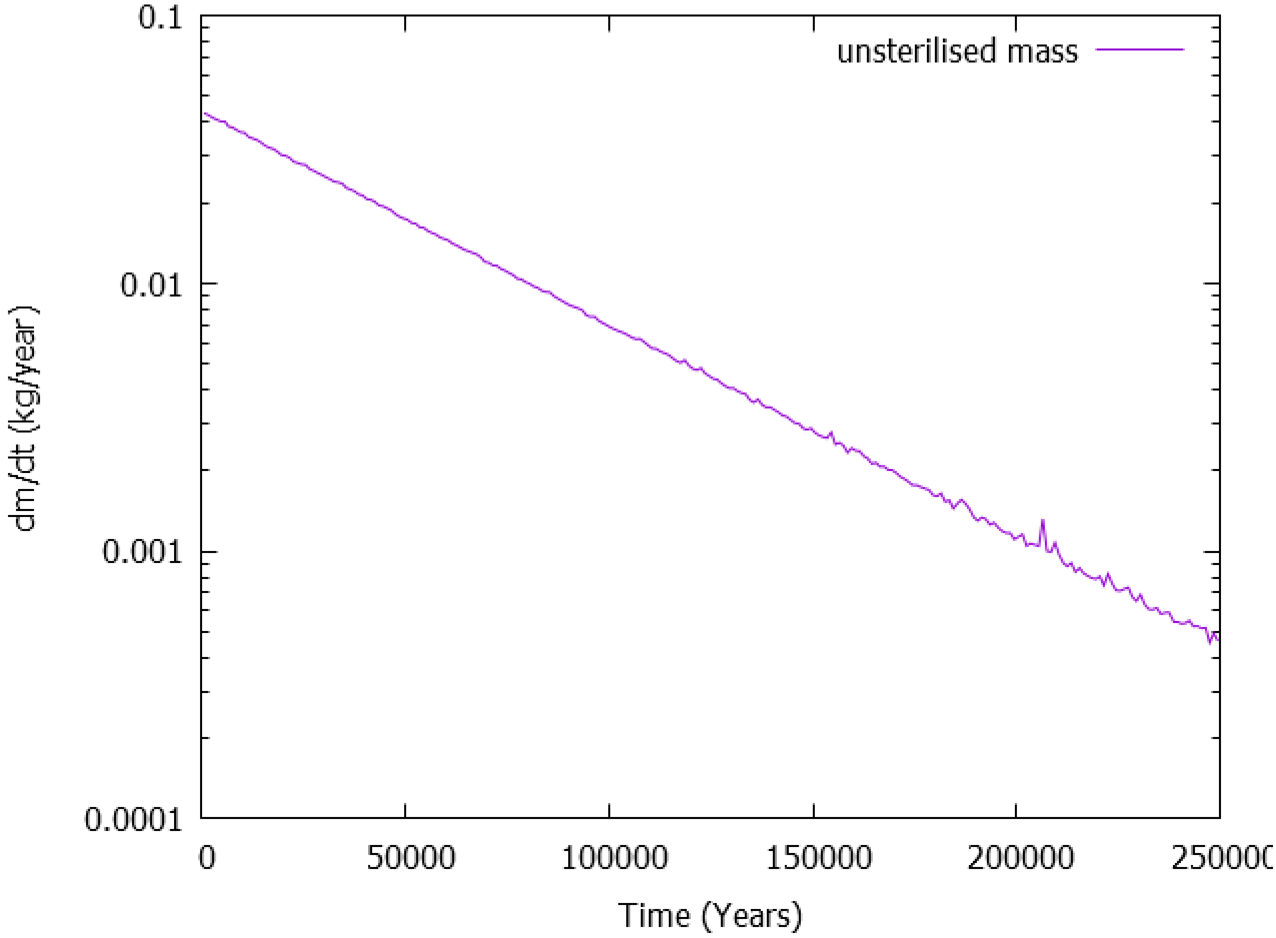

Figure 10-11. When buried there is less radiation, with GCR radiation dominating. This means that the time constant is longer, and this is reflected by the period that material stays unsterilized on Phobos. Plot for the Super Bug.

The time distribution is shown in Figure 10-11. As less radiation is received when at depth, the time constant increases, and this increases the time that material is unsterilized for.

10.4.3. Deimos

The calculation for Deimos follows the same direction as the Phobos calculation:

Organism	Total Mass	Unsterilized mass	Cfu		Cfu/m^2
B. atrophaeus	3.88e4 ± 9.71 kg	11.6 ± 0.009 kg	Low	1.16e6 cfu	2.34e-3 cfu/m2
			Medium	1.16e8 cfu	2.34e-1 cfu/m2
			High	1.16e11 cfu	2.34e2 cfu/m2
B. diminuta	3.88e4 ± 9.71 kg	1.55 ± 0.0012 kg	Low	1.55e5 cfu	3.13e-4 cfu/m2
			Medium	1.55e7 cfu	3.13e-2 cfu/m2
			High	1.55e10 cfu	3.13e1 cfu/m2
D. radiodurans	3.88e4 ± 9.71 kg	45.8 ± 0.0316 kg	Low	4.58e6 cfu	9.25e-3 cfu/m2
			Medium	4.58e8 cfu	9.25e-1 cfu/m2
			High	4.58e11 cfu	9.25e2 cfu/m2
MS2 coliphage	3.88e4 ± 9.71 kg	66.2 ± 0.0499 kg	Low	6.62e6 cfu	1.34e-2 cfu/m2
			Medium	6.62e8 cfu	1.34 cfu/m2
			High	6.62e11 cfu	1.34e3 cfu/m2
Super Bug	3.88e4 ± 9.71 kg	78.8 ± 0.0512 kg	Low	7.88e6 cfu	1.59e-2 cfu/m2
			Medium	7.88e8 cfu	1.59 cfu/m2
			High	7.88e11 cfu	1.59e3 cfu/m2

Table 10-7. Sterilisation caused by both hyper velocity collision and exposure to radiation, when the material is buried during impact, and for three levels of load loading on the Mars Ejecta.

Turning to the area that can be sampled and be compatible with Req-10,

Organism	Cfu		Cfu/m^2	Square mm for a 1e-6 probability
B. atrophaeus	Low	1.16e6 cfu	2.34E-03	427.35
	Medium	1.16e8 cfu	2.34E-01	4.2735
	High	1.16e11 cfu	2.34E+02	0.00427
B. diminuta	Low	1.55e5 cfu	3.13E-04	3194.89

	Medium	1.55e7 cfu	3.13E-02	31.9489
	High	1.55e10 cfu	3.13E+01	0.03195
D. radiodurans	Low	4.58e6 cfu	9.25E-03	108.108
	Medium	4.58e8 cfu	9.25E-01	1.08108
	High	4.58e11 cfu	9.25E+02	0.00108
MS2 coliphage	Low	6.62e6 cfu	1.34E-02	74.6269
	Medium	6.62e8 cfu	1.34	0.74627
	High	6.62e11 cfu	1.34E+03	0.00075
Super Bug	Low	7.88e6 cfu	1.59E-02	62.8931
	Medium	7.88e8 cfu	1.59	0.62893
	High	7.88e11 cfu	1.59E+03	0.00063

Table 10-8. The surface area of Deimos that can be sampled without breaking Req-10.

On Deimos it can be seen that a sizeable sample can only be taken with a low loading of life on the Mars Ejecta, if Req-10 needs to be met.

The dependence on the life loading rate on the Mars Ejecta is shown in Figure 10-12.

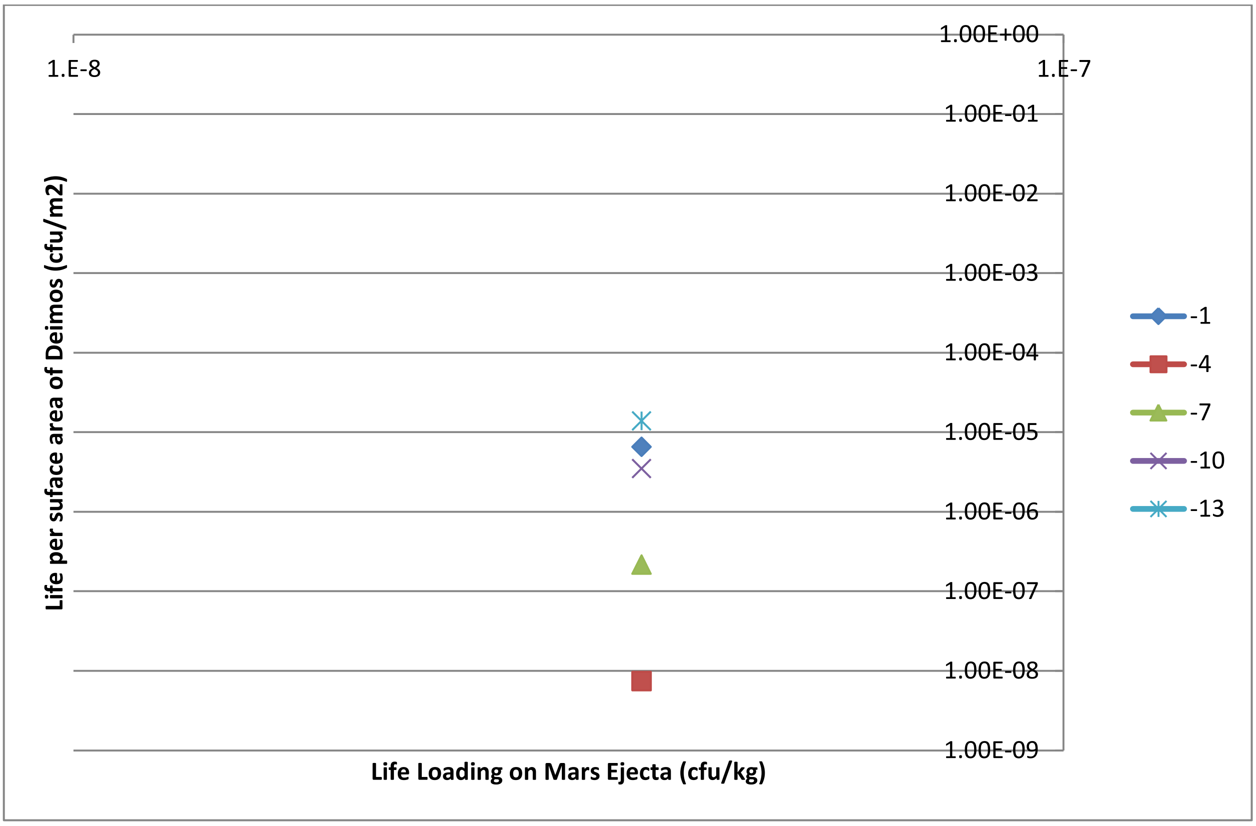

Figure 10-12. The density of life on Deimos as a function of the life loading rate on the Mars Ejecta, when the impact is buried.

11. SYNTHESIS

11.1. INTRODUCTION

This section pulls together the results of all the other sections. In following life through its journey between Mars and Phobos different elements have varying effect. This section pulls out the key areas, simplifying where necessary.

This enables the key assumptions to be questioned, where it can be seen what the drivers are – this identifies the areas to focus on.

Early on in the study, various assumptions were made, some with knowledge, and some unconsciously. With the understanding of the full process that the simulation brings, these areas can be questioned. Here is presented the areas where further developments could be made.

11.2. The Important Bits

11.2.1. Phobos

The most important bits can be encapsulated in a simple equation:

$$\text{Life} = \Delta M \times \frac{\text{cfu per mass}}{\text{Surface Area}} \times S(HV) \times \frac{1}{\text{Total Time}} \times TC(\text{Radiation})$$

Going through each of these terms:

- ΔM is the total material transferred from Mars to a moon, the more material passed, the greater the chance life is passed. Melosh [AD1] had 1.12e6kg transferred to Phobos; this work based on Melosh methods, find slightly higher transfer of 1.63e6kg.

- cfu per mass is how much life the transferred mass can contain. The best information we have on Earth are very dry deserts, for example the Atacama Desert finds biological loading rates of 1e5-1e10 cfu/kg. It should be commented that lower counts in the Atacama deserts come from the dries areas, e.g. Yungay has counts 2e5-5e6 cfu/kg.

- The surface area of Phobos is hopefully uncontroversial, here we use 1548.3km2. Using these first three terms we can establish that in 10MY that ~1e2-1e7 cfu/m2 life forms could be transferred to Phobos

- $S(HV)$ All material that impacts Phobos goes through at least one Hyper Velocity Collision. This collision is a chaotic process, and although parts get very hot, there is a small amount ~10% that has no heating at all. So this limits the sterilisation that the HV impact gives to about 0.1 sterilization at most.

- Total Time again is uncontroversial, it is the time period over which material is considered transferred from mars. This means that average rates of transfer can be established. So in the above example this equals 10MY, which says that 100g/y is transferred on average from Mars to Phobos. In terms of life 1e-5-1cfu/m2/year.

- $TC(\text{Radiation})$ is the time constant given by the radiation and the organism, it is the 1/e period, and this period will contain 63% of all the viable life transferred. This constant was plotted in Figure 10-2, which for the most resilient organisms at the surface gives a value of about 100 years.

Putting all these factors together, to the nearest order of magnitude gives:

$$\text{Life} = 1e6\ \text{kg} \times \frac{1\text{e}5 - 1\text{e}10\ \text{cfu/kg}}{1\text{e}9\ m^2} \times 0.1 \times \frac{1}{10\text{MY}} \times 100Y = 10^{-4} - 10\ \text{cfu/m}^2$$

Which gives a surprisingly accurate (e.g. correct order of magnitude) estimate of how much viable life is on the surface of Phobos.

The beauty of this simplification, is identification of the areas that can be questioned. E.g. is the 1e10 cfu/kg a reasonable estimate for the loading of Martian life on Martian rocks.

The radiation curve identifies the surface as the most hostile place as the surface of Mars, the deeper the material is buried the longer the time scale over which life can survive.

11.2.2. Deimos

For Deimos the same approach applies, two numbers change:

- Mass transferred is reduced: 4.61e4 kg
- The surface area of Deimos: 495.1548 km^2

This changes the equation to:

$$\text{Life} = 4.61\text{e}4 \ \text{ kg} \times \frac{1\text{e}5 - 1\text{e}10 \text{ cfu/kg}}{495.1548\text{e}6 \ m^2} \times 0.1 \times \frac{1}{10\text{MY}} \times 100Y \sim 10^{-5} - 1 \text{ cfu/m}^2$$

So less life than transferred to Phobos, but still at a level that will breach Req-10.

11.3. Assumption Review

11.3.1. Introduction

Of the assumptions presented in section 4, most have been accurate. However ths simulation raises questions against some. These are presented here, as areas that need future study.

11.3.2. Uniform distributions

Phase 1 identified that the first collision with Phobos, after ejection from Mars, distributes material across significantly more than 50% of the surface. Any material ejected to the cloud predominantly hits the opposite side of the planet. So very rapidly material is distributed evenly across the surface of Mars.

This study has confirmed this, with one provision, on arrival at Phobos the material predominantly hits the front face of Phobos, due to the moons orbital velocity (2km/s). This sweeps much of the material onto the front face of Phobos.

Now the range of ejection velocities means there is some variation in the arrival angle on Phobos, so very fast ejectors predominantly hit the side of Phobos facing Mars. Considering all ejection parameters most of the moon is covered.

However there is a slim possibility of a small area close to the tail of Phobos, where it is very unlikely to have an impact of material transferred direct from Mars.

If this is the case, material can only reach this area when going via the cloud, which leads to the second point.

So this suggests a useful addition to the simulation would be to add the area of Phobos where material is deposited.

11.3.3. Life and death in the cloud

Initial in Phase 1 [AD5] identifies that material may orbit in the cloud for "months, years or centuries before re-impacting onto Phobos" in Phase 1 this was seen as far shorter than the 10MY under consideration. This justified not considering sterilisation in the cloud, and it was not included in the original SoW [AD1].

However this report concludes that due to the time constant for decay in viable life due to radiation, that a period of 100 years kills significant amounts of life; by 1000 years most material is sterilised. This shortens the critical period to close to the estimated period in the cloud.

Material in the cloud will be of small size, and so exposed to the full radiation environment. So the rate of depth should be comparable or larger than at the surface of Phobos.

Hence there is a distinct possibility that material in the cloud will be sterilised. This then back up point 1, if there is an area of Phobos which does not receive primary impact direct from Mars.

11.3.4. Radiation out in the wild

In the radiation analysis the radiation from SEP increased toward the surface of the Martian Moon. Eventually this levelled of due to the energy of radiation considered, which was set at 5MeV/nuc.

Now as energy per nucleon decreases, the radiation gets less sterilising, however there is also far more of it. Considering the gamma ray spectrum, as frequency decreases this turns to x-rays, and onto UV light.

Now most of this radiation is very limited in the depth to which it penetrates, however life if exposed will be partially sterilised.

Conversely, the most likely resting place for Martian material is exactly at the surface, for two reasons:

- Phobos Regolith rebound
- Most transferred material is of the smallest size.

This raises the question of the sterilising effect of softer radiation than considered in this project.

11.3.5. Life on the rebound

And critical to the radiation environment, is how close to the surface that material is deposited after the hyper velocity collision. Even just minor burial, significantly decreases the radiation.

This study has primarily studied the hyper velocity impact process, it has not extended into detail into the longer process where material rebounds after impact.

As this rebound is critical for placing material on the surface, where it sees the highest radiation level, does it need more study?

12. DISCRETE MARS EJECTION

12.1. INTRODUCTION

This section considers the extension to the work to consider how the rate of ejection from Mars affects the discrete nature of transfer. In the original Monte Carlo, not only was the transfer of mass from Mars to the Moons considered to be uniform in time, it was also assumed that masses were ejected independent of each other. These assumptions brought great efficiency to the code, but here is questioned how important is the independence of masses ejected from Mars?

Specifically material is ejected from Mars due to hypervelocity collisions, these collisions as well as ejecting material, also make craters. Craters vary in size, and in particular some craters are quite large. For example Mojave crater is 58km in size, and the crater is young (possibly as young as 1 MYear), now a crater of this size will have ejected significant material, and so potentially transferred much material to the moons in a single ejection. That material can be transferred in discrete amounts gives a certain amount of variability in transfer. This is the primary question in this section, what variability is generated in the transfer of life to the moons due to the discrete nature of ejections from Mars.

To establish the rate of mass ejections from Mars, the craters they produce is taken as a marker. The rate of cratering on Mars has long been studied by Bill Hartman, here is used his latest set of Mars Isochron [RD6] – this Iscochron has been updated to include the HiRISE observations of recent cratering rates and is shown below in Figure 12-1.

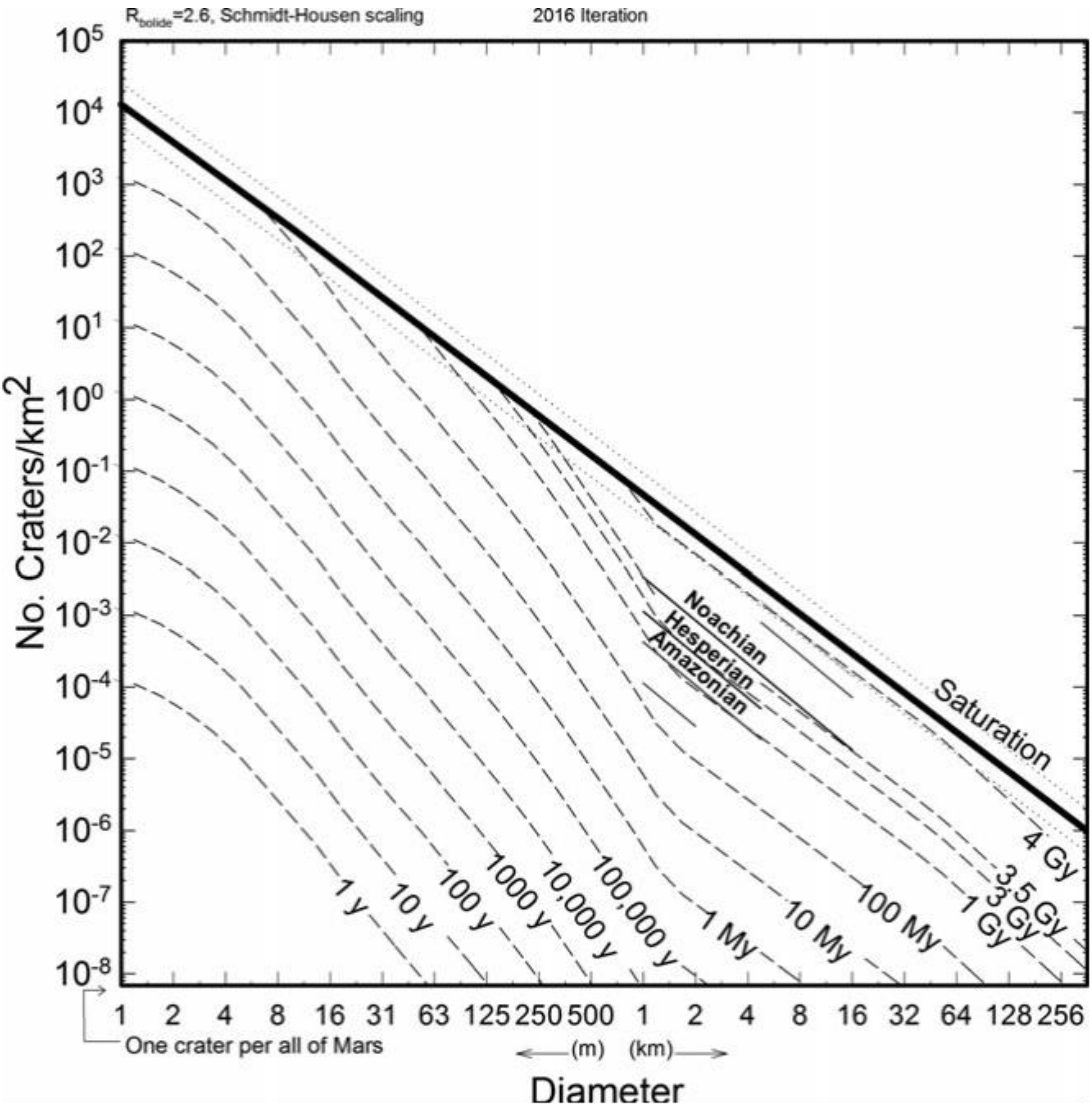

Figure 12-1. Figure 2 from [RD6].

Now important in the updated isochron is the turnover of the graph becoming apparent about 4m. This has the potential to limit the material ejected from Mars.

This enters into a secondary consequence of this work, by modelling the Mass Ejections from Mars, to access the discrete nature, will also give the mass transfer. Hence this work updates the rate of transfer of Martian material to the moon, this gives a consistency check with [AD2]; in particular how this work differs from [AD2] will be assessed.

12.2. CRATERING RATE ON MARS

The first input is the rate of cratering on the whole of Mars. The simulation is configured to generate crater sizes above a certain minimum size. Hence for speed of running the rate of cratering above a minimum size becomes relevant. This is shown in Figure 12-2.

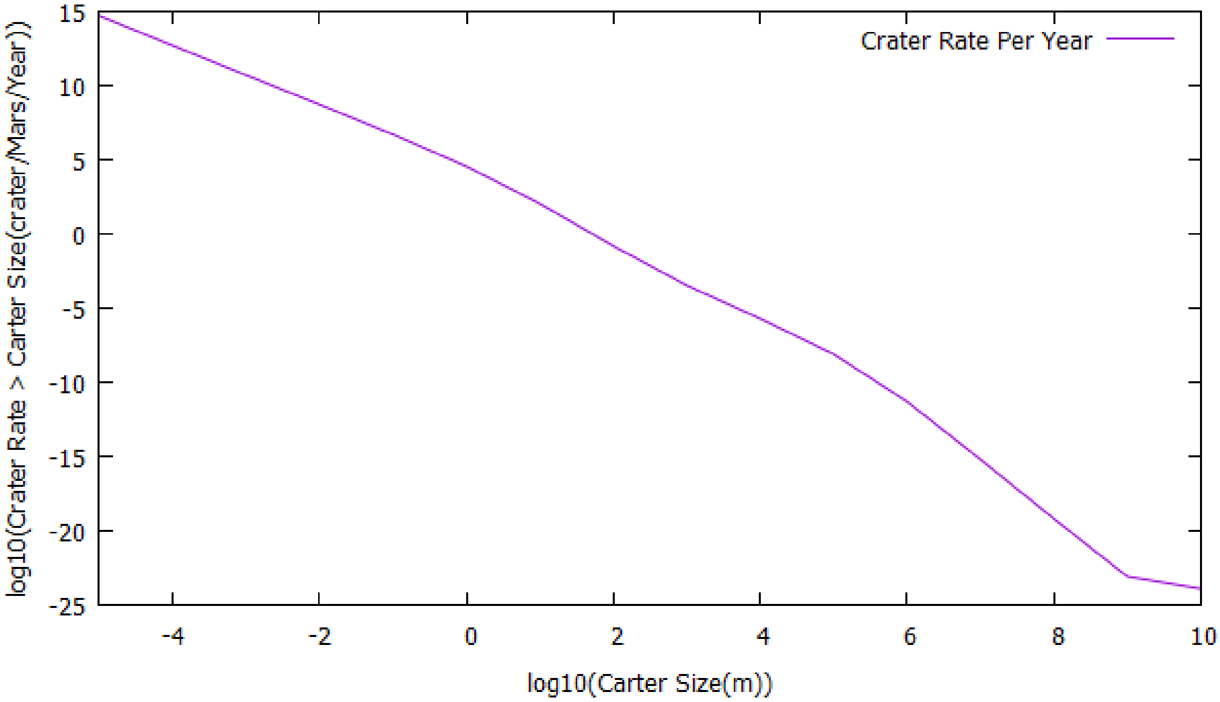

Figure 12-2. The logarithm of the number of craters per year on Mars over a certain size.

As expected from the Iscochrone graph this is very steeply falling, as it is taken across the whole of Mars it gives high rates:

- 1 crater every 6.4 years over 100m
- 109 craters every year over 10m
- 3.6e4 craters over 1m

This has implications for the simulation. If calculating the material transferred in 10MY, this can be performed in about 1e6 steps for craters over 100m, for 1m this takes 3.6e11 – which cannot be performed in a reasonable time.

However this also means that as the time of impact on Mars is uniform, that it affects the variability by the Poisson distribution. In particular:

- The 109 craters over 10m a year, will probably vary by 10 craters, or 10%
- The 3.6e4 craters over 1m a year, will probably vary by about 200 craters a year or 0.5%

So it is clear how different time periods will need to be looked at.

Hence to have the simulation run in a reasonable time, it will be run over various time scales (e.g. not just 10MY) against crater size. For the smaller crater size, the period will need to be significantly shorter than 10MY, so understanding the scaling with time is important. Each time period will be run 100 times, to verify variability. The aim will be to have between 1,000 and

1,000,000 ejections – which will give reasonable accuracy, and more importantly the ability to understand how the results vary with various time steps.

In order to get graphs that can be summed, distributions will be looked at for various ranges of Mars crater sizes, specifically increasing in powers of 10 (e.g. 1m-10m, 10m-100m, etc).

12.3. MASS TRANSFERRED FROM MARS TO PHOBOS

Firstly consider the rate of transfer of material between Mars and Phobos. This is shown in Figure 12-3.

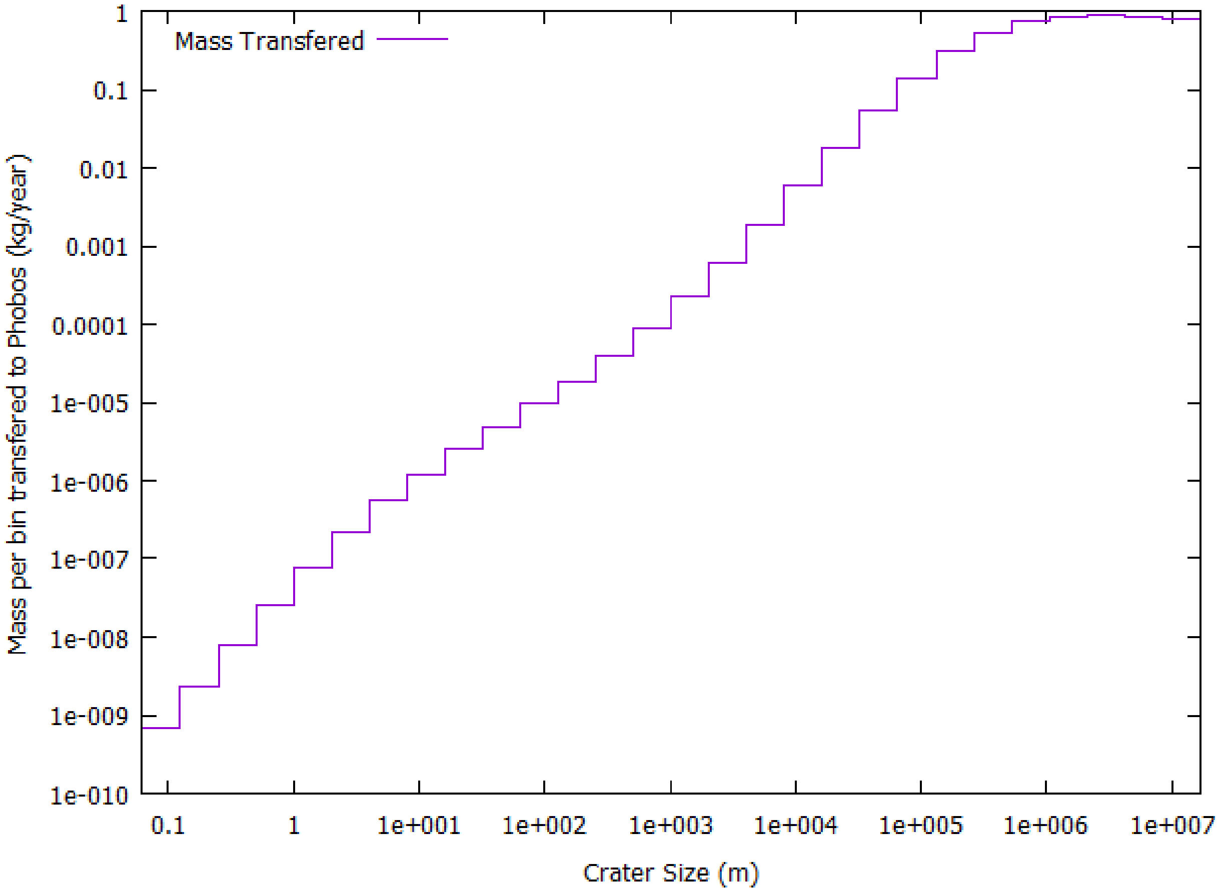

Figure 12-3. The annual rate of transfer of mass from Mars to Phobos.

This shows that little mass is transferred from the smaller craters, the rate grows up to a maximum about 3000km craters, so very large, and only just starting to fall afterwards. Recall that the fit to the Martian crater isochrone artificially had a roll off implemented at 256km, and this is what is responsible for the fall off beyond 1000km, this is driven by where the isochrones curve takes 10^9 years to produce 1 crater on the whole of Mars. It is clear that without the fall off, the rate mass transfer would continue to grow unphysically.

Firstly this should be compared against [AD2], which had 100g transferred per year. Figure 12-3 gives the mass transferred from Martian craters within a factor of 2 in size. The mass from a single bin, peaks at about 0.9kg. So this gives the total mass from craters up to 1.68e4 km in diameter as 5.16kg. So some explanation of mass transfer is needed. Two factors drive the growth:

- Firstly in the isochrone graph of crater size has a change of slope at 1km in size. This drives the bulk of the mass transfer (e.g. if this term is disabled, far less mass is transferred).
- Secondly the relationship between impactor size and crater size increases from ~1/300 at 1m size, to ~1/30 at 1km size. This gives increasing slope to larger crater size – which affects mass transfer as a cube. This significantly changes the shape of the curve.

Now the transfer in mass is dominated by craters of between 1km-1000km in size (where the growth occurs), and over 1000km. The time scales for transfer is shown in Figure 12-4.

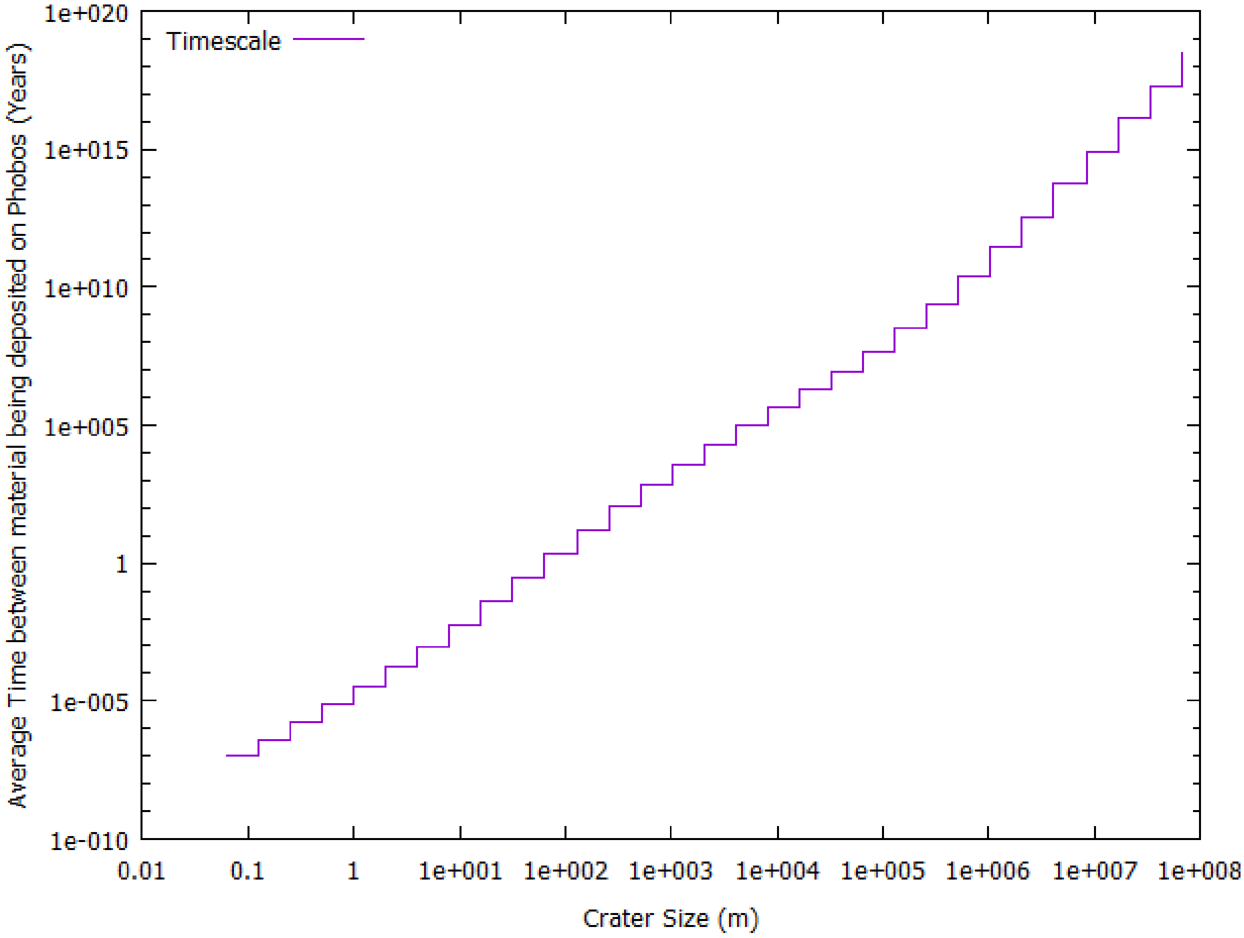

Figure 12-4. Average time to transfer material to Phobos, from Martian Craters. Whereas small craters transfer material regularly, larger craters only very rarely transfer material.

What is clear is although smaller craters (below 100m) transfer mass material very regularly, larger craters are exceptionally rare. So in the ~3GY shown in the isochrones distribution it is rare to expect craters over 300km in size. [Note that this is for a bin of size scale 2 – so integrating over larger bins gives more regular ejections]. This timescale will clearly limit the transfer the transfer of mass, the history of Phobos since its creation will dictate the occurrence of large Martian craters, which transfer significant mass.

This is significant in the context of sterilized material on the Martian moons, when most mass transfer happens over extended time periods, but because of the radiation only recently arrived material will be unsterilized. So it is the radiation environment that will limit the timescale, and hence the material transferred.

12.4. MASS TRANSFERRED PER EJECTION

So with the average time between ejections increasing rapidly against Martian crater size, but the mass transferred per year increasing, it is clear that the mass transferred per mass ejection increases rapidly with crater size. This is shown in Figure 12-5.

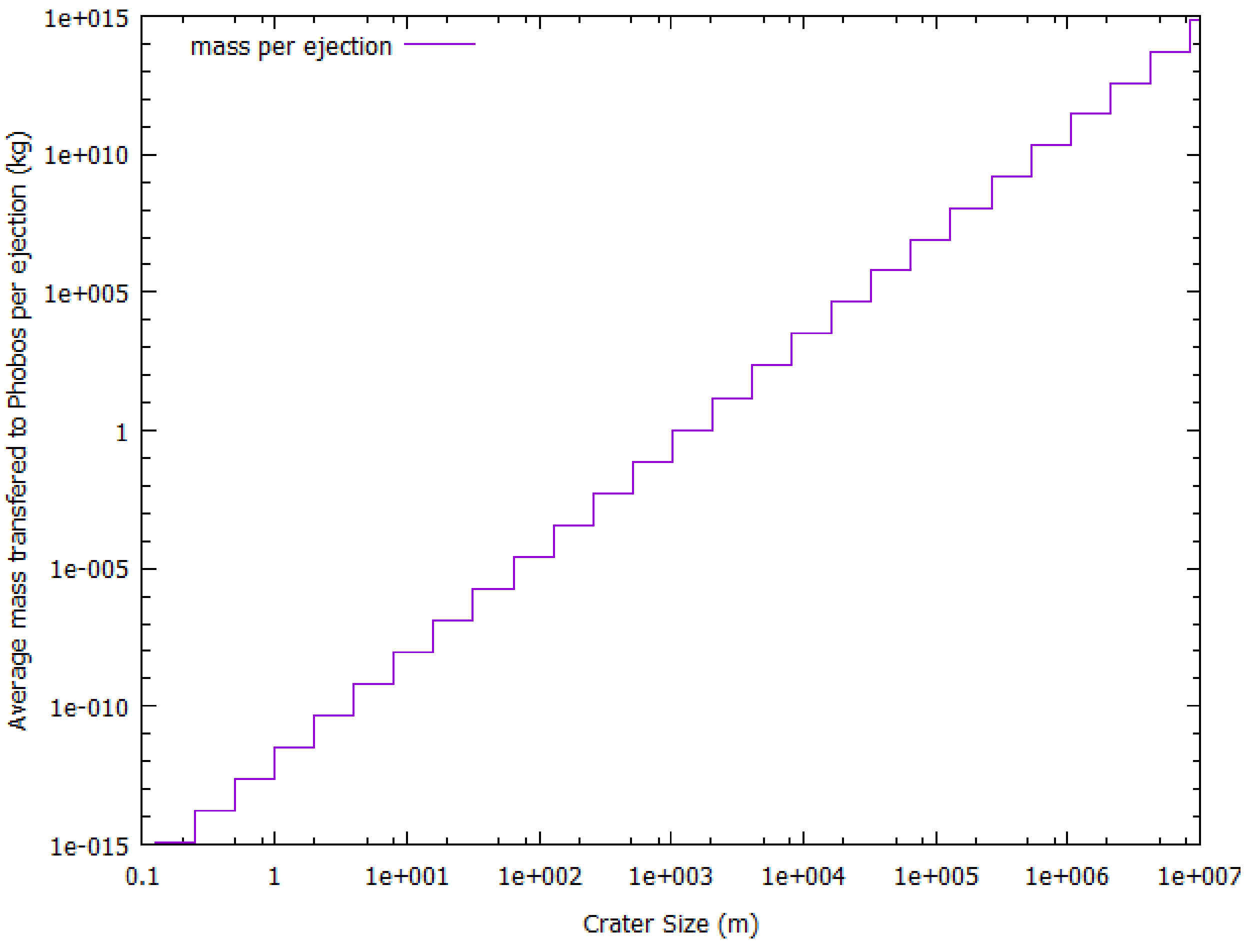

Figure 12-5. The average mass deposited on Phobos per mass ejection, as a function of Martian crater size.

12.5. VELOCITY DISTRIBUTION

The velocity distribution is worth considering. Firstly it gives a good comparison with the first version of the simulation, with discrete ejections from Mars the ejection velocity is modelled differently from before. Also the orbital dynamics is very different, having to cope with material emitted at the same time, but with the point of origin affecting the correlation between material in the ejecta.

This makes this a good distribution to check the logic used in the first simulation, the second simulation due to the extended version of calculations performed is expected to be far slower (which translates into the graphs will not be as smooth).

Secondly, as the impact velocity of Mars is independent of crater size (as material originates from the asteroid belt), and the ejection from Mars scale with the impactor size due to hydrodynamic invariance [RD8], the shape of the velocity distributions should not depend on the crater size that the material originates from. So this tests this, which can be used to simplify the Phobos impact section.

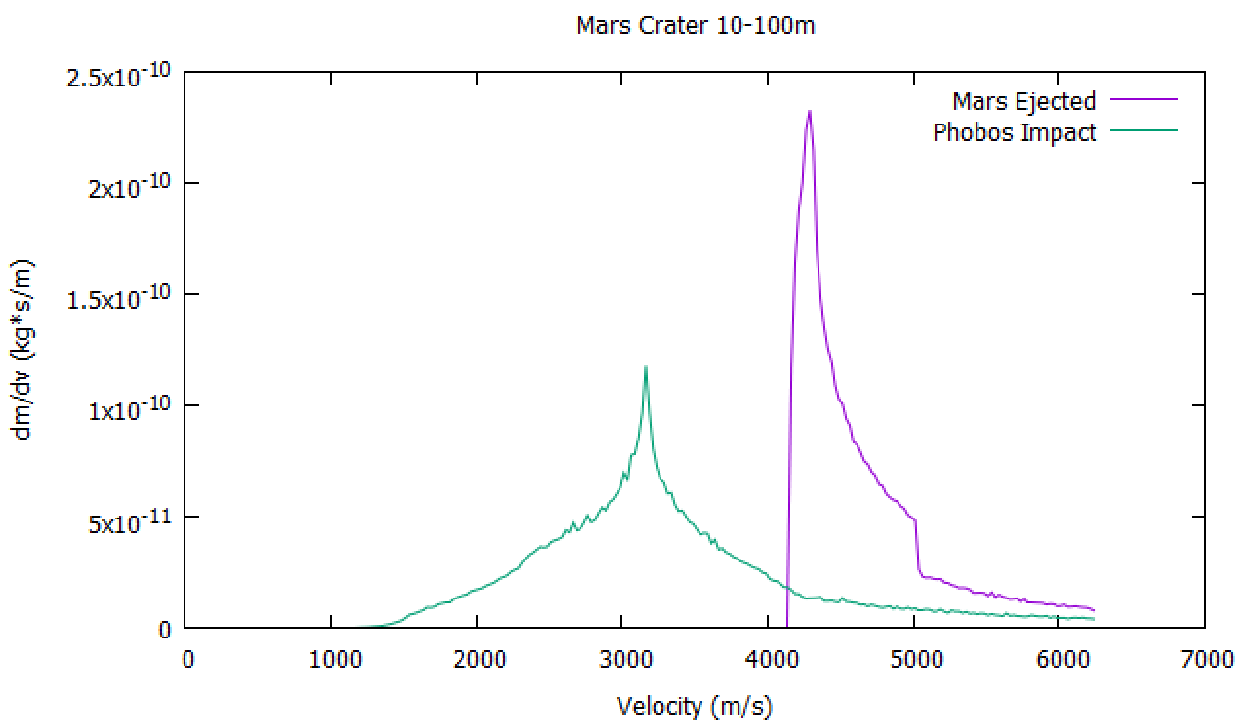

Figure 12-6. The ejection velocity from Mars, and the impact velocity on Phobos compare to Figure 6-3 for the two versions of the simulation. This is plotted for the Mars Ejections that come from 10-100m craters.

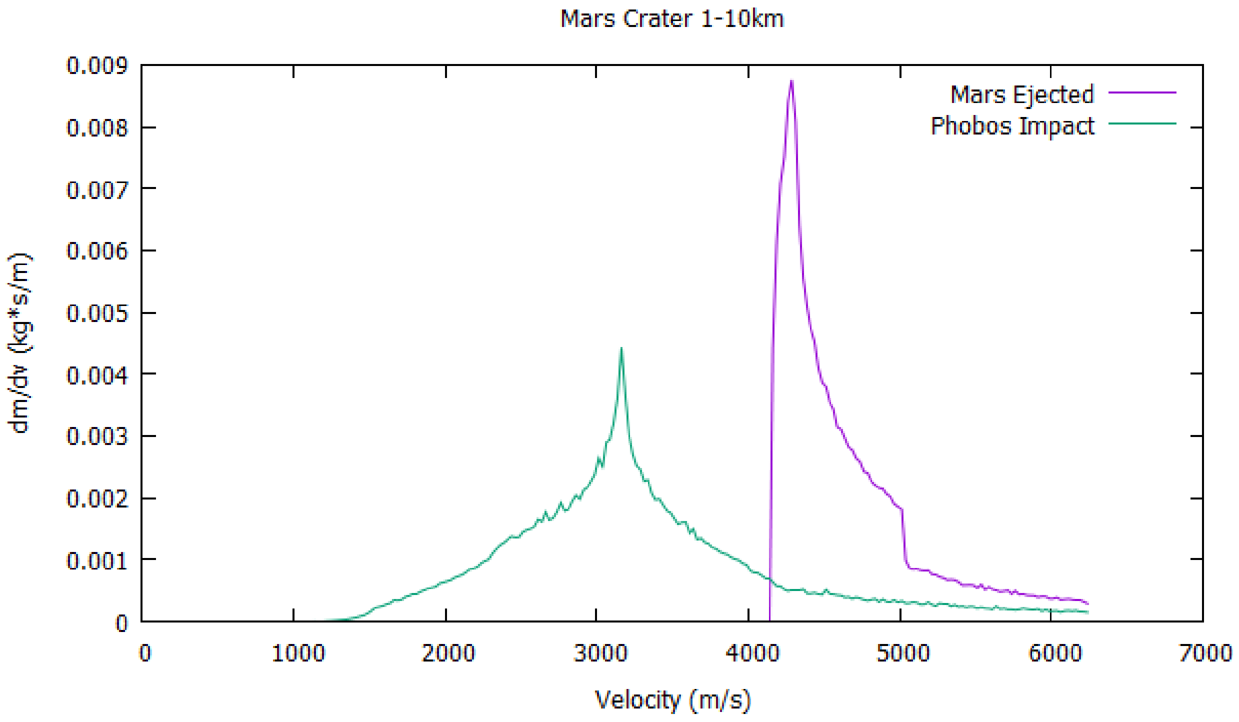

Figure 12-7. The same figure as Figure 12-6, plotted for ejections from Mars craters sized from 1-10km. The normalisation is expected to change, but shape expected to stay the same.

The distributions are shown in Figure 12-6 and Figure 12-7 agree very well with Figure 6-3, which had the same ejection cone as used here (45°), here the step at the Mars escape velocity is clearer – this is caused because ejection below the escape velocity crosses Phobos orbit twice.

The shape of the distributions for ejection from different sized Martian craters does not affect the velocity curves, this means that the sterilization in the Phobos impact should be independent of the size of Martian crater from which the material originates.

12.6. Impact with Phobos

12.6.1. Sterilisation

Moving onto the impact with Phobos, as the potential for significant material to be transferred to Phobos from a single mass ejection from Mars; the question is how does it arrive at Phobos.

- In the ejection from Mars, the material will typically be exposed to great pressure, which would typically mean it is fragmented to small size.
- The finite size of the Phobos impactor, means differential heating through the impactor in the collision.

- If the material arrives at Phobos in a single piece, there is the possibility that it will be buried deeply.

Now the impact with Phobos is an isolated event that produces sterilization, it does not have a time extent.

So care is needed with the conservative approach. To cover the finite size, the impactor is integrated over. This gives significant slowdown in the simulation. As the time period is not important, a simplification is to examine the effect for an average mass ejection from Mars. The time dependence then can be taken from the previous section and Poisson statistics.

The first information is how much of the impactor is sterilized.

Organism	Fraction unsterilized	Variation in sterilization
Deinococcus radiodurans	54%	23%
Bacillus atrophaeus	48%	22%
Brevundimonas diminuta	48%	22%
MS2	48%	22%
Super Bug	58%	22%

Hence as before a fair fraction of the organism survives, although the survivability differs between the organisms the number of organisms that survive is close to 50% of all organisms. This could be explained by the variability in heating through the impactor, with parts that go unheated. In this case all organisms in the unheated part survive, independent of how robust the organism is.

Also apparent is that there is variability in the sterilisation, this is expected due to due to the variation in impact velocity.

12.6.2. Depth Deposited

The exposure to radiation depends on depth deposited. The deposition happens during the HV collision with Phobos. Now the depth that an impact deposits material at is not clear, but is expected to be related to a multiple of the impactor size. In the first part of this work four times the size was used as a conservative value.

Hence a key question is the size of the impactor on the moon. This is not clear, as material originates from ejection from Mars, and that process its itself a hyper velocity collision. Hyper velocity collisions by their nature take material beyond its structural strength, and hence material ejected will to a high degree be turned into dust. However the high pressure generated are released at the surface, also finite sized ejecta have been observed (e.g. the Martian meteorites found on Earth). So as before the question is how to model this conservatively.

Now with discrete ejections from Mars, this changes the nature of the process. With big ejections significant material is transferred to the martian moons in a single transfer, very small ejections though have the possibility to transfer material – but only in small amounts. Small ejections are also unlikely to generate large ejecta. Hence a conservative approach is to determine how much mass is deposited on the moon from each discrete ejection, and then take that material deposited on the moon in a single lump. This is taken to be particularly conservative, and will probably mean that the largest objects will be buried deep enough to only feel the residual radiation.

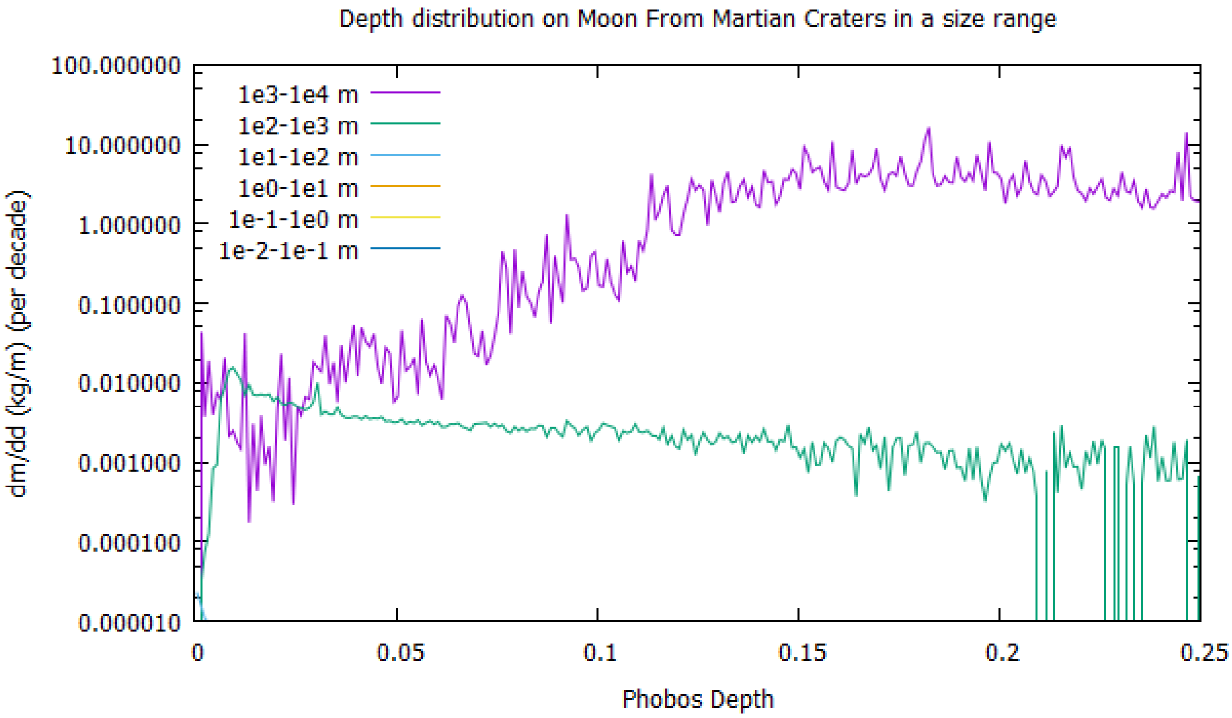

Figure 12-8. Assuming that all the mass that hits Phobos from a single mass ejection, hits the moon as a single object, the resulting depth of deposition. Plotted for ejections originating from various sizes of Martian craters. Note that for craters below 100m the material is close to the surface.

Figure 12-8 shows the resulting depth of deposition, even with the very conservative assumption that the mass hits Phobos in a single object, it can be seen that small Martian craters (below 100m diameter) transfer so little material to Phobos that it will always rest on the surface. For craters between 100m and 1km the material will typically be at a few cm depth, but with some material lower. For Martian craters over 1km in size, if the material is deposited on the moon in large lumps, then it is deposited many 10cms below the surface.

Compared to Figure 12-5, craters over 1km in size only happen every 10^4 years on average.

So this sets the context, smaller Martian craters below ~100m-1km in size eject little mass, and will be deposited on the surface of the moon where radiation is highest. These ejections happen often, but have least effect for transferring life between Mars and its moons. Larger craters both transfer more material and at depth (where radiation is lower), but happen rarely and so material will spend extended periods on the moon.

12.7. Sterilization on the Moon

12.7.1. Material On the Surface - Phobos

Firstly considered is material deposited on the surface of the moon (Phobos), as material transferred from Mars to the moon is the result of a hypervelocity collision and ejection with Mars, that ejection is expected to mainly eject material fragmented to the grain size. Material at the grain size, is almost certain to settle on the surface of the moon, regardless of the impact velocity.

Considering settling on the surface of the moon, is a good place to understand the complexities of the transfer process:

- On the surface, the radiation modelling gives a precise environment, that gives rise to a well-defined time constant at which life dies (see Figure 10-2); this in turn for a set organism gives the time scale that needs to be considered.
- The rate of Mars mass ejections is very dependent on the Martian crater size:
    - Smaller Martian craters will eject material with a time period far shorter than the time constant to sterilize organisms on the moon, hence there will be many ejections over the sterilization period. This will tend to average out, and not vary much.
    - For larger Martian Craters, the rate of ejection will drop below the time constant for sterilization; then the criticality is probability that material is transferred in that period, and the variability that the low probability gives

This gives the approach, first the time period is chosen for the organism. Considered first is the “SuperBug” the organism which is the most resilient, at the surface this has a time constant of just under 100years. Hence the simulation should be run for at least 1000 simulated years (e.g. 10 time constants), to give some margin 10^4 years is chosen.

Now with the largest craters, it still rapidly gets to the stage where it is rare for a crater to be created in 10^4 years, for this case at least one mass ejection is generated, this typically has a period of greater than the 10^4 years. Rather than counting this as a possible history with no transfer of sterilized mass, instead the sterilised mass is calculated with the time of ejection; as this time is over 10^4 years it contributes little to the sterilized mass.

As the dependence on size of the Martian crater is so strong, the simulation is performed in a range of Martian crater sizes, where each simulation covers a variation in Martian craters sizes that vary by a factor of 2. This enables other parameters of the simulation (e.g. number of runs) to be optimised.

For each range of craters sizes, the simulation is run multiple times (in powers of 2, up to just over 1000km). This enables both the average rate of sterilized mass transfer to be calculated, but also its variance. This is shown in Figure 12-9.

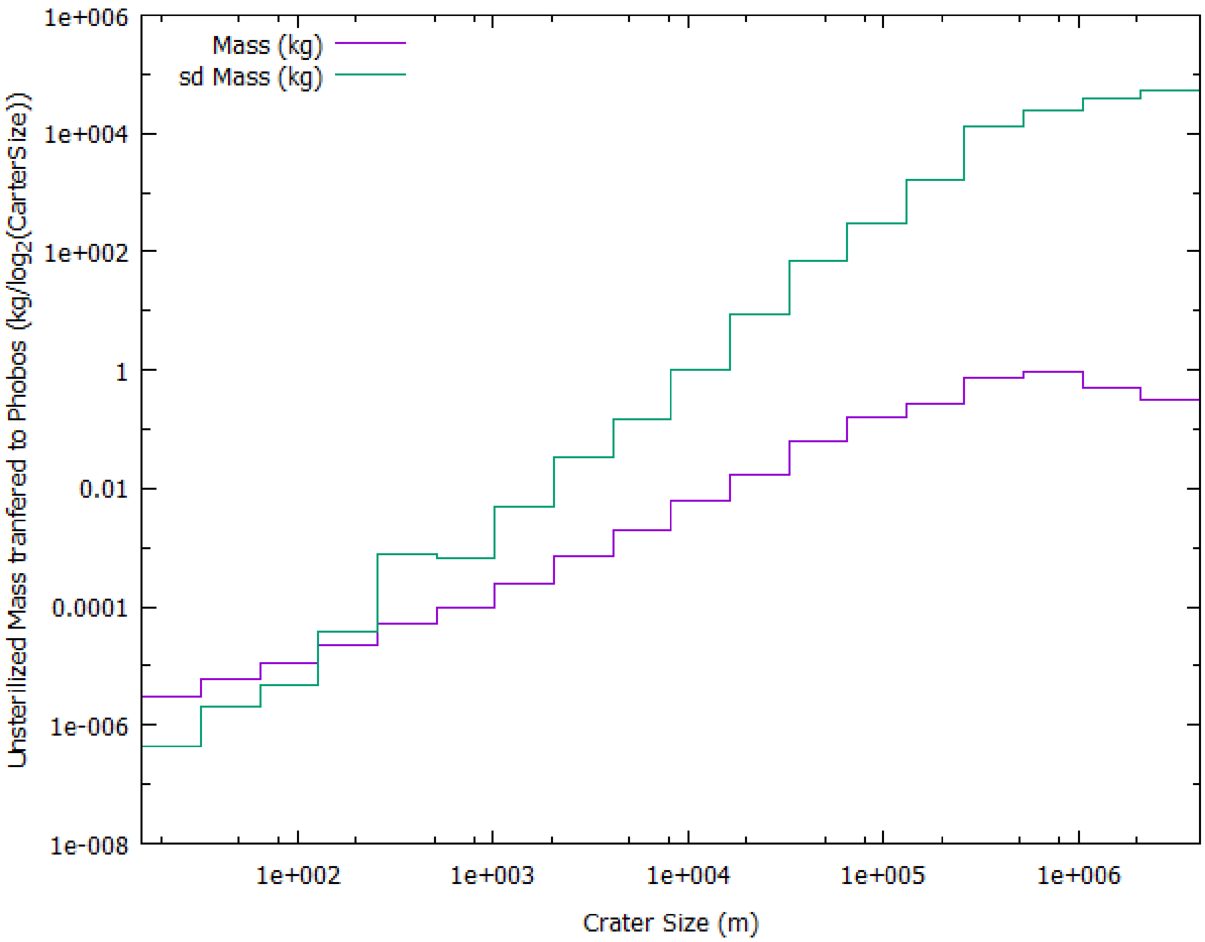

Figure 12-9. The mass transferred to Phobos which remains unsterilized, and the standard deviation in that mass, as a function of size of Martian crater from which it is ejected. This is plotted for the SuperBug, which has the most resilience properties of all organisms tested.

What can be seen is that the greatest amount of mass transferred which remains unsterilized, is from the largest Martian Crater. These craters are relatively rare, certainly far rarer that the 100 year time constant for the sterilization on the surface of Phobos, however if a crater of this size is created in the last 100 years, it transfers such a huge amount of mass that this increases the average.

This can be seen in the variation of sterilized mass transferred, for small craters below 128m in size, material is transferred regularly enough that the variance is below the average rate – this material is transferred consistently, and continuously tops up the unsterilized material on Phobos. However it's a small amount below 0.1g.

How is it possible for larger craters to dominate the transfer of life, when the model used in TN19 [AD3] has such craters produced on time scales of 10^5-10^6 years, vs a time constant of 100 years. The crux is the Poisson distribution, craters on Mars are expected to have a poisson distribution of times of creation, as the time of creation gives the time period that material spends on the moon, and hence the time sterilized in the radiation. The Poisson process is that Mars ejections happen independent of each other, and independent of time. This is what means that there is a probability for even large craters to be produced in the period of the time constant for sterilization. Consider where the average rate of producing a Mars mass ejection which reaches the moon in a period is λ, each ejection on average transfers some mass M, and so on average transfers $M\lambda$ mass for that period. Now for a Poisson process the variance is also λ, so the standard deviation $\sqrt{\lambda}$, and the standard deviation mass transferred $M\sqrt{\lambda}$. Hence it can be seen that when λ is less than 1, that the standard deviation does grow larger than the average rate. Also where that is scaled by the mass transferred per ejection, the rate can also grow, even though the typical number of ejections is falling.

This relation can be made explicit, by converting the sterilized mass transferred and its standard deviation into the average rate of emissions over the sterilization period, and the typical mass transferred per ejection. This is shown in Figure 12-10 and Figure 12-11.

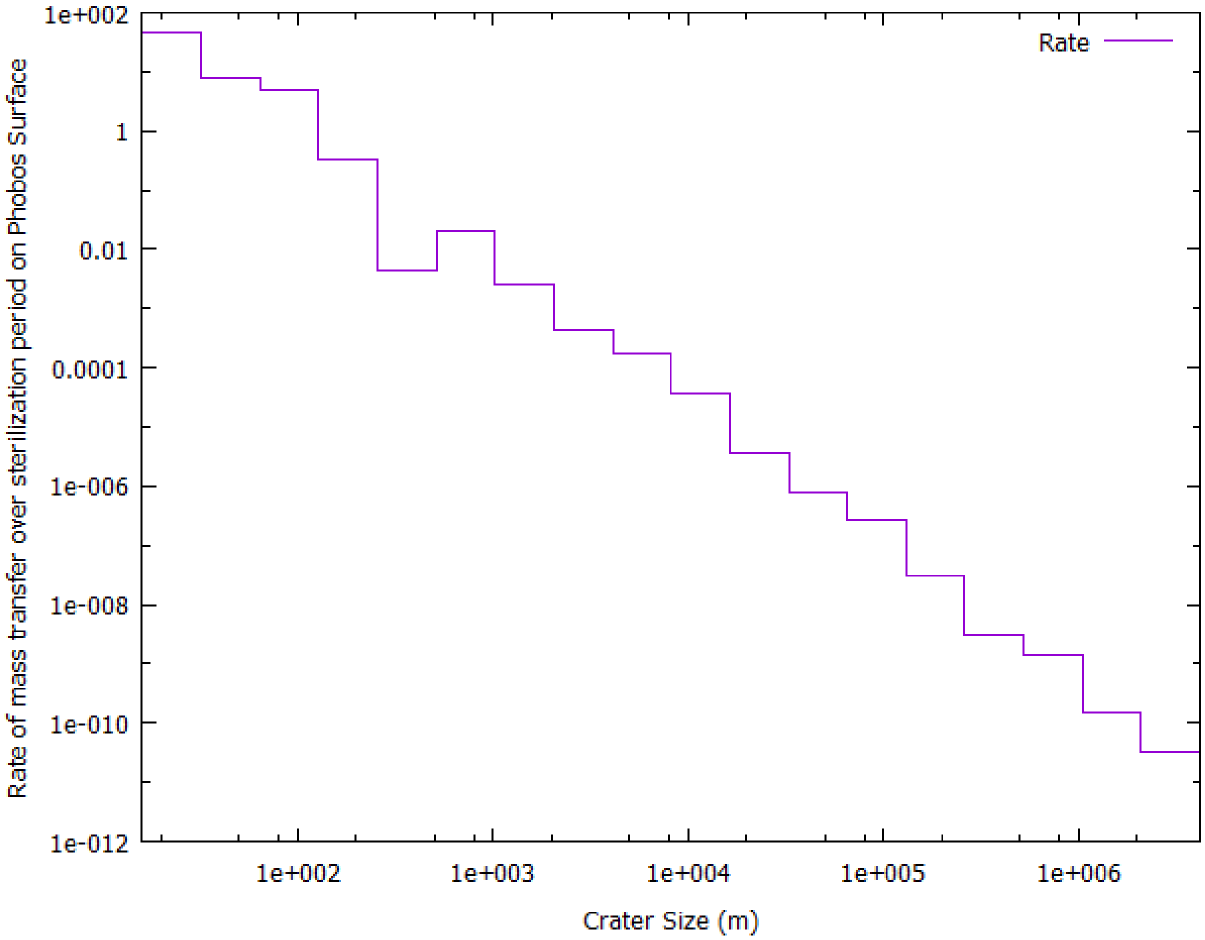

Figure 12-10. Typical Number of ejections in the sterilization time period against crater size – note that this includes all orbital dynamics, mass ejection properties, etc.

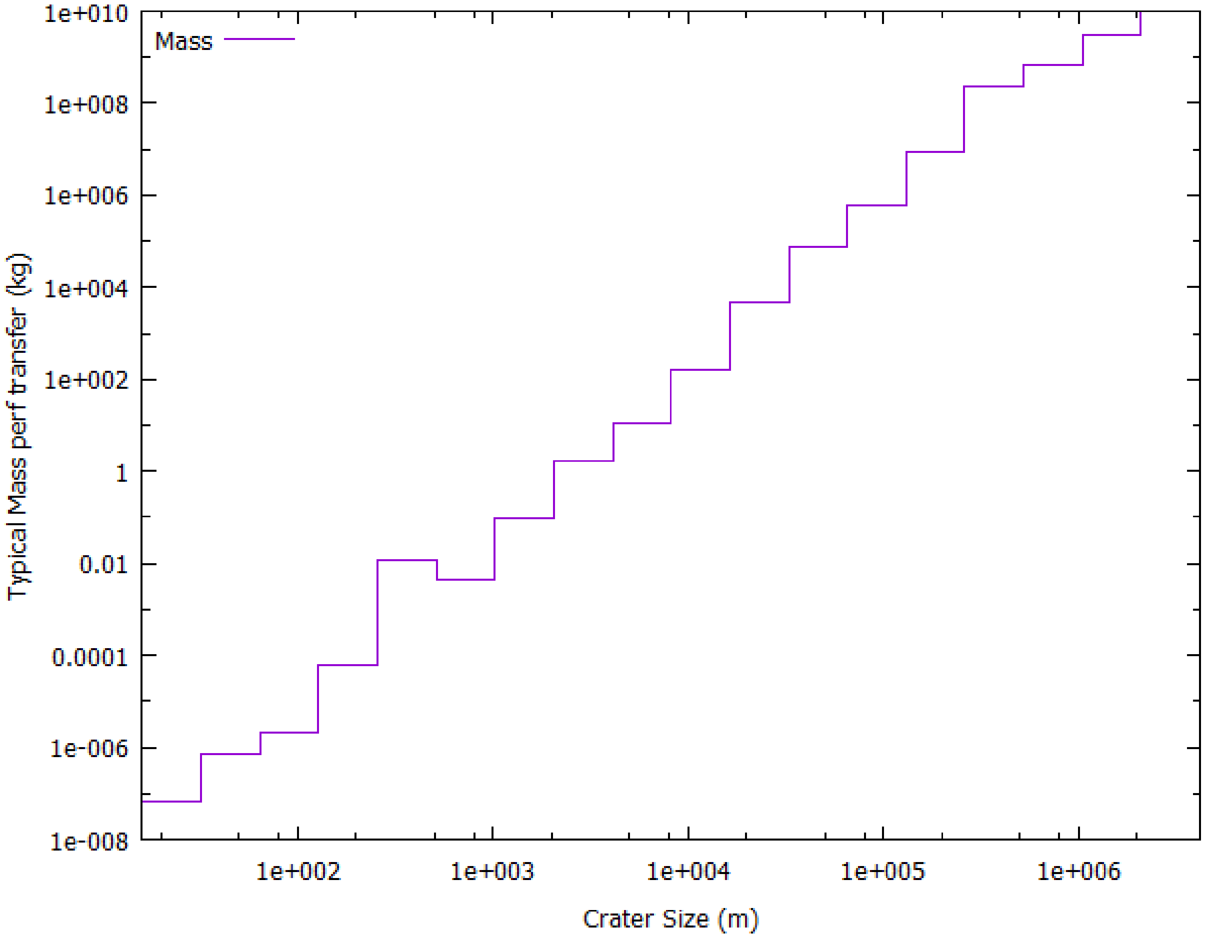

Figure 12-11. Typical Mass transferred to Phobos per Ejection against Martian crater size – note that this includes all orbital dynamics, mass ejection properties, etc.

Although the probability and mass transfer are somewhat synthetic (e.g. as they include all orbital dynamics, ejection properties, etc – they are just a representation of how the transfer breaks down). They do illustrate how the properties of the mass ejection vary with crater size, the typical number of mass ejections in the sterilization period falls below 1 at about 128m sized craters; however the mass ejected and transferred to Phobos grows very rapidly and although the probability of ejection drops the growth in mass wins and so *on average* more mass is transferred.

To make this clear consider the time distribution of unsterilized mass on Phobos, produced from Martian craters sized between 8.192-16.284km. Craters this sized are produced at a rate of 2.3 per 10^6 years, so typically will happen in the distant past. However looking at the age of unsterilized mass, this is shown in Figure 12-12 it is clear that the 2 in 10^4 craters that are produced in the last 100 years dominate the mass transfer of unsterilized mass.

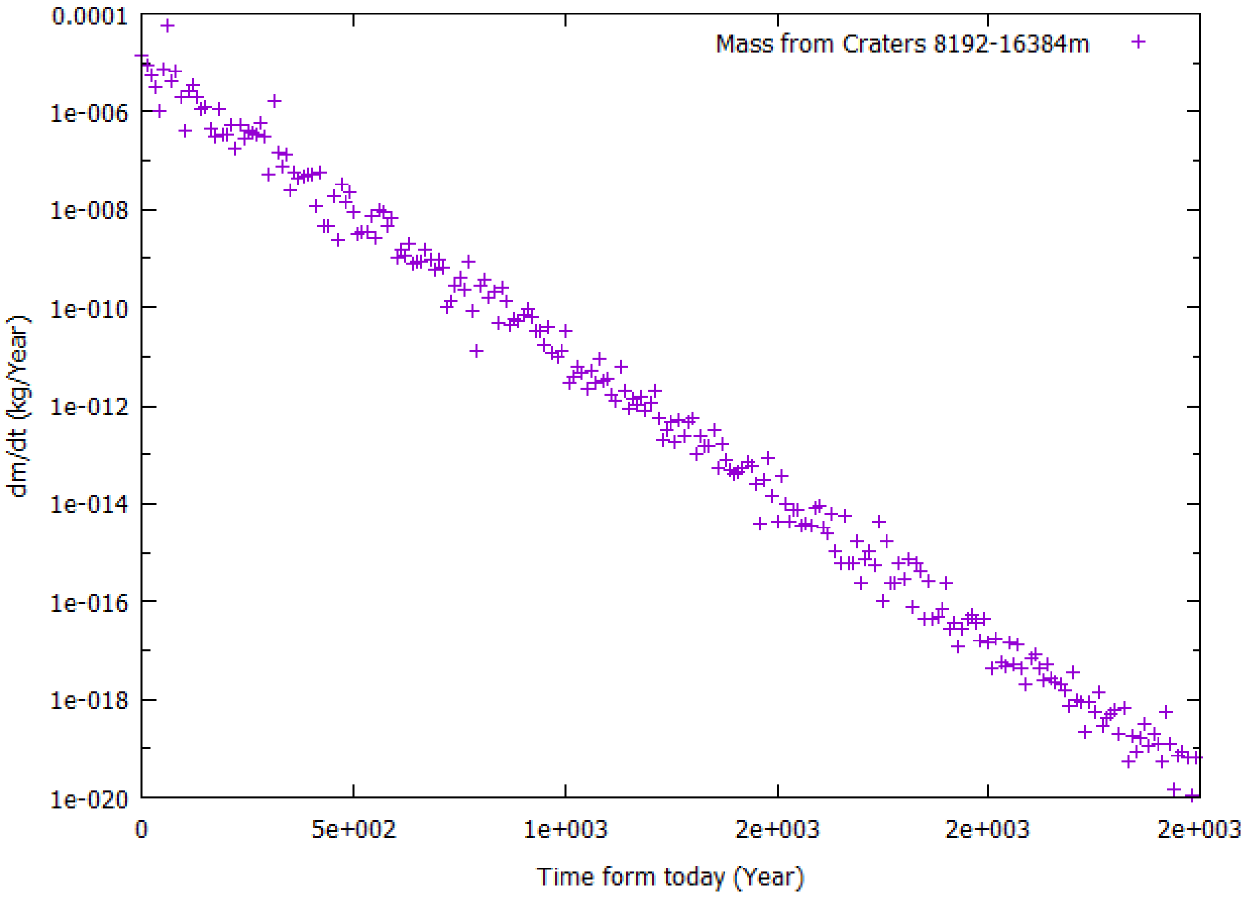

Figure 12-12. The age of unsterilized mass on Phobos, for material from 8.192-16.384km Martian craters, although the average rate of cratering is ~ 2 per 10^6 years, the small fraction which are produced recently dominate the unsterilized mass.

It is important to realise this is due to the probability of large Martian craters ejecting material in the recent past. This give a new question to ask, if all large craters can be dated as happening in the distant past, then it is known that material that they transfer to Phobos will have been sterilized. However where Martian craters cannot be dated, then it cannot be said that they have not been recent, and if they have been recent then they can transfer significant material to Phobos.

This gives another way of looking at the results, the primary requirement [AD1] Req-10 to get the probability below 1 part in 10^6, means when is the probability of a larger Martian crater transfers mass to Phobos below 10^{-6}, in 100 year period which it takes to sterilize material on the surface of Phobos, and this probability happens for craters 100km in size and upward. Hence should one only consider craters smaller than 100km? This lowers the typical transfer of unsterilized mass to 250g.

Consider what this means for life on Phobos, 250g of unsterilized mass on Phobos gives:

Assumption	Cfu/m2 for each 250g mass transferred
Low loading of life	1.6e-5 cfu/m2

Medium loading of life	1.6e-3 cfu/m2
High loading of life	1.6 cfu/m2

Whilst the typical transfer of life for craters that stand a greater than1 in 10^6 chance of being produced in the last 100 years is quite low, the crux is that for these craters not a typical transfer, but a transfer at 99.9999% confidence level. This is where uncertainty arises, whilst the typical mass is 250g, the standard deviation (assembled from sum of squares) for the mass from those craters is 317kg. The distribution of these possible mass transfers, has not been plotted (and being the sum over multiple crater sizes is tricky to plot), but the message is clear in order to reach the 99.9999% confidence level will require a few times the standard deviation. This means that at this confidence level, at least hundreds of kg, and probably 1000kg of transfer needs to be considered.

Hence at the 1 in 10^6 level the loading of life that needs to be considered in approximately 3 orders of magnitude higher than above:

Assumption	Cfu/m2 for each 250kg mass transferred
Low loading of life	1.6e-2 cfu/m2
Medium loading of life	1.6 cfu/m2
High loading of life	1.6e3 cfu/m2

Comparing this to the typical rate of transfer shown in **Table 10-1** and it can be seen that discrete transfer gives the potential to increase life transferred by a couple of orders of magnitude; however the bulk of this variance is coming from the largest craters. This is considered in more detail in the next section on the Zunil crater.

12.7.2. Material On the Surface - Deimos

Turning to Deimos, the unsterilized mass that is left on Deimos, assuming it settles on the surface, is shown in Figure 12-13. As with the average rate of transfer, Deimos being further away, and smaller receives less mass than Phobos. Otherwise the general behaviour is similar to Phobos, for increasing crater size more mass is transferred, but also with greater variance. The turnover in mass transfer for large crater size can't be seen for Deimos, this is probably because the simulation does not go as high in crater size as the Phobos simulation. This is due to the time taken to run the simulation, for the larger crater sizes the chance of mass transfer in recent times is low enough, that 10^{10} simulated histories need to be run – which takes excessive time.

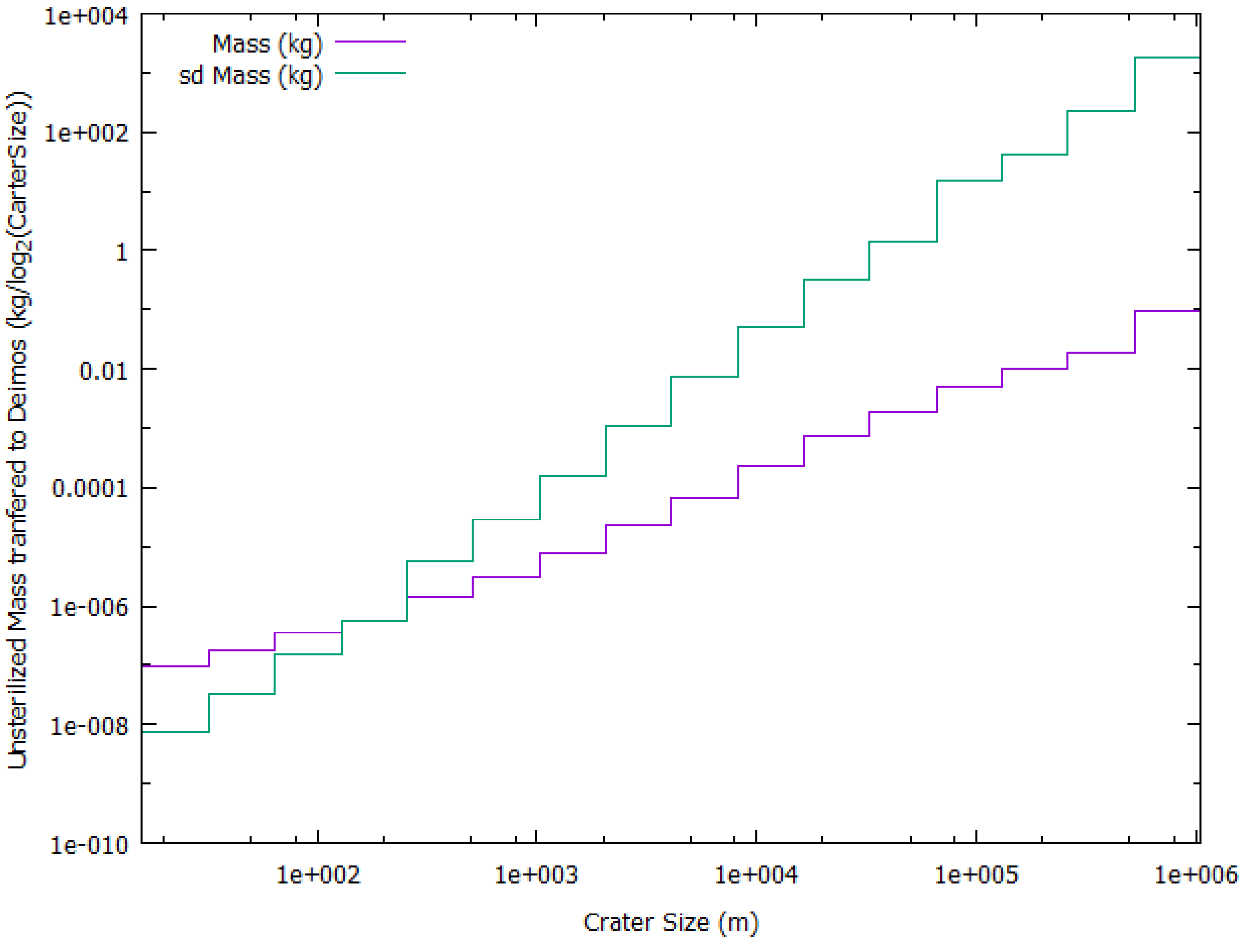

Figure 12-13. Unsterilized mass transferred to Deimos, plotted against Crater size, with the mass transferred shown for each range of craters within a factor of 2 size. This is plotted assuming the transferred material is carrying the SuperBug.

As with Phobos, if we restrict mass transfer to the craters such that the chance of transfer is above 1 in 10^6 in the last 100 years (which is the sterilization time constant), then the craters are restricted to be below 100km in size. For these craters the unsterilized total mass transferred is 8g on average, with 16kg standard deviation. Converting this to the life per m2 for both the typical, and the 3sd value:

Assumption	Cfu/m2 for typical transfer of mass = 7g	Cfu/m2 for 3sd transfer of mass = 45kg
Low loading of life	1.57E-06 cfu/m2	9.54E-03 cfu/m2
Medium loading of life	1.57E-04cfu/m2	9.54E-01 cfu/m2
High loading of life	1.57E-01 cfu/m2	9.54E+02 cfu/m2

So as with Phobos, whilst the typical transfer is below that calculated previously (due to the limit on crater size), the value at 3sd is 2 orders of magnitude higher than the previous value.

12.7.3. Material deposited at depth – Phobos

Here considered is the material is deposited at depth on the moon. For this that material transferred to the moon for each mass ejection, is assumed to arrive at the moon as a single object. This gives the maximal size of the object, and that size is then deposited at four times that depth. This gives a conservative estimate of the depth at which material will be deposited, which in turn gives minimal exposure to radiation. Now as some material is expected to be buried at the maximal depth, and the time constant for sterilization at depth is extensive (Figure 10-2) – approaching 10MY; the extent of the simulation has been set to 10MY.

This extends the run of the simulation, and this limits simulations at smallest crater sizes, where craters are created at a rapid rate, that simulating 10MY takes too long.

As before, plotted against crater size on Mars, is the average mass transfer, and the standard deviation on that. With material deposited at depth, if buried deep enough it has the possibility for surviving for a few 10^6 years. This means that the probability of a crater creation below 10^{-6} the size of the cater needs to be greater than about 2000km, e.g. the size of Hellas Planitia the largest Martian crater, which can be said with certainty (e.g. there is no crater larger than Hellas Planitia).

The mass transferred unsterilized is shown in Figure 12-14.

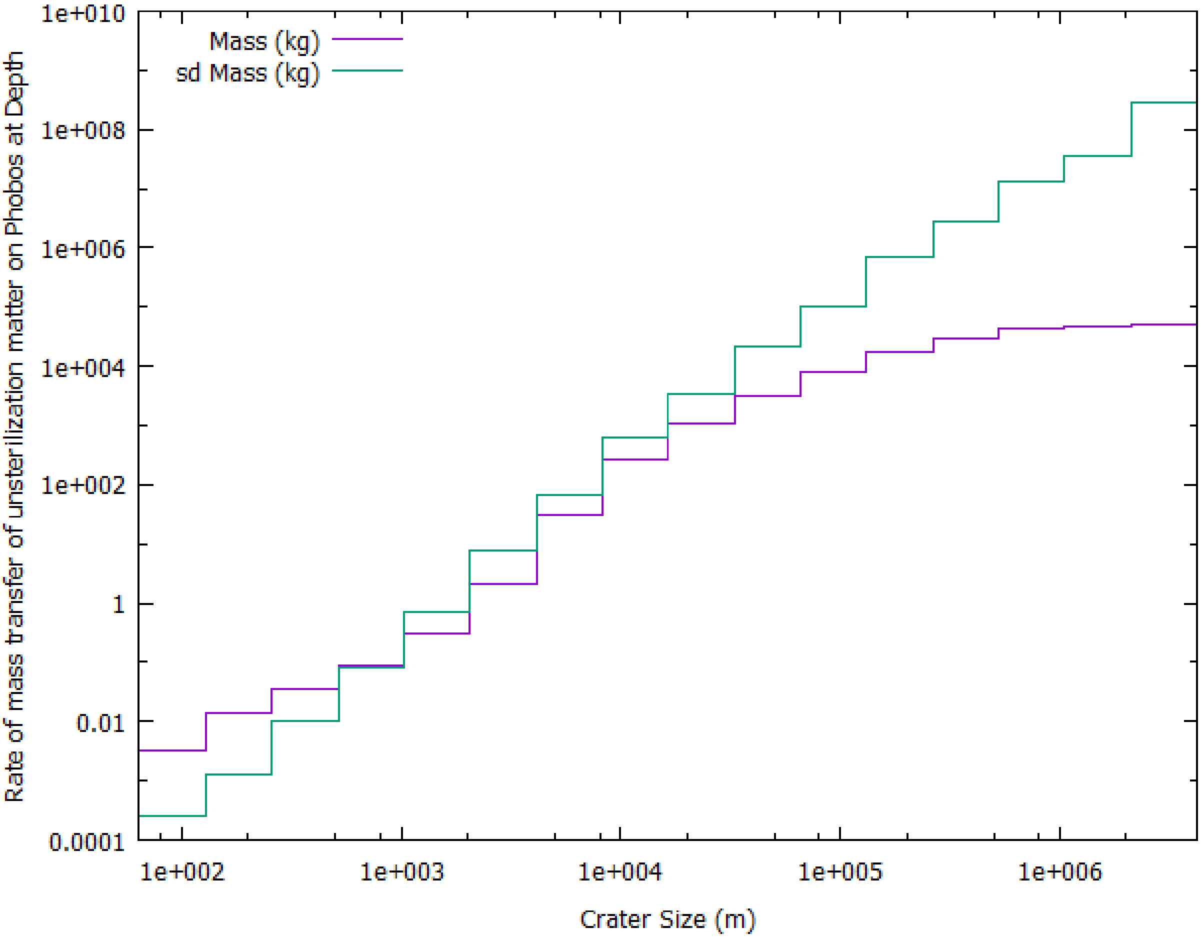

Figure 12-14. Unsterilized Mass transferred to Phobos – where material is buried on Phobos due to the impact. Mass transferred is shown per bin, clearly most mass is transferred from the largest craters.

The total mass transferred (on average) below 2000km is 1.5e5 kg, with standard deviation 3.9e7kg. On Phobos this would give rise to 10 cfu/m2 (low) to 1e6 cfu/m2 (high) for just the typical case, when possible variations are considered due to the standard deviation being two orders of magnitude higher and clearly this will break the requirement on life on Phobos.

12.7.4. Material deposited at depth – Deimos

For material deposited at depth on Deimos the situation is similar to Phobos. It is shown in Figure 12-15.

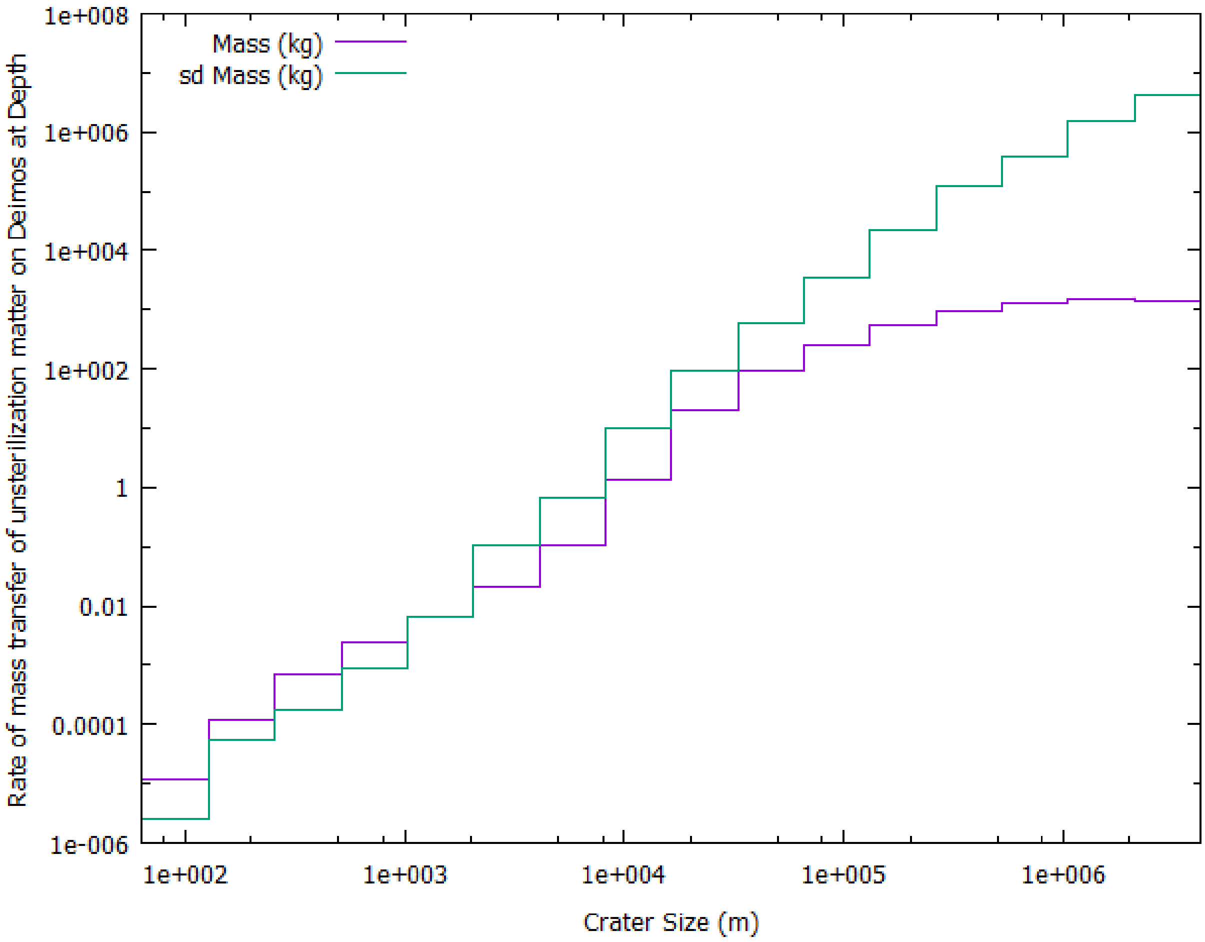

Figure 12-15. Unsterilized mass transferred to Deimos, where material is deposited at depth, sterilization following the SuperBug route, the most resilient organism. The variation, from the larger crater sizes, is far higher than the average value.

The total mass transferred, from craters below 2,000km in size, is 4.7e3 kg, and standard deviation 1.6e6kg. For the average rate this would give 0.3cfu/m2 (low) to 3e4cfu/m^2 (high) on Deimos.

13. ZUNIL

13.1. INTRODUCTION

What section 12, shows as most important about the transfer of material between Mars and its moons, is that most material is transferred from the largest craters. This is understood:

- The Mars isochrones, below 1km would give a flat mass transfer to the Moons, if impactor size is proportional to crater size

- Above 1km and the isochrone graph shows mild growth, however enough that larger craters will dominate

- The ratio between impactor size, and crater size, for the gravity-dominated cratering has a mild power of about 1/3. As mass goes with volume, the cube of size, this increases the growth with crater size to a linear relationship.

Hence the growth of isochrone over 1km, and the gravity-dominated cratering mean that larger craters dominate average mass transfer.

With thought the fall in the *number* of craters with size, the number of craters over a fixed time period shows greater variance the larger the crater size.

The time scales that are relevant though are still driven by the time material spends on the moon, the closer the mass ejection to the current time and this gives least sterilization.

This immediately gives focus onto what drive the mass transfer of unsterilized life, recent larger craters.

The prime example of this is the Zunil crater, studied extensively by McEwen et al [RD7]. This paper concludes:

- A 10.1km sized crater

- Created 10^7 secondary craters from 10-200m in diameter

- The secondaries are arranged in rays, that extend up to 1600km from the crater

- Believed to be the youngest 10km+ sized crater (neither the crater nor the secondaries, have any significant overlap by other craters)

- From the isochrones graph such a crater is expected to be produced on Mars approximately every 1million years on average

- Zunil can only easily be detected (via THEMIS) on maybe 20% of Mars – hence expected to be produced in the last 5 Million years

- Numerical modelling suggests 30km^3 of material ejected, with 1.5km^3 at velocity greater than 1km/s

Hence this is an excellent crater to use as a test case for the effect it has on transferring life to the moons. There seems no information in the literature that says that Zunil could not have been produced recently (say in the last 100 years), however with the typical period to create 10+km size craters, this is unlikely. This is exactly the type of crater that drives the transfer of life to the Moons, although it is unlikely that Zunil was created in the last 100 years, the probability is above the 1 in 10^6 requirement of [AD1] Req-10. Hence the question of can one crater drive the transfer of material to moons, how does this compare against Req-10.

That most material is transferred from the largest craters, and the largest craters are the rarest of all sizes, gives the greatest variability in the transfer of mass, and hence life, to the Martian moons. Now as the time of each ejection is unknown (beyond some simple constraints) this section instead looks at the properties of a single mass ejection, then the probability that the ejection happens in a period when life transferred will survive, becomes the probability to be interpreted in Req-10. This gives a natural method of quantifying the uncertainty in the process.

So this section models a 10.1km crater to answer these questions.

13.2. MASS TRANSFERRED

Simulating the mass transferred from the creation of Zunil sized crater, the average mass transferred is 1900kg. Considering what this means for loading life:

Life loading	Cfu/m^2
Low	0.122
Medium	12.22
High	12220

So it can be seen, that this one ejection can put enough life on Phobos that even with the lowest loading puts it close to the level where it is hard not to return an organism, if the loading is any higher than a minimal value then the requirement of Req-10 will be broken.

This though is for the average mass transferred. More important is how does this depend on the position of Phobos at the time of ejection. This is shown in Figure 13-1 and Figure 13-2. The peak of the distribution is between 300-1300kg, but with a significant tail to larger masses (which drives the average up to 1900kg). The chance of ejection from Zunil missing Phobos altogether is fairly small, and dependent on the angle of the ejection cone, this lowers the expected rate of emission.

In the simulation, this rate at which craters larger than 10.1Km are produced anywhere on Mars is given by 1.9e-6 craters/year, slightly higher than McEwen et al [RD7] but compatible. For ejections that miss Phobos this will lower the rate but only by 20% or so – hence does not change the bigger picture.

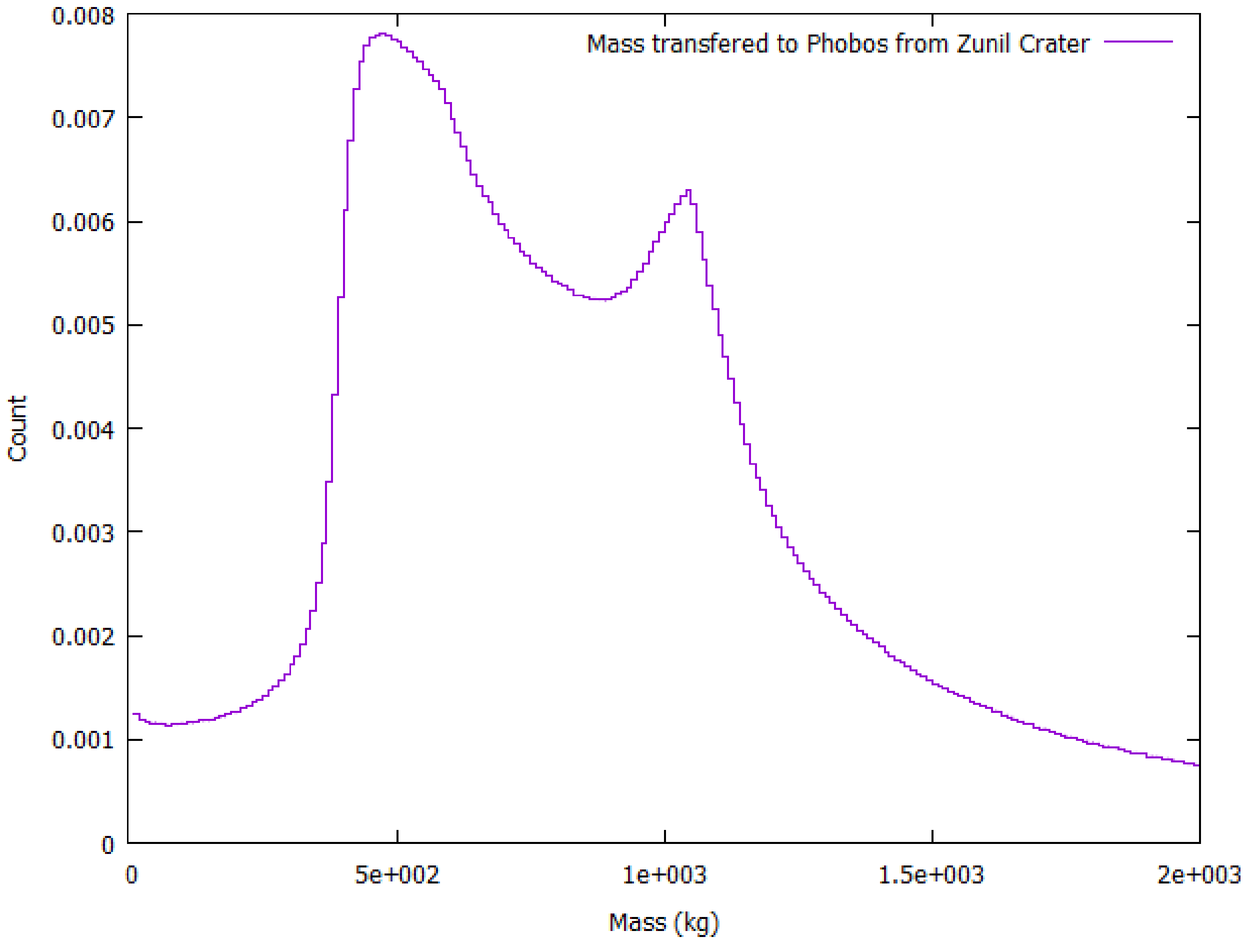

Figure 13-1. The distribution of masses transferred to Phobos from a Zunil ejection. With high probability the mass is between 300-1300kg.

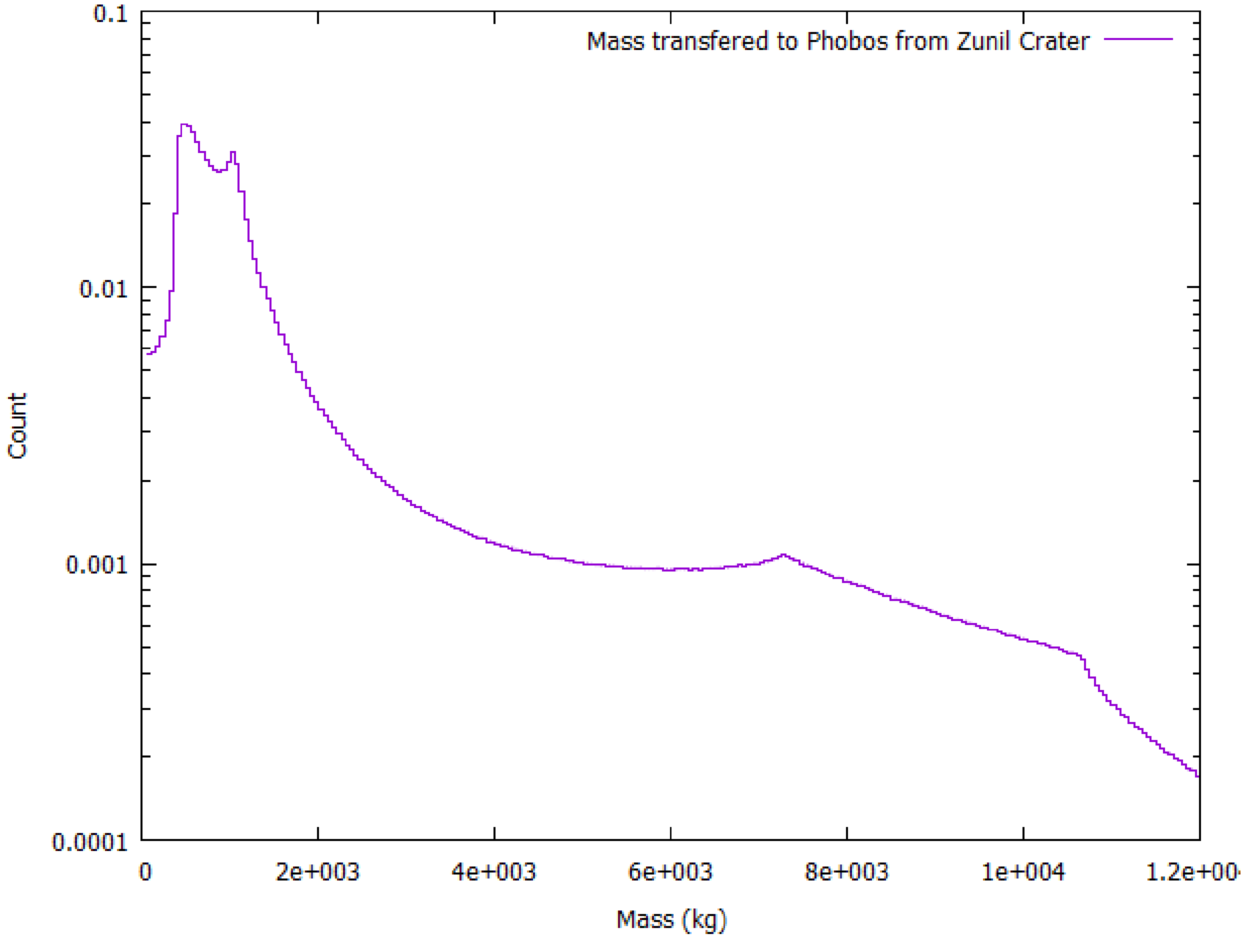

Figure 13-2. As Figure 13-1 plotted with a logarithmic frequency axis, clearly the mass transferred from a Zunil crater has a significant tail to higher mass, it does not start falling sharply till past 10,000kg transferred. This explains the average mass transferred of 1900kg.

Turning to Deimos, the same sized crater transfers 51kg on average to the Moon. The distribution of mass is shown in Figure 13-3 and Figure 13-4.

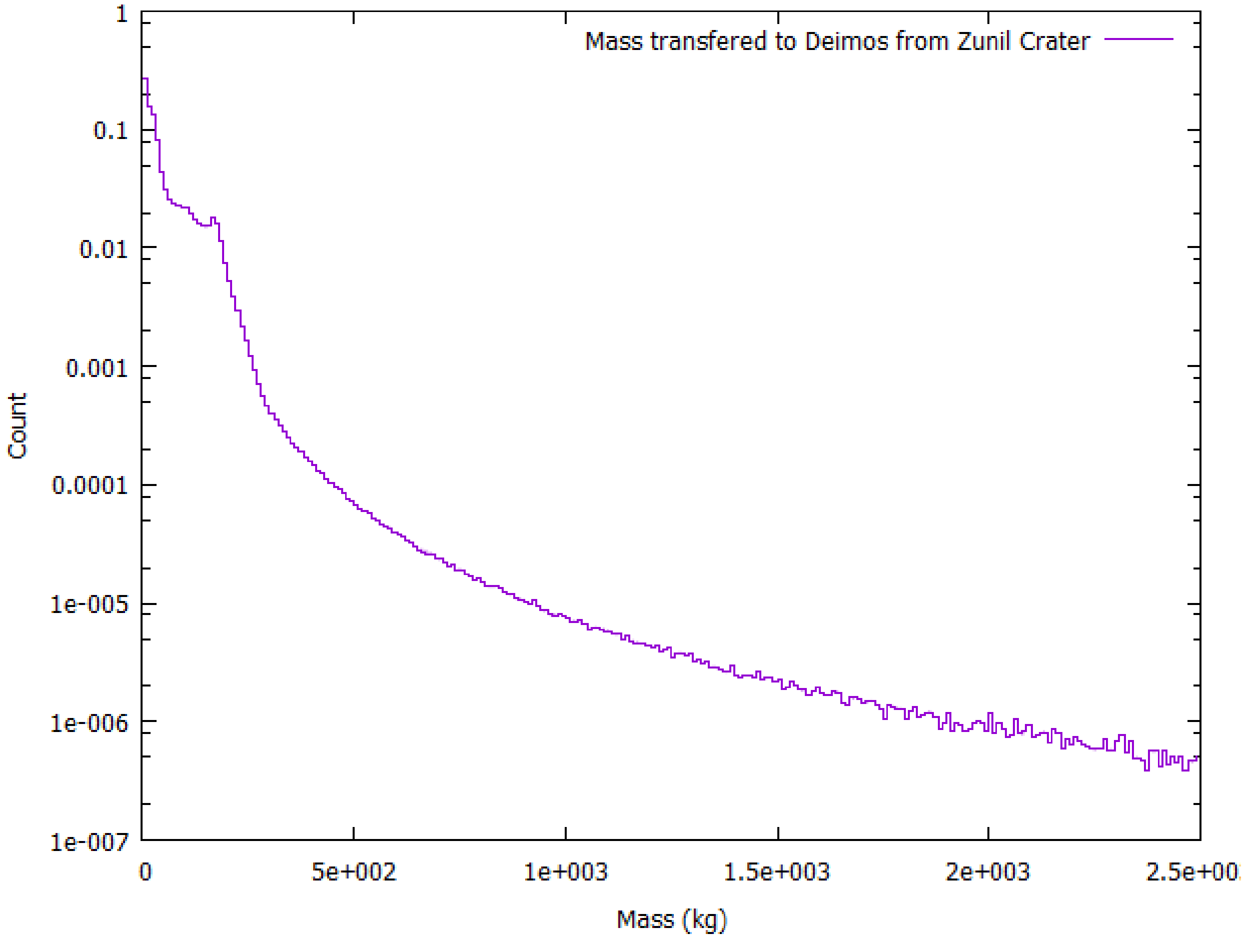

Figure 13-3. The mass distribution of mass transferred from a Zunil crater on Mars to Deimos

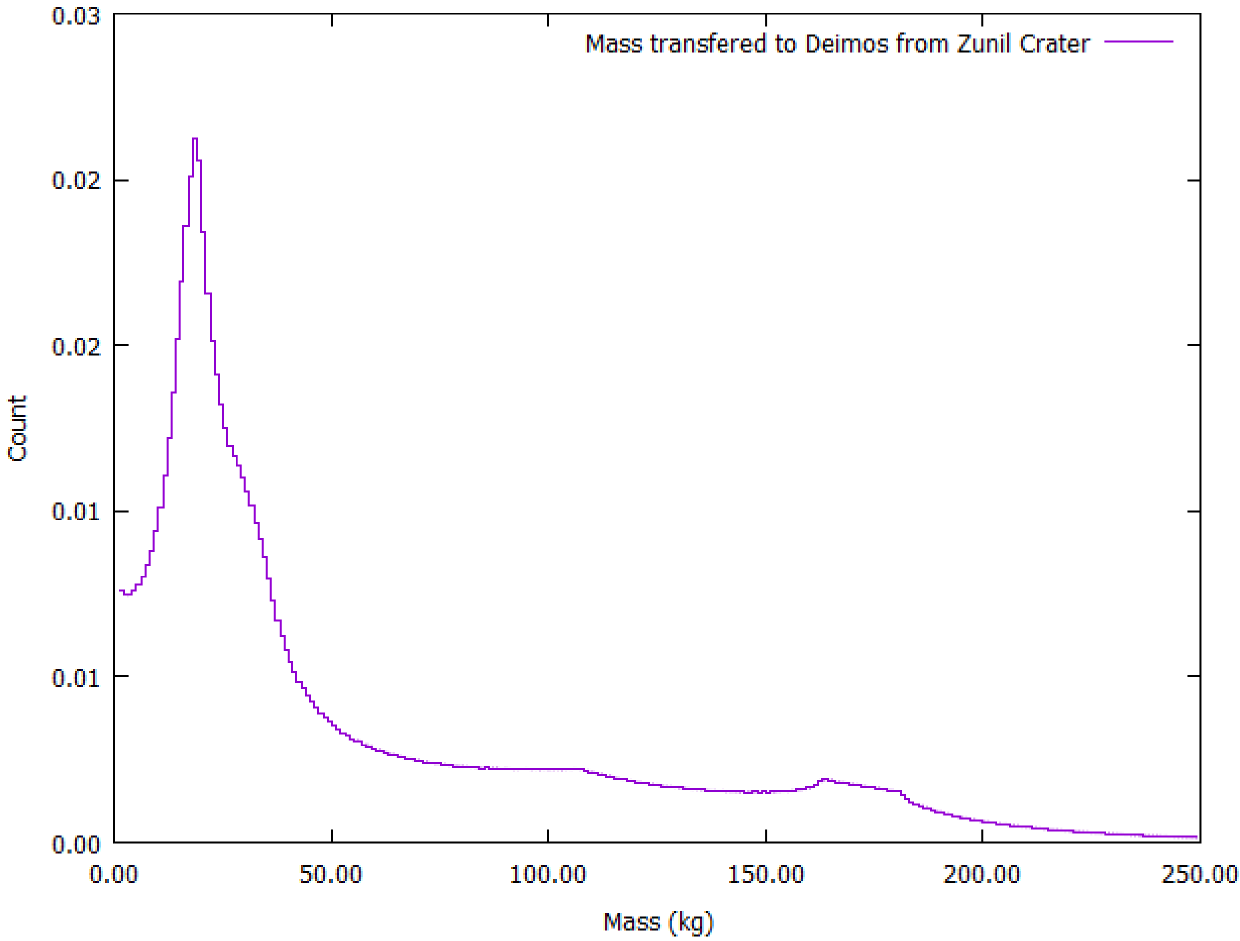

Figure 13-4. Mass distribution of transfer to Deimos from Zunil size crater. The average mass transferred is 51kg, so as with Phobos the long tail pulls up the mean.

In terms of life, the 51kg corresponds to:

Loading of life on ejector	Cfu/m^2 from a single Zunil ejection
Low	0.01 cfu/m^2
Medium	1 cfu/m^2
High	1000 cfu/m^2

Clearly as with Phobos, a single Zunil ejection can transfer enough material to compromise Req-10.

13.3. Geographical Distribution – and Spalation in the ejection?

The phasing of the orbit of Phobos/Deimos and the time of the mass ejection is effectively unknown; however the transit time from the ejection to collision with the moon is relatively short. This means that the moon will typically only see a single part of the ejection curtain. However if the ejection material is distributed uniformly across the curtain it will still cover all of one face of the moon – and so give fairly uniform coverage.

The crux is does the Mass ejection eject a huge number of very small particles, which are distributed over the ejection curtain. Hence the question is of the mass ejection.

Now with Zunil we have two inputs:

- The ejecta which caused the rays about the crater, can be studied from the properties of the rays
- Theoretical modelling of the ejection

[RD7] give the best study of Zunil and its rays:

- "~10^7 secondary craters 10 to 100m in diameter",
- "The number of secondaries >20m in diameter is of order 10^6"

For secondary craters to be created of this size, says that the ejectors from Zunil must in turn be significant in size.

Modelling we take results from [RD8]. This is best illustrated in 3 figures, the ejection velocity, the pressure, and the temperature;

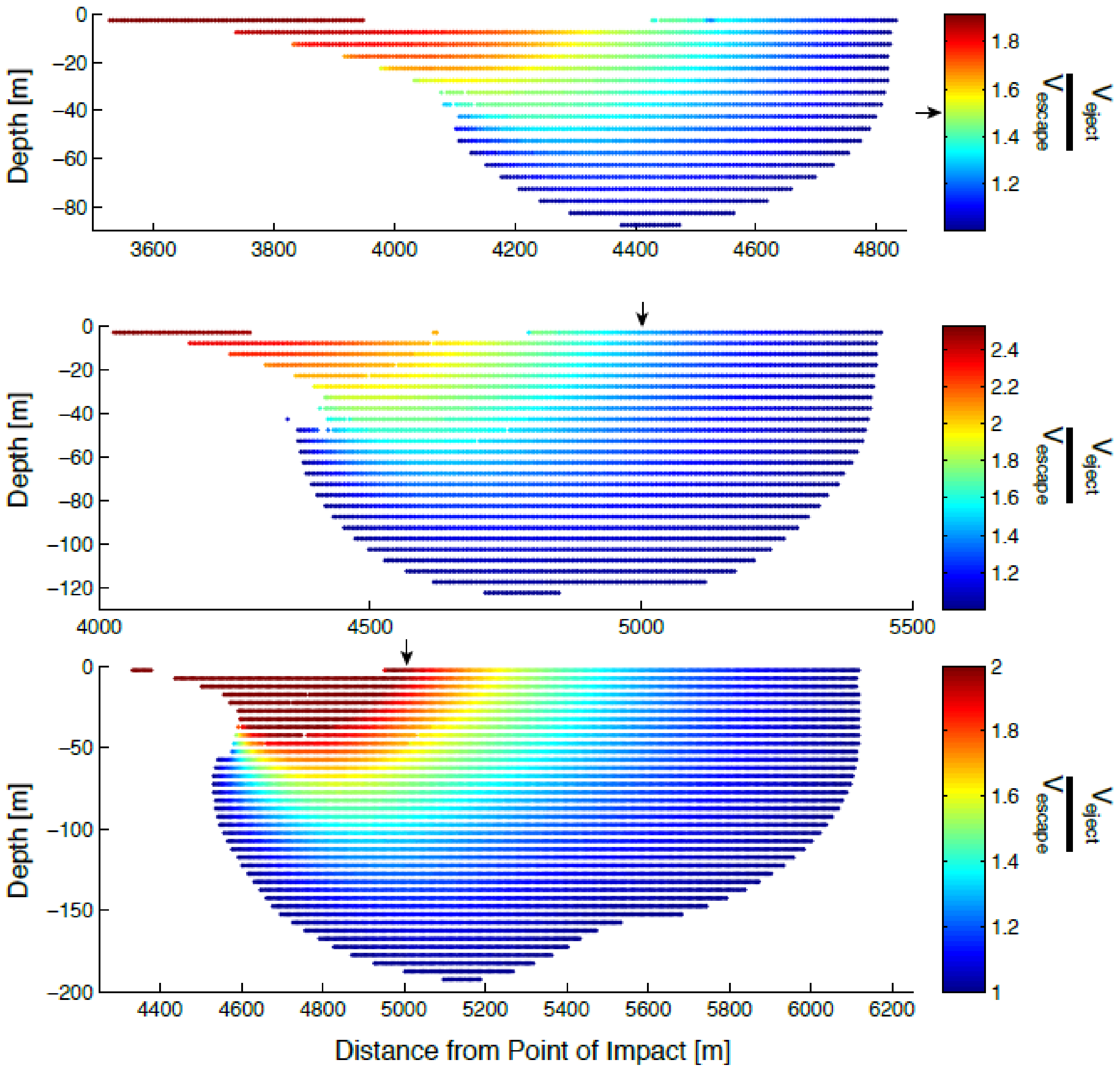

Figure 13-5. Figure 5.2 from [RD8]; Shown for 3 impact velocities 7.5km/s, 13.1 km/s and 20km/s.

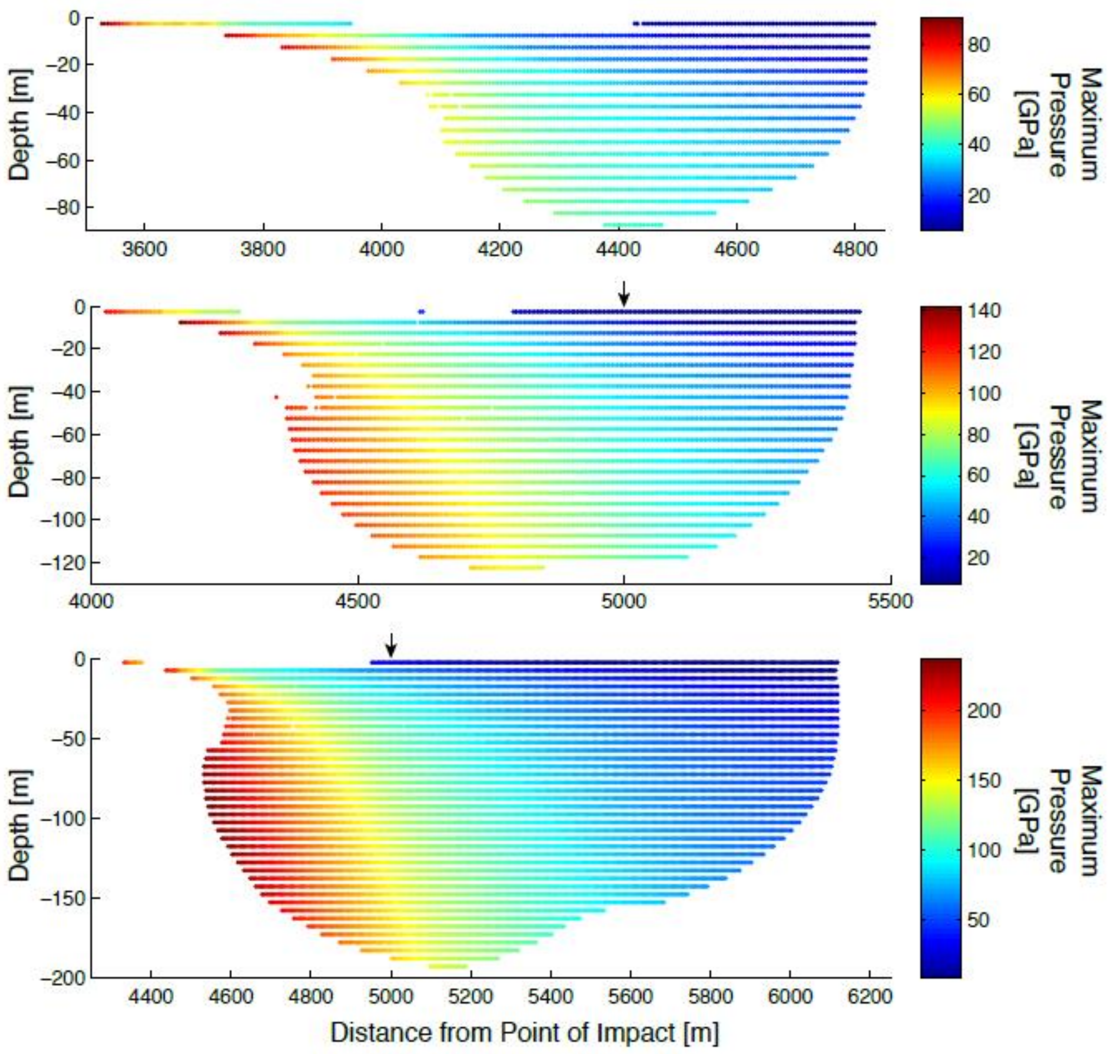

Figure 13-6. Figure 5.3 from [RD8]; the pressure for the same 3 impact velocities, for the region ejected over the escape velocity.

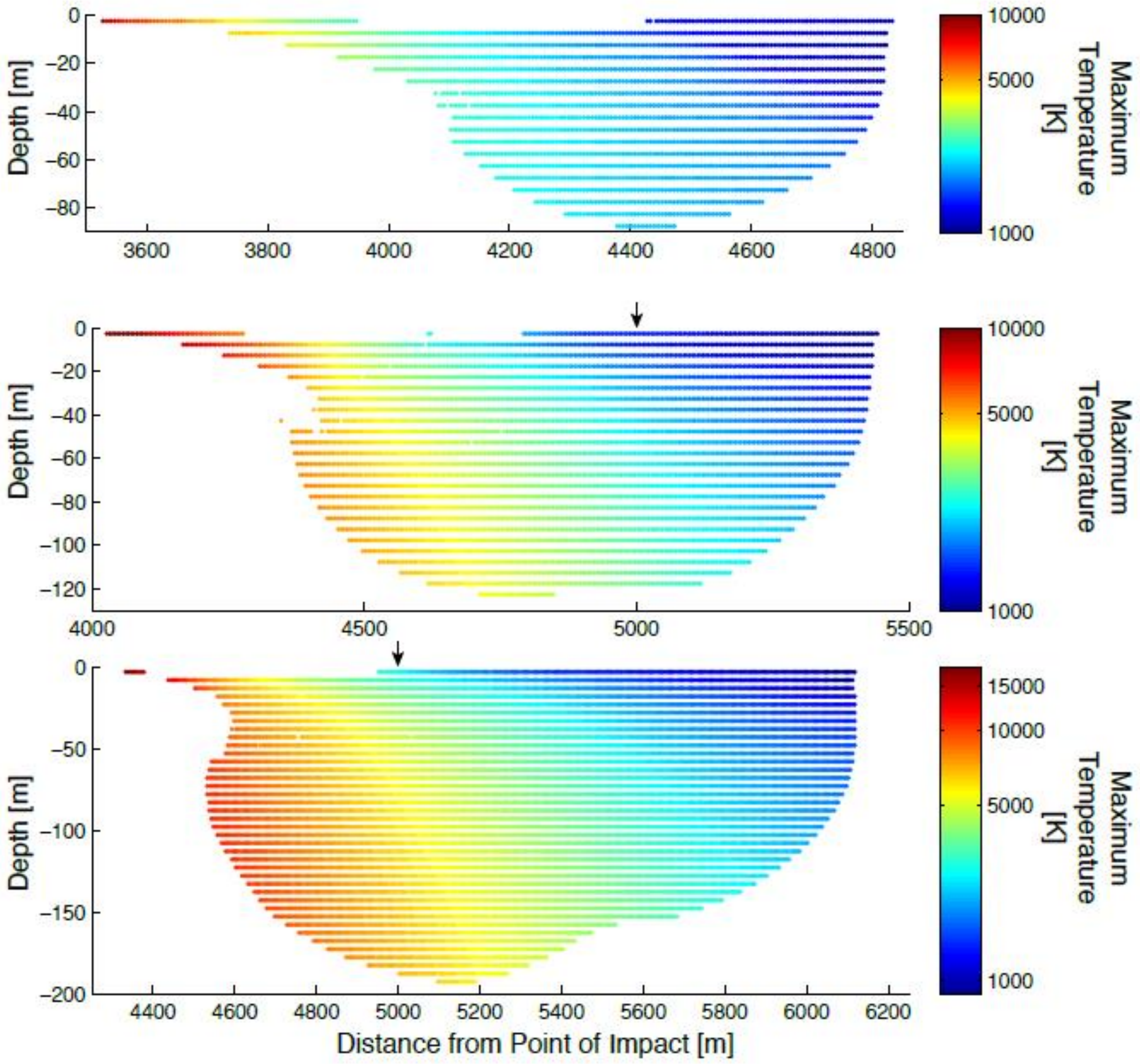

Figure 13-7. Figure 5.4 from [RD8]; the temperature pressure for the same 3 impact velocities, for the region ejected over the escape velocity.

From these figures it can be seen that of the material ejected, it is modelled that most experiences over 20GPa, now Granite has a compressive strength of approximately 150MPa – hence it can be seen that of the material ejected modelling predicts it will be fragmented to the smallest scales.

Now the faster material is ejected is almost certainly correlated with pressure, hence material transferred to the moons is not necessarily correlated with material that creates secondaries on Mars. On the other hand, when pressure wave reach the surface of Mars – the surface (atmosphere) is at effectively zero pressure and so any pressure in the rocks is released. This gives the possibility of spallation.

So the story on the particle size emitted from Mars ejections, and how this relates to distribution on the moon surface, is mixed – with evidence in both directions. However no firm conclusion can be reached.

What can be said with certainty is much (but maybe not all) of the ejected material will be fragmented to the grain size. Hence will be distributed through the ejection curtain. Hence will be widely distributed on the side of the Martian moon which it impacts.

13.4. STERILIZATION ON IMPACT

The velocity of impact with the moon is what drives the sterilization on impact. This in turn is driven by the speed of ejection from Mars, and by the impact velocity on Mars. These are all scale independent, and so the same distributions will apply to ejections from small craters on Mars, to large craters such as Zunil.

Now dependent where in the ejection plume the Moon impacts, will change the velocity. So any particular single ejection, such as from Zunil only a single velocity will impact the moon, so even where the ejecta is fragmented into many small objects, all that impact the moon will have the same velocity (this is given by orbital dynamics).

The location of the organism in the impactor, strongly influences the heating experienced in the impact with the moon, with life on the leading edge of the impactor undergoing more extreme than material on inside and rear faces. Hence this needs integrating over. However this does not depend on the size of the object, and so this is not sensitive to the size of the impactor; the same percentage should be sterilized independent of size.

In section 12.6 approximately 50% sterilization will happen in impacts, all be it with significant variation. However as before this does not significantly reduce life on a logarithmic basis.

13.5. AND TIME ON THE SURFACE

It is on the surface (or buried) that the main effect of discrete ejection from large craters has the most effect.

For craters of size 10km, the simulation suggests 2 will be produced every million years over the whole of Mars. [RD7] estimates 1 every million year, however as the rays of Zunil could only be detected on 20% of Mars surface, says a Zunil style crater should be on average 5 million years. [RD7] gives no other information on Zunil age, it is young becuase of its rays, the youngest of the know large craters – and so probabilistically produced some time in the last 5 million years. For our purposes though, it is not important if the recent large ejection can be detected through rays, what is important is that they happen. Hence for this study the important rate is that 1-2 craters larger than 10km will statistically have been produced in the last million years. When in those million years though, e.g. the distribution of cratering in recent times, cannot be said; the only reasonable assumption is the average rate given in the isochrones is uniform. This is the crux, it means that there is a 0.1% chance of Zunil sized craters being created in the last 1000 years, and a 10^{-4} chance of it being as young as 100 years.

This then need to be taken in the context of the sterilization of material on the surface (or buried) on the moon due to the radiation. This is not uniform in distribution, but geometric; for each doubling of the time gives a quadratic decrease in life that survives. This is a very different dependence that for the distribution in time of when craters appear on Mars.

So if we compare the average rate of Zunil craters of 1 million years, against the timescale to sterilize a suberbug on the surface of the moon of 1 century; then the chance of a Zunil sized crater of happening in the last century is 10^{-4} whereas the probability of a life on the surface of the moon surviving for 1 million years is 1 in 2^{1e4} (5e-3011) or very close to zero.

So the distribution of large craters is what drives the chance of life surviving on the moon.

This can be seen in the transfer of (unsterilized) Mass

Zunil size ejection	Phobos	Deimos
Mass transferred per ejection	1900kg	51kg
Unsterilized mass after impact with the moon	~950kg	~25kg
Time Constant vs time between impacts	1.90e-6*60=1.1e-4	1.1e-4
Estimated mass after sterilization on the surface	108g	2.8g
Numerically calculated unsterilized mass from 1e7 simulations	96g	2.7g

So it can be seen that there is good correlation between the simple calculation and the full simulation (which takes an extended time to run).

Performing the same calculation at where impactors on the moon are buried at depth (given by four times the impactor size, where the mass transferred from a single ejection arrives at the moon as a single object).

Zunil size ejection, deposited at depth	Phobos	Deimos
Numerically calculated unsterilized mass from 1e6 simulations	3521kg	9.5kg

This says that in the typical time to sterilize material at depth is longer that the average time between ejections from Mars for Phobos, for Deimos the number is lower as impact velocities on Mars are lower, and the total mass transferred is lower.

13.6. Different organisms at 1cm and 1m

With the approximate analytic calculation of life, from mass transferred from a Zunil scale ejection, with the mean transferred life is given by:

Depth of 1cm on Phobos					
SuperBug	B Atro	B Dim	Drad	MS2	
16542.3	2920.01	382.411	10240.5	16542.3	Time Constant (Years)
0.03143	0.005548	0.000727	0.019457	0.03143	TC * Average Rate
29.85885	5.270618	0.690252	18.4841	29.85885	Average Sterilized mass deposited on Phobos
0.001928	0.00034	4.46E-05	0.001194	0.001928	cfu/m2 low
0.192849	0.034041	0.004458	0.119383	0.192849	cfu/m2 Medium
192.8493	34.04132	4.458127	119.3832	192.8493	cfu/m2 High

Depth of 1cm on Deimos					
SuperBug	B Atro	B Dim	Drad	MS2	
16542.3	2920.01	382.411	10240.5	16542.3	Time Constant (Years)
0.03143	0.005548	0.000727	0.019457	0.03143	TC * Average Rate
0.785759	0.1387	0.018165	0.486424	0.785759	Average Sterilized mass deposited on Deimos
0.000159	2.8E-05	3.67E-06	9.82E-05	0.000159	cfu/m2 low
0.015869	0.002801	0.000367	0.009824	0.015869	cfu/m2 Medium
15.86896	2.801154	0.366845	9.82367	15.86896	cfu/m2 High

Depth of 1m on Phobos					
SuperBug	B Atro	B Dim	Drad	MS2	
135655	23945.4	3135.95	83976.6	135655	Time Constant (Years)
0.257745	0.045496	0.005958	0.159556	0.257745	TC * Average Rate
244.8573	43.22145	5.66039	151.5778	244.8573	Average Sterilized mass deposited on Phobos
0.015815	0.002792	0.000366	0.00979	0.015815	cfu/m2 low
1.581459	0.279154	0.036559	0.978995	1.581459	cfu/m2 Medium
1581.459	279.1542	36.55874	978.9948	1581.459	cfu/m2 High

Depth of 1m on Deimos					
SuperBug	B Atro	B Dim	Drad	MS2	
135655	23945.4	3135.95	83976.6	135655	Time Constant (Years)
0.257745	0.045496	0.005958	0.159556	0.257745	TC * Average Rate
6.443613	1.137407	0.148958	3.988889	6.443613	Average Sterilized mass deposited on Deimos
0.001301	0.00023	3.01E-05	0.000806	0.001301	cfu/m2 low
0.130133	0.022971	0.003008	0.080558	0.130133	cfu/m2 Medium
130.1333	22.97073	3.008304	80.55841	130.1333	cfu/m2 High

These rates presented are the average rate of cfu transfer from a Zunil scale ejection. With all the rates it can be seen that it is practically impossible to collect a sample from a small enough area that the probability of collecting a viable cfu is below 10^{-6}.

13.7. Reflections on Discrete Ejections

Pulling together the message from discrete ejections, where the rate of ejections is driven by the Mars isochrones for craters. What first drives the process is that material transfer from Mars to the moon. The larger the crater size, the greater the rate of mass transfer:

- The $1/s^4$ law between 4m and 1km crater size give a mild logarithmic growth
- Over 1km the $1/s^3$ law gives a more extreme linear grow at large size
- The gravity dominated cratering prediction gives proportionally larger impacts need for the larger craters. This gives a $^1/_3$ power law in size, or linear in mass

All of these increase the *rate* of mass transfer with size, and this applies to any time period, e.g. in the last 1, 10, or 100 years, it is the largest craters that have appeared that will have transferred most mass to the Martian moons.

The isochrones graph is time invariant, so craters arrival times is Poisson distributed.

Req-10 gives a level of assurance of 10^{-6} however, should this be with life on the moon we have a probability below 1 in 10^6 of collecting the life, or given 10^6 planets with moons comparable to Mars and its moon, of missions to all only 1 should return life. The first question is what the initial version of the simulation was sensitive to, the second question is what drives the second version with discrete ejections.

In both simulations what drives sterilization is the radiation on the moon, this is very dependent on the depth that material is deposited at in its impact. This cannot be well predicted.

Where material is deposited on the surface, the time constant is expected to be below 100years – which sets the time scale. This means what dominates the variation in mass transfer, is just the chance that a large ejection happened. This can most simply be performed by taking this probability to be the 10^{-6} needed in Req-10.

A 10km crater, such as Zunil, is at the limit where a single ejection will typically (but not always) put enough mass on the moon, to be close (or over) the life limit given by Req-10. Such a size crater will happen once on average per million years, this gives rise to a 1 in 10^4 chance that such large craters have happened in the last 100 years.

This is the key point, it is the age of the largest (10km and over) craters that drives the transfer of life to the moons. Key is the aging of craters.

From the isochrones graph, there is no way to limit the age of the crater. Techniques though have arisen:

- Rayed craters, particular via the TEMIS instrument on 2001 Mars Odyssey detects rays from craters over ~20% of Mars. How the rays overlay other craters, and other rayed systems, can give relative ages. Via this method Zunil is expected to be the youngest large crater on the 20% images by TEMIS

- HiRISE Mars Reconnaissance Orbiter gives hi resolution pictures of Mars, the evolution of which can indicate craters, an example of which is shown in Figure 13-8.

Figure 13-8. 30m crater that appeared on Mars between July 2010 and May 2012, located at 3.7°N 53.4°E on Mars

These though do not give sufficient information to rule in or out a recent transfer. A 30m crater such as Figure 13-8 does not transfer sufficient mass to the moons to invalidate Req-10. Study of the rayed craters identifies young craters, but only on a cratering time scale – e.g such as identifying Zunil as a particularly young (<5Million year) crater.

Now identification of possible craters that could transfer significant mass to the Martian Moons, does change the question. Whilst the probability that is that some have happened in the last century with probability over 10^{-6}, many can also be identified. This means they can be studied in more detail, e.g. Figure 13-9 shows a landslide imaged on the Zunil crater, can such images by used to place limits on the age of the crater – e.g. if the time scale of landslides is far longer than 100 years does the existence of one make Zunil likely to be older?

Figure 13-9. Landslide imaged on the Zunil crater.

This aging of larger craters is critical. The geological aging, and the history of crater build up, and evolution, gives basic aging. Typically though the aging does no better than million year resolution. Where the time constant for sterilization by radiation on the moons is far shorter than this million year scale, the probability that the crater is recent needs to be established. For the youngest large craters, with ages estimated as a few million years, a 10^{-6} probability has them produced in the last few years – and this is the period that will dominate transfer of life to the moons. Hence key is establishing rigorously the minimum possible age of the largest craters.

14. ERRORS AND UNCERTAINTIES

14.1. INTRODUCTION

The analysis described in this paper has been designed to be state of the art on potential life transferred between Mars and its moons. However in performing the analysis there are clearly areas of uncertainty. Some of these uncertain areas have little effect on the transfer of life, whilst others have a huge effect. This section draws together these uncertainties so they are all presented in one place. The significance of each is described. This section describes the major uncertainties.

14.2. LOADING OF LIFE

One of the greatest uncertainties is the amount of life that is present on the Mars ejecta in the first place, this directly drives the life that ends up on the moon. If there is no life on Mars, then none will be transferred to the moon; if however the loading of life is comparable to that found on Earth, then just small amounts of transferred mass has the potential to carry huge amounts of life.

In this study we have not attempted to define the loading of life on Martian material, but instead we have presented examples of low, medium and high levels of biological loading, by taking the loading of life in the Atacama desert. This is the area of Earth whose conditions are closest to Mars, in particular it is exceptionally dry similar to Mars. The amount of water is known to be key, as there is no known life that can grow without water.

Now in the Atacama, although it is generally dry, some areas are drier than others. In particular the damper areas (still exceptionally dry) and samples taken still show 10^{10} cfu/kg. Whereas in the driest areas around Yungay from five measurements [RD5] one had life at the level of 10^{7} cfu/kg, whilst the other four showed no signs of life. [RD5] estimated that they would not be able to detect life at the level of 10^{5}cfu/kg.

So for the Atacama desert, even there the loading of life shows at least 5 orders of magnitude variance. This gives the greatest uncertainty, it also drives home the point that if Mars contains no life, neither will the moons – this point becoming if we can't detect life on Mars what does this imply for the moons. Unfortunately Planetary Protection is not defined on measurable life, but on the mere presence of life, so this gives no escape.

Hence it should be concluded that from Yungay there is at least 2 orders of magnitude of uncertainty, from Atacama 5 order of magnitude of uncertainty. And as life cannot be detected below 10^{5}cfu/kg, additional orders of magnitude of uncertainty that cannot be quantified.

14.3. AGE OF CRATERS

The uncertainty in the age of craters is subtle, it depends on the interaction between the age of craters and the time constant that it takes to sterilize life on the moon (through radiation).

This is best explained through an example, for depths between 1cm and 1m, the time constant for one log die off is approximately 10^5 years. Now the Zunil crater has been aged through the rate on subsequent crater build up, there are two possible ages:

- From the cratering inside the Zunil basin [RD10] estimates the age of Zunil as 10^5year
- From the cratering on the ejecta blanket surrounding the crater [RD10], Zunil is estimated as 10^6 years old

This makes Zunil one of the most accurately aged craters on Mars, however the range of ages is very comparable to the time constant for sterilization.

It says that if material from Zunil is deposited below 1cm that:

- Zunil is 10^5 years old: life sterilized by a factor of 0.37
- Zunil is 10^6 years old: life sterilized by a factor of 4.5E-5

As Zunil by itself transfers enough material to Phobos to put it on the limit of PP protection, it can be seen that one age makes it questionable, whilst the greater age says there will be almost no viable life.

So although this age can be seen to have a large effect on the sterilization, it is only important for specific craters whose age is close to the time constant. Craters far older than the time constant and all transferred material will have been sterilized, whereas craters far younger that the time constant and there will be little sterilization; for both these cases the process is not so sensitive to the crater age. However where the age is comparable to the time constant, such as for Zunil – and the analysis is very sensitive to this.

14.4. PHASING OF THE MOON

Even if a crater can be aged exactly, whilst the position of the crater is known, the position of Phobos/Demios in its orbit cannot be known.

Now depending on the crater, this can have a big effect on the mass transferred. For the crater McMurdo at the Martian south pole, both Phobos and Deimos being equatorial, ejected material has to travel one quarter of the way round Mars to hit the moon. This is independent of the phasing of the moon.

For equatorial craters such as Mojave or Zunil, the phasing of the moon is far more critical. Where the moon is directly overhead at the time of the mass ejection, probably no material will hit the moon. On the other hand, for most positions of the moon and Zunil could transfer life at the limit of Planetary Protection; Mojave could transfer maybe 10^3 times the Planetary Protection limit.

Now the uncertainty caused by the phasing of the moon will never be resolved, it is fundamental to the process. The probability that a certain mass will be transferred can be probabilistically calculated, as performed in §13.2.

14.5. THE DEFINITION OF PROBABILITY

The definition of probability concerns an ambiguity in Req-10 that the probability of having life on a sample is below 10^{-6}. The question is below 10^{-6} of what?

The two ways that the study has been performed give the key difference.

- In the first version documented in up to §11, the model calculated the most likely number of viable organisms in a sample. Now if this could be reduced to below 10^{-6} organisms per sample (on average), then 10^6 samples can be taken without collecting life.
- The second version documented in Sections §12 through §13 emphasises how the mass transferred to the moons in any time period, is typically dominated by the largest crater in that time period. This means that the material transferred over time varies enormously, as some periods contain a large crater, whilst others do not. This work suggested this variability should be what is controlled with the 10^{-6} period. Specifically, if a 10km crater happens in the sterilization time period with probability greater than 10^{-6}, such a crater would transfer enough life to the moon to make Planetary Protection questionable

Now the crux between these two is how time affects different properties. In the sterilization due to radiation on the Moon, the decay of life is exponential; whereas the time of creation of craters is linear within the average period. The different dependence of each of these leads to a different result.

Now this is an ambiguity in Req-10, the planetary protection requirement. As the requirement is an agreed convention, it can similarly decide which definition of probability is preferred. Hence this issue should be resolvable.

14.6. THE DEPTH THAT MATERIAL IS DEPOSITED AT ON THE MOON

How fragmented the material is on the mass ejection from Mars is unclear, some material is ejected in large lumps, much material is fragmented down to the grain size. However it is very hard to say exactly how much material is fragmented.

The size of the fragmentation affects the size of the object that impacts the moon, and this in turn affects the size of crater created, and the depth at which material is deposited. This in turn affects the radiation exposure, and the time taken to sterilize material.

Now what drives this the mass ejection from Mars, and how fragmented the material is, is one of the more difficult questions in the modelling of hyper velocity collision. Since consideration of the size and condition of material during Mars ejection was defined as beyond the scope of the original study, there is no clear conclusion possible in this respect.

Practically this uncertainty can be controlled, as any mission has a depth of sensitivity, be that sample depth, or depth of feet, or depth of any harpoon to anchor the craft to the surface. Now the sterilization time constant can be calculated for that depth, and at a worst case assume that all mass is deposited at that depth. Now whilst this is a conservative approach, it will also rapidly limit the life potentially transferred.

15. CONCLUSIONS

This study looked at transfer of mass between Mars and its moons, and how that mass is sterilized.

The total mass transferred to Phobos over a 10MY period was estimated as 1.63e6kg, compared to [AD2] this was an increase from 1.12e6kg – the difference arising as [AD2] cut off mars Ejecta velocity above 5.5km/s.

The most critical parameter of the study is the loading of life on the Mars Ejecta. Where this loading is compatible with the lowest levels seem in the Atacama Desert of 1e5 cfu/kg, then a typical sample can of the size of 100g. With careful tool choice, sampling from such a small area is viable.

If the loading is at the highest levels seen in the Atacama Desert of 1e10 cfu/kg, the Req-10 is breached under almost all circumstances.

Hence it is critical for the output, what assumption is made over the loading of life on the Mars Ejecta, with low loading rates Req-10 can be met, with high loading rates – under many conditions the Req-10 will be breached.

The first process considered, the hyper velocity collision with Phobos, gives little sterilisation. This is because the collision is a chaotic process, with some parts of impactor being heated, whereas other parts have almost no heating. Organisms in the latter receive almost no sterilisation, so even if it is just a few percent that are unheated, this limits the amount of sterilisation produced.

The radiation environment on the moons gives the major sterilisation. This sterilisation is dependent on the time on the Martian moon, with the longer duration giving greater sterilisation. Conversely material that is on the moon for a short period receives little sterilisation. The critical time period, for the most resilient organisms, is of order of centuries. Hence any viable life on the surface of the moon, is expected to be from the recent past.

The depth distribution on Phobos is unclear, with the most likely depth being on the surface. This is where the organism receives most sterilization. If the impactor is buried, the depth is expected to be dependent on the impactor size. The impactor size is dependent on the Mars ejeca size, and this is a poorly understood variable – with most transfer expected to the smaller size. Hence if material is deposited, it is expected near the surface. Now if the impactor is buried just 1cm (or more) the level of radiation drops by a factor of 10^3, which significantly increases the life that survives. Whilst this is not the primary expectation – it does show a criticality of the study.

That material is close to the surface under all circumstances, is why life is reported per surface *area* of Phobos (and Deimos), it is the area of the moon that is sampled that drives the potential to pick up life. Hence a sampling instrument which minimises the surface area sampled, will typically limit the Martian life collected.

A key finding is that any life transferred to Phobos/Deimos, that is still viable, must have been transferred in the recent past. For material deposited on the surface, almost all will have been transferred in the last century, almost no material will date from more than a thousand years ago. Similarly the life will date from the recent past of Mars history.

Although not studied in detail in this work, the distribution of material on Phobos will not be isotropic. In particular the orbital motion of Phobos means most material direct from Mars accumulates on the front face of the moon, with almost nothing on the rear side. Now material which enters the cloud around Mars, but subsequently impacts Phobos, will populate this rear face. How this changes the density of unsterilized material on Phobos is not clear.

In particular material which enters the cloud about Mars will be in the cloud for “months, years or centuries” [AD5]; the material is predominantly expected to be of small size, and hence exposed to the full effect of the radiation. Whilst not studied in this work, the possibility exists for significant sterilisation. Hence this may not bring life to the shadow area on Phobos (Deimos). Confirmation of this would require further work.

The work was extended under a CCN to include the effect of discrete ejections from Mars, modelled based on the crater isochrones curves. This extends the simulation to cover the variation in how material is transferred between Mars and the moons. The simulation developed for discrete ejections is exceptionally slow, mainly being needed to have been run multiple times over a tight range of crater size. This is needed because the isochrones gives rapidly falling rate in crater production with increasing size; however simulation shows that the increase in mass transfer from larger craters is what dominates, and hence large craters dominate mass transfer, whilst being the least likely to be simulated.

The dominance of large craters in the average rate of transfer, changes the interpretation of the probability given in Req-10. Specifically if the typical rate of mass transfer from large craters means they are unlikely to have happened in the sterilization time period on the moon, but yet they are responsible for most of the mass transfer on average, this can only be from the rare possibility that large craters have been created on Mars recently. This is verified in the simulation.

This changes the understanding of the question of transfer from life from Mars to the Moons, it is driven by the small possibility of large craters. Hence the probability of Req-10 is best applied to the probability of large craters.

This change in perspective makes it more likely for the Moons to have life transferred from Mars, for Phobos in particular. Deimos does not suffer so much, as due to its smaller size, and greater distance from the moon there is less opportunity to transfer large masses and only with the highest loading rate of life does Deimos break Req-10, if Mars has life at levels below the driest most sterile parts of the Atacama desert – then Deimos probably has low enough levels of transfer life to be compatible with Req-10.

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